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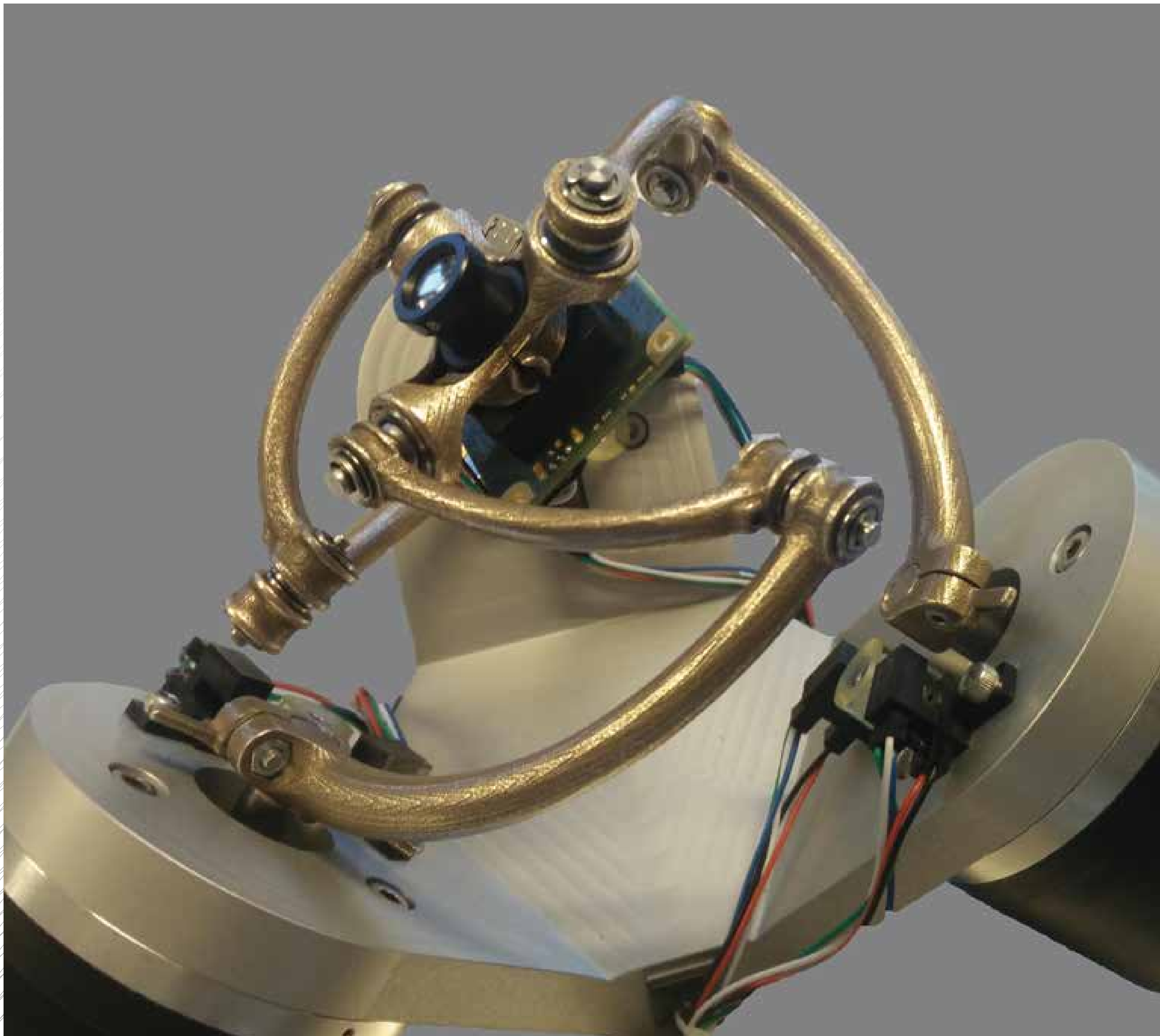
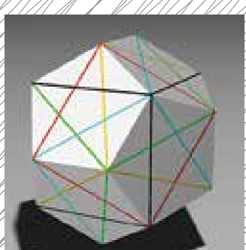
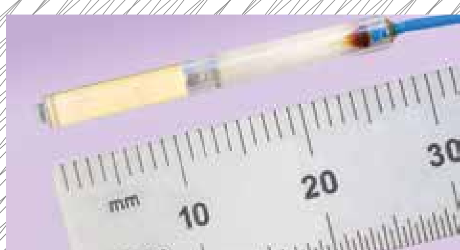
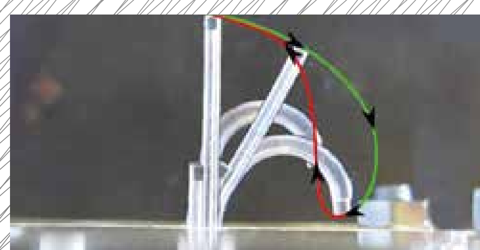


- DEMO DESIGN: **AGILE EYE**
- **MICROFLUIDICS**: NATURE'S WAY
- **SUB-NM** COMPACT FIBRE INTERFEROMETER
- **DIAMONDS** ARE FOREVER







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The journal is read by researchers and professionals in charge of the development and realisation of advanced precision machinery.

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The main cover photo (featuring the VIRO Agile Eye) is courtesy of VIRO. Read the article on page 10 ff.

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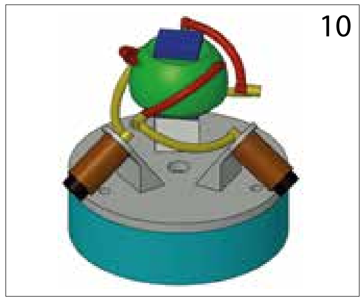

FEATURES

PRECISION ENGINEERS REQUIRE MORE **DIGITAL SKILLS**

Thirty years ago, I worked with robots operating with 1 mm precision. Higher accuracies were already possible with CNC machining, thanks to expensive, programmable numerical controllers. CAD, CAM and CIM (Computer Integrated Manufacturing) were the abbreviations of the day. It was only in the nineties that mechatronics was introduced.

Today, it is all about the fourth industrial revolution. Smart Industry means the digitalisation of our industry. The Internet of Things is connecting everything to everything, resulting in smart manufacturing, smart products, smart services, etc., and digital twinning, artificial intelligence and blockchain are accelerating this revolution. It has become possible to reduce delivery times, while zero-defect has become a must. More and more we see that all processes need to be under precise control, with every production step controlled 100% to stay within specs. Simple random inspection is not enough. And with artificial intelligence/machine learning, we can continuously improve control algorithms.

Thirty years later, and with a lot more processing power and software, wafer stepper mechatronics++ enables us to achieve overlay positioning in the order of 1 nm at speeds CNC could only dream of 30 years ago. All this would not have been possible without the digital skills of the many architects and engineers involved. Digitalisation is rapidly providing more opportunities to create new solutions. For example, with advanced digital controls, TNO is now able to manufacture freeform optics. So now we need to be able to design such optics. That also requires digital design tools.

Precision engineering is and will stay a mechanical design science, but today it is also about digitalisation and digital skills. My message in this editorial is that skilled people should understand their profession thoroughly, including all the newest digital means. In Smart Industry, we see that craftsman aged 35 years and older face the problem that 20 years ago, in 1997, their schools did not have Internet access. These people will work for another 35 years (or so) until retirement at 70. We can't afford to lose them. So, with the acceleration of digitalisation, we now need to develop their digital skills to complement their initial professional training. The challenge for Smart Industry is to enable life-long learning for everyone.

The demand for more digital skills from precision engineers and system architects will also accelerate. It might be that in the future we will not position objects more precisely by making them stiffer, but by using digital control we will position them more intelligently. The success of lithography machine world market-leader ASML, at the borders of technological capabilities, lies in the multidisciplinary attitude of Dutch science and engineering. To continue to make a difference as a small country, we now need to focus on training and retraining everyone, including precision engineers, even at 35, 45, 55 and 65 years old, to boost their digital skills.

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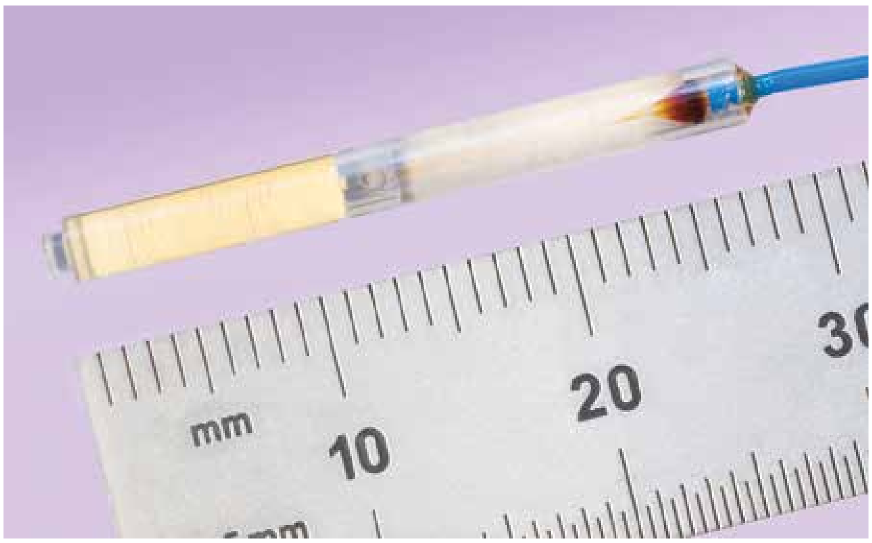
ABSOLUTELY: SMALL SENSOR, BIG PERFORMANCE

Interferometric metrology is the mainstay of many precision positioning applications. Interferometers typically measure displacement, i.e., changes in position rather than the absolute position. The short-range fibre interferometer system described herein combines the traditional advantages of interferometric systems with the ability to measure the absolute position of a target with sub-nm precision, all in an ultra-compact sensor envelope.

VIVEK BADAMI AND ERNESTO ABRUÑA



AUTHORS' NOTE

Vivek Badami is a senior scientist within the Innovations Group at Zygo Corporation, headquartered in Middlefield, CT, USA. He has worked on the development of new interferometric measurement technologies (among other things), taking a precision and systems engineering perspective.
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Introduction

Interferometric displacement metrology is the method of choice for precision positioning applications, finding use in both measurement and control. In many applications, interferometric systems using bulk free-space optics monitor tens of displacement axes simultaneously. These systems often require measurement of displacement over hundreds of millimeters, e.g., steppers and scanners used in photolithography, using heterodyne interferometry in conjunction with a single frequency-stabilised Helium Neon (HeNe) laser source to obtain exceptionally high signal-to-noise performance [1].

There also exist an entire class of applications that not only require many synchronised axes, but also the ability to measure absolute distance (as opposed to displacement) from a datum over much shorter (~millimeter) measurement ranges. Such applications abound, including metrology of deformable mirrors, monitoring of structural deformations in high-precision machines, positioning of lens elements within a lens assembly, position control of short-stroke fine stages, in-situ metrology of synchrotron mirrors, and so on.

In nearly all these applications, the ability to return the system to a known initial position (homing) to nanometer levels is critical – a functionality lacking from traditional displacement interferometers. One example of this requirement is the need to return the elements of a lens assembly to their optimal positions after transporting the assembly to the customer site, e.g., after powering down the system, to produce a desired wavefront. In such an application, a solution that can regain the absolute position of components within the system after the system has been power-cycled, transported and otherwise perturbed is key.

This type of functionality is analogous to that of a capacitance gauge with the key difference that an interferometric sensor does not suffer from the range vs. resolution trade-off typical of capacitance gauges. This allows for a superior dynamic range (picometer-level resolution over millimeter range) as compared to that of a capacitance gauge of comparable size, as well as absolute position measurement with higher (sub-nanometer) precision and stability.

An interferometric system to meet these requirements requires a completely new approach, which is embodied in the new Zygo ZPS™ system [2]. Some key details and applications of this system are discussed in the following sections.

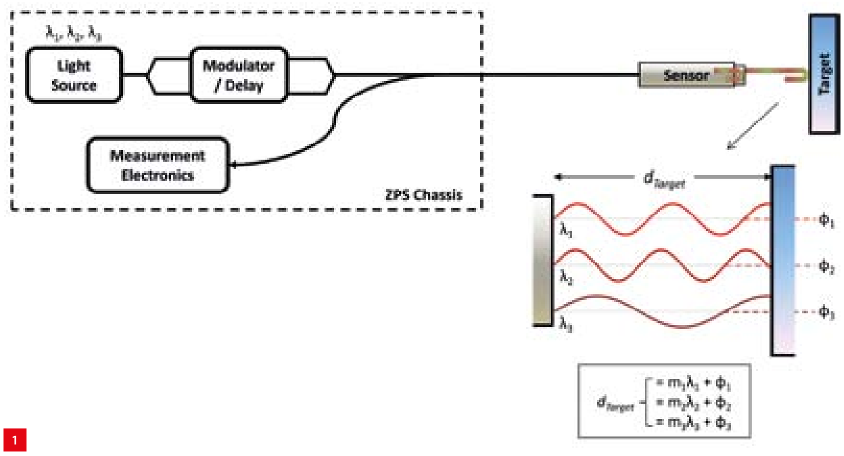

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Table 1. Summary of key specifications.

Measurement channels	up to 64
Working distance	3.5 mm
Full stroke range	±0.6 mm
Tilt range	±1 mrad
Noise density (3σ)	0.02 nm/√Hz
Stability	1 nm/day
Absolute position repeatability (3σ)	0.5 nm
Nonlinearity	±1 nm
Digital resolution	0.01 nm
Data rate	up to 208 kHz
Operating wavelength	~1,550 nm
Data interface	sRIO, Ethernet

1 Light source cycles through three discrete output wavelengths ($\lambda_1, \lambda_2, \lambda_3$), while the electronics measure the associated phase ($\varphi_1, \varphi_2, \varphi_3$). Simultaneously solving the system of equations for the fringe order (m_1, m_2, m_3) gives the distance to the target d_{target}. The complete process takes approximately 1 second regardless of the number of channels.

2 Principle of operation of displacement tracking. Displacement is tracked with a data rate of 208 kHz.

Table 1 summarises the salient specifications of the sensor system. The system is a low-noise absolute distance measuring device with ±0.6 mm (1.2 mm total) range around a working distance of 3.5 mm. Key to its function as a homing device are its excellent long-term stability and absolute position repeatability. The noise specification as a spectral density allows the user to calculate the performance based on the bandwidth of the measurement. The worst-case value at the extremes of the measurement range is specified, with significantly better performance (0.005 nm/√Hz) at the center of the measurement range, as discussed in the following sections. The system can handle high-bandwidth applications with a maximum data rate exceeding 200 kHz, using a high-speed sRIO interface. An Ethernet interface is provided for lower-bandwidth applications. The sensors are vacuum-compatible.

Principle of operation

The absolute position of the target relative to the reference surface of the sensor is established in a separate initial step using the Method of Exact Fractions [3], a well-known technique implemented to measure the absolute position (distance) of the target using multiple illumination wavelengths in succession as described in Figure 1. The system then tracks the position of the target using the displacement tracking modality described below. The absolute position measurement establishes the initial position of the target and reacquires the absolute position of the target if the beam is interrupted.

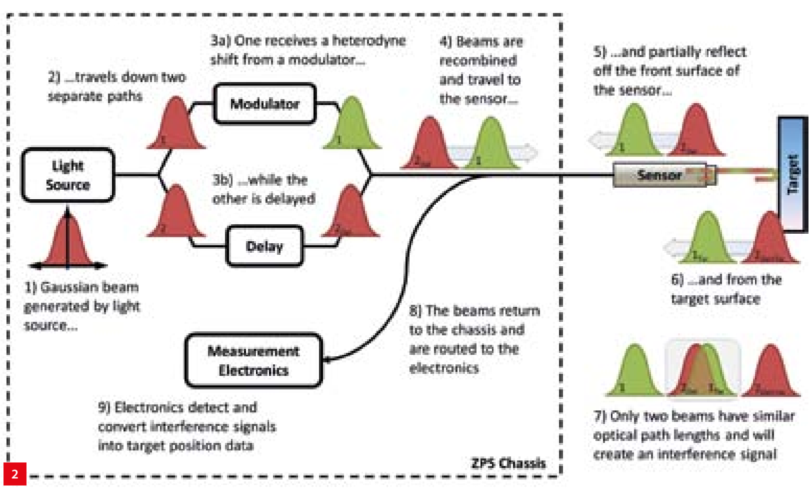

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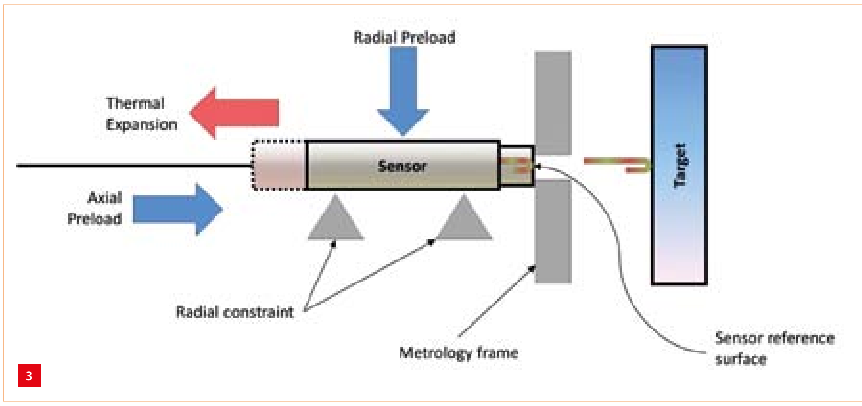
Figure 2 describes the operating principle of the displacement tracking modality of the system. A broadband emitter of carefully chosen spectral width functions as the light source. Light from the source divides into two paths, with phase modulation being applied along one path and a phase delay along the other. The modulation is the basis of heterodyne techniques to achieve measurement noise at the pm/√Hz level. Heterodyning is a spectral shifting technique that shifts the measurement signal from around DC to a much higher frequency to eliminate the noise contributions from the ambient and thermal/statistical sources which scale inversely with frequency [1].

The modulated and delayed copies of the source illumination combine and are delivered via an optical fibre to a sensor, where part of both are reflected from the sensor reference surface and the target. The short coherence length of the source ensures that interference signals are obtained only between pairs of reflections that have travelled the same optical path length. This means that only the unmodulated (delayed) light reflected from the reference surface interferes with the modulated light reflected from the target. These reflections travel back along the fibre and produce a signal at the modulation frequency at the detector; this signal is then processed by the measurement electronics to extract the phase change resulting from the changes in target position.

Position data are output at a maximum data rate of 208 kHz per channel, independent of the number of channels, making



3 *The front surface of the sensor is the measurement reference and is accessible to enable direct referencing of the sensor to a metrology frame.*

4 *The compact size of the sensor, just under 3 mm in diameter and ~30 mm in length, makes it suitable for applications with limited space.*

5 *The refractometer is a specialised sensor (sectioned view on the right) that measures the optical path length of the fixed, stable etalon of known length to determine the index. The system uses the measured ambient index to calculate the absolute distance for each sensor. The etalon is open to the medium in which the sensors operate.*

it possible to use the system in high-bandwidth applications. Precise synchronisation of sampling between channels enables simultaneous data collection over all channels. This is particularly critical when measuring multiple degrees of freedom to provide coordinated motion or when measuring a parameter based on multiple measurements, e.g., angle from the difference of two displacements [1]. Each system can be configured to support up to 64 channels of measurement; in applications requiring more channels, multiple systems can be linked together to provide synchronous data collection.

The sensor

The sensor is fundamentally a miniature Fizeau interferometer with interference occurring between wavefronts reflected from the sensor reference surface and the target. The front surface of the sensor serves as the

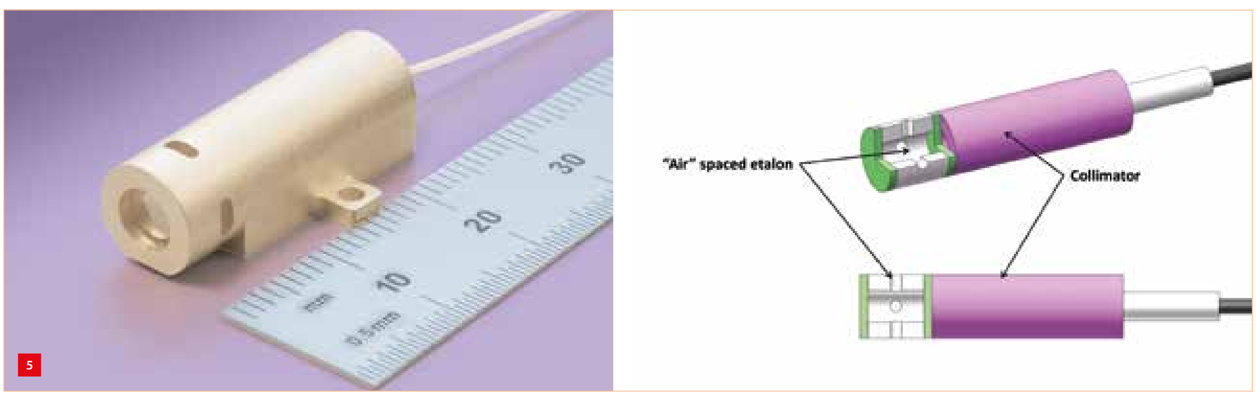
reference for the measurement as shown in Figure 3. This feature differentiates the sensor from other fibre sensors in that the measurement reference is well defined and designed to be accessible so that the measurement reference can be mechanically registered to a metrologically relevant point within the application, which may be for example an overall metrology frame. Further, in a well-designed mounting scheme registration of the sensor reference to the metrology frame eliminates the effects of the thermally induced dimensional changes of the sensor itself.

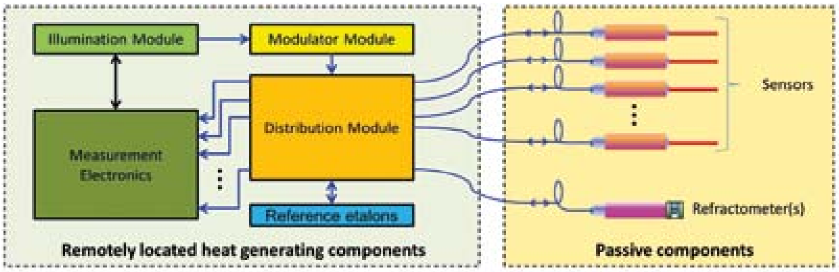
The compact size of the sensor (Figure 4) is well suited for applications with space limitations. With no active components, the sensor dissipates nearly no heat, a critical factor in heat-sensitive applications, especially in vacuum. Delivery of the light and return of the signal via fibre simplifies routing and eliminates the complexities of beam routing encountered in standard free-space interferometers.

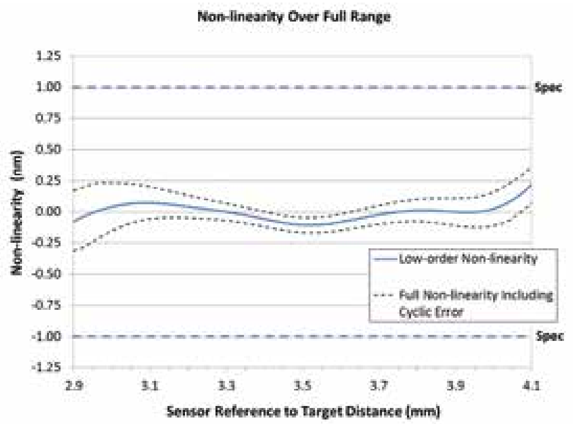
Like for all interferometric systems, a knowledge of the refractive index of the medium of operation is important for the precision and accuracy of the measurement. In contrast to the usual method of calculating the index based on the pressure, temperature and humidity via the Edlén equation [4], a compact refractometer (Figure 5) makes a direct determination of the refractive index which is used to compensate the other measurement channels in real-time. This approach has the further advantage that the system automatically accounts for index changes due to changes in the composition of the medium, something that calculation-based systems are blind to.

System architecture

The system architecture separates the active heat-generating components from the passive components (sensors/refractometers) as shown in Figure 6. The active components can thus be remotely located from the thermally sensitive areas. Long-life, high-reliability sensors are embedded within the application while components that may need servicing are located in an accessible location to minimise downtime. Like for all interferometer systems, the stability of the wavelength of the light source is critical.







6 *The system architecture separates active and passive components.*

7 *Differential measurement configuration using a common target mirror to calibrate the ZPS system.*

8 *Overall linearity over the full stroke range. The full nonlinear deviation has a low-order term combined with cyclic errors which are minimised through active compensation. The specification limits of ±1 nm are also shown.*

9 *Noise density at various positions within the stroke range with a noise figure of ~2 pm/√Hz (3σ) at the nominal working distance. The noise specification at various positions is also shown.*

10 *Absolute position repeatability as measured by repeated measurements of the absolute distance of a target rigidly affixed to the front face of the sensor. Measurements performed under ambient conditions on multiple sensors (test cavities).*

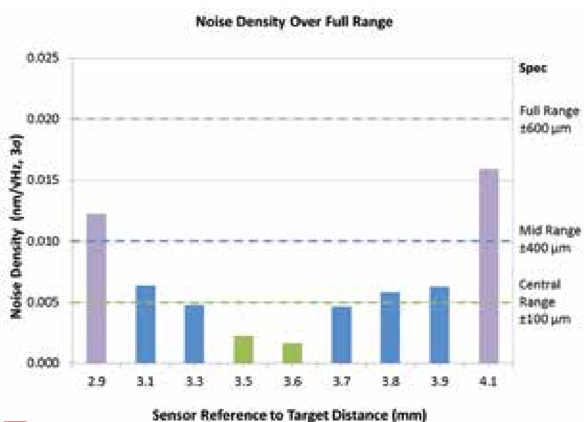
Stable internal reference etalons monitor changes in the wavelength and compensate the measurement calculation.

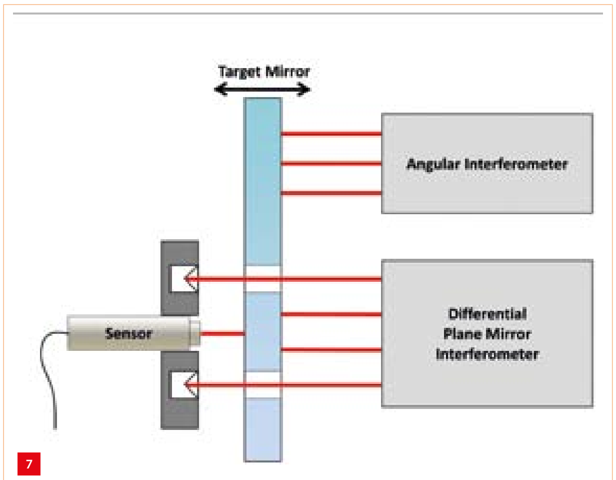
Performance

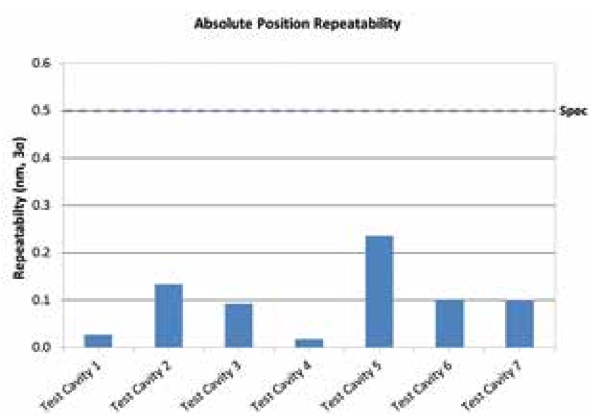
Calibration with a Zygo ZMI™ heterodyne displacement measuring interferometer with a frequency-stabilised HeNe laser source operating near 633 nm provides traceability to the international standard meter. The comparison relies on a differential measurement arrangement shown in Figure 7 wherein both interferometers measure the motions of a common target mirror [5]. The source wavelength is calibrated against an iodine-stabilised HeNe laser whose wavelength is known to ~$2.5 \cdot 10^{-11}$. The set-up is arranged to minimise Abbe offset between the measurement axes of the two interferometers, and angular motions of the mirror are monitored to compensate for contributions from any residual offsets.

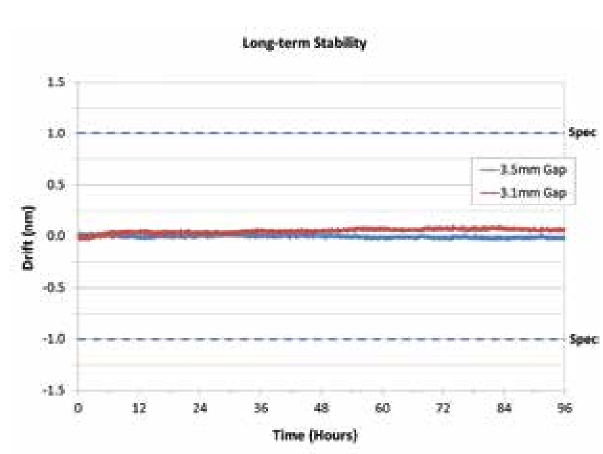
Measurements of pressure, temperature and humidity establish the initial absolute value of the refractive index of air. A wavelength tracker measures subsequent index changes which are used to compensate the displacement measurement. The measurement electronics compensate cyclic errors of the calibration interferometer. This set-up also verifies the specified linearity of the system, the typical behaviour of which is shown in Figure 8.

Other performance characteristics, such as the noise performance, absolute position repeatability and long-term stability, are evaluated using stable low-expansion etalons. Index compensation using the refractometer is applied where appropriate.

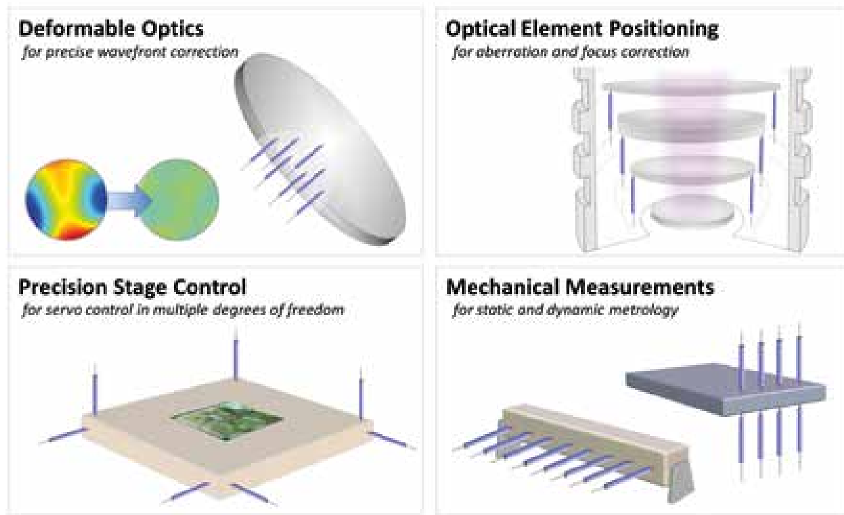








11 *Long-term stability for two different distances between the sensor reference surface and the target (gap) showing long-term drifts well below the specification of 1 nm over a four-day period.*



12 *Some examples of applications for the ZPS sensor technology.*

Figure 9 shows noise density at various positions within the stroke range, while Figure 10 and Figure 11 show the absolute position repeatability and long-term stability, respectively.

Applications

The short-range absolute position sensing technology – the video [V1] shows how to align the ZPS sensor – finds use in applications which require absolute position metrology over a short measurement range. Figure 12 provides a few examples of applications. These include deformable optics, where it is important to regain the absolute mirror shape after a system reset such as a system power down. Deformable optics are used in astronomical telescopes, photolithography tools, and synchrotron x-ray beam delivery systems.

Optical element positioning is another application wherein the compact size of the sensors and absolute position capability allows the system to 'home' to a known starting position. Precision stage control for short-stroke stages is an obvious application, while a not so obvious one is the use of additional sensors to provide feedback for controlling over-actuated stage systems. A final example is the use of the large number of available channels to provide a distributed array of sensors for monitoring deformation of mechanical structures due to inertia and thermal loads.

In summary

Zygo's new ZPS™ sensor system provides high-precision, synchronised absolute position measurement for highly-parallel metrology applications. In contrast to traditional interferometers and other fibre displacement systems, the ZPS reports the absolute position of a target surface, making this sensor ideal for not just displacement but also for homing or initialising systems. And all of this in a tiny package. ■

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VIDEO

[V1] How to align a ZPSTM sensor: *www.youtube.com/watch?v=RdHMzgJX1s8*

DEMO DESIGN: THE VIRO AGILE EYE

A new design of the Agile Eye, a parallel manipulator with three rotational degrees of freedom, has been realised and validated. The original design was mechanically overconstrained, whereas the new design is not. Also, the advantages of 3D printing have been exploited in the link design. A real-time controller was developed that implements, by use of inverse kinematics, the motion planning for the intended applications: vision-based object tracking or laser manipulation. Performance in terms of workspace, velocity and acceleration is above specification. This paves the way for interesting vision and laser applications in robotics.

EDITORIAL NOTE

This article is based on the Bachelor thesis of Stijn Lohuis [1] and the internship reports of Mohamed Abdelhady [2] and Samer Abdelmoeti [3]. These students did their projects at VIRO under the supervision of Theo de Vries, department head Software & Control, Electro & Instrumentation at this company, and associate professor at the University of Twente, the Netherlands.

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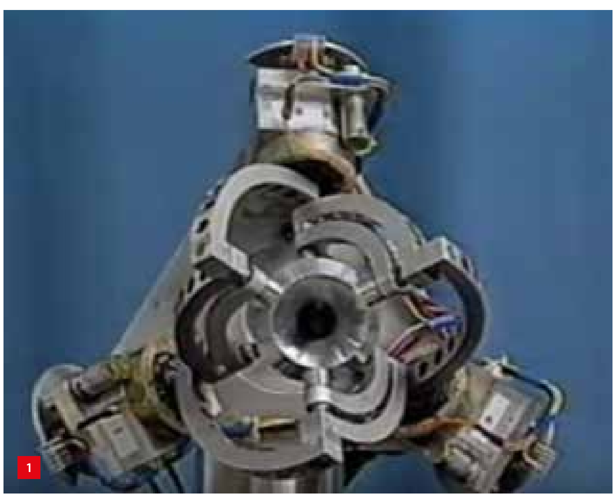
The Agile Eye is a spherical parallel manipulator capable of orienting a camera or a laser pointer with high speed and accuracy in three rotational degrees of freedom (DoFs). For vision applications, for example in robotics, this mechanism can achieve better performance than the human eye in terms of angular velocity and visual range. Also, it outperforms the classical serial mechanisms for tracking fast-moving objects due to its high acceleration and 3-DoF orientation. The first working prototype of the Agile Eye was designed 30 years ago [4] and constructed in 1993 [5] by the Laboratoire de Robotique of the Université Laval in Quebec, Canada [6]. See the video [V1] for an impression; Figure 1 gives a screenshot. More Agile Eye projects and simulations [V2] can be found online.

VIRO, an international engineering firm [7] specialising in engineering and project management, headquartered in Hengelo (Ov), the Netherlands, decided to develop a new version of the Agile Eye – designated as the VIRO Agile Eye for clarity – as a demonstration device matching the performance of the original Canadian prototype, and use rapid prototyping (3D printing) in the realisation phase, for increased design freedom and cost constraints. The video [V3] gives a short overview of the project.

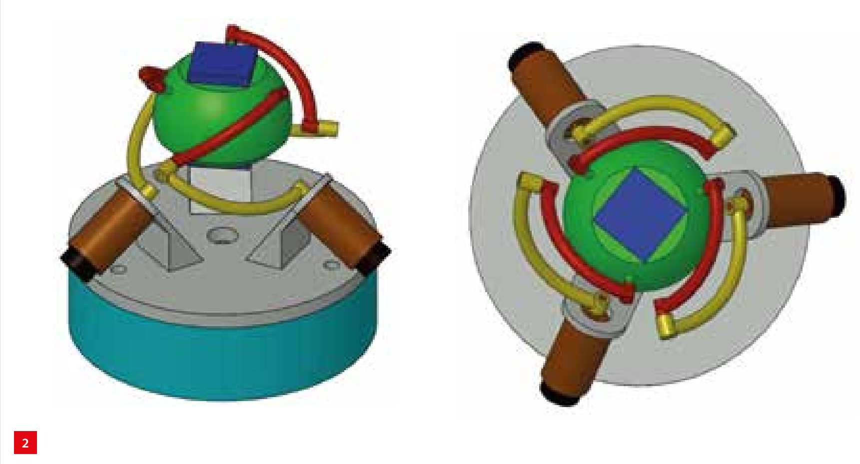


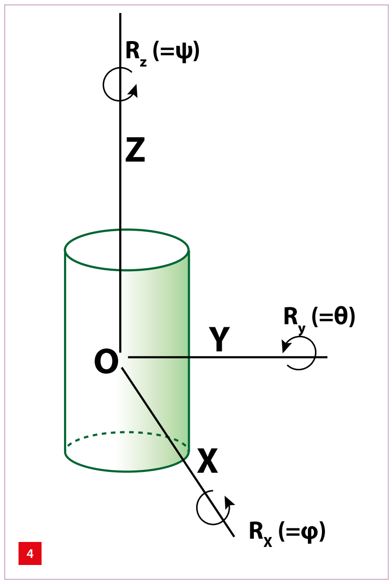
1 *Screenshot of a video [V1] demonstrating the original Agile Eye.*

Geometry

Figure 2 shows the mechanical concept of the VIRO Agile Eye. The central component, called the end-effector, can rotate in three directions and is driven by a symmetrical threefold parallel mechanism. Each part of the mechanism comprises a proximal link (fixed to the motor axis) and a distal link, connected via a line hinge to the end-effector. The proximal and distal links are connected to each other via a line hinge. Just as in the original prototype, the geometry has been designed such that all hinge axes intersect in the rotational centre of the mechanism, where the end-effector is positioned. However, the original design featured a perpendicular angle in the proximal link that was removed in the VIRO design (as has been done previously in other Agile Eye design projects).

An in-depth geometrical study [5] provided the design rules for choosing dimensions for the mechanism. From this study the optimal configuration of the line hinges was derived, yielding high stiffness and an unlimited orientation workspace not divided by singularity surfaces (which should be avoided, because otherwise the equations of motion do not yield unique solutions), and hence the largest rotational freedom of the end-effector. This configuration was found to be orthogonal: the intermediate hinge, connecting the proximal and distal links, is orthogonal to





2 *Mechanical concept of the VIRO Agile Eye in side and top views. Turquoise: stable base frame and cabinet for electronics. Brown: motors. Grey: motor support. Yellow: proximal links. Red: distal links. Green/blue: end-effector.*

3 *Functional system architecture. Sub-systems 3 to 6 define the VIRO Agile Eye.*

4 *Definition of the end-effector rotational coordinates.*

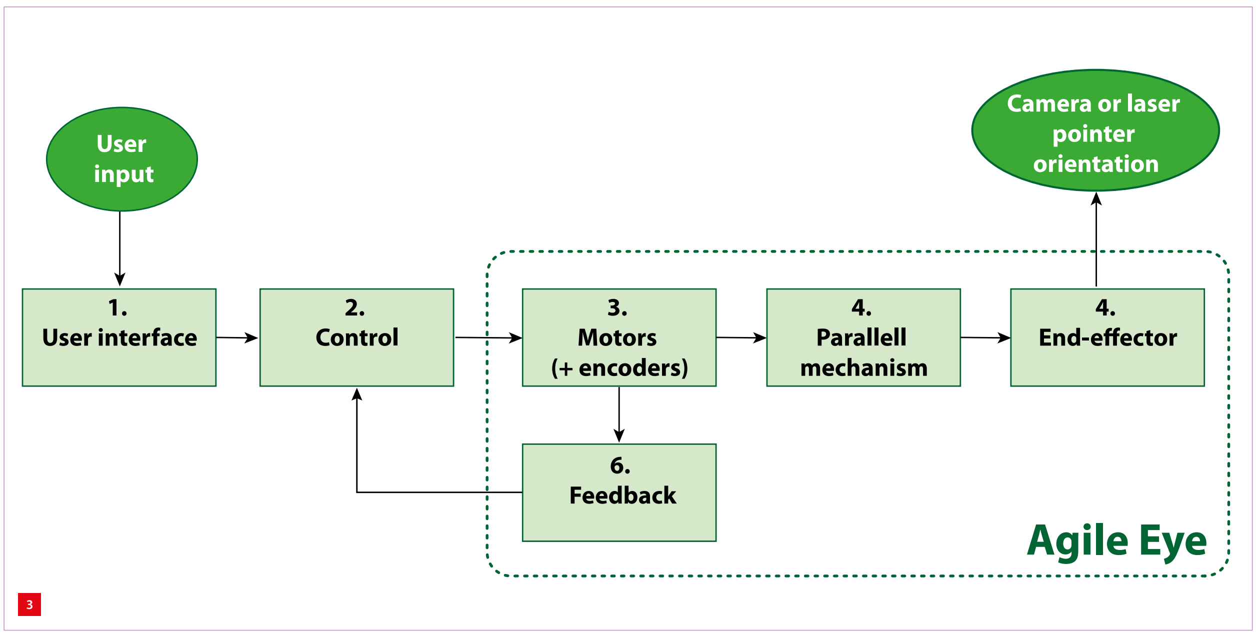
the motor axis as well as to the end-effector line hinge. Within this design space, a trade-off can be made between workspace and attainable speed/acceleration; this trade-off is parametrised by the angle of the motor axis relative to the base platform. For the VIRO Agile Eye, the optimal angle of the motor axis with the base platform was determined to be 54.74°.

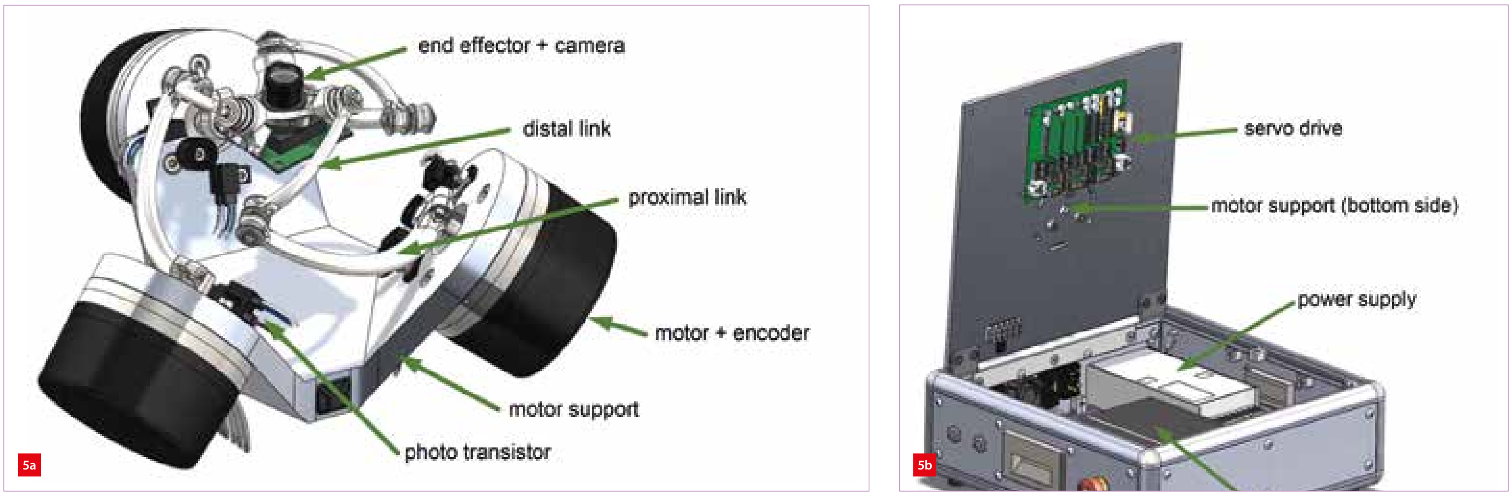
A straightforward realisation of the Agile Eye mechanism is overconstrained, i.e. there are more mechanical constraints than DoFs. Using Grubler's analysis [8], the number of overconstraints can be determined. Seven bodies (three proximal links, three distal links and one end-effector) each with six DoFs yield a total of 42 DoFs. With three DoFs to be left unconstrained, 39 DoFs remain to be constrained by the mechanism. The constraints are provided by nine line hinges (three at each motor axis joint, intermediate joint and end-effector joint), defining five DoFs each (and leaving one DoF unconstrained), yielding a total of 45.

This analysis thus presents a (45 – 39) sixfold over-determination. In practice, this means that for a straight-forward realisation, manufacturing tolerances have to be tight, to prevent excessive friction or even blocking of motion. For the VIRO Agile Eye, it was decided to resolve the overdetermination by adapting the design of the line hinges. This is elaborated further below.

Requirements

For the complete system six sub-systems can be distinguished; see Figure 3.
Two modes of operation have been defined for the VIRO Agile Eye:
- tracking a trajectory with a laser pointer (pointing/writing);
- tracking an object with a camera attached to the end-effector (vision-in-the-loop).





5 *Construction of the VIRO Agile Eye.*
(a) Main components.
(b) Housing with the electronic components (room for the embedded computer indicated).

6 *Design of hinge connections.*
(a) Spherical hinge connection between the distal link and the end-effector.
(b) Line hinge connection between the proximal and the distal link.

The specifications were derived for the vision-based object tracking application. For the end-effector, the rotational range (see Figure 4) is specified as $\varphi_{max} = \theta_{max} = 60°$ around the in-camera-plane axes and $\psi_{max} = 30°$ around the normal of the camera plane. The positioning accuracy during motion has to be better than ±0.2° over the full trajectory. This leads to a required maximum measurement uncertainty of ±0.02° at the motor axes. To match the specs of the original Agile Eye [10], a velocity of 1,100°/s and an acceleration of 33,000°/s^2 were specified for the motors.

Acceleration is the most critical performance parameter. Therefore, motor dynamics are critical and the design has to be optimised for low mass moments of inertia. With the expected parameters, it was calculated that an estimated nominal motor torque of 0.13 Nm is required.

Design and realisation

Figure 5 shows the main components of the VIRO Agile Eye and the interior of the housing with the electronic components.

Mechanics

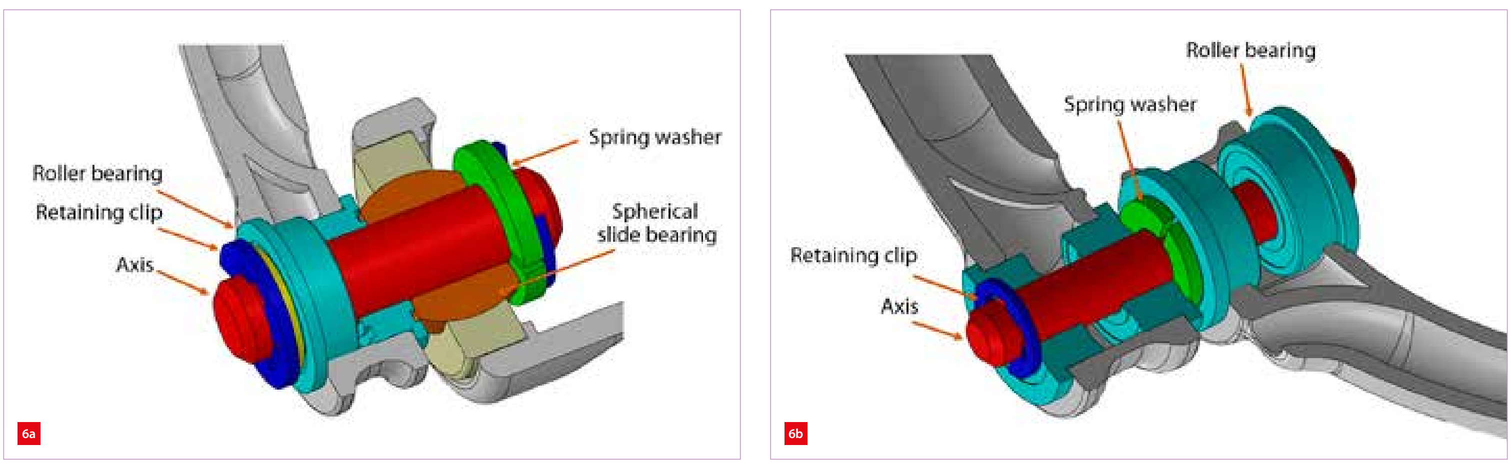
- Dimensions

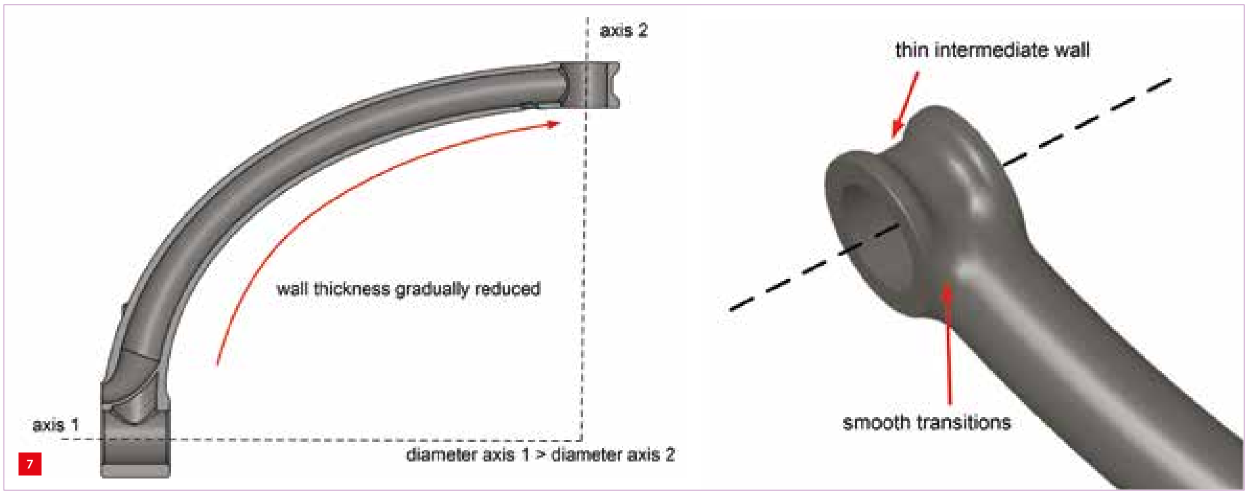
The dimensions of the VIRO Agile Eye were determined as a trade-off between size (large enough for demonstration purposes and fairs, yet portable) and performance (the smaller the size, the better performance: lower inertial moments enable higher accelerations, given the available motor torque), taking into account the dimensions required for the end-effector. From the space taken up by the end-effector and its external interface (connecting it to the mechanism), the minimum dimensions of the parallel mechanism were determined. The end-effector was 3D printed so that an optimum geometry with minimum weight and volume could be achieved.

- Joints

The construction of the original Agile Eye with line hinge joints is overconstrained. Therefore alternatives were considered. One option was to make the links compliant to some extent, to accommodate for manufacturing tolerances and prevent excessive friction/blocking. The disadvantage of this option is that eigenfrequencies are lowered. Hence, a more fundamental alternative connection principle was chosen: replacing three line hinges with spherical joints, releasing three times two DoFs and hence removing all overdetermination.

A spherical hinge takes up more space than a line hinge, thus limiting the rotational range. To minimise this negative





7 *Modifications, based on finite-element analysis, to the original design of the link.*

effect, it was decided to integrate the spherical hinge into the end-effector (Figure 6a). It is implemented as a spherical slide bearing, with two roller bearings on the distal link to compensate for the high friction coefficient of the slide bearing. The proximal-distal joints were realised as line hinges (Figure 6b), just as in the original Agile Eye design.

The motor axis is connected to the proximal link through a slotted clamping connection that can be fixed with a bolt. As the motor axis has no flat side, slip can occur when the clamping force is insufficient. This potentially negative effect is turned into an advantage by using it as a safety factor, preventing damage in the case of wrong control settings.

- Links

The shape of the links determines the rotational freedom of the end-effector. The largest rotations can be achieved when the angle between the two axes connected to a link is 90°, as discussed above. The link has an elliptic shape, which allows the hinge of a proximal link connected to one motor to move over the axes of the other two motors.

The next step is to optimise the dynamic properties of the system. To minimise vibrations during rotation, the stiffness of the parallel mechanism has to be maximised, while at the same time minimising the mass (Figure 7). From finite-element analysis, it became clear that most of the stresses occur at the interfaces between the elliptic link and the hinges, so at that location, material had to be added. A round hollow tube is the best option for the link as it is stiff in all directions and is suitable for dealing with torsional forces.

Inox was selected as the material for the links, as it yields a higher lowest eigenfrequency (which in turn enables a higher control bandwidth) than most other materials that can be 3D printed. In the end, to limit the cost, the links were printed from a 60% inox-40% bronze composite, which only slightly lowers the final value of the lowest eigenfrequency.

- Motor support

The motor support was CNC milled as a monolithic part, as this yields maximum accuracy in the motor axis orientation and position, in this case +/– 0.03 mm. Aluminium was the material of choice because of its favourable stiffness-mass ratio (mass was restricted for ‘portability’ reasons).

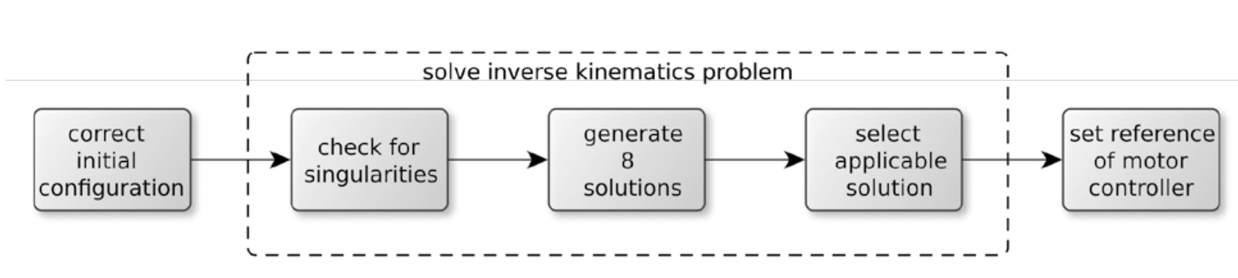
Electronics

The type of motor affects system performance, so a careful selection was made from three alternatives:

- DC motor: this type is not suitable for high-frequency, start-stop operations, because of rapid heat generation and mechanical commutation wear.
- Stepper motors: suitable for dynamic applications and relatively cheap; their disadvantages are torque loss at high velocities, resonance and noise production (dependent on the controller).
- Brushless DC motors: perfect for start-stop operations and applications requiring high torque density over the full velocity range. Despite the high cost price, this option was chosen.

The Maxon EC 60 Flat motor was selected because of its good performance (torque)-price ratio and high-dynamics load capacity (as confirmed by simulations); the favourable cost price of the motor-encoder combination; and the fact that no transmission between motor and proximal link is required. The encoders that were selected lack an index signal, therefore a photo transistor had to be mounted on each axis as a homing sensor, reporting the motor axis angle at start-up. An additional photo transistor acts as an electronic end-stop that is activated before the mechanical end-stop is reached, thus allowing the control system to prevent damage due to malfunctioning.

For the electronic system, the combination of an embedded PC and a three-axis servo drive coupled to the PC via EtherCAT was selected.



8 *The implemented approach of solving the real-time inverse kinematics problem.*

Control

- Kinematics

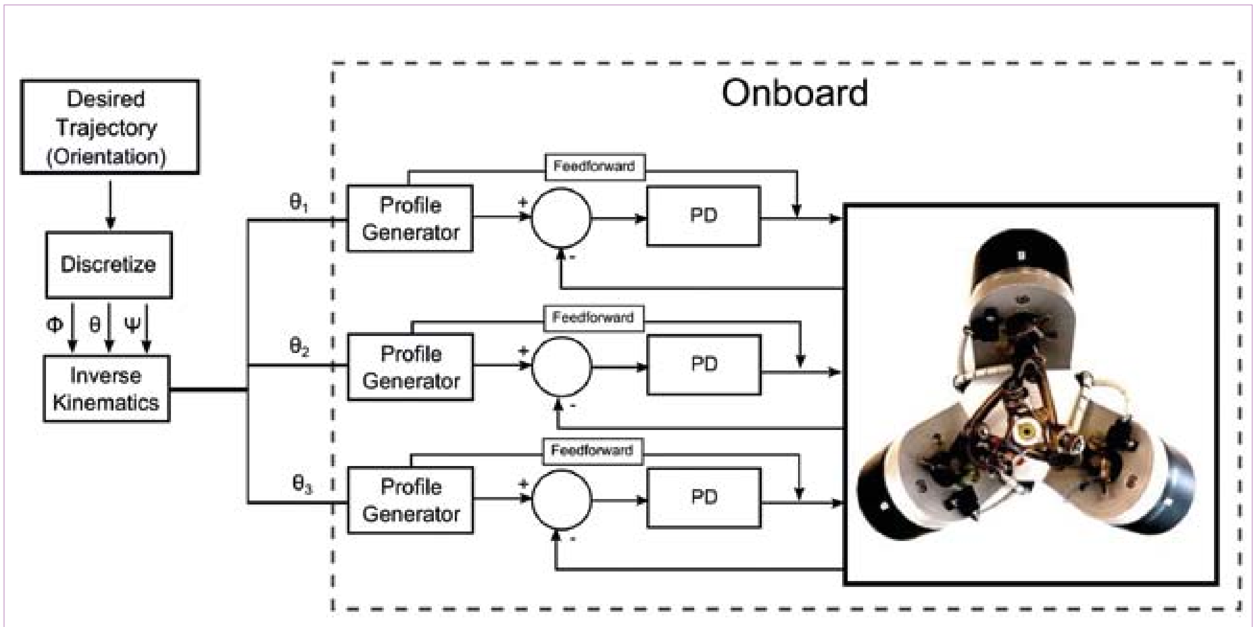
The end-effector is the part of the manipulator that performs the desired tracking or pointing. Therefore, motion commands for realisation of visual object tracking or laser pointing are conveniently defined in end-effector coordinates. However, the system is physically driven by the actuators, and hence actuator control is performed in terms of (rotational) actuator coordinates, i.e., the motor angles. Inverse kinematics is the computation of the actuator motion that results in the desired end-effector motion. For the design of the VIRO Agile Eye controller, the first step was formulating a system model to derive these inverse kinematics.

For conventional serial manipulators (with only one kinematic chain), the inverse kinematics is usually an implicit function with a number of solutions, while the forward kinematics is typically an explicit function with a unique solution. In the Agile Eye case of a spherical parallel manipulator, due to its special properties, both forward and inverse kinematics are provided by an explicit function. This reduces the computational complexity, especially for the inverse kinematics. However, the challenge appears in the non-uniqueness of both the forward and inverse kinematics.

The full elaboration can be found in [3]. Two solutions exist for each actuator, because the derivation involves an inverse tangent function that for each value has two solutions over the 0-2π motor angle range. Hence, for the 3-DoF manipulator, eight solutions are obtained. This leads to a dependency of the inverse kinematics solutions on the actual manipulator assembly, the so-called assembly mode.

Fortunately, the Agile Eye is a so-called 'non-cuspidal' manipulator [11], which can only switch from one assembly mode to another, if and only if it passes through a singularity. Or stated the other way around: as long as singularities are avoided, the manipulator cannot change its assembly mode, i.e. adopt another solution to the inverse kinematics. This property significantly simplifies the real-time implementation, as compared to the cuspidal manipulator case.

The approach (Figure 8) is to start with the correct initial assembly mode. Then, the inverse kinematics problem is



9 *Joint space control architecture utilising three SISO joint space controllers: φ, θ and ψ are the rotational coordinates of the end-effector (see Figure 4), θ_i (i = 1-3) are the motor angles. Here the inverse kinematics, concerning the transformation from end-effector trajectory coordinates to motor angle coordinates, is executed in real time. The desired trajectory is from a path generator or, in case of visual servoing, from the vision software component.*

solved for the desired end-effector orientation and the solution is selected that corresponds to the actual assembly mode, while checking that it is not passing through singularities (the analysis yielded four singularities). Finally, the resulting angles are applied as the setpoints of the reference motion profile of the actuators.

In principle, a Cartesian space control architecture is preferred over a joint space control architecture, because in the case of dynamic couplings, an overshoot in one of the joint coordinates can affect the other coordinates, whereas the Cartesian coordinates are controlled independently. However, it was demonstrated that in practice overshoot problems can be limited by properly choosing joint controller parameters. Therefore, a joint space control architecture (Figure 9) was implemented, as this is computationally more efficient than Cartesian space control, as well as more intuitive.

- Control scheme

The joint space controller was realised as three Single-Input-Single-Output (SISO) PD controllers, one for each joint. Additionally, acceleration feedforward is proposed for each joint. Reference inputs are defined by a motion profile generator that is programmed based on the chosen controller. Setpoints of the generated profiles are determined by the output of the inverse kinematics solution that lets the end-effector track the desired trajectory in the Cartesian space.

The joint controller is provided with PD feedback for dealing with the imperfections of the developed feed-forward controller due to disturbances and model uncertainty (e.g., varying mass on end-effector), as well as those of the couplings between joints. The motion planner (see below) produces a time series of setpoints for the controller. A second-order motion profile is generated between those setpoints as the reference for the PD controllers. However, since the joints are always following a trajectory, the deceleration part of the profile would produce an undesirable stand-still at each setpoint. Therefore, a continuous motion profile without a deceleration part is generated, i.e., velocity is not reduced to zero before the next setpoint. Hence, a smooth motion is achieved.

Acceleration feedforward is applied based on the required joint motion profile, with constant acceleration, and is tuned using the Technosoft iPOS drives software, simultaneously with the feedback controllers. The real-time control software is implemented in C++ on a Linux platform, using the Orocos real-time toolkit [12], and communication is provided by the CAN application protocol over EtherCAT (CoE).

Motion planning

In the case of trajectory tracking (laser pointing/writing), the trajectory input is defined in terms of x-y coordinates on a predefined plane, for example a ceiling or a wall. In order to track trajectories in Cartesian space, the desired trajectory is discretised to an n number of points depending on the required speed of the trajectory, with a minimum n_{min} points that guarantee resolution and a maximum n_{max} that ensures that the points can be tracked well by the joint space controllers.

For camera-based object tracking, the orientation of the end-effector is set by a ‘vision-in-the-loop’ control mode. The x- and y-errors, used for keeping the tracked object in the centre of the image, are calculated cyclically using image processing techniques and are fed to the vision control loop.

It is worth noting that an open-loop configuration is only possible if the distance between the camera and the tracked object can be determined, so that the relation between the x-y and φ-θ coordinates can be calculated. This could not be achieved with sufficient accuracy and, therefore, a closed-loop (vision-in-the-loop) configuration was implemented.

The sample frequency is set depending on the mode of operation, where 33 Hz is chosen for trajectory tracking and 200 Hz for the setpoints generated by the camera loop for object tracking.

Validation

The system requirements of the VIRO Agile Eye were validated using three straightforward tests.

System performance

To test the requirement of surpassing the original Agile Eye performance, specified as a maximum velocity of 1,100°/s and acceleration of 33,000°/s^2, a step response was generated on one motor while the other two motors remained stationary. To imitate application conditions, the camera module was mounted as the end-effector. Accelerations above 75,000 °/s^2 were obtained, well above spec. The maximum angular velocity was 1,050 °/s, slightly below spec, but this value could have been surpassed easily if the angular step amplitude had been increased. It can be concluded that the requirement has been satisfied even without driving the full motor current.

Rotational range

The rotational range of the VIRO Agile Eye was tested using a laser pointer as the end-effector. Starting from its reference position, all required angular positions could be reached. It was confirmed that the end-effector exhibits a singularity in four positions, as the kinematic model had predicted, near which the mechanism becomes highly instable due to play and static deviations. In a singularity, the links are moving while the end-effector remains stationary, hence the system itself cannot escape this situation. The trajectory generator has been implemented so as to avoid the approach of these positions. The 'impact range' of the singularity positions can be decreased by minimising play in the joints.

Positioning accuracy

For this test, the laser pointer was also used as the end-effector and was repeatedly driven to point at the same target position. From the variation in the results, an angular position accuracy of ±1.0° was obtained, which is much larger than the specified ±0.2°. This appears to be due to sub-optimal assemblies in the line hinges and spherical joints. These problems are a consequence of the way in which the 3D-printed parts were post-processed before assembly. Due to shape inaccuracies, the spherical joints have to accommodate relatively large motions, which deteriorates the system accuracy.

Conclusion

A new design of the Agile Eye has been realised (Figure 10) and validated (see the video [V3]). The overconstraints in the original design have been eliminated. Based on the implementation of the inverse kinematics, a real-time controller was developed for generating the motion planning for the intended application: object tracking or laser pointing, respectively. Performance in terms of velocity and acceleration is above specification. The system accuracy demand was not met, due to sub-optimal assemblies in the line hinges and spherical joints. This can be improved by tightening the manufacturing tolerances for the 3D-printed parts. ■

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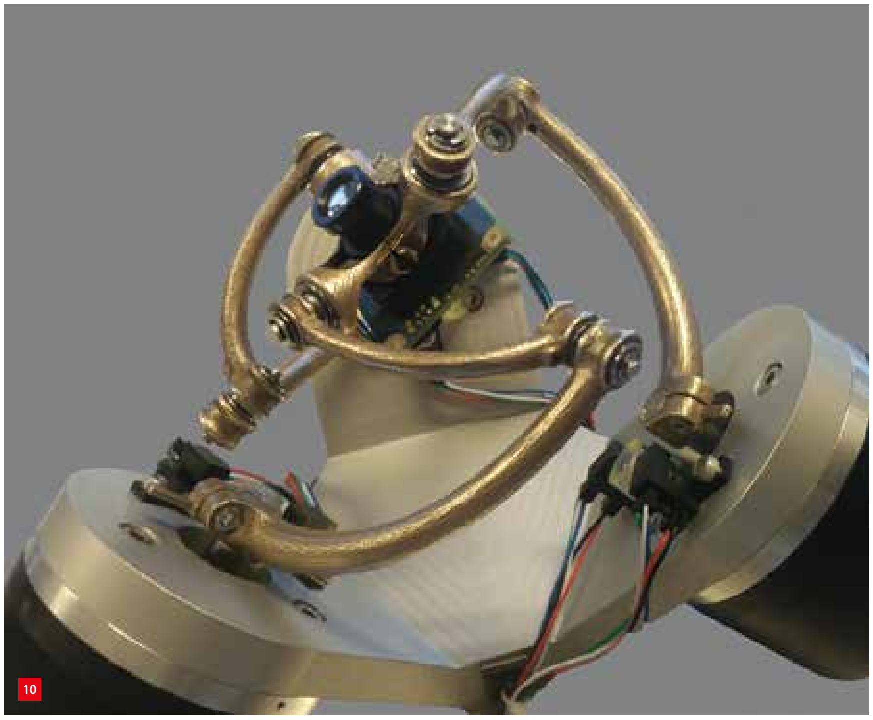

10 *Close-up of the final realisation of the VIRO Agile Eye.*

VIDEO

[V1] Original Agile Eye: *www.youtube.com/watch?v=gVlqjA1EKE4*

[V2] Simulation: *www.youtube.com/watch?v=JhEulT-C4CI*

[V3] VIRO project Agile Eye: *www.youtube.com/watch?v=IO9LXoEDbbU*

Affordable interferometers by applying integrated photonics

Typically, photonic integrated circuits (PIC) for sensing applications are still considered a topic of limited to basic research, illustrated by the numerous academic papers published every year. The growing number shows that the topic is gaining interest, however the number of industrial available products is still rather modest. Compared to its "older brother" integrated electronics, integrated photonic technology is not yet at the same level of maturity, however its commercially availability is catching up quickly.

In the past few years Technobis has introduced its Gator product range: a plug&play desktop Fiber Bragg Grating (FBG) interrogator, a spectrometry-based product that are OTS commercially available. Technobis is also introducing another state-of-the-art ASPIC-based product line: the Chiroptera, an ASPIC based fiber-optic interferometer. The Chiroptera a solution for extreme sensitive, accurate and high-speed measurements of target displacement without the need to physically connect a sensor to the object of interest.

Chiroptera: a compact interferometer

In contrast to linear-encoders and 'classical' geometrical optical interferometers, a PIC-based interferometer consists of a small-formfactor package and a fiber-optic sensor to be aligned to a target (Fig 1).

To overcome the fiber lead sensitivity, which is inherent to the three-phase configuration (principle first demonstrated in 1981 by S. K. Sheem et al, JAP 52, 3865), multiple wavelengths can be applied. Each wavelength will be aligned to its own target, being able to reject common-mode behavior (like fiber temperature- and vibration noise). Within integrated photonics a combination of three-phase interference principle and a dense wavelength division (de) multiplexing becomes feasible.

In addition to the specific design of the Photonic circuit, the following key aspects need to be considered to optimize the three-phase interferometric signal: the optical efficiency, thermal management and low-noise electronics of the photonic package, and both Reference/Probe and Target laser quality. The performance of a PIC-based interferometer requires optimization of all these parameters together in order to achieve λ/10000 interpolation, i.e. sub-nanometer displacement resolution.

Displacement measurement

By eliminating the displacement noise originating from the fiber, the resolution limit is dominated by the laser phase noise and electronic noise (optical power level). The following plots demonstrate the sensitivity and dynamic range of the Chiroptera with the target displacement measured in two different applications: manual micrometer-screw displacement (Fig 3) and piezo step modulation (Fig 2).

Our results (Fig 2) show that sub-nanometer displacement resolution is feasible using integrated photonics. The resolution limit in these setups is understood, well under control and has room for improvement.

Depending on the application different choices can be made to accommodate the Chiroptera to the requirements of the targeted measurements, e.g. a high- or low-end lasers, high-speed or low-speed electronics, few or multiple measurement points, etc., if cost-performance balance needs to be optimized.

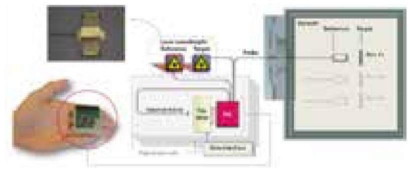

Figure 1. Chiroptera Layout. A PIC-based dual wavelength three phase interferometer integrated with a Reference (A) and Target/ Probe (B) laser. The system has a FOS head and can be inserted in various applications.

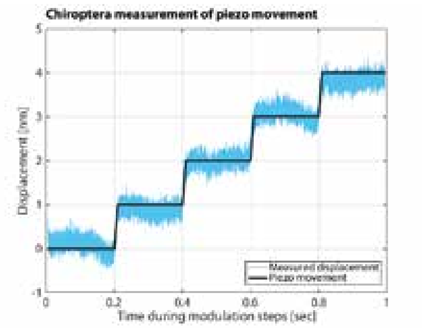

Figure 2. Results (blue) of a PIEZO step (black) modulation of 1 nm.

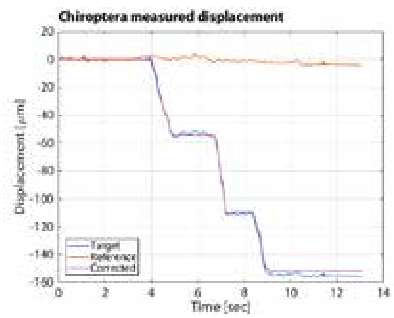

Figure 3. Result (purple) of manual steps of roughly 50 μm. The result is the measured "target" corrected by the "reference" measurement

Summary / conclusion

We demonstrate the use of commercially available interferometers that utilize integrated photonics for accurate remote sensing. The Chiroptera includes the state-of-the-art integrated photonics packaging solution that enables small volume, and low-cost devices for a broad range of new applications that suffer from the limitations of conventional systems. Further developments are ongoing in collaborative projects with leading companies such as Lionix and Settels.

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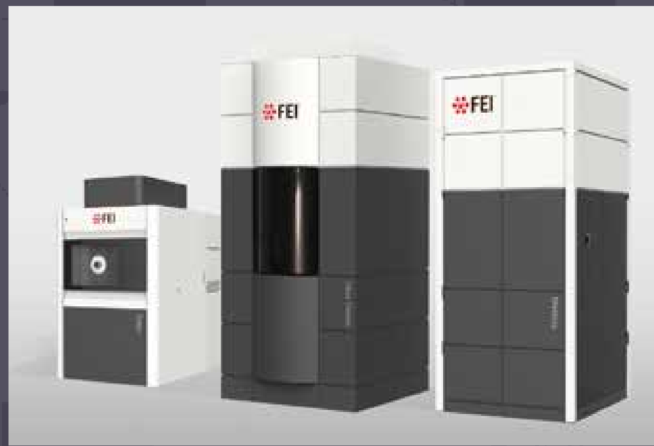
CONFERENCE HIGHLIGHTS

Jim Stolze hosts a masterclass about artificial intelligence and blockchain in the industry



Discover how Thermo Fisher integrates smart maintenance in its systems and organization

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The conference programme of this year's edition will focus on industrial internet of things, cobotics and design for additive manufacturing

Vanderlande sees a bright future for cobots in logistics. Get inspired by their plans

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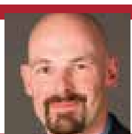
PROGRAMME

09:30	Introduction by Maarten Steinbuch, TU Eindhoven		
09:45	 **What's next for digital and blockchain?** Jim Stolze, Aigency		
10:30	**Break**		
	Industrial internet of things	**Cobotics**	**Design for 3D**
11:00	**Getting 3D printing ready for high mix and high volume** Stefan Rink, Shapeways	**Future of robotics within logistics, technology push and market pull** Jalte Norder, Vanderlande	**Optimizing designs for 3D metal printing** Jeroen Jonkers, NTS
11:30	**Smart Industry: putting words into actions** Timo Roestenberg, Demcon	**Software platform for robots in distribution centres** Heico Sandee, Smart Robotics	**3D food printing to create texture** Pieter Debrauwer, AMSystems Center
12:00	**Human robot collaboration and operator support in assembly work** Gu van Rhijn, TNO	**Behavioural-full complex system design: domain knowledge beats agility** Herman Bruyninckx, KU Leuven	**Applications and opportunities of additive manufacturing in die bond equipment** Patrick Houben, Ralph Huybers, Nexperia
12:30	**Lunch**		
	Industrial internet of things	**Cobotics**	**Design for 3D**
14:00	**Goodbye traditional industry, hello Smart Industry** Theo de Vries, Viro	**Exoskeleton Project March aims to give back full mobility to paraplegics** Lennart Schut, TU Delft	**Surprising business for 3D** Jaap Bulsink, Kaak
14:30	**Artificial intelligence: condition monitoring at scale** Simon Jagers, Semiotic Labs	**Navigation of a semi-autonomous aquadrone** Rob Hendrikx, Nobleo Technology	**Computational design optimization for additive manufacturing** Matthijs Langelaar, TU Delft
15:00	**How to integrate smart maintenance in your organization** Martijn Miedema, Thermo Fisher	**Measurement automation with cobots** Theo Drijfhout, Gibas & Jos Willemsen, Polymount	**The power of (re)design for additive manufacturing** Dries Vandecruys, Materialise
15:30	**Break**		
16:00	Introduction by Elena Lomonova, TU Eindhoven		
16:15	 **Embedded micro mechatronics: key factors to foster innovation** Yves Perriard, École Polytechnique Fédérale de Lausanne (EPFL)		
17:00	**Drinks**		

Subject to change

MICROFLUIDICS: NATURE'S WAY

Billions of years of evolution have provided nature with a solution for small-volume fluid propulsion: cilia. These small, hair-like structures are present in many biological systems, and could serve as a propulsion method in microfluidics. Their working principles at low Reynolds numbers have been studied intensively, but are still not entirely clear. Many theoretical models exist, but they have never been benchmarked to a realistic physical model. This article presents the conception of such a physical model, consisting of pneumatic actuators serving as cilia, and tests for observing the flow around them.

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AUTHOR'S NOTE

Sam Peerlinck is a project engineer at Atlas Copco, based in Wilrijk, Belgium. He is the recipient of the Wim van der Hoek Award 2017, for his thesis "Asymmetrisch bewegende cilia voor vloeistofpropulsie bij lage Reynoldsgetallen: een fysisch model". In 2017 he obtained his M.Sc. degree in Mechanical Engeering at KU Leuven University in Leuven, Belgium.
Special thanks go out to Benjamin Gorissen, for his support and guidance during the thesis project.

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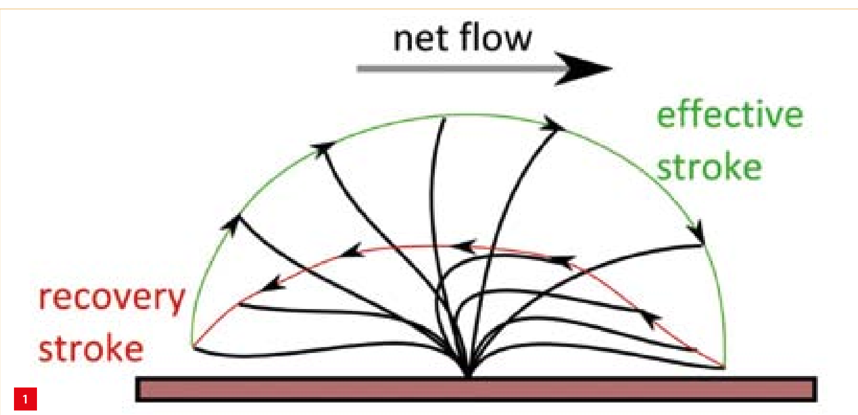
One of the most fundamental building blocks in biological organisms is the transport of fluids. Peristaltic systems like the heart, which transports liters of blood through the human body, immediately come to mind. However, transport of small volumes of fluid is just as vital. Examples are the transport of oocytes (egg cells) through the Fallopian (or uterine) tubes of female mammals, the displacement of mucus through the trachea, the propulsion of fluid through brain ventricles, or even the propulsion of micro-organisms in a fluid environment.

Not only biological systems show the presence of propulsion systems for microsized volumes of fluid, the emerging field of microfluidics proposes other methods for flow induction. These methods, like electro-osmosis or acoustic flow induction, are the result of only a few decades of research. Billions of years of evolution, on the contrary, have delivered a different solution for this microscale transport of fluids: cilia [1]. Cilia are cell organelles of only several tens of micrometers, and move in a typical beating pattern, illustrated in Figure 1.



1 *Typical (asymmetric) beating motion of natural cilia.*

The beating motion of cilia features four types of asymmetry:
- temporal asymmetry, which indicates a difference in speed in different stages of the stroke;
- orientational asymmetry, indicating an oblique position of the mean pose of the cilium;
- spatial asymmetry, a difference between the paths of the recovery stroke and the effective stroke;
- metachronal asymmetry, which denotes a phase shift in the motion of consecutive cilia when in a large group, resulting in a wave-like beating pattern.

These types of asymmetry all influence the propulsion of fluids at low Reynolds numbers [2], where viscous particle forces dominate inertial forces. Spatial asymmetry, however, is an essential type of asymmetry in these conditions, as a net flow can only be induced when the effective stroke follows a different path compared to the recovery stroke.

Although a general idea of fluid flow induction at low Reynolds numbers exists, the exact hydrodynamic principles are not certain yet. Numerous theoretical studies exist that simulate flow induced by ciliary motion, but the calculated optimal beating patterns do not correspond with the motion of natural cilia. Does this mean that theoretical models are still not representing nature correctly, or has evolution not succeeded in finding an optimum after all? To answer that question, this article presents the conception of a physical model of artificial cilia, in which the induced ciliary flow can be accurately observed, to validate existing theoretical models.

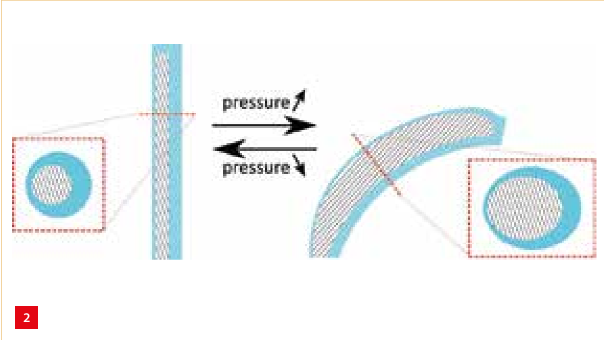
Several approaches to the fabrication and control of artificial cilia already exist in literature, ranging from

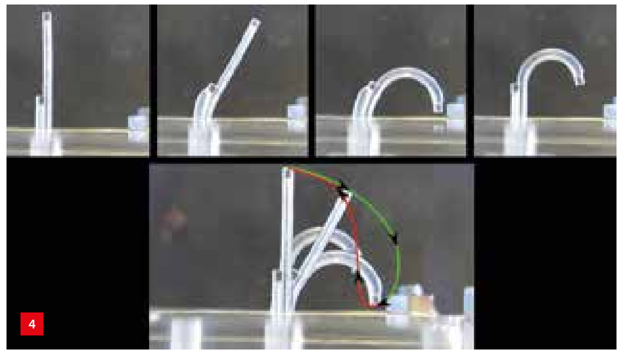
2 *Working principle of the single-DoF pneumatic actuator: bending due to pressurising the internal channel, recovery due to depressurising.*

3 *Working principle of the dual-DoF pneumatic actuator, used as artificial cilium.*

4 *The spatially asymmetric beating pattern of an artificial cilium.*

5 *The beating pattern in an array of cilia, with a wave fitted, showing metachronal asymmetry.*





flexible rods that are electrostatically or magnetically controlled, to more rigid mechanically driven structures. However, none of the existing solutions for artificial cilia feature the necessary types of asymmetry – spatial and metachronal asymmetry in particular – in a controllable manner. The design of the physical model presented here relies on the use of flexible pneumatic actuators, with two degrees of freedom (DoFs) in each cilium. The combination of these actuators in an array forms the most complete and realistic set-up of artificial cilia to date.

Pneumatic artificial cilia

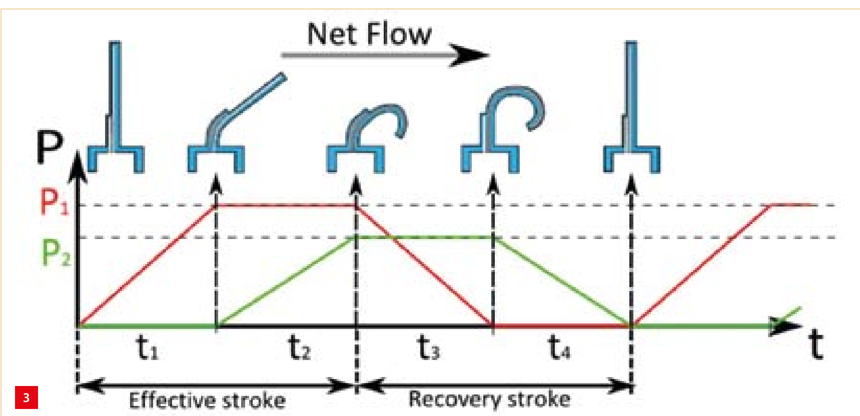
The pneumatic actuators used as artificial cilia are slender rods, made from the silicone rubber polydimethylsiloxane (PDMS). Their asymmetric cross-section, due to an eccentric position of the internal channel, causes a difference of stiffness across the section. When the internal channel is pressurised, this stiffness gradient induces a bending moment, deflecting the actuator to the stiffer side, as is illustrated in Figure 2. If only one such channel is present, the actuator has only one degree of freedom.

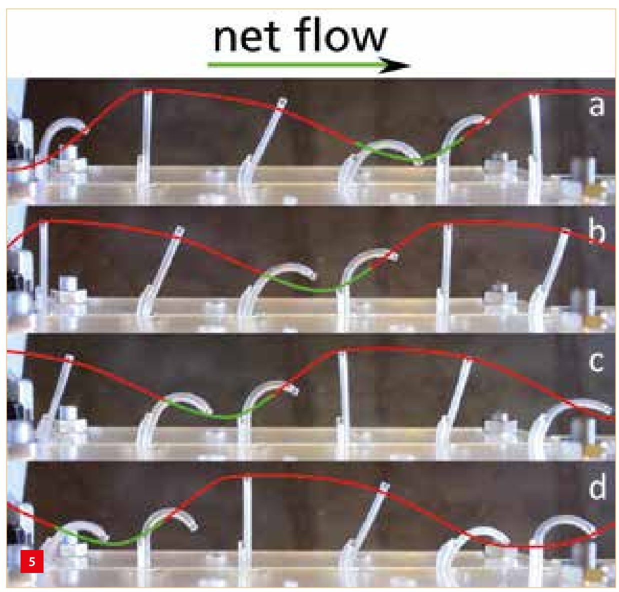
By adding a second internal channel, while maintaining the cross-sectional asymmetry, two DoFs are created, as seen in Figure 3. When a specific pressure profile is then imposed on the internal channels, a spatial asymmetric stroke is generated, which corresponds well to the stroke of natural cilia.

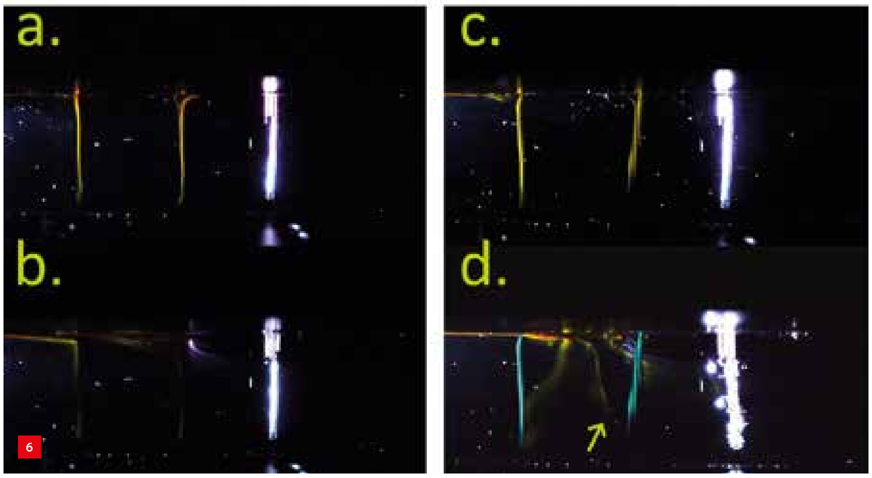
The pneumatic artificial cilia are fabricated by moulding a specific mix of PDMS and curing agent into a custom-made aluminum die. The internal channels are made by inserting microrods into the die. After curing the PDMS rubber by heating the die, the actuator can be taken out, a meticulous process, impeded by the flexibility and fragility of the actuators, having wall-thicknesses of only a few tens of micrometers. The result is a flexible actuator of around 15 mm high and 1 mm wide, with internal channel diameters of 0.5 mm.

After the fabrication of the actuator, small tubes are inserted into the channels, permitting to impose a pressure profile on the channel. This periodic profile (seen in Figure 3) consists of a linearly rising pressure, followed by a stable pressurised state and a linearly decreasing pressure, to be concluded by an idle state, in which no pressure is exerted. The profile in the second channel is similar, only with a phase lag of one-fourth of a period. The resulting beating pattern of the actuator is shown in Figure 4.

The actuation pressure profile can be repeated for several neighbouring cilia in an array. And when a phase lag is imposed between them, the collective metachronal asymmetry can be observed in addition to spatial asymmetry. This is depicted in Figure 5 and in a video [V1]. By changing the imposed pressure profiles in amplitude and







6 *Tests of net fluid flow at low Reynolds numbers as induced by a single cilium (glowing white), using ink droplets for visualisation.*
(a) Start situation of 120 symmetrical beats.
(b) End situation of 120 symmetrical beats.
(c) Start situation of 100 asymmetrical beats.
(d) End situation of 100 asymmetrical beats (with the effective stroke to the right). The start position of the ink (two yellow lines) has been superimposed (in blue/green) on the end situation for reference. The shift of the ink to the right is indicated by the arrow.

timing, the magnitude of both types of asymmetry can be varied, making this physical model of ciliary beating patterns the most complete and realistic to date.

Fluid flow induction

Now the beating patterns of the artificial cilia have been established, the question rises how they behave in a fluid. To check the fluid-dynamic effect of the cilia at low Reynolds numbers, a highly viscous fluid is selected: glycerol, which is 1,000 times more viscous than water. In order to observe a fluid flow in glycerol, a D-shaped closed loop is fabricated where the cilia are bundled in the straight part of the channel and enclosed by glass walls, to make observation possible.

To establish that the cilia can induce a net fluid flow at low Reynolds numbers, some qualitative tests have been performed; see the video [V2]. Ink droplets injected in the fluid enable the visualisation of a net flow. First, a spatially symmetric beating pattern was imposed on a single cilium (by using only one DoF), which is glowing white in the pictures of Figure 6.

After 120 symmetrical beats no shifting of the ink lines has been observed, as can be seen when comparing the yellow ink lines of Figure 6a before and Figure 6b after actuation. As was expected, no net fluid flow is induced by a symmetrically beating cilium at low Reynolds numbers. Only a slight leftward movement of the ink is seen in Figure 6b, which is caused by an emerging air bubble pushing the fluid to the left.

After 100 asymmetric cilium beats have been imposed to the fluid, a clear movement of the fluid can be seen by comparing the yellow ink lines of Figure 6c before and Figure 6d after actuation. The shift (to the right) of the ink in Figure 6d has been indicated by an arrow. So, this test shows that the asymmetrically beating cilium induces a net fluid flow to the right, in the same direction as the effective stroke, at a low Reynolds number.

In order to make precise, quantitative observations of the induced ciliary flow, a new testing procedure and set-up has been devised. This consists of a particle image velocimetry (PIV) test, which implies dissolving fluorescent tracer particles in the fluid, and tracking those particles with a high-resolution camera. The preparations of these tests have been conducted, down to selection and requirement of the particles and camera system, but the actual tests were not yet performed in the scope of the thesis work.

Conclusion

The working principles of both natural cilia, present in countless biological systems, and artificial cilia, possibly useful in microfluidics, at low Reynolds numbers have already been rigorously researched, but still remain unclear. Many theoretical models exist, but never have they been benchmarked to a realistic physical model, as was done in the presented thesis. The physical model contains dual-DoF pneumatic actuators, serving as artificial cilia and showing the necessary asymmetries to induce fluid flow at low Reynolds numbers. These actuators are fabricated and controlled by a pressure profile.

Qualitative tests show both the necessity for spatially asymmetrical beating patterns at low Reynolds numbers and the ability of the proposed artificial cilia to induce a fluid flow in these conditions. Finally, a set-up for quantitative PIV tests has been prepared, which in a next step can provide results of ciliary fluid propulsion. Whether the results will confirm or reject the theoretical models, the outcome will be an important result to clarify nature's solution for propulsion of minimal volumes of fluid, cilia. ■

REFERENCES
[1] *en.wikipedia.org/wiki/Cilium*
[2] *en.wikipedia.org/wiki/Reynolds_number*

VIDEO
[V1] Spatially asymmetric cilia – metachronal waves: *youtu.be/JBnQM0LAhHA*

[V2] Spatially asymmetric cilia – ink test: *youtu.be/7QyxQtIjDs4*

Phaer – high-end computer vision components, services and expert knowledge

Since its incubation in 2007, Phaer has grown into a leading supplier of high-end computer vision components, services and expert knowledge. Computer or machine vision has become an essential ingredient in industrial automation. Knowhow and expertise are the core business of Phaer. The company provides application development support services and vision components from technology-leading vision component manufacturers, and offers business progress to OEM companies and system integrators in the Benelux who lead in vertical markets, from automotive and semiconductors to food and aerospace.

In the evolution towards a smart industry, computer vision can help Western European society maintain a globally competitive economy. It is the ambition of Phaer, based in Gentbrugge, Belgium, to contribute by inspiring 'local' industrial parties to stay up-to-date in computer vision. Customers include OEM companies and start-ups who can gain a competitive edge by applying the latest vision technology in their products and machines, and system integrators who integrate vision solutions in their projects.

Components

In the Benelux, Phaer is an exclusive distributor of high-end vision components that have been selected for their high performance, reliability, low cost of ownership and long-term availability. Components such as cameras, sensors, lenses, lasers, filters, framegrabbers, cables and lighting are provided by renowned manufacturers including Bitflow, CEI, CCS, Imperx, Kowa, Osela, Photonfocus, Schneider and Teledyne e2v. With the aid of local R&D partners or the manufacturer's R&D department custom-made components can be designed and produced.

Services

Phaer also provides application development support services, ranging from advice to 'light studies' and fully-fledged R&D projects. These services aim to assist the customer with quickly validating vision concepts. To that end, in the early stage of a project Phaer can supply vision components and engineering support for the evaluation of vision solutions. This scrum-like approach will speed up design projects. In the same manner, Phaer's support helps to shorten R&D projects.

1 *Koenraad van de Veere, general manager of Phaer: "It is our ambition to help companies stay up-to-date in computer vision."*

Knowledge

Underlying all services is a deep understanding of optics, photonics and computer vision, in-depth knowledge of the available components and extensive experience in vision consultancy and R&D. In essence, Phaer is a knowledge transfer company maintaining close relationships with manufacturers and researchers. These contacts provide not only the latest information on vision components and solutions, but also knowledge of market trends and insights into R&D directions and technology roadmaps. The current state-of-the-art includes 3D vision and hyperspectral imaging (HSI). For instance, Phaer inspired and supported start-up company Delft Robotics in applying 3D stereo vision to win the Amazon Picking Challenge. And imec, a Belgian world-leading R&D and innovation hub in nanoelectronics and digital technologies, invited Phaer to market the HSI toolkit it has developed.

Future-proof

The vision portfolio includes smart cameras and sensors. However, Phaer's motto is: "Don't buy smart, be smart", because 'standard' smart components usually cannot 'stretch' to meet the application-specific requirements which emerge during the development phase. Being smart implies incorporating all the available options and knowledge to realise the best possible vision solution – future-proof.

Vision Expert Day

On 26 March 2018, Phaer will be hosting the Vision Expert Day in Ghent (Belgium), where leading international experts will outline the hardware technology drivers for future vision systems. The high-tech event targeting CTOs and vision system design engineers explores the intersection between sensor and camera design, as well as communication standards, embedded vision and optics.

WWW.VISIONEXPERTDAY.EU

INFORMATION
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DIAMONDS ARE FOREVER

James Bond had to defeat Blofeld to prevent the execution of evil plans with diamonds as the fatal stakes… Generally, these minerals derive their value from their application in precious jewellery, but more interesting here is the application of this hardest of all materials in the machining of metals for precision technology. Contour Fine Tooling in Valkenswaard, the Netherlands, have mastered as no other company has the grinding, lapping, polishing and mounting of tiny diamonds in high-precision tools.

FRANS ZUURVEEN

AUTHOR'S NOTE

Frans Zuurveen, former editor of Philips Technical Review, is a freelance writer who lives in Vlissingen, the Netherlands.

How did these diamond activities land in a small town like Valkenswaard, when Amsterdam and Antwerp were traditionally the famous diamond centres? For an answer to this question we have to go back in history [1]. More than a century ago, incandescent lamp manufacturers tried to find a metallic alternative for their fragile, short-lived carbon filaments. They experimented with pastes containing tantalum, osmium or tungsten particles, from which they extruded thin wires. Sintering transformed these vulnerable products into – still fragile – metallic filaments. Thus the origins of the famous brand Osram, named for filaments from both osmium and tungsten (Wolfram in German).

In 1911, messages reached Eindhoven that engineers at General Electric had succeeded in drawing tungsten filaments, thanks to the discovery that tungsten becomes ductile by swaging and hammering. This news urged Anton Philips to travel immediately to the United States to visit hammering and drawing equipment manufacturers. On 23 October, Anton telegraphed to his brother Gerard regarding his findings on the machining of tungsten: "...swaging red hot (stop) starting one quarter inch gradually to one quarter millimeter (stop) drawing on small wirebanks to 0.03 mm through 97 diamond dies..." In November, Anton returned by steamer to Europe, taking with him in the ship's hold hammering machines, wire-drawing banks and, last but not least, diamond drawing dies.

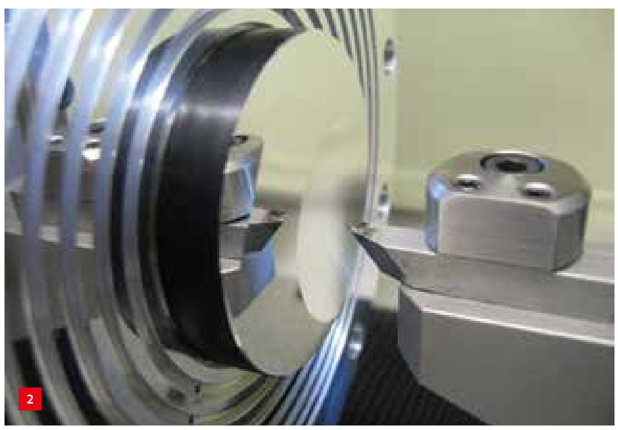
This energetic action from Anton Philips may be regarded as the start of the application and machining of diamond in the Eindhoven area. After the fabrication of countless diamond-drawn tungsten wires in the factory at the Emmasingel in Eindhoven (see Figure 1), Philips' Metaal-Gloeilampenfabriek, the original name, opened a sister factory in nearby Valkenswaard for the production of drawing dies from diamond.

Over the years, this diamond expertise centre evolved into the current company Contour Fine Tooling, CFT (see Figure 2), associated with Technodiamant in Belgium. Together with the Esteves Group, CFT belongs to the Diamond Tools Group (DTG). Today CFT focuses on the application of diamond in machining tools, whereas diamond drawing dies belong to the Esteves delivery programme.

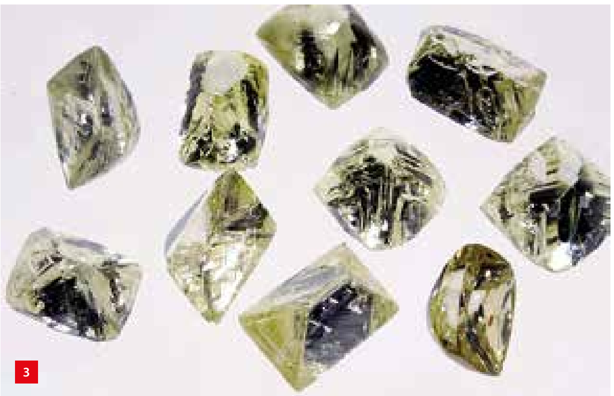
1 *Mounting metal filaments in the former Philips incandescent lamp factory at the Emmasingel in Eindhoven [1].*

Types of diamond base material

The first differentiation in the diamond material used by CFT is between the natural and the synthetic type. In fact, the majority of this expensive CFT base material is of natural origin, mainly supplied by South African mines (see Figure 3).



2 *Machining an optical freeform surface with a solid-shank tool with diamond slice from CFT.*



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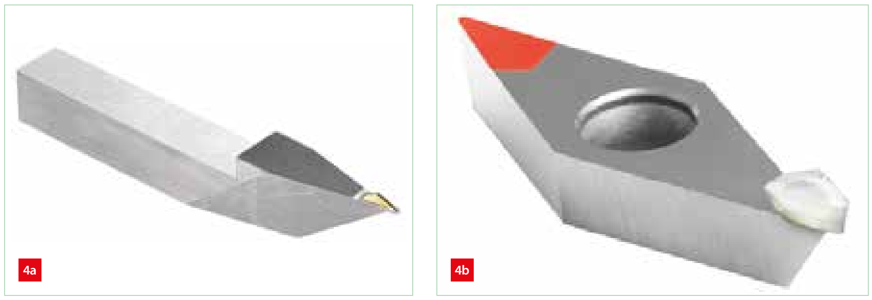


4a 4b

3 *A selection of rough natural monocrystalline diamonds used by CFT.*

4 *Methods of mounting a small diamond slice in a machining tool.*
(a) Soldering at the end of a solid shank.
(b) Soldering at the corner of a standardised rhombic insert.

The oldest process for making synthetic diamond is called HPHT, meaning the application of extremely high pressure and temperature under tightly controlled growth conditions. General Electric succeeded in 1970 in making synthetic diamond under laboratory conditions with a temperature of about 2,000 K and a pressure of 5.5 GPa, or 55,000 bar.

Another process that produces synthetic diamond is CVD, chemical vapour deposition. It uses plasma in a gas mixture of methane and hydrogen, the latter because it selectively etches off non-diamond deposed carbon. The advantage of this process is that high pressures are not required. When growing diamond by CVD on a substrate, the grains grow larger as the layer gets thicker. With an average grain size of about 20 µm, this makes CVD diamond a polycrystalline material.

Another polycrystalline material is PCD, polycrystalline diamond. This semi-synthetic material uses a sintering process to bond tiny diamond particles together. It means that both CVD and PCD diamond materials have soft and hard grains oriented in different directions, locally affecting the wear characteristics. Due to a random orientation of diamond particles, these materials have a rather uniform hardness and an abrasive resistance in all directions, contrary to the properties of monocrystalline diamond.

Impurities in diamond base material cause dislocations in the crystalline structure. The most commonly occurring impurities are due to nitrogen, which gives diamond a yellow or even brown colour. That's the reason why CFT mainly uses diamonds that are as clear as possible, with only a small trace of yellowness.

Machining with diamond

Unfortunately, diamond slices can only be used for the precision machining of non-ferrous metals and plastics. The hardest of all materials cannot machine steel, because diamond reacts with the carbon in steel. Consequently, the diamond gets 'graphitised', resulting in an unfavourable crystal structure. This problem can be overcome by applying slices of boron nitride with a cubic crystalline structure, which nearly achieves the same hardness as diamond. The polycrystalline structure is called PCBN, polycrystalline cubic boron nitride. Incidentally, CFT applies PCBN for special customer requirements.

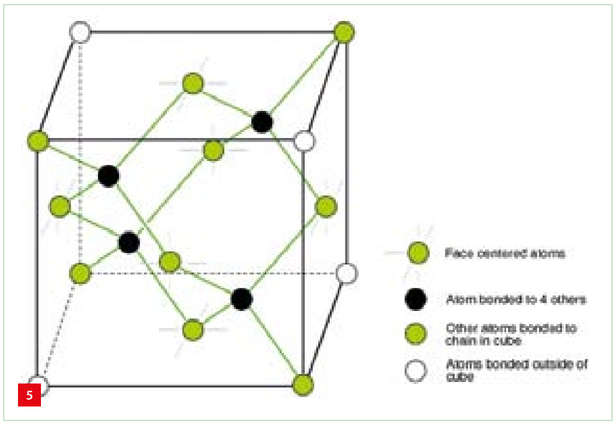
A rather recent solution for the machining of steel with diamond slices is an ultrasonic tooling system operating at up to 120 kHz with an amplitude of some tens of micrometers. Companies like Tara, Son-X and Innolite offer systems that enable the tool tip to vibrate in a tangential direction in relation to the product centreline in turning machining centres. It is not completely understood, however, why this ultrasonic tool point movement helps to prevent graphitising, but applications have shown its effectiveness in reaching optical surface finishes in hardened steel and even glass substrates.

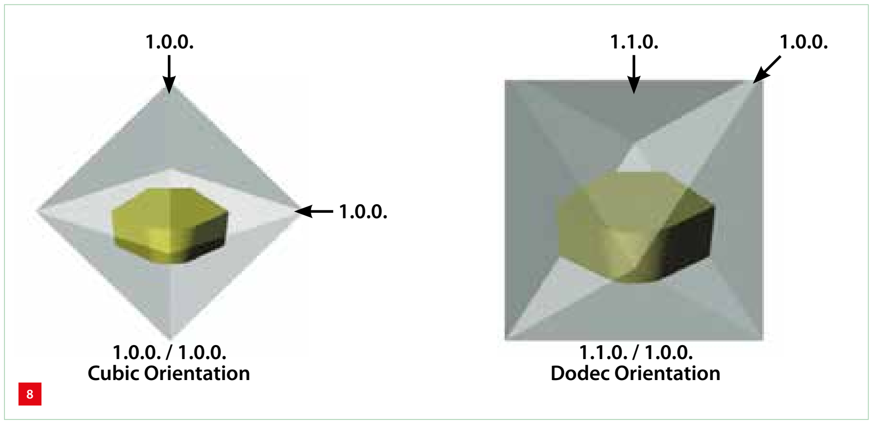
CFT applies two methods of mounting a small diamond slice in a machining tool (see Figure 4). The first is soldering the slice at the end of a solid shank of molybdenum steel or hastelloy (Figure 4a). According to an ISO standard, this shank is 6.35 mm square in cross-section and 50 mm long. The second method is soldering the slice at the corner of a rhombic insert from carbide (Figure 4b), dimensioned according to another ISO standard. This insert can be screwed onto a tool holder of roughly equal dimensions to the solid shank referred to above.

The advantage of the shank-insert combination is that it is easy to change the insert after a diamond slice has worn out. This makes realigning the tool and workpiece unnecessary. The soldering of diamond on the insert or shank using soldering paste is a long-lasting, hard-brazing process done in a furnace with an oxygen-free environment to prevent oxidation.

Lattice structure details

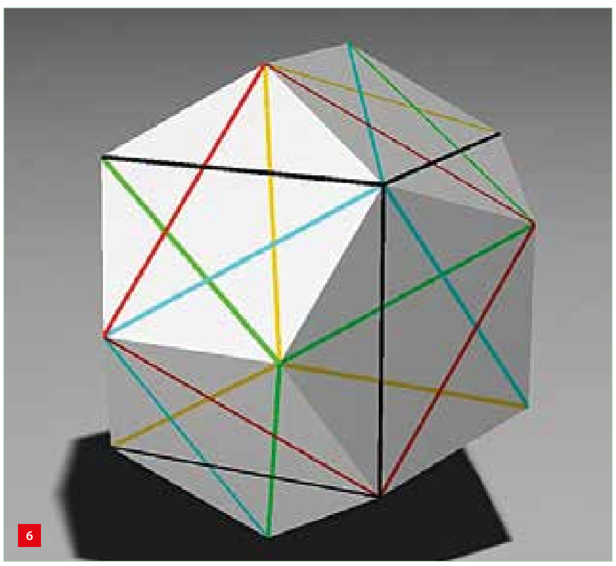
Figure 5 shows a unit cell of the diamond crystal lattice structure. It is a variation of the face-centred cubic crystal structure with each carbon atom covalently bonded to four surrounding atoms. The configuration of the atoms in the face-centred cubic lattice can also be regarded as a lattice of





coupled octahedrons or of coupled rhombic dodecahedrons. This becomes easier to understand with careful observation of Figure 6.

An octahedron consists of eight equilateral triangles in a combination of two five-sided pyramids with a common square bottom plane (Figure 7a). A rhombic dodecahedron consists of twelve faces, each equal to a rhomb (Figure 7b). CFT defines the octahedron structure as cubic, the rhombic dodecahedron structure as dodec. Figure 8 shows how these two configurations are used to find the best orientation for a diamond slice to have optimal cutting qualities, with the dodec orientation as the preferred one for less wear.



5 *A unit cell of the diamond crystal lattice, which is a variation of the face-centred cubic crystal structure with each carbon atom covalently bonded to four surrounding atoms. (Source: Indian Institute of Technology, Delhi)*

6 *The relation between the face-centred cubic and the dodecahedron structure lattices. (Drawing by Simon Tatham)*

7 *Alternative views of the atoms in the face-centred cubic lattice.*
(a) An octahedron consisting of eight equilateral triangles.
(b) A rhombic dodecahedron consisting of twelve rhombic faces.

8 *CFT-defined optimal cutting diamond orientations in a cubic (octahedron) and a dodec (rhombic dodecahedron) lattice. This last orientation is preferred for less wear.*

9 *A Coborn PG3 diamond grinding machine. At mid-height on the left is the tool shank holder, placed on a turntable to enable a high-precision radius at the diamond slice point to be made.*

Machining diamond

The main challenge when making diamond cutting tools lies in machining this material, as it has the highest hardness rating possible, a 10 on Mohs' scale. This scale characterises the scratch resistance of various minerals via the ability of a harder material to scratch a softer material. The only material that scratches diamond is diamond, making the production of accurately formed diamond slices a time-consuming process.

CFT grinds, laps and polishes diamond by applying grinding discs with tiny diamond particles or by using copper discs with diamond grains in oil. For that purpose, CFT uses Coborn grinding machines (see Figure 9) or machines developed in house. Having high-quality grinding spindles is a very important condition for accurate finishing. Their rotational accuracy enables them to reach tolerances better than 2 μm for the ground diamond planes.

In general, diamond slices are already pre-prepared by CFT's sister companies, thus CFT needs only to remove 20 to 50 μm material, which nevertheless asks for many hours of work. Making sharp cutting edges is quite challenging. The smallest radius that can be accomplished is only 1 μm, but more often accurate larger radii are necessary. Below is an explanation of how the diamond tool radius influences surface quality and product form.

Tool radius influence

CFT helps customers to select tools and processes for the accurate machining of their precision products. Before providing those tools, however, CFT discusses with potential customers which tools and application data will optimally help to fulfil the machining demands. During this preliminary discussion process, identifying the best tool radius is an important item.

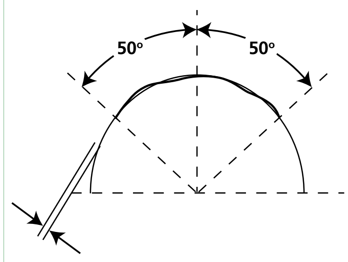
The tool radius influences the product geometry in two ways. Firstly, there exists a correlation between surface roughness and tool radius (see Figure 10). With increasing tool radius and decreasing feed rate, the roughness value becomes smaller and thus the surface quality better. Secondly, the tool radius influences the form of the generated surface: the orbit path of the centre point of the tool radius is not equal to the shape of the form being cut. This can be compensated for by the CNC software programme.

Both influences demonstrate the importance of the tool radius' dimensional accuracy, generated by CFT grinding and lapping equipment. A third argument is that in some cases, the tool slice form is directly reproduced in the product. That's why the lapping process can be optically monitored during operation.

The importance of radius accuracy asks for the delivery of controlled-waviness tools by measuring the deviation of the radius shape from a true circle. For that purpose, CFT measures the peak-to-valley value over a given arc, the standard for which is 100°, but it can be 120° or even 130° for special applications. The results of this waviness measurement (see Figure 11) are shown on a chart that is supplied with the tool.

To conclude

Diamond is the hardest of all materials and consequently one of the most difficult to machine. That's why it is highly beneficial for the precision engineering world that Contour Fine Tooling has succeeded in mastering these difficult diamond machining processes. CFT makes diamond machining tools available for all customers who struggle with precision machining problems in the production of optical components, complicated moulds and many more precision products in a wide variation of materials. ■



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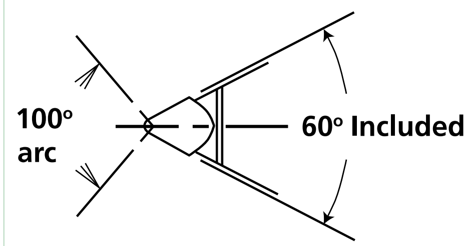

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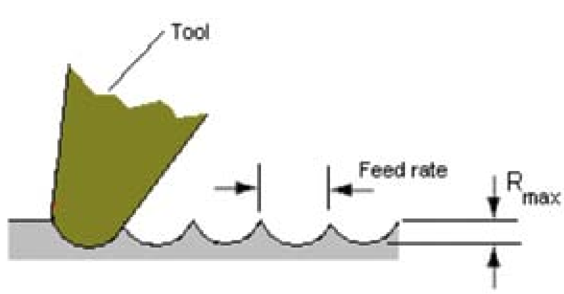

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10 *Influence of tool radius on surface quality. (Drawing: G.V. Dasarathi, www.cadem.com).*

11 *Waviness measurement for a diamond tool point.*
(a) Definition of peak-to-valley value of waviness for an arc of 100°.
(b) Standard arcs.

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INFORMATION
WWW.CONTOUR-DIAMONDS.COM

Technobis mechatronics – specialist in innovative series production

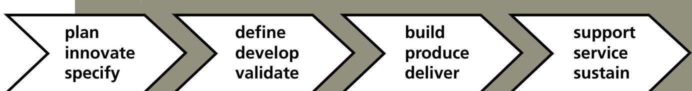
Technobis Group, based in Alkmaar, the Netherlands, is a group of companies that provide innovative series production support to market-leading high-tech equipment companies. Technobis services can range from R&D, engineering and prototyping to manufacturing and supplying products. The business unit Technobis mechatronics specialises in developing, realising and sustaining series products, modules and systems. Serving demanding customers – SMEs and large companies as well as knowledge institutes – in medical, life-science and high-tech industries, Technobis mechatronics is driven by technological innovation and entrepreneurial spirit.

The Technobis group comprises four business units:

- Technobis mechatronics: complete product development, from idea to production ready for the market.
- Technobis tft-fos: development and supply of fibre-optic sensing systems and applications, primarily based on integrated photonics.
- Tipps: solutions for PIC (photonic integrated circuit) evaluation & packaging, including dedicated and mid-range volume packaging services.
- Technobis crystallisation systems: crystallisation technology for solid-state research, process development and formulation.

Product lifecycle management

Technobis mechatronics is specialised in carrying out complete product development projects, going from an idea to a successful prototype, one-off or series product. The focus is on turnkey products, modules and systems, ready for immediate integration in the customer's business process. Projects can cover the full scope of product lifecycle management:



Design and engineering

In close collaboration with the customer, Technobis mechatronics engages in defining product- or process-related requirements and specifications, developing concepts, drawing up system architectures and generating models. Building on extensive experience in precision mechanics, high-tech instrumentation and medical technology, designs are created. Reviews, model calculations, simulations and rapid prototyping technologies are used to test concepts and validate designs. Services include project management and the supervision of CE and other certification procedures.

Manufacturing

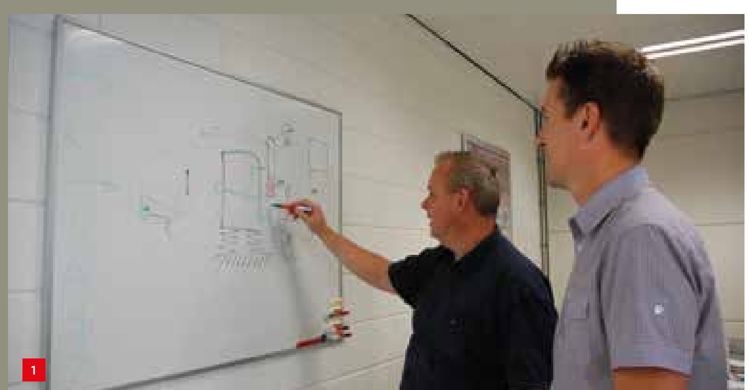
Technobis mechatronics can take full responsibility for prototype, one-off and series production, including supply chain management. Following an optimal system breakdown in the design phase, an efficient assembly procedure can be established for which state-of-the-art facilities and competences are available. Testing procedures and facilities are set up to validate the process and assembly manuals are generated and maintained for internal and external use.

Sustaining

In the sustaining phase of the product lifecycle, Technobis mechatronics takes care of document management, traceability (recording product or system history) and cost optimisation (value engineering). The Technobis quality management system complies with ISO 13485 (medical devices).

Inspiring products

Employing its full range of competences, Technobis mechatronics realises inspiring products for demanding applications. Examples include a special anaesthetic instrument / intensive care unit ventilator, mechatronic units which are used in radioactive environments for producing nuclear medication, and the world's first instrument that combines optical tweezers, confocal microscopy and advanced microfluidics.



1 *In close collaboration with customers, Technobis mechatronics engages in defining product- or process-related requirements and specifications, and developing concepts. On the left: Alex de Leth, general manager.*

INFORMATION
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MASTERING THE MAKING OF MICRO-HOLES

Posalux means "put the light on". Posalux, located in Biel in the heart of the Swiss watchmaking industry, focuses its light on the manufacturing of holes down to a diameter of 50 μm. For that purpose, Posalux delivers machines that apply three different technologies: micro-EDM (electrical discharge machining), femtosecond-laser ablation, and high-precision micromilling. Needless to say, these versatile machines do a lot more than 'simply' making holes.

FRANS ZUURVEEN

Posalux is a rather small company, employing a workforce of about a hundred skilled men and women. It was established more than 70 years ago and has a history of several technological innovations, among them a numerically controlled multi-spindle machine launched in 1975. One of its recent activities is the micromachining of glass using SACE technology (spark-assisted chemical engraving) for lab-on-a-chip products, to mention just one impressive example. Posalux's craftsmanship in making tiny precision holes is applied widely in the automotive industry for fuel injection applications; gasoline direct injection and diesel injector nozzles, using EDM.

AUTHOR'S NOTE

Frans Zuurveen, former editor of Philips Technical Review, is a freelance writer who lives in Vlissingen, the Netherlands.

Micromilling

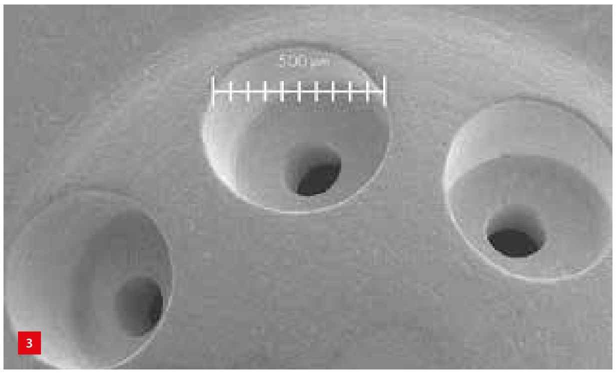
Instead of milling with cutting fluid, Posalux uses a dry milling process in its FP1 machine (see Figure 1). The advantage of this dry air-jet process is that it avoids the contamination of workpieces that can occur when cooling with cutting fluid. The Posalux FP1, designed for mass production, enables the micromilling of hard materials up to 67 HRC. In most cases, hard-milling requires that the cutting edges, called flutes, have a negative rake angle. But a process such as hard-milling can only be performed on a machine with high stiffness and stability, in order to avoid vibrations (a notorious phenomenon called *Ratter-schwingungen* in German). An innovative main spindle design also helps to improve machine stability. The X-, Y- and Z-axes are provided with linear motor drives facilitating a positioning accuracy for drilling of 10 μm.

1 *A Posalux FP1 micromilling machine with X-, Y-, and Z-strokes of 300, 300 and 70 mm, respectively, and Siemens 840D numerical control.*

The main spindles that accommodate micro-end-mills are not made by Posalux, but are provided by Levicron from Kaiserslautern, Germany. These high-precision spindles have air bearings, which results in a dynamic tool run-out smaller than 0.5 μm and a shaft centre error of less than 30 nm. The Levicron spindles used by Posalux have a rotational speed of 60,000 rpm, optionally even 100,000 rpm. They are provided with an integrated synchronous motor, a precision HSK-E25 collet with diameters of 3, 4 or 6 mm, and a thermo-controlled fluidic cooling system.

Figure 2 shows an FP1 machine at work. Figure 3 depicts a micromilled stepped hole and a femtolaser-machined spray hole for fuel injectors, with diameters of 500 and 100 μm, respectively. It would be interesting to know which micro-milling tools are used to make such tiny holes in very hard material, but understandably Posalux is reluctant to provide details about their microtools. The only publicly released information is a claim of tool life before failure of up to 5,000 fabricated holes.

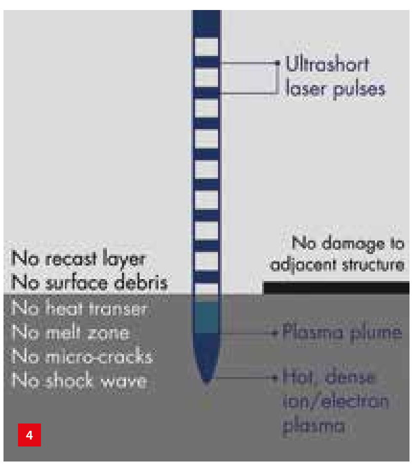
It would be not far from the truth to suggest that Posalux (or an external supplier) uses grinding wheels with

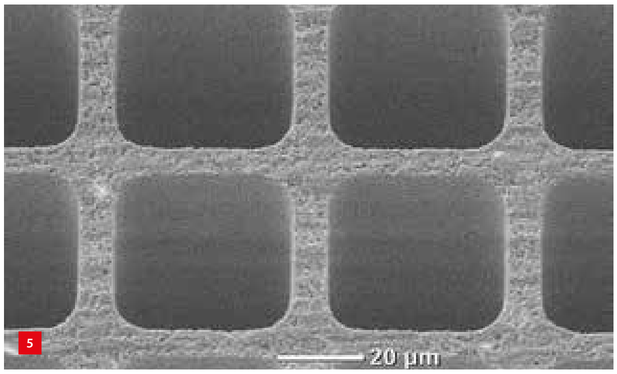


extremely small diamond particles to make micromilling tools. An earlier article in Mikroniek [1] described the production of micro-end-mills from solid carbide, typically with a cutting diameter of only 100 µm, by Van Hoorn Carbide in the Netherlands. This ultra-hard material is characterised by tungsten-carbide grains in – mostly – a cobalt substrate. It is probable that similar tools are used for holes like the ones in Figure 3, perhaps with another base material such as ultra-hard ceramic.

Femtosecond-laser micromachining

A rather recent micromachining technology uses a pulsed laser. Thanks to an ultra-short pulse time of down to 230 fs, several materials including hard ceramic and ruby material do not melt, but only vaporise. This minimises the heat influence outside the focus area with a diameter of some





micrometers [2]. Figure 4 schematises the femtosecond-laser ablation process.

Posalux has designed three versions of its Laser-F micro-machines: the Mono with one femtosecond laser; the Twin with two workpiece stages for mass production; and the Combi with micromilling and femtosecond lasering combined into one prototype-research machine. Here it should be highlighted that Posalux is always prepared to co-operate with clients to find dedicated solutions for micromachining problems.

Figure 5 demonstrates that a Posalux Laser-F machine is also capable of making square micro-holes in hard ceramic materials. Depending on material thickness a process cycle time of less then 1 s is possible.

Micro-holes with EDM

The Posalux HP4 machine has been designed for mass production in micro-EDM technology. The smallest electrodes applicable have a diameter of no more than 35 µm. They are able to rotate with up to 3,500 rpm, resulting in better hole geometry, shorter erosion times and better dispersion of material ablation. Figure 6 illustrates the micro-EDM machining of a deep hole in hard material. Figure 7 shows how a four-spindle design helps to shorten production times. Figure 8 depicts a micro-EDM-fabricated nozzle, where each hole has a diameter of 100 µm

2 *The interior of an FP1 machine with inaccuracies of ±1 µm for the three linear axes and ±0.04° for the two rotational axes.*

3 *A micromilled stepped hole and a femtolaser-machined spray hole for fuel injectors, with diameters of 500 and 100 µm, respectively.*

4 *Schematic drawing of the femtosecond-laser ablation process with a presentation of its strong points.*

5 *Femtosecond-laser-ablated square holes: 40 x 40 µm² in Si_3N_4. The pitch is 50 µm, so the wall thickness is only 10 µm.*

6 *A conical hole produced by micro-EDM.*

7 *Four spindles in an micro-EDM machine for shorter production times.*

8 *A nozzle produced by micro-EDM.*

minimally. The only limitation of micro-EDM is that the material needs to be electrically conductive. Micro-EDM provides very smooth surfaces with R_a values of 0.25 µm.

To conclude

Whatever the precision-hole making problem may be, Posalux has a solution in its high-precision technologies programme: milling, laser ablation or micro-EDM. Finally, Posalux is more than a simple hole-making specialist: its knowhow in micro-hole making is far more widely applicable than just for precision machining for fuel injection in the automotive industry. ■

REFERENCES

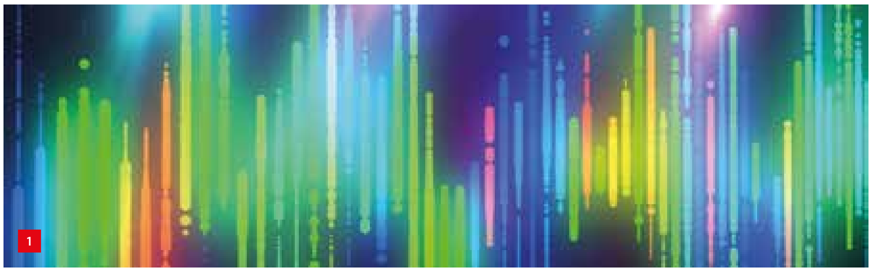
[1] F. Zuurveen, "Mastering carbide machining of precision end mills", *Mikroniek*, vol. 55 (1), pp. 8-11, 2015.

[2] F. Deiter, "Laserlicht für die perfekte Düse", *Mikroproduktion*, 16 (4), pp. 56-59, 2016.

INFORMATION
WWW.POSALUX.CH
WWW.LEVICRON.COM

A BRIGHT FUTURE FOR OPTICS PRODUCTION

The Aachen Optics Days on 10-12 April 2018 will celebrate the bright future for optics production at two conferences. The two-day Aachen Polymer Optics Days event is devoted to injection-moulded optics, line production of planar optics and sheets, new materials and applications for plastic optics, light sources and optical systems. The two-day International Colloquium on Glass Optics covers glass optics and photonics featuring sessions on material, display, imaging, and infrared. A combined session is dedicated to the digitalisation of optics production.



1 *The Aachen Optics Days 2018 cover a broad spectrum of optics production-related topics.*

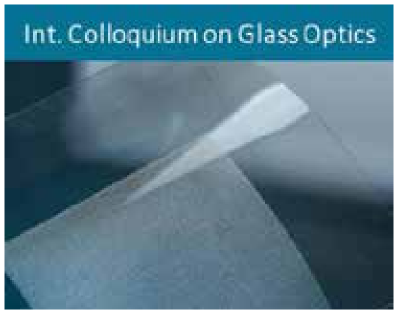
Aachen is traditionally a major site for high-tech developments, due to the presence of Germany's largest university for technical studies, RWTH Aachen. In addition to traditional mechanical engineering disciplines, optics and especially their production-related fields of fabrication, metrology and assembly have gained in importance for the technology region of Aachen. During the past few decades, numerous spin-off companies have evolved to become worldwide renowned leaders in their technology. In addition, the strong research efforts from diverse university institutions also helped Aachen to grow into an international hotspot for the production of optical components and systems.

Two events

By means of joint efforts, industry and research continue to pioneer new fields in optical technologies in Aachen. This not only includes single technological developments and leading products, but also comprehensive approaches to optics production, such as optics manufacturing in a digitalised production environment. To present the current developments and latest trends in these fields to the optics community, the Aachen Optics Days international conference will be held on 10-12 April 2018.
The organising committee comprises Fraunhofer IPT (Production Technology) and ILT (Laser Technology), and the Institute of Plastics Processing (IKV) in Industry and the Skilled Crafts at RWTH Aachen University.

This major event combines two conference tracks with each their own material focus:

Aachen Polymer Optics Days, 10-11 April 2018, organised by Fraunhofer IPT and ILT, and IKV.



International Colloquium on Glass Optics, 11-12 April 2018, organised by Fraunhofer IPT and ILT.

While the Aachen Polymer Optics Days shed light on the development and manufacture of innovative concepts in the field of optical polymers, the International Colloquium on Glass Optics focuses on technologies involving glass optics production.

Manufacturing technologies and applications in the field of optics are at the centre of the Aachen Optics Days and will be explored in over 45 expert presentations by international speakers from industry. Visitors will have the option of either taking part in one of the two specialist conferences focusing on one of the materials, depending on the individual interests and subject specialisms, or attending the Aachen Optics Days as one entity encompassing both conferences.

EDITORIAL NOTE

This preview was contributed by the organisers of the Aachen Optics Days 2018.

Besides the technical presentations, attendees can participate in a tour through the laboratory and test bench facilities at Fraunhofer IPT and ILT, as well as the Plastics Processing Institute IKV. Moreover, the conference provides for broad networking possibilities with coffee breaks in the industry exhibition area and two evening events.

Digitalisation

In addition to the material-oriented emphasis in each of the events, they also provide a shared session on the subject area of digitalisation, accessible as a higher-level platform to participants of both conferences. The presentations in this session will provide insights into current approaches to the modelling of complex production chains in the manufacturing of optical elements and systems. Rather than only returning information back to previous process steps as a basis for iterative process improvement (= feedback), these approaches also supply information to process steps still to come (= feedforward), in order to manipulate their parameters depending on the individual component manufacturing history.

For this combined feedback-feedforward approach to production, not only detailed component information is required, but also an in-depth knowledge of the corresponding production chain and its correlations. To facilitate this kind of adaptive production process, suitable models are required, which not only incorporate ingeniously used optical design software but also the combination of, for example, finite-element simulation of thermomechanical stress and robust design optimisation in order to identify and prioritise the most important correlations. The design of these models, the kind of data needed and the corresponding metrology systems required will be elaborated from different perspectives. ■

2 *Digitalisation allows gaining valuable insights into the process of precision glass moulding.*

INFORMATION

WWW.IPT.FRAUNHOFER.DE/EN/DATES/CONFERENCES/AACHENER-OPTIKTAGE.HTML (REGISTRATION)
WWW.AACHEN.POLYMEROPTICS.DE
WWW.OPTIK-KOLLOQUIUM.DE

Brecon Group – when the right conditions are crucial

The Brecon Group develops and builds innovative controlled-environment concepts for working in clean air and thus preventing contamination for humans or products. In all activities, Brecon Group tries to create added value for its stakeholders on an economic, social and ecological level.

Brecon works with various wall and ceiling systems, all developed over the years and constantly optimised with regard to their properties. Since a number of years, Brecon has been working for the GMP-related market (GMP = Good Manufacturing Practice) with BCPS (Brecon Cassette Panel System). This is a completely flush executed wall and ceiling system with beautiful single and double doors, available in steel or in HPL (High-Pressure Laminate) finish. Food-safe or bactericidal finishes are also possible.

In addition to its own direct activities, Brecon is also the initiator of the successful PP4C partnership on the Dutch market. Internationally, this partnership operates in a slightly different composition, under the name PP4CE. In both concepts, the goal is to deliver complete turnkey cleanrooms or laboratories that meet the GMP and/or ISO 14644 qualifications.

A correct design process on the basis of the customer's programme requirements (URS, User Requirements Specification) and the qualitatively correct delivery, construction and end-qualification of a cleanroom is the basis of a correct and pleasant (GMP-grade) working environment at the highest level. Once delivered and classified at the required level, it is also important that the required conditions are maintained during the period of use. That requires not only good maintenance and an annual integrity test. The right code of conduct, a good cleaning plan and correct clothing regime are at least as important. Many new, but also experienced, cleanroom users are not always aware of this.

With its diversity of services and products, the Brecon Group tries to offer an 'all-in-one concept' for optimal controlled-environment technology. The various Brecon components are guaranteed for the completion of this assignment and are provided with the required knowledge and experience to serve customers correctly.

Anyone needing a new facility or having renovation plans for a cleanroom or laboratory, or looking for a good partner for the design and construction of a cleanroom in general or expert support in determining the right clothing regime or the periodic maintenance plan, can turn to Brecon. They will receive a further introduction to its 'all-in-one' package of services, and enjoy the experience of working with a company where flexibility, quality, reliability and honesty have been core values for more than 27 years. ■

1 *Brecon offers a total turnkey cleanroom, from walls, ceilings, floors, doors and windows to cleanroom furniture, cleaning and training services.*

2 *Example of a Brecon cleanroom project.*

INFORMATION
WWW.BRECON.NL

UPCOMING **EVENTS**

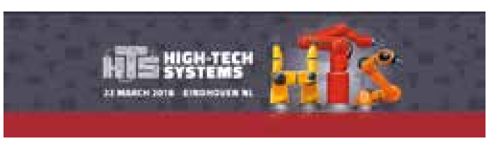
7-8 March 2018, Veldhoven (NL)
RapidPro 2018
The annual event on prototyping, (low-volume) production and product development. An important prototyping and production technology at RapidPro is 3D-printing. Also many other technologies will be comprehensively presented, "from design to manufacturing".
WWW.RAPIDPRO.NL

20-22 March 2018, Cranfield (UK)
European Conference on Nano Films
This fifth edition of ECNF is open to researchers and industrialists working on coatings and nanofilms created by a wide range of processing techniques.
WWW.ECNF2018.ORG

20-23 March 2018, Utrecht (NL)
ESEF 2018
The largest and most important exhibition in the Benelux area in the field of supply, subcontracting, product development and engineering, showcasing the latest innovations.
WWW.ESEF.NL

21-23 March 2018, Dresden (DE)
Conference on Thermal Issues in Machine Tools
This conference is organised by CRC/TR 96 and euspen (Special Interest Group Thermal Issues), which have been working to solve the conflict between reducing energy consumption and increasing accuracy and productivity in machining since 2011.
WWW.EUSPEN.EU

22 March 2018, Eindhoven (NL)
High-Tech Systems 2018
One-day conference and exhibition with the focus on high-end system engineering and disruptive mechatronics. See also the preview on page 18 ff.

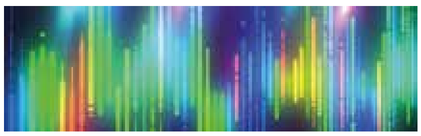


WWW.HIGHTECHSYSTEMS.EU

26 March 2018, Ghent (B)
Phaer Vision Expert Day
Leading international experts will outline the hardware technology drivers for future vision systems. See also page 25.
WWW.VISIONEXPERTDAY.EU

29 March 2018, Eindhoven (NL)
Dynamics for Precision Engineering
This workshop – organised by Mikrocentrum, with the support of TU Delft and DSPE – provides an overview of the challenges and solutions involving dynamics and control in precision engineering at all length scales.
WWW.MIKROCENTRUM.NL

10-12 April 2018, Aachen (DE)
Aachen Optics Days 2018
Event combining two conferences: the Polymer Optics Days conference (10-11 April) and the International Colloquium on Glass Optics (11-12 April). See also the preview on page 34 ff.



AACHEN.POLYMEROPTICS.DE
WWW.OPTIK-KOLLOQUIUM.DE

30-31 May 2018, Veldhoven (NL)
Materials 2018
Trade fair, with exhibition and lecture programme, targeted at product developers, constructors and engineers.
WWW.MATERIALS.NL

4-8 June 2018, Venice (IT)
Euspen's 18th International Conference & Exhibition
This event will cover the latest advances in fields such as metrology, ultra-precision machining, additive and replication processes, and precision mechatronic systems & control. New topics include robotics and automation, and Industry 4.0 for precision manufacturing.
WWW.EUSPEN.EU

6-7 June 2018, Veldhoven (NL)
Vision, Robotics & Motion 2018
Exhibition and conference devoted to the future of human-robot collaboration within industry.
WWW.VISION-ROBOTICS.NL

7 June 2018, Eindhoven (NL)
Martin van den Brink Award
During the Dutch Technology Week, the Martin van den Brink Award, for the best system architect in precision engineering, will be handed out for the third time. See also the call for nominations on page 39.
WWW.DSPE.NL

19 June 2018, Enschede (NL)
Photonics Event 2018
Event devoted to photonics, one of the key enabling technologies of the 21st century. The event serves as an appetiser for the World Technology Mapping Forum (20-22 June 2018), where the global roadmap for integrated photonics will be drafted.
WWW.PHOTONICS-EVENT.NL
WORLDTECHNOLOGYMAPPINGFORUM.ORG

4-5 September 2018, Sint-Michielsgestel (NL)
DSPE Conference on Precision Mechatronics 2018
Fourth edition of conference on precision mechatronics, organised by DSPE. The target group includes technologists, designers and architects in precision mechatronics, who are connected to DSPE, Brainport Industries, the mechatronics contact groups MCG/MSKE or selected companies or educational institutes. This year's theme is "Precision Imagineering", inspired by the notion that every enterprise starts with a dream or 'imagination', but that it takes 'engineering' to actually transform the initial idea into a successful product, service or business.
WWW.DSPE-CONFERENCE.NL

8-12 October 2018, Delft (NL)
European Optical Society Biennial Meeting 2018
The conference features nine topical meetings, including Freeform Optics for Illumination, AR and VR; Optical System Design, Tolerancing, and Manufacturing; Frontiers in Optical Metrology; and Adaptive Optics & Information-driven optical systems.
WWW.MYEOS.ORG/EVENTS/EOSAM2018

ECP² COURSE CALENDAR

COURSE (content partner)	ECP² points	Provider	Starting date
FOUNDATION			
Mechatronics System Design - part 1 (MA)	5	HTI	9 April 2018
Fundamentals of Metrology	4	NPL	to be planned
Mechatronics System Design - part 2 (MA)	5	HTI	29 October 2018
Design Principles	3	MC	26 September 2018
System Architecting (S&SA)	5	HTI	19 March 2018
Design Principles Basic (MA)	5	HTI	to be planned (Q2 2018)
Motion Control Tuning (MA)	6	HTI	13 June 2018
ADVANCED			
Metrology and Calibration of Mechatronic Systems (MA)	3	HTI	6 November 2018
Surface Metrology; Instrumentation and Characterisation	3	HUD	to be planned (May 2018)
Actuation and Power Electronics (MA)	3	HTI	20 November 2018
Thermal Effects in Mechatronic Systems (MA)	3	HTI	12 June 2018
Summer school Opto-Mechatronics (DSPE/MA)	5	HTI	-
Dynamics and Modelling (MA)	3	HTI	26 November 2018
Manufacturability	5	LiS	to be planned
Green Belt Design for Six Sigma	4	HI	6 March 2018
RF1 Life Data Analysis and Reliability Testing	3	HI	12 March 2018
SPECIFIC			
Applied Optics (T2Prof)	6.5	HTI	to be planned
Applied Optics	6.5	MC	20 September 2018
Machine Vision for Mechatronic Systems (MA)	2	HTI	3 July 2018
Electronics for Non-Electronic Engineers – Analog (T2Prof)	6	HTI	to be planned (October 2018)
Electronics for Non-Electronic Engineers – Digital (T2Prof)	4	HTI	to be planned (February 2019)
Modern Optics for Optical Designers (T2Prof)	10	HTI	to be planned (September 2018)
Tribology	4	MC	6 March 2018
Basics & Design Principles for Ultra-Clean Vacuum (MA)	4	HTI	12 June 2018
Experimental Techniques in Mechatronics (MA)	3	HTI	19 June 2018
Advanced Motion Control (MA)	5	HTI	5 November 2018
Advanced Feedforward Control (MA)	2	HTI	21 March 2018
Advanced Mechatronic System Design (MA)	6	HTI	26 September 2018
Finite Element Method	5	ENG	in-company
Design for Manufacturing – Design Decision Method	3	SCHOUT	in-company
Precision Engineering Industrial Short Course	5	CRANF	to be planned

ECP² program powered by euspen

The European Certified Precision Engineering Course Program (ECP²) has been developed to meet the demands in the market for continuous professional development and training of post-academic engineers (B.Sc. or M.Sc. with 2-10 years of work experience) within the fields of precision engineering and nanotechnology. They can earn certification points by following selected courses. Once participants have earned a total of 45 points, they will be certified. The ECP² certificate is an industrial standard for professional recognition and acknowledgement of precision engineering-related knowledge and skills, and allows the use of the ECP² title.

ECP2EU.WPENGINE.COM

Course providers

- Engenia (ENG)
  WWW.ENGENIA.NL
- The High Tech Institute (HTI)
  WWW.HIGHTECHINSTITUTE.NL
- Mikrocentrum (MC)
  WWW.MIKROCENTRUM.NL
- LiS Academy (LiS)
  WWW.LISACADEMY.NL
- Schout DfM (SCHOUT)
  WWW.SCHOUT.EU
- Holland Innovative (HI)
  WWW.HOLLANDINNOVATIVE.NL
- Cranfield University (CRANF)
  WWW.CRANFIELD.AC.UK
- Univ. of Huddersfield (HUD)
  WWW.HUD.AC.UK
- National Physical Lab. (NPL)
  WWW.NPL.CO.UK

Content partners

- DSPE
  WWW.DSPE.NL
- Mechatronics Academy (MA)
  WWW.MECHATRONICS-ACADEMY.NL
- Technical Training for Prof. (T2Prof)
  WWW.T2PROF.NL
- Systems & Software Academy (S&SA)

CALL FOR **MARTIN VAN DEN BRINK AWARD** NOMINATIONS

This year, the Martin van den Brink Award will be presented for the third time. The award, named after ASML's current president and CTO, reflects the importance of system architecture in the development of high-tech equipment and underlines the role that system architecture plays in the success of the Dutch high-tech systems industry. The Dutch high-tech community is called upon to nominate suitable candidates for the award.

A long list of criteria annex qualifications and competences has been drawn up for Martin van den Brink Award candidates:

- The best contribution in precision engineering from both a system architecture and business development perspective.
- Unorthodox thinker.
- Contributor to innovation and new business creation.
- Highly experienced in interdisciplinary collaboration and a master in using soft skills to achieve results.
- Open to unconventional solutions and ready to go places where others think the limit has been reached.
- Taking practical realisation into account.
- A complete system overview for well-founded decisions on module implementation in either hardware, electronics or software.
- A thorough overview of all system modules and their connections and interfaces, keeping future developments in mind for easy reuse.

In 2012, the first Martin van den Brink Award was bestowed upon Erik Loopstra, program system engineer at ASML, and in 2016 to Jan van Eijk, former CTO of Mechatronics at Philips Applied Technologies and emeritus professor of Advanced Mechatronics at Delft University of Technology. The 2018 jury is composed of Jos Benschop (ASML), Martin van den Brink (ASML), Pieter Kappelhof (DSPE), Hans Krikhaar (DSPE) and Adrian Rankers (Mechatronics Academy).
Suitable candidates can be recommended before 28 March to DSPE president, Hans Krikhaar, hans.krikhaar@dspe.nl.

The award ceremony will be held on Thursday 7 June 2018, during the Dutch Technology Week, at a gala dinner held in the Evoluon in Eindhoven. Preceding the ceremony Ph.D. students from Dutch universities of technology will present their work. Companies that want to partner with the Martin van den Brink Award organisation can sponsor a dinner table in the Evoluon, to which they can invite guests. For information and reservations, please contact Annemarie Schrauwen, info@dspe.nl

OPTICS ON THE MOVE – DSPE PARTICIPATION IN DUTCH OPTICS CENTRE

In 1671, Dutch microscopist, Antoni van Leeuwenhoek, was the first person to observe bacteria and protozoa. For that he used one of the very first microscopes. Optics have always been an instrument to extend the exploration of science and technology, even until today, with the photonics revolution promoting yet more optics development. Over the years, Dutch industry has not always been at the highest level of participation in optics research. However, things are about to change. In 2016, the Dutch Optics Centre (DOC) was established to stimulate research and the industrial application of optics in the Netherlands.

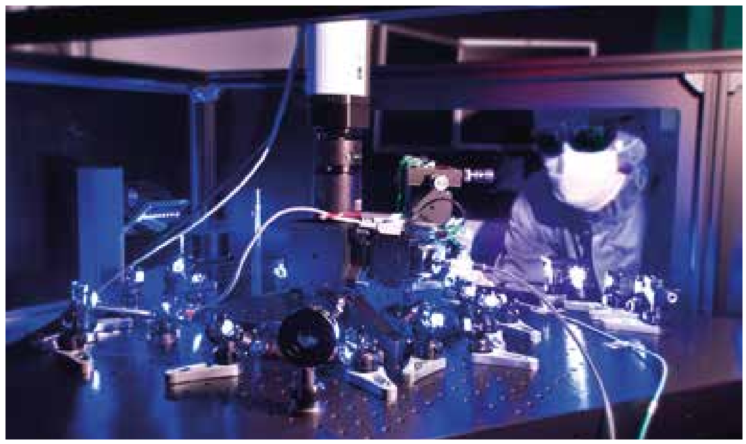
DOC is an initiative of TNO (business developer Bart Snijders and business director Erik Ham) and Delft University of Technology (professors Paul Urbach and Just Herder, and business relations manager Anke Peters) aimed at boosting Dutch industry in the field of optics and optomechatronics to increase utilisation of Dutch science through joint R&D. Knowledge institutes providing excellent research facilities team up with a world-class manufacturing industry; producing opto-mechanical components for high-precision products like satellites, telescopes, microscopes, inspection instruments.
At the start, as many as 20 industrial SMEs were already involved in the initiative, some of them partnering in R&D projects. Recently, DOC was awarded the Smart Industry Fieldlab status.

In recent years, DSPE decided to strengthen its focus on optics, opto-mechanics and opto-mechatronics because these are key disciplines for high-tech equipment and instrument development. DSPE's intention is to connect the precision engineering industry to the DOC consortium and to intensify its relationship with DOC, in order to increase the R&D focus on industrially relevant applications, from which both research and industry will benefit. TNO and TU Delft welcome the increased participation of DSPE in DOC.

Opportunities for DSPE involvement in DOC's research areas are, e.g., dual-frequency comb spectroscopy; particle contamination; and instruments for NO_2 sensing and air quality monitoring. Tropomi, the tropospheric air quality monitoring instrument, was recently launched on board an ESA satellite and new instruments are under development.

DSPE (members) can participate in DOC in the following areas:
1. Joint innovation for next-generation optical instruments.
2. Optical systems design to support the purely optical design of researchers (opto-mechanics).
3. Input of industrial topics for development within the framework of DOC development projects, resulting in industrial products.
4. Development of a course on opto-mechanics design.
5. Promotional contribution (Mikroniek, DSPE Conference, DSPE Optics Week) to increase the focus on optics in the Netherlands.
6. Information sharing between the DSPE and DOC networks, in order to help DSPE members find the right directions/solutions in optics.

For further inquiries please send an email to info@dspe.nl



■ *Breadboard of Rapidnano, an instrument for nanometer particle detection for the semicon industry.*

WWW.DUTCHOPTICSCENTRE.COM

Compact brushless DC motor

With the high-torque EC-i 30, maxon motor is introducing a new brushless DC motor (BLDC). It has a diameter of only 30 mm. Like its predecessors with bigger diameters, this motor stands out for its high dynamics, low cogging torque, and high torque. It is available in two lengths, each in a Standard and a High Torque version, with a maximum nominal torque of up to 110 mNm at 75 W. Because of their cost-effective and compact design, they are especially suited for handheld devices and applications in robotics. In all versions, the new EC-i 30 motors can be expanded with encoders, gearheads, servo controllers, or positioning controllers from maxon motor.

WWW.MAXONMOTOR.COM

400 mm³ for 5 arcsec resolution

The AKP18 is the latest and the smallest supplement to Sentech's programme for absolute magnetic encoders: 22 mm long, 6 mm wide, 3 mm high. With these dimensions, the AKP18 fits into the smallest installation spaces and delivers absolute measurements where it was not possible until now. Sentech, the sensor integrators, delivers and can integrate this encoder from BOGEN Electronic. Robot designers get new design possibilities due to AKP18's smaller size, higher resolution and accuracy better than 15 µm. Using rotary scales with a diameter of less than 13 mm the resolution is 15 arcsec, and at 50 mm it is 5 arcsec, whereas in linear applications the resolution is below 1 µm. The hollow shaft offers room for cables and other components. Both linear and rotary scales with different dimensions are available via Sentech. The AKP18 will be presented by Sentech at High-Tech Systems 2018 (see page 18 ff).

WWW.SENTECH.NL

Mikrocentrum relocating to Veldhoven

In the summer of 2018, Mikrocentrum, the nationally operating knowledge and network organisation that has been based in Eindhoven since 1976, will move to a building in Veldhoven, the Netherlands, which previously served as a holding company office of ASML. The easily accessible building near the Eindhoven ring road will provide space for the growth of Mikrocentrum. The building will be renovated and expanded in the coming months to make it optimally suitable for the various activities of Mikrocentrum, such as providing courses and organising events.

Mikrocentrum foresees a trend towards a greater diversity of small-scale meetings in various forms, for a few dozen to hundreds of participants. The new Mikrocentrum building will be flexible, multifunctional and equipped with state-of-the-art technologies for many such meetings. The first floor will be fully equipped for courses, including the practicals for measuring technology, optics, electrical engineering, mechatronics and industrial automation.

The formal opening of the new Mikrocentrum building will take place shortly after the summer holiday in 2018, in time for the start of the autumn season and for the celebration of the 50th anniversary of Mikrocentrum on 30 October 2018.

WWW.MIKROCENTRUM.NL

Matching the intensity of a laser to its speed

The performance of precision, multi-axis positioning solutions for laser processing depends both on the mechanics and the drive type selected, and also its automation controller. For example, to achieve consistent path quality during laser cutting, the intensity of the laser and the speed of the moving components must be precisely matched to each other to cut as consistently as possible and in the shortest possible time.

A system that provides consistent contouring that is independent of the profile pattern is an important feature for laser users. However, this cannot always be guaranteed in the case of challenging tasks such as laser marking, cutting, welding and laser engraving, particularly when high throughput is required at the same time. When cutting an edge for example, it may be necessary to reduce the speed of the laser in relation to the workpiece in order to avoid high axis acceleration during changes in direction. The process therefore takes longer and the throughput decreases. However, there are additional disadvantages: the depth and width of the cutting contour changes and the processing quality suffers as a result. Synchronising the pulse repetition rate and the intensity of the laser with the motion then is a practical solution. However, this makes additional requirements on the automation controller and the positioning system.

As a solution supplier for drive technology and positioning systems, PI (Physik Instrumente) has accepted this challenge. Together with the controller platform company ACS Motion Control, PI can provide single-source automation solutions for the industrial laser market that allow both high quality, and high throughput rates. The ACS motion controllers now support both position- and speed-dependent laser triggering and analog control.
The consistent distant firing of the laser along a path and its power control, determine the quality of the cutting line. An optimised algorithm in the controller synchronises the motion of the workpiece with the laser pulses so that the pulse size and the gap between adjacent points remain consistent even while cutting features like arcs and circles. The algorithm avoids inaccuracies that are caused by possible fluctuations in the motion behaviour when moving along lines that are not straight. Cutting is therefore no longer dependent on motion parameters.

The mechanics used in positioning systems for laser processing need to be designed with high bandwidth so they react to the controller commands with minimum delay. They should be designed for high acceleration and repeatability, in addition to low thermal expansion. A gantry systems designed by PI with a high-stiffness but lightweight motion platform offers high throughput with low levels of resonance. Optimised cable and services management allows the addition of a vertical stage, autofocusing sensors and a laser delivery system. The design permits the part to be stationary and the laser head and optics to be moved above. PI's preference for dual absolute encoders avoids the requirement of homing on start-up which eases system initialisation. Excellent results were achieved in laser microprocessing by a control module specially developed by ACS for this application field. It allows direct control of the laser source to increase precision and throughput.

The gantry system with a high-stiffness but lightweight motion platform offers high throughput with low levels of resonance. (Image: PI)

Automation Technology

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