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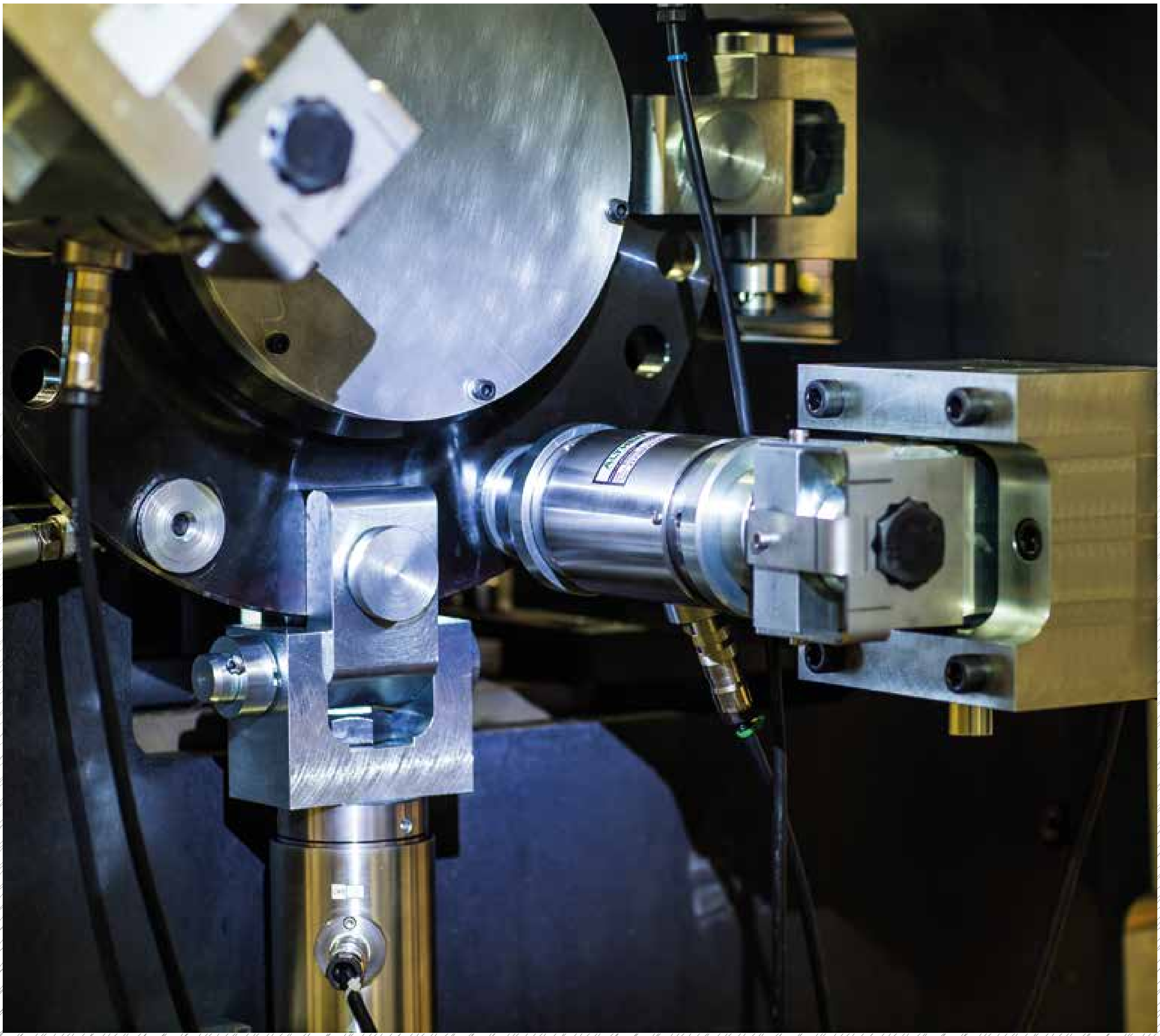
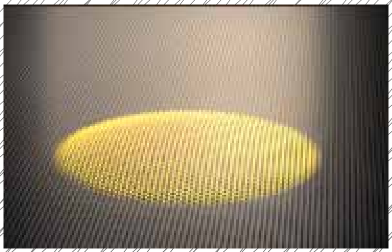


- THEME: **PRECISION BEARING TECHNOLOGY**
- KNOWLEDGE **SHARING**
- **LEVITATING** HIGH-PERFORMANCE MACHINING
- **SERVICE** ROBOTICS



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The main cover photo (featuring a sensor-bearing calibrator) is courtesy of Ingrid Bussemakers/Nobleo Technology. Read the article on page 5 ff.

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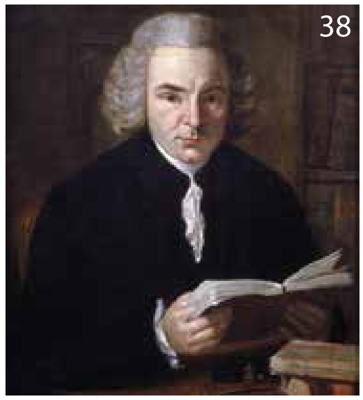
Theme: Precision Bearing Technology



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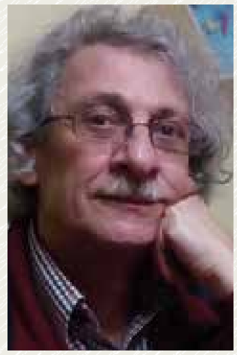

(Photo: Wannes Vermeir)

NO TECH WITHOUT **BEARINGS**

The purpose of a bearing is to transport a load over an interface, subject to certain requirements. The most important of these requirements are that the bearing provides low, well-behaved friction, as well as smooth, precise motion and high stiffness in the directions orthogonal to the motion direction. It can safely be asserted that technology would have been unthinkable without bearings: after all, objects need to be moved relative to one another in a controlled, predictable manner, and bearings play a key role in that.

Bearings and bearing systems evolved over thousands of years from plain and lubricated sliding contacts and later rolling contacts into a wide variety of technologies responding to the ever-increasing demands of industry. In addition to the conventional types that remain the most popular, we have witnessed the steady development of fluid film bearings, both self-acting and externally pressurised (EP). Although the majority of these fluid film bearings still use oil, others use almost all known fluids and some even use air, which is abundant, stable and environment-friendly.

EP gas bearings can maintain a stable air/gas film between the moving surfaces, which smoothens surface undulations by averaging, so that the resulting motion is more precise. Rotary tables, such as those produced by LAB Motion Systems in Belgium, easily achieve less than 50-100 nm axis-of-rotation error. Moreover, the air film is not necessarily bound to one particular surface. This idea inspired IBS Precision Engineering in the Netherlands to swap the roles and so develop a roll-to-roll foil handling in which the rollers do not roll while the foil glides over them separated by the air film.

Then there is the class of passive and, in particular, active magnetic bearings, where the bearing surfaces are kept apart by controlled magnetic, e.g. Lorentz, forces. These bearings can work in a vacuum, maintaining very precise and nearly frictionless motion.
Active and semi-active fluid bearings use ferrofluids, electro- or magnetorheological fluids, or liquid crystals, which influence rheological properties, such as the apparent viscosity of the fluid. These fluids help achieve beneficial effects in the bearing film, in particular regarding stiffness, damping and sealing behaviour. These effects are being researched by Delft University of Technology (TU Delft) in the Netherlands.

This brings us back to the function of a bearing in a contemporary high-performance, often mechatronic, setting. Ultra-high-speed applications demand surface speeds approaching that of sound, while maintaining low frictional dissipation and good stability, i.e. stiffness and damping. However, there are also the ultra-high-precision motion-control applications where error motions at a submicron, often nanometer level are required over very large strokes. This becomes increasingly difficult without mastering the mechatronics' active compensation approach that is enabled by the ever-advancing actuator/sensor technology and system control, i.e. measuring the position of the borne object and feeding it back through the control to a piezo system actuating the bearing film force. This is quite costly and complex however and as such hinders widespread application.

A trend in bearing technology is to combine bearing and drive functionalities, which are separate in conventional machines, in the same system, e.g. in piezo steppers. KU Leuven has been conducting research in this area. TU Delft has recently been researching a non-contacting variant, using the viscous motor principle, by which the air that is eccentrically fed to the air bearing gap drags the borne surface in a controlled and highly dynamic way.

In conclusion, I hope that readers enjoy learning about the various developments in this fascinating and important field of scientific and technological endeavour.

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WHAT BETTER LOCATION TO MEASURE LOAD?

AUTHORS' NOTE

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Rob Lansbergen is the founder of Lans Engineering, based in Schiedam, the Netherlands.

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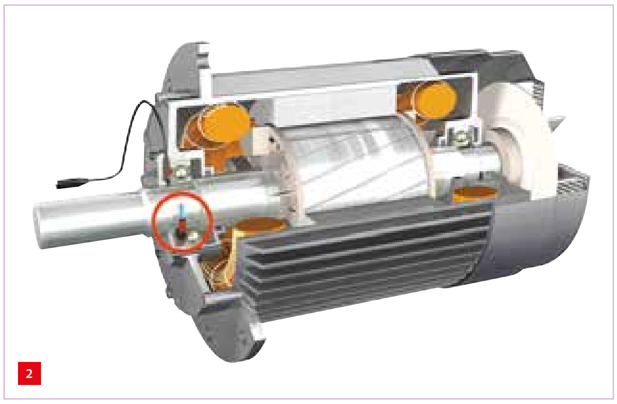
Sensor bearings, e.g. roller bearings fitted with load sensing, hold great promise for the improved functionality of the systems in which they are used. Load-sensing bearings, however, require external calibration. This article outlines the design and realisation of a calibration tool for this purpose. The tool covers up to five degrees of freedom, i.e. the ones that the bearing constrains. The primary design challenge was to create a system that is capable of applying up to 100 kN radial and 50 kN axial force, measure and control the force with an accuracy better that 5% and use electrical actuation.

FRANK SPERLING, RIK HOUWERS, GERARD DUNNING AND ROB LANSBERGEN

Introduction

Sensor bearings (Figure 1), i.e. the combined function of a roller bearing with the sensing of physical properties such as position, velocity, vibration, temperature and load holds great promise for the improved functionality of nearly all systems that use bearings, from heavy industrial equipment to automobiles. Load sensing in a roller bearing is a particularly attractive proposition, as the roller bearing is usually located where practically all of the forces and loads that the two bodies exert on each other are 'concentrated', i.e. where the force lines travel through a defined small number of Hertz contacts. This is much like the typical application shown in Figure 2.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So what's the best location to measure these forces? Several concepts for load sensing have been developed through the years – the first patents are from the early 1990s – and practically all of them rely on strain measurements inside the bearing body. Since a bearing is inherently statically overdetermined, these strains do not uniquely map to the external forces. In addition, thermally induced strain and stress also impact the strain measurement. What's more, measuring strain with strain gauges also implies a relative measurement. Hence, all of the above makes an external calibration of the load-sensing bearing unavoidable.

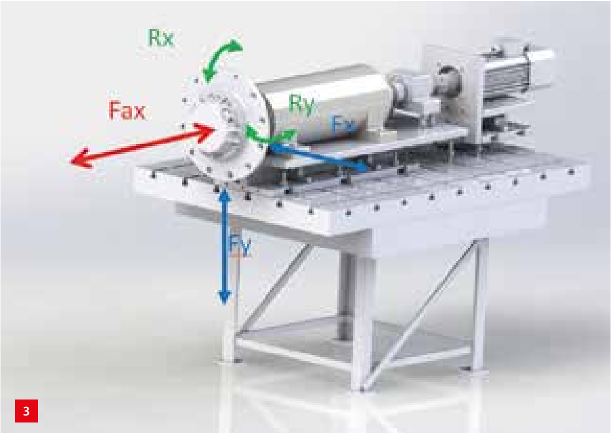

1

1 *Typical sensor bearing.*

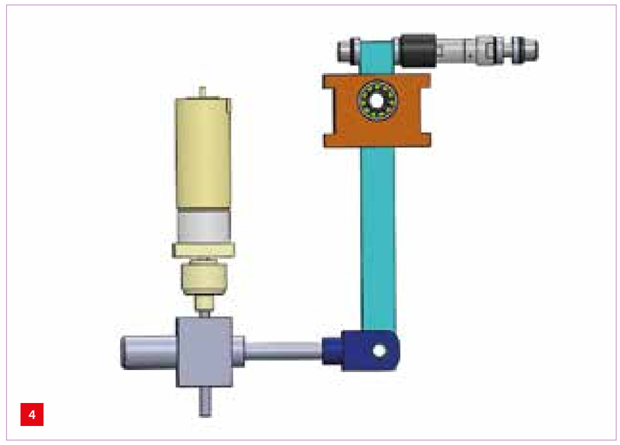
2 *Typical sensor bearing application.*

For a proper calibration tool, the following primary requirements were defined:

1) The tool should allow a rotating bearing to be loaded in five degrees of freedom (DoFs): two radial DoFs, x and y; one axial, z; and two rotations, Rx and Ry (the DoFs and loading directions are depicted in Figure 3).
2) The maximal loading forces are 100 kN in radial direction and 50 kN in axial direction, and maximum torques are 10 kNm.
3) The measured forces should have an accuracy better than 5%.
4) Actuation should be done electrically, preferably with low power.



3 *The sensor-bearing calibrator and its five DoFs.*



4 *Basic concept: a double lead screw and lever – the grey unit at the short end of the lever is the force sensor measuring directly at the bearing housing plate.*

Ad 3) Since a typical load-sensing application does not require the same kind of accuracy that a dedicated measurement device has – often the data is used for monitoring, remaining lifetime prediction or vehicle dynamics enhancements – the measured signals should show a good resolution and linearity, while absolute accuracy can be typically in the 1-10% range. As a consequence the calibration procedure, i.e. a calibration device, needs to have an accuracy and reproducibility that is a fraction of that number; in this case, 5% accuracy was specified.
Ad 4) Nobleo's customer expressed the explicit desire to avoid the use of hydraulic systems in order to eliminate the cost and volume of large hydraulic pump units and the risk of oil leaks and spills.

Concept

In order to achieve the desired force levels at acceptable (motor) power levels and to make the system as safe as possible for use, the first concept decision was to design with high system stiffness in mind, since the amount of energy required to deform an elastic system with a prescribed force is inversely proportional to its stiffness, i.e. the extreme case of an infinitely stiff mechanism requires zero power to create a force. Stiffness in this sense refers to the total amount of elastic energy stored in the system when a bearing is loaded with a prescribed force and is expressed in terms of the force over displacement at the bearing.

The force is measured by a load cell (preferably as closely as possible to the bearing load), the displacement is calculated from the actuator motion (i.e. the encoder) and the kinematic transmission ratio of motor revolutions to bearing displacement. As such, the stiffness includes the transmission system, hinges and supports, the frame and the bearing being tested.

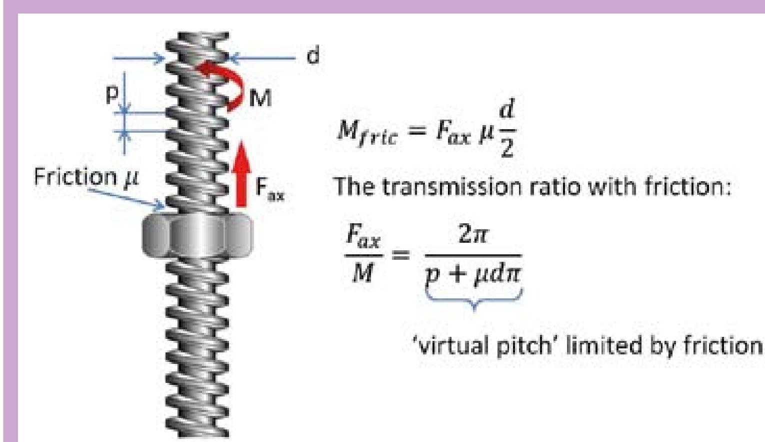
On the other hand, an upper limit to the stiffness is also given by the (allowable) motion inaccuracies of a revolving bearing, estimated at max 10 μm. A stiffness, measured at bearing level, of $C = 1{\cdot}10^8$ N/m was set as a design goal, resulting in an estimated (repetitive) error force from the bearing with an amplitude of 1 kN, which is well within the 1% of the required measurement range.

Electrical actuators typically provide a moderate torque at high revolutions, so the motion transformer from a rotary motion torque (order of magnitude 0.1-10 Nm) to a translational force (100 kN) calls for high gearing ratios and triggered exploration of various concepts of special motion transformers.

The basic concept of a double lead screw system with a lever (as shown in Figure 4) is straightforward. The motor axis rotates a vertical screw, which in turn rotates a nut on the horizontal (lead) screw jack. Finally, a lever (5:1 or 7:1) is used. The lead screw and screw jack suffer from friction limiting their efficiency and the achievable force trans-

Transmission ratio

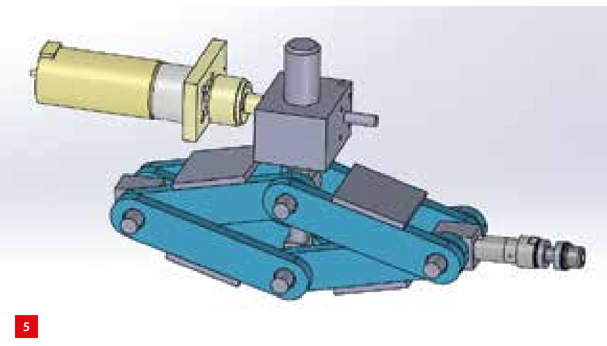
Friction forces limit the transmission ratio. In an ideal, friction-free case; a motion transformer's force transmission ratio is identical to the reciprocal of its kinematic transmission ratio. However, for a leadscrew system employing sliding friction the achievable force transmission is limited by the Coulomb friction.



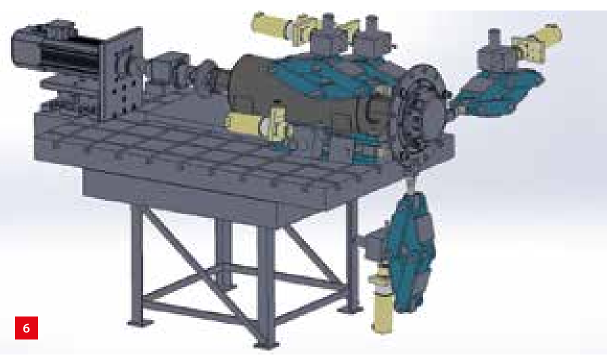
mission ratios (see text box); the lever, which is the last transmission mechanism in the concept, hardly suffers from this effect.

The 'scissor jack' concept (as shown in Figure 5) can theoretically create extreme transmission ratios, up to infinity when the angle between the two 'scissor blades' goes to 0. In practice, however, the angle is limited by the volume and bulkiness of the components. Figure 6 shows a practical implementation of such a system with transmission ratios from (preferably) 10 down to 5.

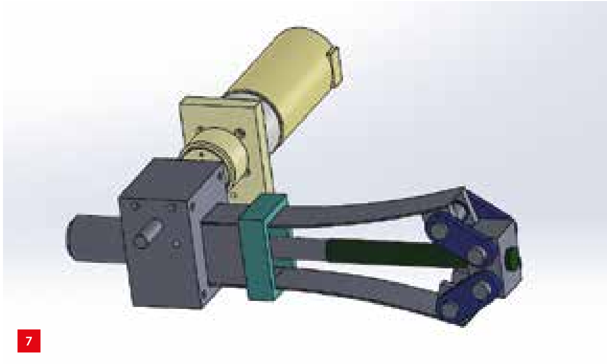
A very promising concept is the series connection of a positive with a negative spring, a typical example of which is shown in Figure 7. This fundamental concept is being studied by the group of Prof. Just Herder at Delft University of Technology. To elaborate on the principle of this research would go beyond the scope of this article. Suffice it to say that such systems can apply large forces without the necessity of (large amounts of) power. Much like a resonating mass-spring system transfers energy from kinetic (moving mass) to potential (loaded spring) energy, these systems transfer energy from a positive to a negative spring system.
One drawback of the negative spring stiffness realisation is that the negative stiffness needs to be properly tuned to the stiffness of the 'actuated system', which in the case of the calibrator includes an unknown, i.e. the bearing being tested. The extra complexity of the required adjustability was considered a trade-off that would become beneficial with larger loads, but not for the 'modest' (100 kN) case in question.



5 *A linkage transmission with high transmission ratios.*



6 *All five DoFs using the 'scissor jack' concept.*



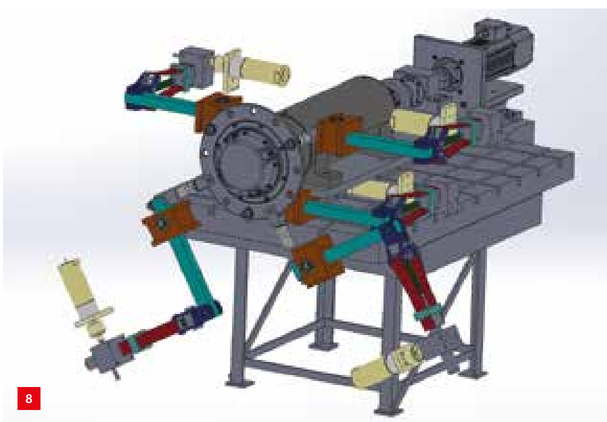
7 *Actuation with a negative spring stiffness – when placed in series with a positive stiffness it can operate in an energy-neutral mode.*

Design and accuracy

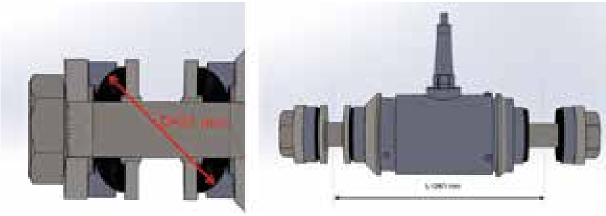
Considering all options and respecting the number one design rule in engineering, i.e. KISS (keep it simple, stupid), the double lead screw and lever system was selected as the preferred concept. Rx, Ry and Z loading has been realised by three identical actuation units acting in a symmetrical triangular fashion in the axial direction with respect to the bearing being tested (see Figure 8). The radial load was realised by two actuation units at a 90° angle allowing the 'loaded zone' to be moved with respect to the 'sensing zone' of the bearing.

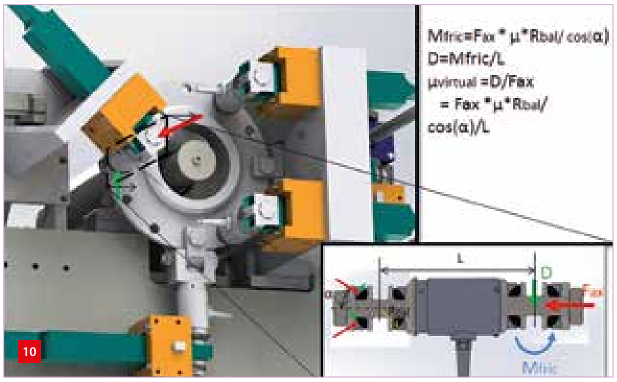
Each actuation unit consists of a double lead screw, a lever (5:1 for the axial loads, 7:1 for the radial loads) and a force sensor – the latter providing a direct measurement between the end of the lever and the bearing housing.
The outcome of kinematic analysis of the concept and the desire to avoid an overconstrained mechanism requires that the force sensors be mounted as 'ideal trusses' between two ball-type joints. Figure 9 shows the realisation of sensors.

Conceptually, the five force sensors directly measure the load that the bearing is subjected to. This, however, only holds for the ideal case with ideal, friction-free ball joints. An analysis that considers the effect of friction in the ball joints with the dimensions as shown in Figures 9 and 10 and assuming a friction coefficient of μ = 0.1-0.2 results in radial forces that are easily 1% of the axial load. Although this



8 *The basic concept – a geometric study to position all five DoFs.*





9 *Force sensor unit (L = 261 mm) with ball joint detailed on the left.*

10 *Friction force analysis.*

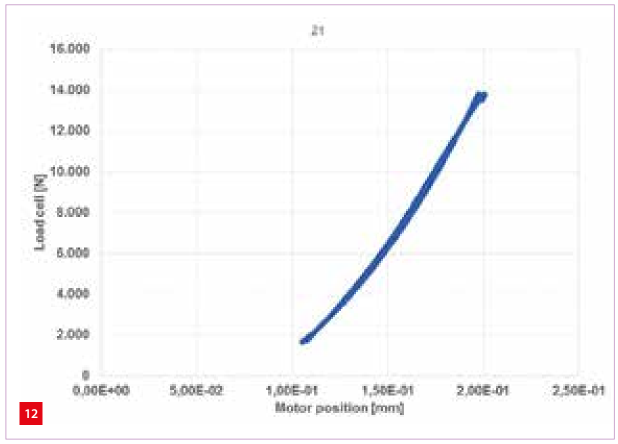
11 *The final design, using box-type construction elements to achieve high frame stiffness.*

12 *Stiffness of the axial loading measured from motor Z1; $C > 1.2 \cdot 10^8$ N/m.*

13 *Detail of the system: force sensor interface to the bearing measurement plate. (Photo: Ingrid Bussemakers)*

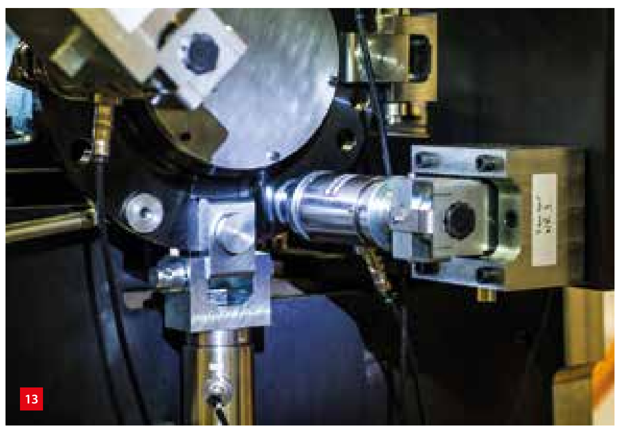
14 *Front view of the calibrator with two of the designers/authors.*

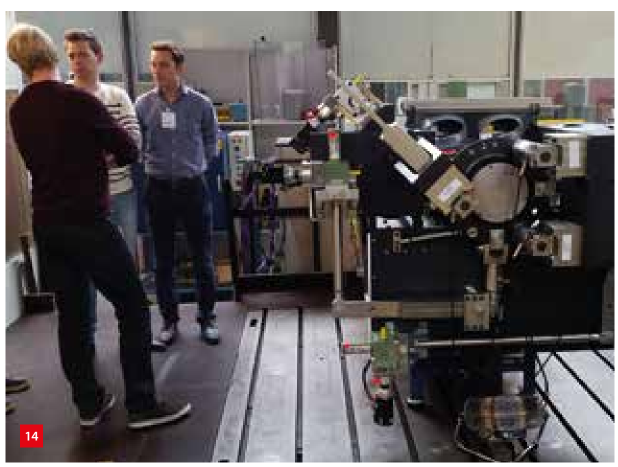
limits the achievable measurement accuracy, the errors remain well within the realm of the original requirements (1-10% accuracy). The final sum of all the measurement inaccuracies amounted to approx. 5%, depending on the load case in question.



Realisation

The final design (Figure 11) was realised using box-type construction elements to achieve high frame stiffness. Figure 12 shows the stiffness measured from one of the axial loading motors. The force is measured at the load cell and the displacement is the motor angle, translated back to the bearing motion based on the kinematic transmission ratio. The design goal of $C > 1 \cdot 10^8$ N/m was achieved.
Figures 13 and 14 show some details of the final realisation of the calibrator. ■





UNEXPECTED ENCOUNTERS

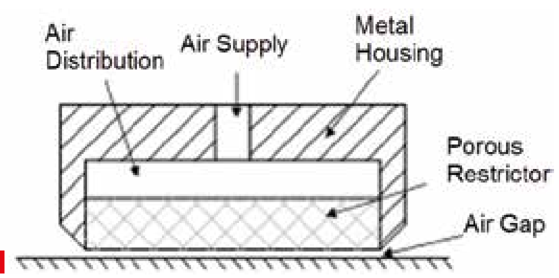
Rolling-element bearings developed in the last century were a revolutionary improvement over the plain bearings that had been pushed to their limits in applications like electric motors and automobile wheels. Air bearings can likewise be seen to represent the next logical step in bearing design. These may be exploited by mechanical engineers to extend their design capabilities for precision manufacturing systems.

THERESA SPAAN-BURKE

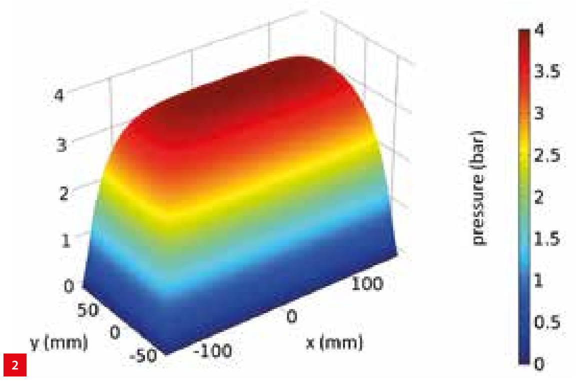
Air bearings use a thin film of pressurised gas to provide a low-friction, load-bearing interface between surfaces. As the two surfaces do not touch, the traditional bearing-related problems of friction, wear, particulates, and lubricant handling can be avoided. The use of air bearings in certain precision systems is well established due to the distinct advantages they offer in precision positioning, such as zero backlash and constant static/dynamic coefficients of friction, so no stick-slip. Thus they have been exploited in applications such as ultra-precision lithography machines and coordinate measuring machines (CMMs).

Low friction also means less heat generation, so less thermal disturbance, and minimal power loss for high-speed applications, such as precision spindles. While any heat generation is of course not zero, relative surface speeds of the order of 30 m/s must be reached before significant heat can be measured.

In the field of air bearings, separation is typically made between aerostatic and aerodynamic bearings. In aerodynamic bearings the cushion of air is formed through the relative motion of static and moving parts; in contrast aerostatic bearings are externally pressurised. This article will focus on the application of aerostatic air bearings, with examples of recent applications where you might not expect to see air bearings.



1 *Cross-section of a typical porous air bearing.*



2 *Simulated air gap pressure distribution for a 150mm x 300mm rectangular porous air bearing.*

Surprising load capacities

The fluid film in an aerostatic bearing is achieved by supplying a flow of air through the bearing face and into the bearing gap. This is typically accomplished through an orifice or a porous medium, which restricts or meters the flow of air into the gap (Figure 1). Porous-media restrictors have the advantage of offering greater uniformity and stability (Figure 2). The restriction is designed such that the flow of pressurised air through the restriction is sufficient to match the flow constantly escaping from the bearing gap. The restriction maintains the pressure under the bearing and supports the working load. It is used to optimise the bearing with respect to lift, load, and stiffness for particular applications.

Figure 3 shows the typical load capacity for rectangular (porous) air bearings across a range of bearing sizes. The load capacity can be surprisingly high – for example a bearing just 40 mm x 80 mm in size can support the weight of a typical (European) female and a 150mm x 300mm bearing the 15,000N load of a fully grown rhinoceros. At a load of 11,000 N, such a bearing can provide stiffness (Δload/Δlift) of 1,645 N/µm at a fly height of 5 µm. Or in other words, it will displace 0.6 nm for each extra load of 1 N.

EDITORIAL NOTE

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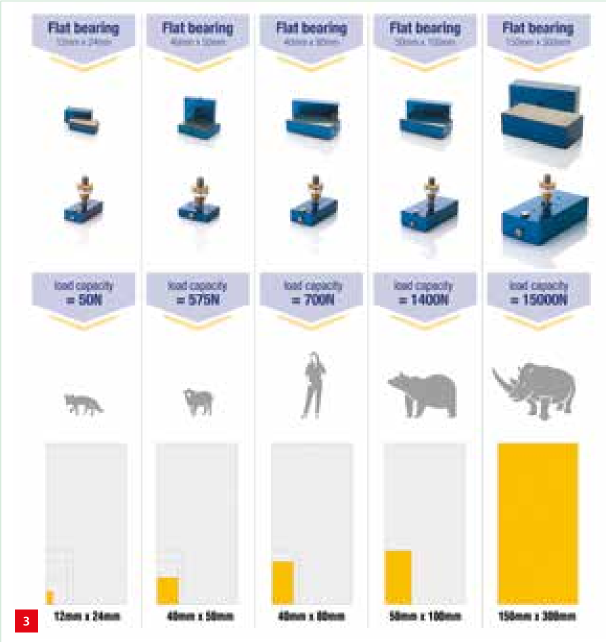

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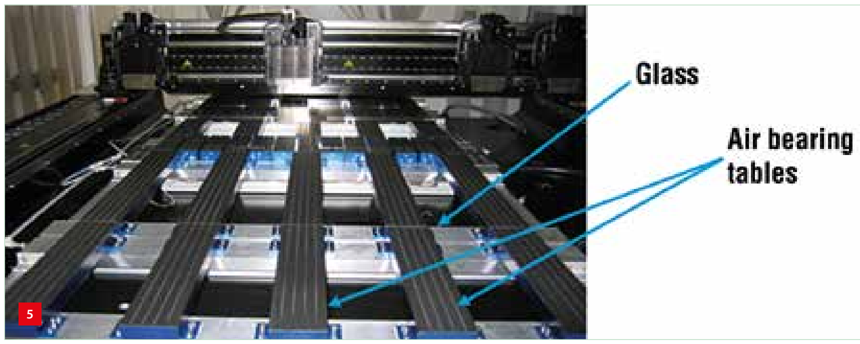

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A recent example of an instrument required to move such a large mass with great precision is the new high-resolution soft X-ray spectrometer (RIXS) at the ESRF (European Synchrotron Radiation Facility) in Grenoble, France. This flagship instrument is required to rotate 6.3 ton (62,000 N) of detector continuously through 100° about the sample at a radius of 11 m to capture a precise 3D image. This is achieved on only eight 300mm diameter round air bearings (Figure 4). The designers of this instrument were recently announced winners of the 2018 Europhysics Prize of the Condensed Matter Division of the European Physical Society.

Stiffness

The typical fly heights for loads on porous air bearings are of the order of 10s to 100s of μm. In some applications vertical positioning and stiffness in the z-direction is critical. The flat-panel display manufacturing industry, for example, has stringent requirements for the handling, processing and inspection of the glass. Precision, non-contact handling of the glass is required for both optical inspection and for LCD printing (Figure 5).

4

Here, air bearings with so-called vacuum pre-loading are used to control the vertical height within ±5 μm. In such air bearings, regions of sub-atmospheric pressure ('vacuum holes or grooves') are distributed within the bearing region and used to reduce the levitation height and improve the out-of-plane stiffness [1]. The vacuum channels act as the equivalent of a preload, reducing the sensitivity to variation in the transported substrate, with zero additional mass. Similar techniques are also used in photovoltaic solar panel processing.

Roll-to-roll

The development of flexible devices for use in consumer electronics has recently attracted much interest. In addition, Internet-of-Things technology requires low-cost ubiquitous and disposable electronic devices. Roll-to-roll (R2R) manufacturing is a highly productive manufacturing process that can be used to print electronics and resolve issues of cost and flexibility [2].

Three main process parameters are important in R2R manufacturing: 1) web tension; 2) web position/speed; and 3) printing force. As printed electronics become more sophisticated and more integrated, these parameters require higher accuracy. Furthermore, newly developed functional inks for printed electronics are typically very sensitive; thus contact with the printed surface should be avoided wherever possible.
The application of air bearings in R2R processes offers improvements in the accuracy of the web positioning and speed. Avoiding web contact also offers reduced damage and contamination on sensitive foils.

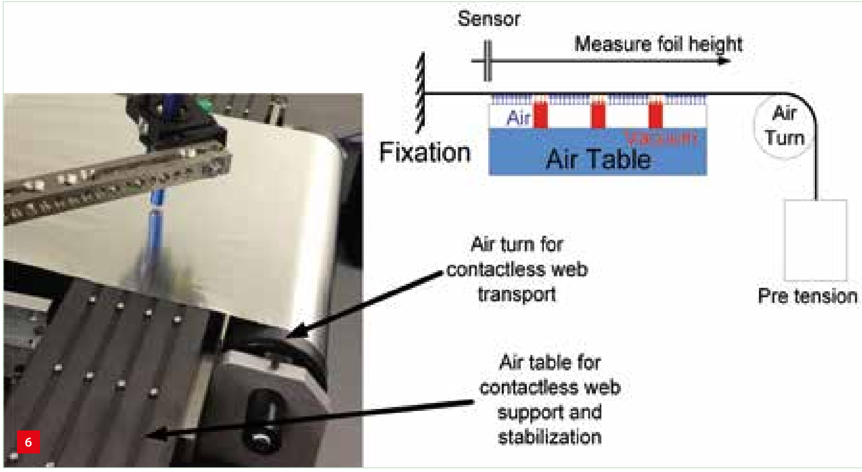
Non-contact conveying

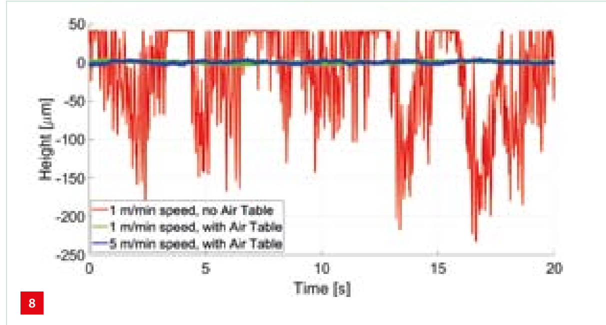
Conveyor air bearings, or air tables, normally used for transport of rigid substrates, may be applied for web transport. In such air tables, vacuum grooves are used to pull the supported web towards the air bearing, improving stiffness and stability at a given fly height. Using a capacitive sensor and a metal-coated foil as shown in Figure 6, fly height and deformation of a flexible foil can be investigated. In this instance a 300mm wide, 50μm thick foil has been assessed.

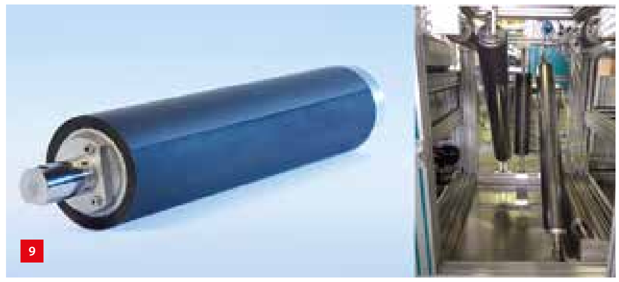
3 *Precision and strength combined; typical load capacity for rectangular air bearings.*

4 *RIXS spectrometer of the ESRF ID32 beamline. The detector can sweep a 100° circle segment about the sample moving on 300mm diameter round air bearings. (Credit: ESRF/Stef Cande)*

5 *Flat-panel display glass processing unit showing air bearing tables for glass transport.*







6 *Air table measurement set-up.*

7 *Air table with vacuum grooves (left). Foil fly height above the air table (right) in the tension direction using 2 bar air pressure, 0 to –0.3 bar vacuum (i.e., below ambient).*

8 *Foil height over time with and without air table support.*

9 *Cylindrical air turn (left) installed in an R2R line (right).*

10 *Foil fly height as a function of position over a 300mm diameter air turn.*

Figure 7 shows the fly height and form in the length (tension) direction of the foil, as a function of vacuum pressure with the air bearings pressurised to 2 bar. This data confirms that at optimal vacuum/pressure settings, a foil height variation < 5 μm over 55 mm can be achieved in the tension direction. The height variation in a lateral direction was less than 15 μm, measured over 200 mm of foil width.

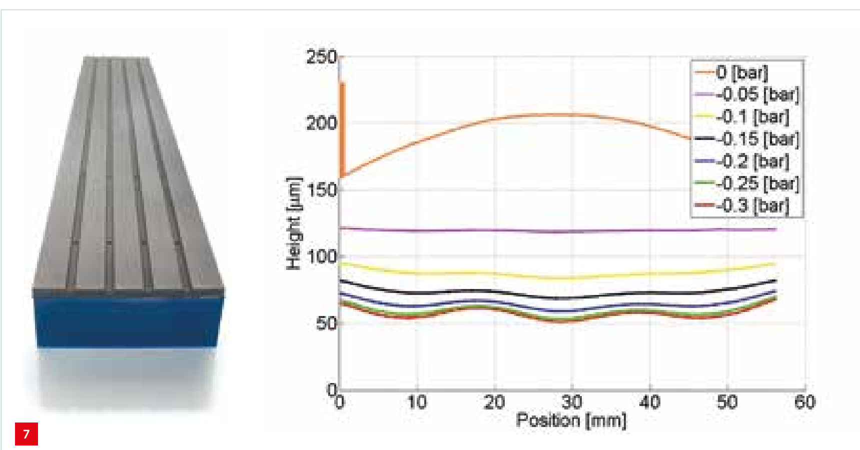
To test the capability of the air table to reduce vibrations in a moving foil, measurements were completed in cooperation with Eight19, Cambridge, UK. Integrated in an R2R line, the foil height was measured with a capacitive displacement sensor. Without support by the air table, vibrations of more than 250 μm were seen in the foil (Figure 8). With the air table, these vibrations were reduced to < ±5 μm. The measurement was repeated with 1 and 5 m/min foil velocity. No significant difference between these measurements was seen. Such foil stabilisation has important advantages for applications such as inkjet printing where foil stabilities in the vertical direction below 50 μm are often required.

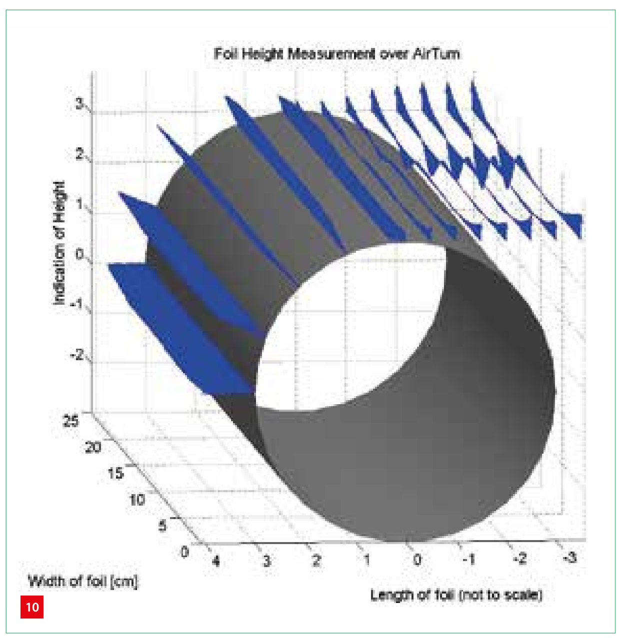
Porous-media air bearings are often used in cleanroom applications. Results of tests done by the manufacturer indicate that the porous air bearings produce less than 1,000 particles > 0.1 μm per m^3 of exhausted air.

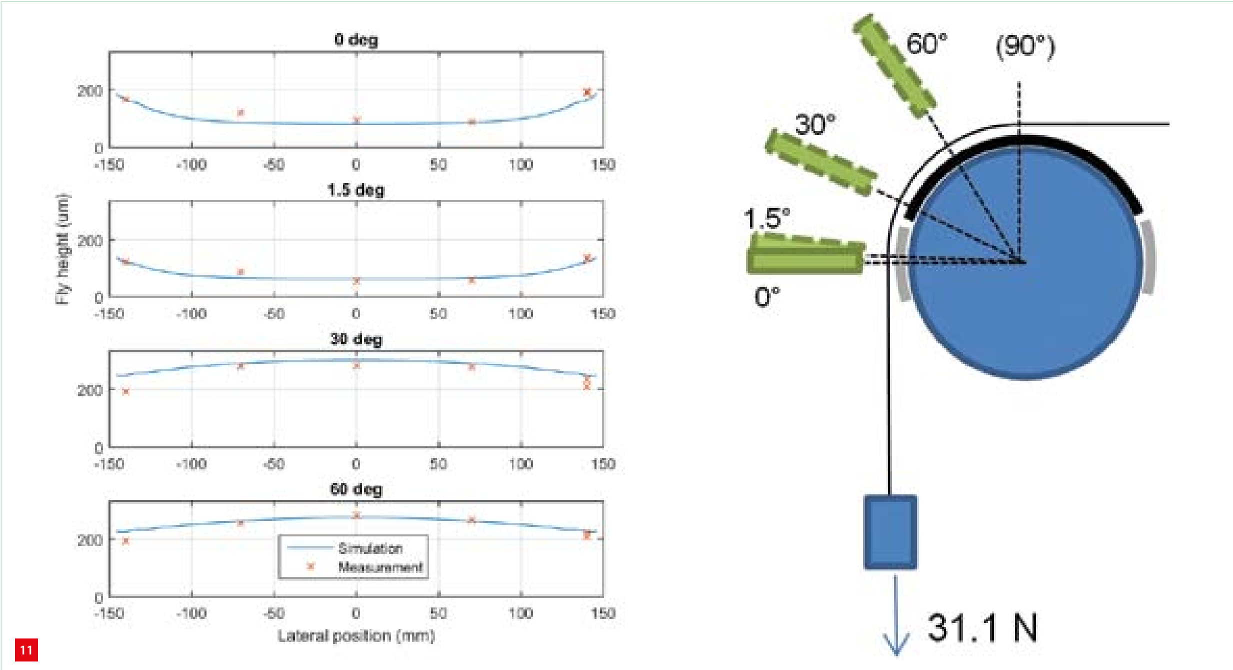
Contactless rollers

Cylindrical porous-media air bearings, or air turns, can be used as replacement idler rollers, i.e. non-driving contact rollers, for web transport, as shown in Figure 9. A web can be wrapped over the air turn, in the same way as with a roller. In this case, the air layer not only supports the foil without contact but also serves to flatten out any wrinkles as seen in Figure 10.

For traditional rollers, foils such as PET can become charged by the order of 5 keV as they pass over an individual roller. Such static build up has to be compensated to prevent disruption to processes. For such air turns, as the foil does not touch the roller, no charging occurs. This removes the need for static discharge bars to be applied before printing actions that can be sensitive to a charged foil, such as inkjet printing.





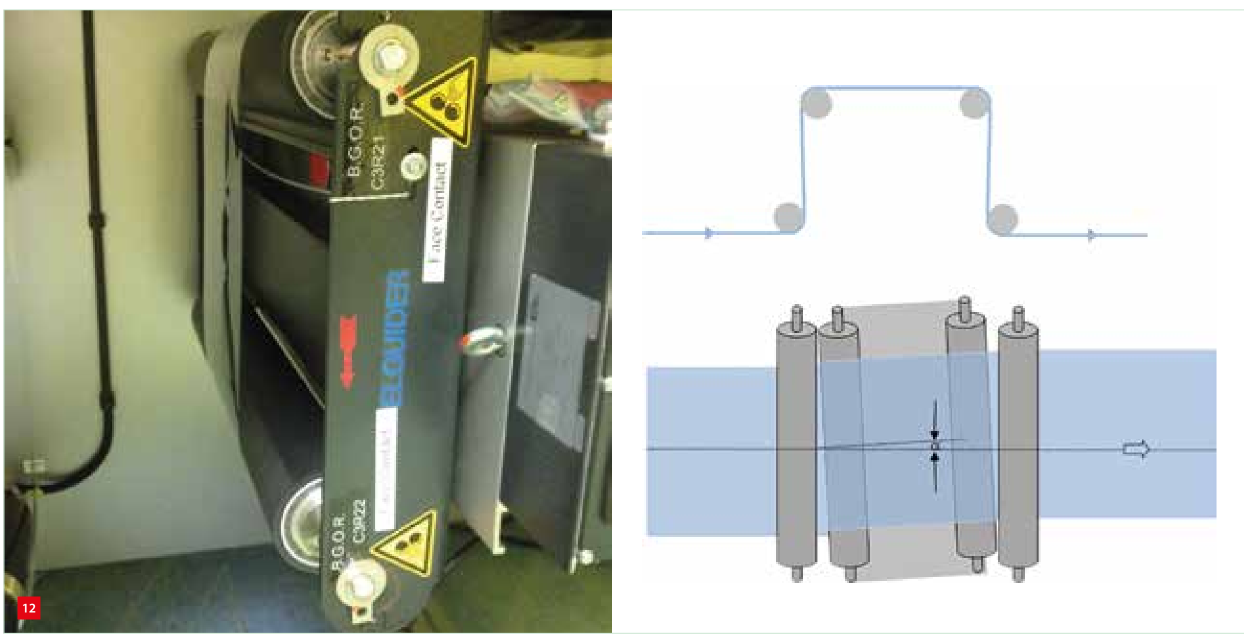


Detailed investigation of the form of the foil as it moves over the air turn has allowed for simulation models to be developed. From these models optimum configuration of the air bearings has been identified for in-line use, including air turns with dual zones (Figure 11).
Not only plastic foils can be supported by air turns. Transport of paper is also possible. Here, the permeability of the paper should be considered. Higher permeability leads to a higher percentage air loss through the paper, which will in turn reduce the fly height and stiffness. Thus the paper tension when contact occurs is directly linked to the permeability. However, papers have been found to be supported at tensions of 50 N or more for a range of papers (tested to 52 g/m^2) and speeds of 10 m/min.

Contactless web steering

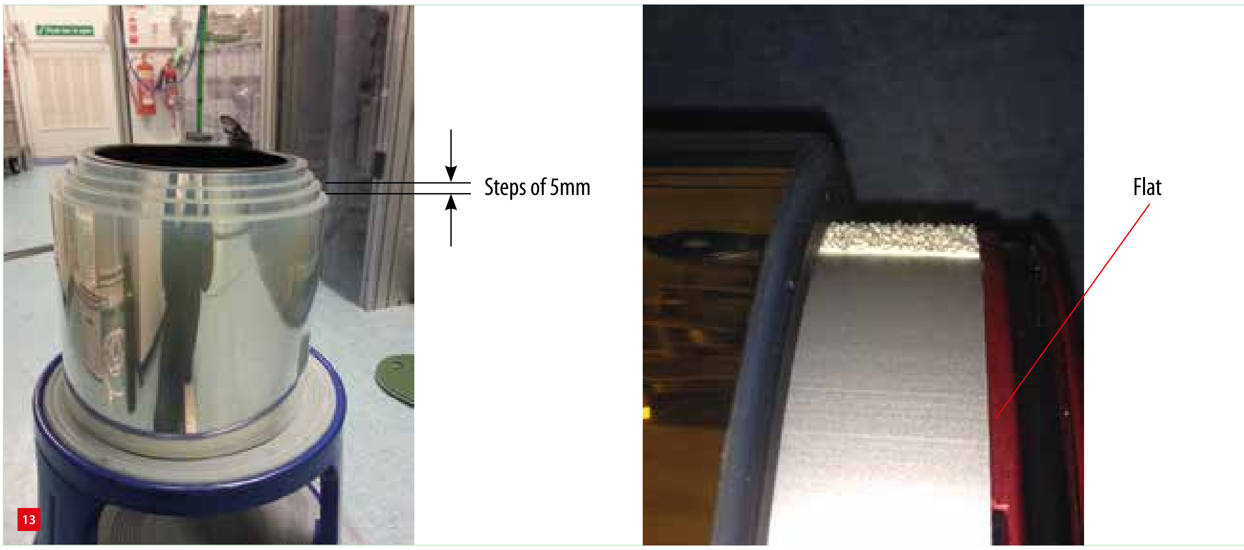
Steering units are commonly used in R2R lines to maintain the lateral position, orthogonal to the travel direction. Such units are typically composed of four rollers, where the front side of the web is made to come in contact with two of the rollers (see Figure 12). The central rollers in the steering frame can be replaced by air turns to avoid frontside contact. Using an edge sensor, the lateral position of the web can be tracked.

Trials have been carried out by IBS where the web response to 5mm stepwise changes in the sensor position have been applied. The web was shown to be stable within the required ±0.2 mm. 5mm steps in reference position were clearly visible



11 *Measurement of foil shape as a function of the position on a dual zone air turn.*

12 *Typical steering roller configuration (right upper and lower image). Air turns retrofitted to a standard steering frame (left).*



13 *5mm steps can be clearly seen in foil wound using a steering frame retrofitted with air turns (left). The sharp edge of wound foil shows effective steering control (right).*

in the roll after winding, as shown in Figure 13. In addition, the steering range was seen to be increased from approx. 3 to 20 mm. The steering response to a step in the reference position, as measured by the edge sensor, was seen to be significantly faster.

Conclusion

Porous-media air bearings provide a unique technology for the delivery of precision machines and processes for industrial manufacturing. Whilst well established in the precision engineering field, they offer a surprising range of new avenues for exploitation.

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The author would like to acknowledge funding received from the European Union's Horizon 2020 research and innovation programme as part of the project SmartLine (*www.smartline-project.eu*) in the writing of this paper. This FOF (Factories of the Future) project is creating intelligent and zero-defect manufacturing processes by developing robust and non-destructive in-line metrology tools to achieve reliable, closed-loop manufacturing of organic electronic devices (OPVs, organic photovoltaics, and OLEDs, organic LEDs) by unique R2R printing and OVPD (organic vapour phase deposition) pilot lines.
The contribution of Ivo Hamersma, Teunis van Dam and Peter Overschie of IBS Precision Engineering is acknowledged in regards to the air bearing simulation and measurement data presented. ■

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TASTINGS AND THEORY

AUTHORS' NOTE

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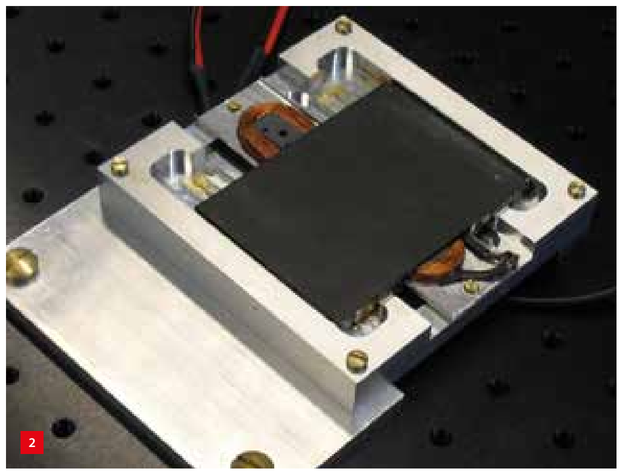
Ferrofluid bearings have recently been successfully implemented in precise positioning systems. This article gives an overview of systems built in the Department of Precision and Microsystems Engineering at Delft University of Technology in the Netherlands. Most applications are in microscope stages, where high accuracy is important while stroke and speed attain only moderate levels. Furthermore, some basic theory is provided on ferrofluid bearings that can help engineers incorporate ferrofluid bearings in their designs.

STEFAN LAMPAERT, RON VAN OSTAYEN AND JO SPRONCK

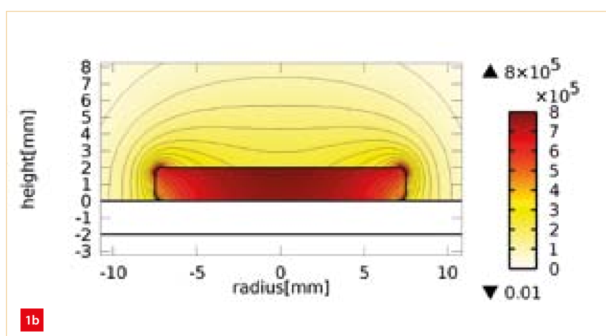
A ferrofluid is a type of fluid with magnetic properties, and its most important property is that it is attracted by a magnet (Figure 1). This is due to the tiny magnetic nanoparticles about 10 nm in size suspended in the fluid. Ferrofluids can be used to make bearings that generally differentiate themselves from other bearings by their simplicity, low cost, inherent stability, viscous damping with low friction and absence of stick slip [1] [2]. These characteristics make ferrofluid bearings a low-cost alternative in systems with a moderate stroke and speed that are currently using air bearings or magnetic bearings to achieve similar specifications.



Precise positioning systems

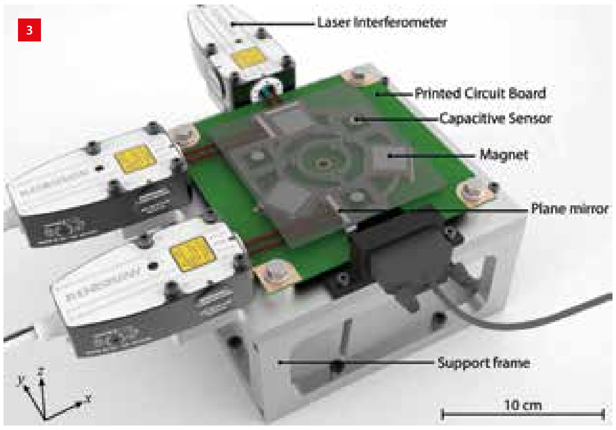
The first in the Delft series of precise positioning systems with ferrofluids was built by M.Sc. student Simon van Veen (Figure 2) [4]. The primary goal of his work was to understand and demonstrate the behaviour of ferrofluid bearings. The complete absence of stick slip and pure viscous friction made it a very interesting and simple linear bearing concept for precise positioning. The final system could be positioned in one degree of freedom (DoF) with a precision of $\sigma = 10$ nm over a range of 20 mm.

This 1-DoF system was followed by a (2+4)-DoF positioning system built by Max Café [5]. This system was able to make two large translational movements (10 mm x 10 mm) and four small correctional movements in the other



1 Ferrofluid bearing principle.
(a) A disc magnet with ferrofluid on a steel plate. The ferrofluid (black) is drawn towards the highest magnetic field strength, at the edge of the magnet. The disc positioned in the centre is the magnet.
(b) The associated magnetic field. The colours show that the magnetic field intensity is highest at the corners of the magnet, which confirms that the ferrofluid follows the contour lines of the magnetic field. The model was made using COMSOL Multiphysics® [3].

2 Overview of the 1-DoF positioning system built by Simon van Veen [4]. The black body in the middle is the dynamic part of the system. The system is actuated electromagnetically; the coil is visible underneath the black body.



3 *Overview of the (2+4)-DoF positioning system built by Max Café [5]. A printed circuit board with coils is used to actuate the magnets placed on the moving part of the system. The magnets are additionally used to create a ferrofluid bearing. Three laser interferometers and three capacitive sensors are used to measure the position and orientation of the system.*

DoFs (Figure 3). In this system, the magnets fulfil a dual role: they hold the ferrofluid for the bearing function and they provide the magnetic field for the coils of the 6-DoF Lorentz actuators (Figure 4).

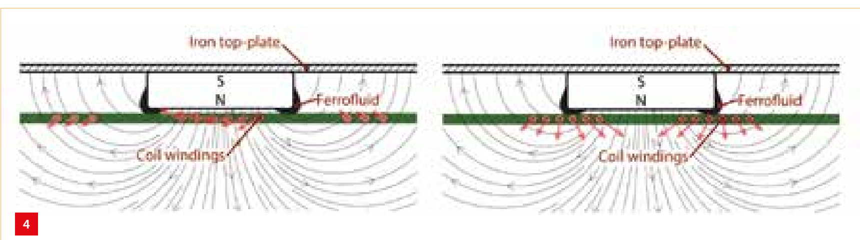
The primary goal in this instance was to understand and demonstrate the behaviour of the ferrofluid bearings in a multi-DoF positioning system. An additional goal was to solve the problem of so-called trail formation of the bearing. When moving, the ferrofluid bearing leaves behind a trail of ferrofluid on the contact surface that reduces the amount of ferrofluid actually used in the stage's support. This causes the bearing to slightly decrease in fly height, i.e. 2 μm per mm translation for this system. This decrease in fly height can be compensated for by active control of the Lorentz actuators. The final system was able to take in-plane steps of 0.1 mm with a control bandwidth of 500 Hz with a 1% settling time of 0.02 s, and out-of-plane steps of 250 nm with a bandwidth of 100 Hz with a 1% settling time of 0.1 s.

The system's planar performance was mainly limited by the performance of the actuator and the sensors, and not by the performance of the bearings. This showed that the ferrofluid bearing is an interesting concept for high-speed precise positioning in multiple DoFs. It also showed that good system integration can be achieved by using the magnets required for Lorentz actuation to also generate the magnetic field used in the ferrofluid bearings.

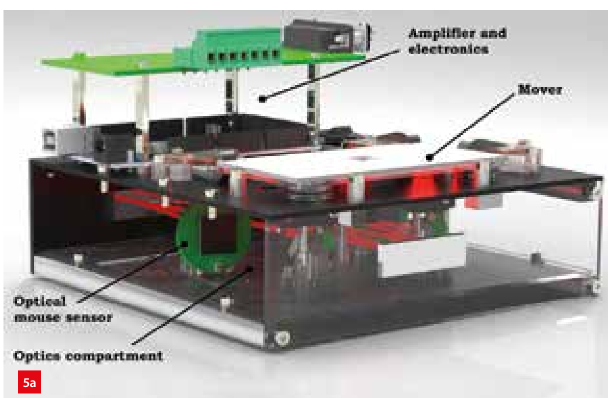
The successful completion of these projects created a certain confidence in the properties of ferrofluid bearings. As a result, ferrofluid bearings have been used in subsequent projects as a simple bearing solution in positioning systems. One such example is Gihin Mok's project [6], which examined the potential of using a low-cost optical mouse sensor for a positioning sensor. A full stand-alone positioning system with two DoFs was realised, using three ferrofluid bearings to accommodate planar movements only (Figure 5).

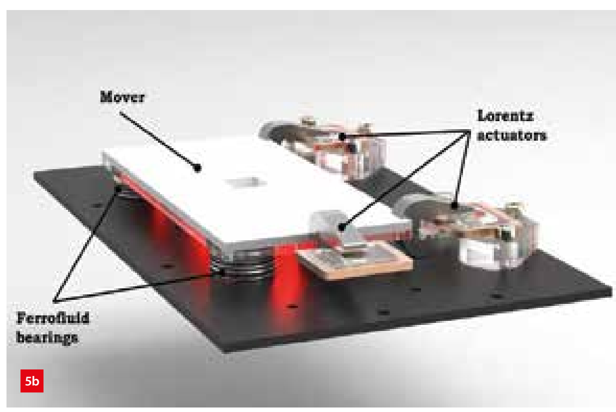
A second example is Haris Habib's project [7], in which an XY360 3-DoF positioning system was designed, built and tested. Here, the goal was to demonstrate the concept of measuring a planar position and orientation with a 2-DoF optical position-sensitive detector (PSD) (Figure 6). The sensor and actuation system allowed for a full rotation in combination with a translational range of 9 mm x 9 mm.

The final system was able to take planar steps of 0.1 mm with a settling time of less than 0.1 s and with an accuracy of 0.2 μm (3σ). A rotational step of 10° took 0.18 s to settle with an accuracy of 0.15 mrad (3σ). The speed of the system was mainly limited by the friction in the bearings. This friction was apparently higher than was modelled using the basic model developed in advance. This eventually caused excessive heat to develop during operation.

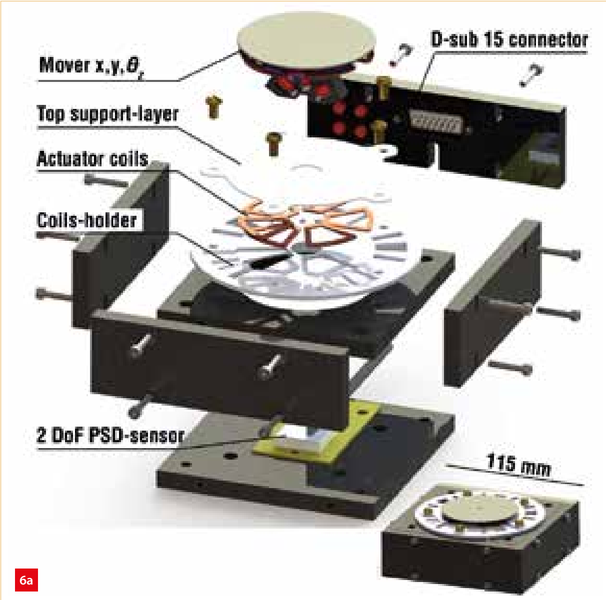


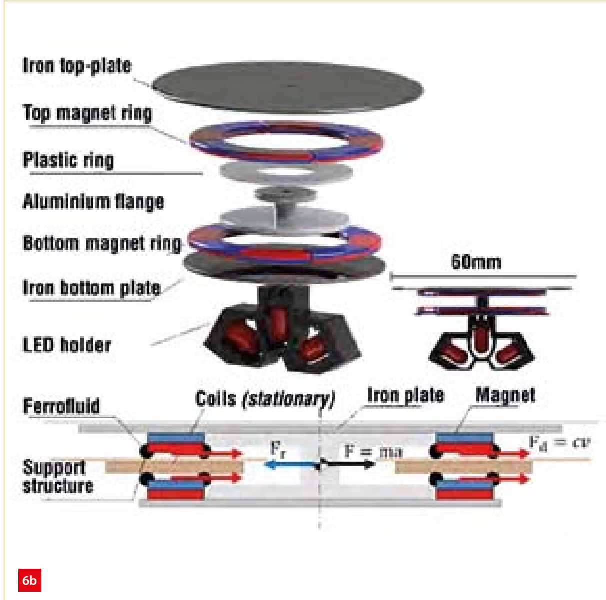
4 *The actuation system of Figure 3 consists of three magnets and six coils in a PCB board: two layers contain coils for the out-of-plane actuation and two layers contain the coils for the in-plane actuation. Both sets of coils use the same magnet, which is also used to hold the ferrofluid for the bearing [5].*





5 *Renderings of the planar 2-DoF positioning system built by Gihin Mok [6].*
(a) Overview of the complete stage.
(b) The base.





6 *Renderings of the XY360 3-DoF positioning system built by Haris Habib [7].*
(a) Overview.
(b) Cross-section showing two LEDs used to sequentially illuminate the PSD so that the location and the orientation can be measured, and a third LED used to increase the range of motion.

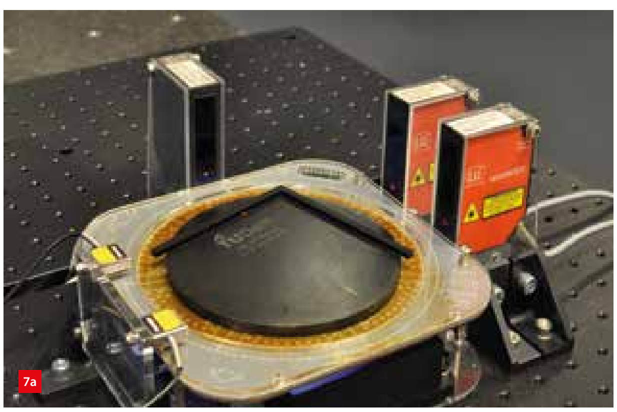
For this reason, a new project was launched by Stefan Lampaert, the aim of which was to draw up improved theoretical models to be used for generating an accurate prediction of the bearing properties (see below) [8]. This work resulted in validated models that accurately describe the load and stiffness of ferrofluid bearings. A friction model directly derived from these improved models was later validated in [2] [9] by a redesign of the system presented in [4] to obtain an accurate measurement for the friction of the bearings.

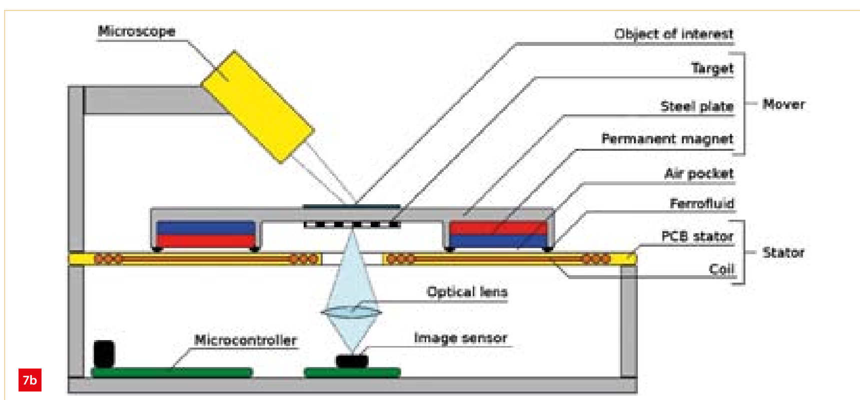
A third example in which ferrofluid bearings and an improved understanding of their functioning has been used is Len van Moorsel's project. Here, the newly derived models of ferrofluid bearings were used in the design of a 3-DoF precise positioning system using fully contactless vision with a single image sensor as position sensor [10]. The final system had a mover that could be actuated in all the in-plane DoFs; commutation of the Lorentz actuators made it possible to make infinite rotations (Figure 7). All the remaining DoFs where constrained using a ferrofluid bearing. The theoretical models facilitated a more balanced design between actuator and bearing so that no excessive heat developed during operation.

Basic theory

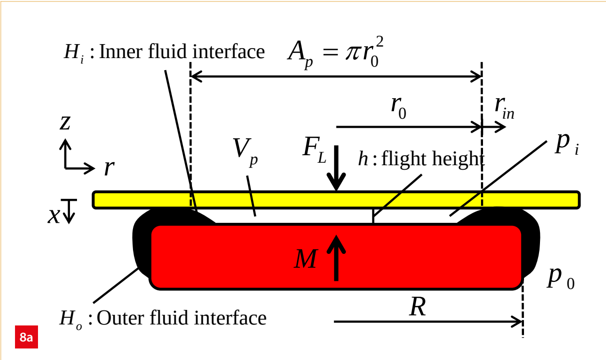
A ferrofluid can basically be used in two different types of bearings [11] [12]. In both bearing types, the ferrofluid acts as a lubricant and a load-carrying component, even at zero speed. The first bearing type is the so-called ferrofluid pocket bearing that encapsulates a pocket of air to carry a load (Figure 8a). The second one is a so-called pressure bearing that works solely by floating the mover on a layer of magnetically pressurised ferrofluid (Figure 8b).

The load capacity of a pocket bearing ($F_{L,pocket}$) is generally a function of the surface area of the pocket of air A_p and the pressure difference that is built up across the seal. This pressure difference is a function of the magnetisation strength of the fluid (M) and the difference in field intensity between the inner fluid interface (H_i) and the outer fluid interface (H_o). The load capacity of a ferrofluid pressure





7 *The 3-DoF (XYθ) positioning system built by Len van Moorsel [10]. The moving part of the system contains magnets that are used for the ferrofluid bearing and the Lorentz actuator. The other half of the Lorentz actuator consists of a PCB board in which coils have been etched.*
(a) Overview showing the black body in the middle as the moving part of the system.
(b) Rendered cross-section showing the image sensor, located underneath the black body, used for contactless optical measurement of the position of the system.



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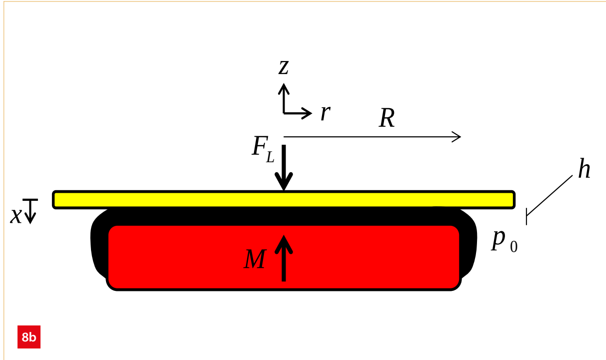


8b

8 Schematic representation of two types of ferrofluid bearing [8].
(a) Pocket bearing: the load is carried by an encapsulated pocket of air.
(b) Pressure bearing: the load is floated on a layer of magnetically pressurised ferrofluid.

9 Translating the bearing leaves behind a trail of ferrofluid [8].

10 Fluid flow profile with no net fluid transport along the length of the bearing [8].

bearing ($F_{L,pressure}$) is solely defined by the pressure built up in the fluid due to the magnetic field at the load-carrying surface of the bearing.

$$F_{L,pocket} = \mu_0 M A_p (H_i - H_o)$$

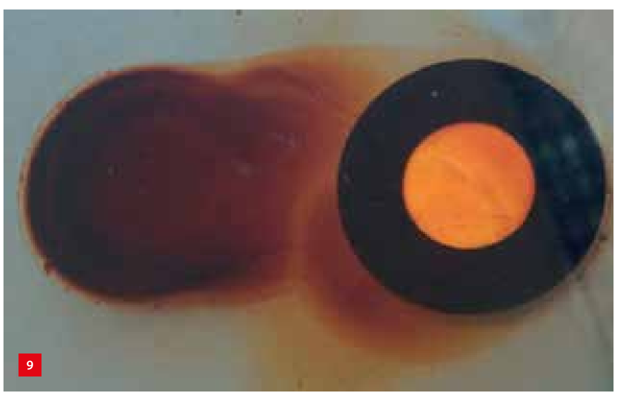
$$F_{L,pressure} = \mu_0 M \int H \, dA$$

The stiffness for a pocket bearing (k_{pocket}) is mainly defined by the change in pressure across the seal with a change in fly height. This means that this stiffness is mainly defined by the gradient of field intensity across the seal. In general, only the inner fluid interface contributes to the stiffness. The term dr_0 / dz in the formula below is called the pneumatic leverage and relates to the movement of the inner fluid interface with the change in fly height. The stiffness for a ferrofluid pressure bearing ($k_{pressure}$) is mainly defined by the gradient in the magnetic field at the load-carrying surface.

$$k_{pocket} = -dF_{L,pocket} / dz = -\mu_0 M A_p (dH_i / dr_0)(dr_0 / dz)$$

$$k_{pressure} = -dF_{L,pressure} / dz = -\mu_0 M \int (dH / dz) \, dA$$

Translating the bearing leaves behind a trail of ferrofluid that has three effects on the bearing's performance (Figure 9). The first is a reduction in fly height due to a reduced load capacity caused by less fluid being available for levitation. The second is an increase in damping due to the reduced fly height. The third effect is a time- and path-dependent force between the ferrofluid trail and the magnet. Upon translation of the bearing, it appears that the majority of the fluid remains between the bearing surfaces.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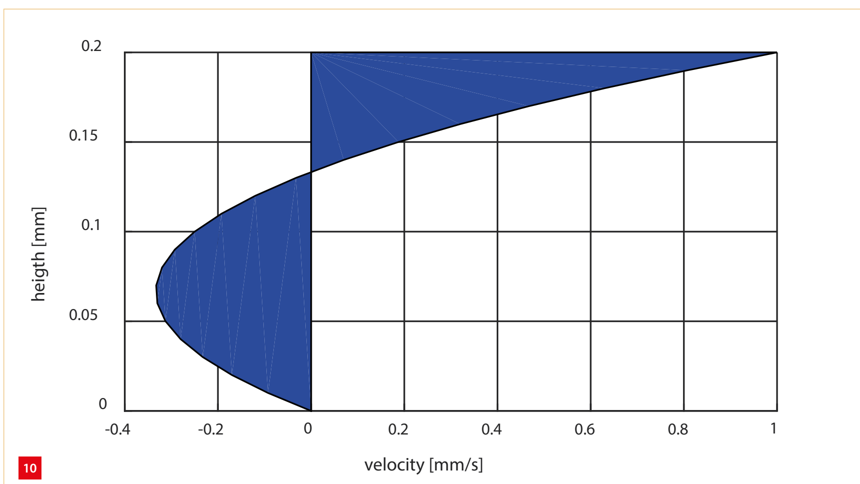
This means that there is a fluid flow with no net fluid transport along the length of the bearing. Figure 10 presents the flow profile that meets this condition. This flow profile basically consists of the summation of a Couette flow caused by the relative movement of the bearing surfaces and a Poiseuille flow caused by the magnetic body force. The model is validated by the work presented in [2] [9]. The viscous-like friction force can be described as follows:

$$F_{fric} = c\,U = 4\,\eta\,(A / h)\,U$$

Conclusion

The various systems described in this article demonstrate that ferrofluids can provide a simple and cost-effective bearing solution for high-precision positioning. The models presented can be used in the design of ferrofluid bearings. The equations show that the magnitude of the magnetic field is important for the load capacity, while the gradient of the magnetic field is important for the stiffness. The model for the friction shows that the bearing can be taken as a pure viscous damper.



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Current and future developments

What started as a simple research project on ferrofluid bearings is now growing into a new research area at Delft University of Technology. Projects have been started that focus on the application of magnetic fluids in different industries. These projects now also include the application of magnetorheological fluids, a type of non-Newtonian magnetic fluid that becomes more viscous in response to a magnetic field. Applications currently being investigated include seals, large-scale bearings and active dampers. ■

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ALL POSITIONING STAGES ARE NOT CREATED EQUAL

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Most motion applications are perfectly well-served by mechanical bearing guidance; but there are many cases where precision, angular repeatability, and geometric performance must be optimal or where submicron bearing rumble is problematic. In these situations an air bearing stage can help: a rotary or linear positioner that floats on a cushion of air, using one of several preload mechanisms, nearly eliminating mechanical contact and thus wear, friction, and hysteresis effects. An overview of the most common indicators that an air bearing stage might be the right choice for a given application.

MATT RECK

In motion applications where precision, angular repeatability, and geometric performance must be optimal or where submicron bearing rumble is problematic, an air bearing stage can help. Figure 1 shows a typical implementation.

Frictionless high-precision positioning

A direct-drive motor and high-resolution encoder can position a moving carriage supported by an air bearing to within nanometers in a linear application or within tenths of arcseconds in rotational applications. The lack of friction and mechanical contact means there is minimal hysteresis or reversal error, making it highly repeatable and ideal for many inspection and manufacturing operations. Stiction is virtually eliminated, improving resolution capabilities and reducing in-position 'hunting' (limit cycling), and position repeatability can be obtained within a few fundamental encoder counts.

Similar precision can be obtained by piezo-flexure-guided stages, however over much smaller travel ranges. Magnetic levitation is another option.

Velocity stability and scanning

The lack of mechanical bearing elements means there is nothing to get in the way of smooth, controlled velocity (stability to better than 0.01%). Experiments and processes like inertial sensor testing, tomography, wafer scanning, and surface profiling requiring continuous motion at tightly controlled speeds are best served by air bearing systems.

Very low error motions

Linear air bearing stages have incredibly straight and flat travels, and pitch, roll, and yaw errors can be measured in tenths of arcseconds. Rotary stages can have tilt (wobble) errors less than 1 arcsecond.

Additionally, the angular performance of an air bearing is remarkably repeatable. This guarantees optimal part quality and measurement reliability for applications like mirror and optics inspection, semiconductor inspection, and medical device manufacturing.

Travel requirements

Piezo-driven flexure stages and actuators can satisfy many high-precision positioning applications. However, these

1 *Three-motor planar XY air bearing stage with active yaw control. (Image: PI)*

2 *Miniature air bearing linear stage. (Image: PI)*

3 *Rotary air bearing. (Image: Nelson Air)*

designs are usually limited to a few millimeters of travel. An air bearing linear stage can be used for travels of 25 mm or more (Figure 2). Travels up to a meter are available, and even greater with a custom design.

Wobble-free or high-speed rotary motion

Rotary air bearings (Figure 3) are exceptionally stiff and can deliver highly precise rotary motion. Radial, axial, and wobble error motions are much smaller than most mechanical bearing solutions can provide, and the rotary motion is very smooth, since there are no roller elements. Rotary positioning stages generally can achieve speeds up to 600 rpm, while air bearing spindles are used in higher-speed applications. Rotary bearing designs can be mounted with the plane of the table in either the horizontal (i.e. turntable) or vertical orientation.

Minimal maintenance

There are no contacting parts to undergo wear and tear, and no regular maintenance procedures to be performed like lubrication. An air bearing stage is essentially maintenance-free. Further, the system is highly stable, since there is no wear; the performance characteristics should not change over the life of the system. There is little need for recalibration. Moving cables and hoses are often the onlyitems subject to wear in an air bearing system.

Cleanliness

Because air bearings are wear-free, they generate virtually no particulates that can become airborne. This makes them ideal for cleanroom applications like optics inspection, wafer inspection, bio-pharma research, and flat-panel display inspection. For extremely clean applications, it is recommended that the air bearings operate using 99.9% pure nitrogen.

Precise force control and sensing

Air bearings are virtually frictionless, which means when they are coupled with a direct-drive motor or voice coil, they are ideal for micro- and nanonewton force control

4 *Spherical air bearings can be used to simulate zero gravity. (Image: Nelson Air)*

applications (Figure 4). Such applications can include pick & place of delicate items, materials testing, and coordinate measuring applications.

When to avoid

- Vacuum environments:
  While it is not impossible to operate an air bearing in a vacuum, it is challenging. Vacuum applications should generally be avoided and instead mechanical bearing, maglev, or flexure systems should be used (Figure 5).
- Very dirty applications:
  Air bearings are generally used in clean environments. Applications where heavy amounts of dust, dirt, debris, and fluids are present should generally be avoided.
- Pressurised air or nitrogen is not available:
  Air bearings require a continuous supply of clean compressed air or nitrogen. If the application does not allow for such a supply to be present, an air bearing cannot be used.

More details on the qualification of air bearings in terms of the straightness and flatness of travel can be found on the next pages.

Video

[V1] *www.youtube.com/embed/l2B12U6NtQw?rel=0&start=61*

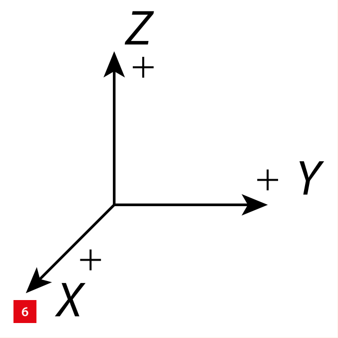
5 *A flexure-guided, UHV-compatible XYZ piezo nanopositioning stage. (Image: PI)*

Straightness and flatness of air bearings

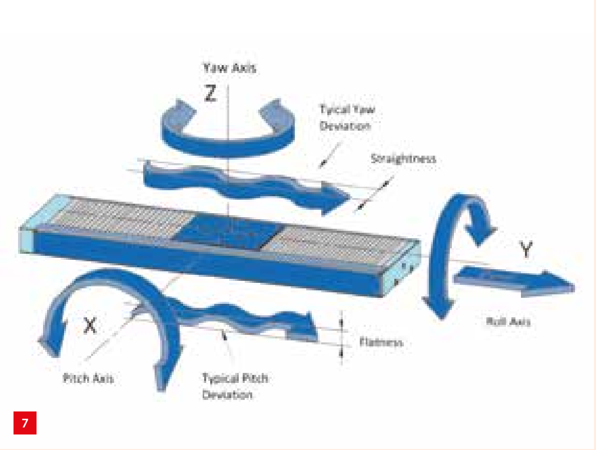
The quality of motion of an air bearing can be described in terms of the straightness and flatness of travel. Here, several aspects will be discussed: the error motion over full travel, impacts on error motion, the repeatability of the error, and the short-term errors.

Definitions

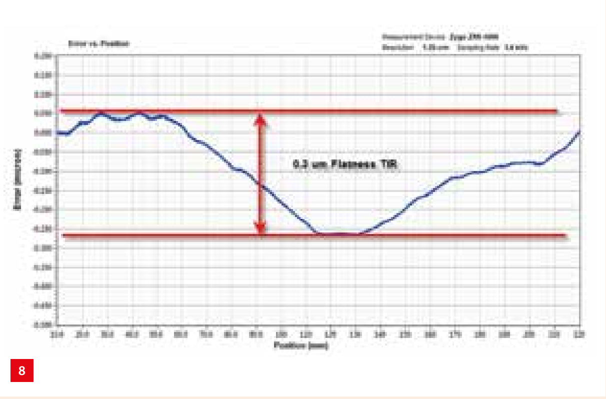
Take a coordinate system as defined in Figure 6. If X is the axis of motion for a linear stage, the straightness error motion ('straightness') is defined as the error motion in the Y direction. As the stage travels along the X axis, the motion deviates from the perfect line by some amount. The flatness error motion ('flatness') is defined as the error motion in the Z direction. Again a deviation from the perfect line. Figure 7 shows typical error motions.



6 *Coordinate system.*



7 *Typical error motions.*



8 *Straightness measured over full travel: error (–0.500 to +0.200 micron) vs. position (10.0 to 200 mm). Resolution 1.25 nm, sampling rate 3.6 kHz.*

Error motion over full travel

The total error motion over full travel is usually specified in 'microns TIR'; TIR means Total Indicator Reading. When TIR is used, the peak-to-peak measurement of error motion is specified, no symmetry about a zero reference being assumed. Figure 8 shows a measured straightness error plotted over 210 mm of travel. The TIR reading is 0.3 µm. Air bearing stages can typically achieve better than 1 µm flatness and straightness TIR for every 200 mm of travel.

Error motion impacts

Besides the inherent quality of the stage or bearing itself, straightness and flatness error motions of air bearings can be affected by several outside influences:

- Quality of the mounting surface:
  Air bearing stages require a very rigid, clean, flat surface for mounting. Any irregularity in the surface, debris, burrs, or dirt, can have a noticeable impact on the stage's error motion, particularly flatness. Figure 9 shows the difference in flatness for a stage mounted to a granite surface plate of high quality vs. mounted to an optical breadboard. The breadboard mounting adds a full micron of flatness error motion to the stage.
- Length of travel:
  Since air bearing precision is in many ways a function of machining and grinding tolerances, which are inherently harder to hold over larger surfaces, longer travel stages will often have larger straightness and flatness error motions than shorter travel stages.
- Size of stage:
  Stages with a larger footprint or with a larger separation between bearing surfaces will usually have smaller straightness and flatness error motions than a smaller-sized stage. Greater separation between bearing surfaces allows angular errors to translate into smaller lateral errors. Larger bearing surfaces increase the averaging effect (see Figure 10) of air bearings and reduce the error motions.

- External perturbations:
  As with any measure of ultra-precision, air bearing stages can have their straightness and flatness error motions impacted by external forces. These forces can come from sources such as cable tracks, machine vibrations, and environmental changes (particularly temperature).
- Mounting orientation:
  The typical assumption is that the stage will be mounted on a flat horizontal plane. If the mounting orientation is to be something else (vertically, as in a Z axis; or on the side, as in an overhead bridge), then the specifications will typically require larger error motions. Side mounting can be especially challenging for straightness. The gravity load on the stage base and the bridge beam induce sagging, and therefore straightness errors.

Repeatability of straightness and flatness error motion

Air bearing stages can claim not only very low overall straightness and flatness error motions, but also extremely repeatable and stable errors as well. Figure 11 shows the flatness error measurements taken from the same stage five successive times. The 2-sigma repeatability of the flatness error is less than 50 nanometers in this case. Since air bearings contain no wear items, one can assume this level of performance will not change over time, unless the machine installation and/or operating conditions are somehow changed.

Short-term error motion

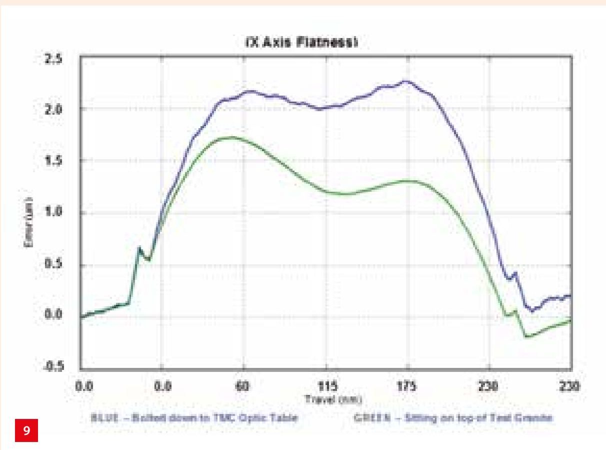
The most exceptional example of the extreme precision of air bearing stages can been seen when the short-term effects of straightness and flatness error motions are examined. Figure 12 shows the straightness data for a stage taken over 10 mm of travel. The TIR measurement in this case is less than 15 nanometers. Errors over any 1mm segment are less than 10 nanometers.
Such performance can be achieved regardless of scanning speed. Performance levels such as this are simply not possible with mechanical bearing technologies.

9 *Straightness measured over full travel on granite (green) vs. optical (blue) table, for a PIglide LC 230-mm travel stage.*

10 *Error averaging effect.*

11 *Straightness repeatability.*

12 *Straightness measured over 10 mm for a PIglide LC 230-mm travel stage: error (–0.050 to +0.050 micron) vs. position (65.0 to 75.0 mm), 48 mm/sec. Resolution 1.25 nm, sampling rate 4 kHz.*



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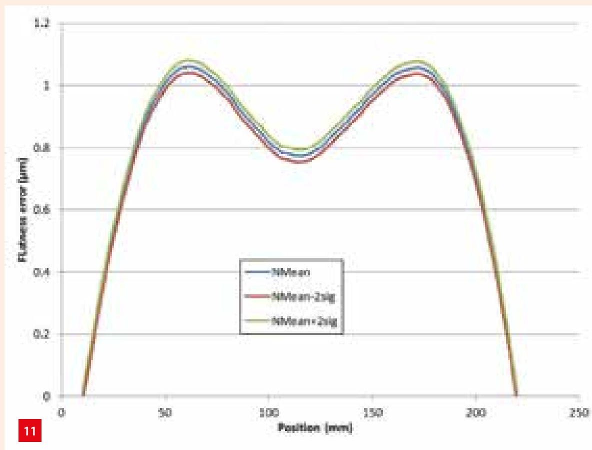

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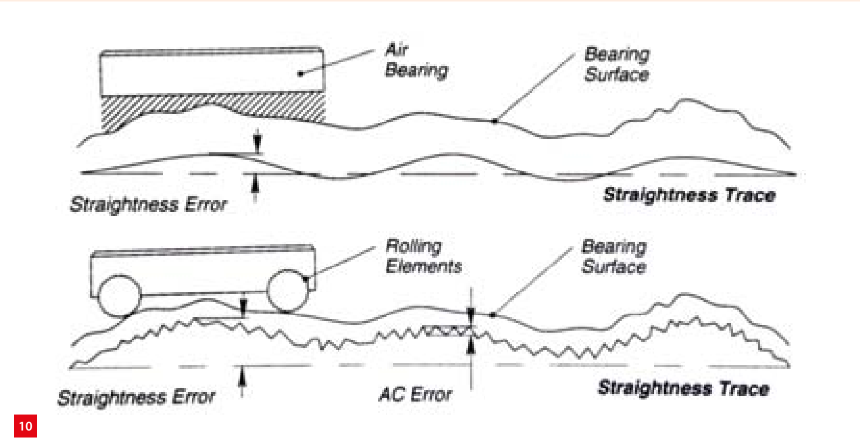

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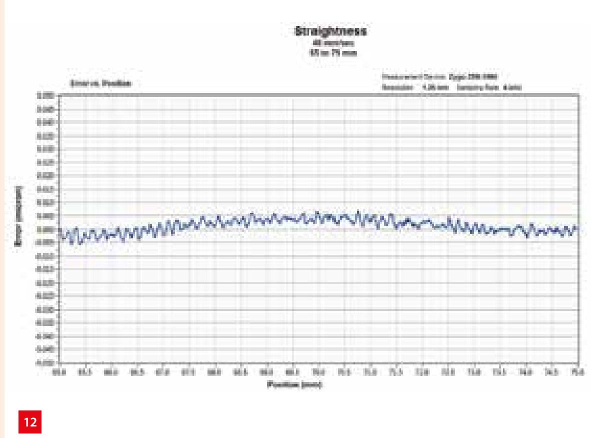

12

MOVING DOWN TO MICRON ACCURACY

As a specialist in bearings and positioning systems, PM (formerly PM-Bearings) develops high-precision cross roller guides. These bearings offer extremely smooth and accurate movement, as well as a high level of stiffness. This requires special measures in the design and manufacture for preventing cage creep and applying the correct pre-tension.

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In cross roller guides (Figure 1), rollers are positioned crosswise so that they can receive loads from above and below, and from the sides. The rollers move between two sharpened V-shaped grooves, with a cage holding the rollers in place. The cage prevents the rollers from making contact with each other, avoiding unnecessary friction and wear between these surfaces. The cage also makes assembly easier and keeps the rollers in place.

Depending on the application, different types of cages can be used. The variation can be in the type of material, e.g. POM (polyoxymethylene), PEEK (polyether ether ketone), brass, steel, stainless steel, aluminium, etc., but also in the pitch between the rollers. The shorter the pitch, the more rolls fit into a certain cage length, which in turn results in a higher stiffness and load-bearing capacity.

Anti-cage creep

A common problem with cross roller guides is the cage slipping out of position between the guides. This phenomenon is called cage creep and over time it results in the cage colliding with the end screw attached to the end of the rail. This can result in damage or rolls exhibiting increased dragging/sliding, which in turn can result in extra heat generation and more resistance. As such, the cross roller guides end up with a shorter lifespan.

To prevent cage creep, there are various cage types available equipped with a gear in the middle; Figure 2 shows an anti-cage creep solution. The gear wheel runs over an integrated gear rack incorporated in the bottom of the V-groove. There are several options available here for different applications. A brass rack or a stainless steel/gold-plated one can be glued (possibly using a vacuum glue) into the freewheel, the lowest point of the V-groove.

For special vacuum applications, there is the option of integrating a gear rack into the guide using electrochemical machining. This process is a contactless operation that doesn't add any heat or tension to the material.

Cross roller guides vs. monorail

A frequently used product for positioning applications is the monorail or linear motor guide. One of the advantages of the monorail is that the length of the rail determines the maximum stroke of the carriage. The disadvantage, however, is that the balls go in and out of pre-tension due to the re-circulating movement. This causes vibrations, while in a cross roller guide rollers are in a constant state of pre-tension, so there are no vibrations. This constant pre-tension combined with the high accuracy of the guides and rollers ensures an extremely smooth and precise movement.

1 *A set of linear cross roller guides.*

2 *An anti-cage creep solution with a gear in the middle of the cage. The inset shows the rack over which the gear wheel runs.*

The length of the rail in combination with the length of the cage, however, limits the stroke of the cross roller guide. If that is what's required or is permissible, then cross roller guides offer major advantages over monorails. The use of rollers (line contact) instead of balls (point contact) allows for higher loads and also provides more stiffness. Cross-roller guides are most often used in the high-accuracy segment, where smooth movement and low frictional resistance are required. Whether or not the cross roller guides are used in combination with a high load, positioning at micron or submicron level is possible.

Cross roller guides vs. air bearings

As part of precision-produced positioning systems, cross-bearing guides can match the accuracy of air bearings. Air bearings are known for their extremely smooth movement and high load-bearing capacity, but are not on a par with mechanical bearings when it comes to stiffness. Air bearings are also more complicated to use and are, as a rule, more expensive to buy.

Another factor that makes cross roller guides even more attractive to use are their mirror-ground running surfaces that minimise the resistance between the roller and the running surfaces. This option is known as 'super finish' (SF). Due to the low surface roughness (R_a < 0.05 µm) of the SF option compared to the standard surface roughness of the V-groove (R_a < 0.15 µm), these cross roller guides are ideal in microscope tables, imaging systems in life sciences and lithography systems in the semiconductor industry.

Pre-tension

In addition to the individual components, the assembly mode of cross roller guides also helps achieve submicron accuracy. Pre-tension can be applied to a cross roller bearing by tightening a screw against the guide using a specific moment, as happens at a roller table that has cross roller guides inserted (Figure 3). This requires considerable professional skill however. Applying too much pre-tension can result in small indentations in the rollers in the V-groove, which reduces movement accuracy. If there is not enough pre-tension, play will occur. When a cross roller guide has different pre-tension levels, the running resistance during an inward stroke will differ from that of an outgoing stroke, for instance.

3

4

3 Roller table with built-in cross roller guides (partly uncovered). Applying pre-tension to a cross roller bearing requires considerable professional skill.

4 PMMR micro-roller table.

Another way to apply the pre-tension bias is to 'sort' all parts, i.e. to match their individual dimensions to the cage they have to fit in. One example of this is the micro-roller table type PMMR (Figure 4). In the table part, the V-groove is accurately ground with a deviation in the parallelism from groove to groove smaller than one micron. The centre guide also has the same degree of parallelism, better than 1 µm on both grooves. By matching these two parts and then using a roll grading (roll-cage fit) of 0.5 µm, the pre-tension can be applied very accurately and evenly.

Some of these miniature tables with rollers are used in pick & place modules for the semiconductor industry, e.g. for SMT machines. Surgical robots like the Da Vinci also use these tables to make very fine and smooth movements. Service life and reliability are very importance in these cases.

From bearings to positioning systems

Based in Dedemsvaart, the Netherlands, PM (formerly PM-Bearings) has been producing and supplying bearings to international players in the semiconductor, optical and medical industries, amongst others, for more than 50 years. One of the main reasons behind the company's name change from PM-Bearings to PM last December was to avoid the assumption that the company only produces bearings.

With its extensive knowledge of the production of high-precision guides and all associated components, PM decided in the late nineties to also enter the market for complete positioning systems. The integration of linear guides, but also the use of rotation and gonio bearings – all of which are produced in-house – gives PM a competitive advantage. In addition to manufacturing catalogue products, PM also develops and manufactures many client- and application-specific guides and roller tables.

WWW.PM.NL

MINIMISING DEAD VOLUME AND SELF-EXCITED VIBRATIONS

Air bearings are very important elements in high-precision machinery. In many cases the ultimate accuracy limit is determined by the bearing properties. With the patented micro-nozzle technology from AeroLas, air bearings can be manufactured that exhibit outstanding performance and are optimised to customer demands. This article presents the technology and its benefits.

THOMAS HOFMANN

1 *The key feature of AeroLas air bearings are laser-induced micro-nozzles which are distributed over the surface.*

In high-precision applications any disturbances to the moving parts have a negative effect on the accuracy. Especially, friction between moving and fixed parts, leading to stick-slip behaviour, limits the ultimate performance. Additionally, rolling-contact bearings can induce short-wave deviations from a linear movement due to imperfections in the sliding surface and tolerances in the ball diameters. In contrast, air bearings provide a contactless support of moving parts with minimal friction. As an effect, the disturbances to the moving parts are minimised. Additionally, surface imperfections on a small length scale are averaged out by the air film and only long-range deviations in the sliding surface are passed on to the slider. These can usually be compensated for with little effort.

The great advantage of quasi-friction-free support comes with a disadvantage: air bearings exhibit low load capacity and stiffness compared to rolling contact bearings of similar size. However, in most cases this drawback can easily be compensated for by a system design which explicitly takes the air bearing into account. For example, the load capacity can often be increased by integrating the air bearing into the surface of the moving part rather than using standard bearing pads with limited area.

Due to the low viscosity of air the intrinsic damping of the air film is low. Therefore, air bearings can exhibit self-excited vibrations with large amplitudes under certain pressure and load conditions. This instability must be avoided under all circumstances. Especially bearings with large dead volumes like pockets or grooves in the bearing surface are prone to these vibrations [1]. Hence, one important design criterion for air bearings is to minimise the dead volume.

For air bearings with low dead volume the instability arises if the dynamic stiffness, which is equal to the stiffness of the gas spring represented by the air bearing gap, is lower than the static stiffness. To increase stability, the ratio of dynamic to static stiffness has to be increased. Additionally, the resonance frequency of the bearing should be as high as possible. Therefore, the mass of the bearing must be as low as possible and preloading by mass should be avoided.

Vibrations which cannot be avoided represent so-called intrinsic air bearing noise. It is caused by the air flow in the bearing gap which may be turbulent in certain regions, e.g., at the transition region between the nozzles and the gap. As an effect, random vibrations in the range of a few nanometers occur. Especially in high-precision applications these vibrations limit the performance of the system. Again, minimising dead volume in the gap helps a lot to decrease air bearing noise. Further reduction can be achieved by reducing the velocity of the air flow to minimise turbulences. Therefore, the supply pressure should be as low as possible.

Micro-nozzles

The key feature of AeroLas air bearings are laser-induced micro-nozzles [2] which are distributed over the surface as shown in Figure 1. This technology provides several advantages over other air bearing types:

- Pressure distribution and air flow can be varied in a broad range and adapted to the application.
- Dead volume in the bearing gap is minimised.
- Regions of turbulent flow in the bearing area are minimised.
- The bearing surface can be manufactured from a broad range of materials.
- The shape of the bearing surface is only limited by manufacturing processes.

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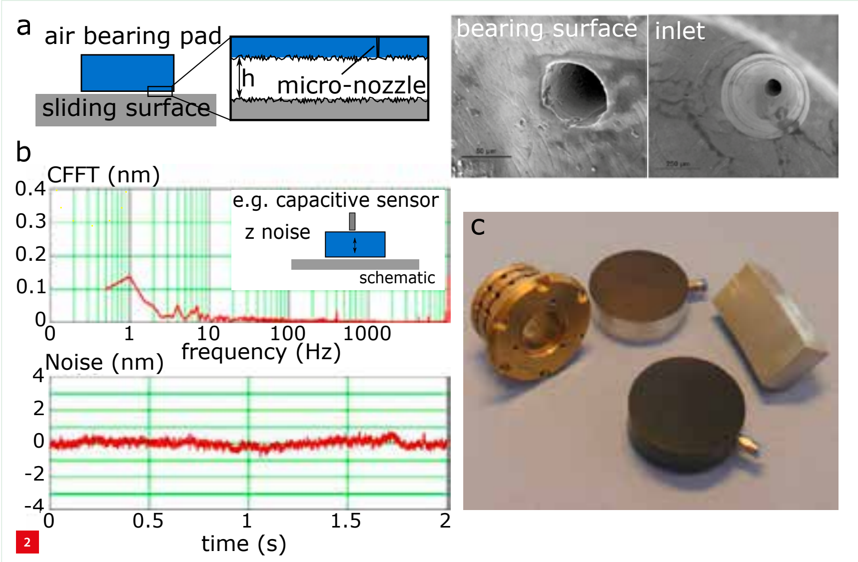
Due to the flexibility in the choice of materials, AeroLas bearings are especially suited for applications where only certain materials are allowed; for example, machinery operated in a cleanroom environment or high vacuum, or high-temperature or harsh-environment applications. Additionally, bearings with an epoxy coating are suitable for cost-sensitive, high-volume applications. Only static air bearings are available, which need to be supplied with pressurised air. Hence, in general, their application is limited to cases where pressurised air with at least 4 bar is available.

Usually, the nozzles are drilled from the backside of the bearing surface through blind holes. The focused laser beam heats up the material until it evaporates. This leads to a cone-shaped hole with the tip of the cone pointing towards the bearing surface, as can be seen in the SEM image of a nozzle from the gas inlet side in Figure 2a.



2 *AeroLas micro-nozzle air bearing technology.*
(a) Schematic of an air bearing on a sliding surface (height h). The amount of dead volume is only determined by the roughness of the air bearing and sliding surface. The SEM images show a nozzle with an approximate diameter of 50 μm.
(b) Measured z noise (the noise in the z-direction motion) of a vacuum-preloaded slider with AeroLas standard bearing pads (the inset shows a schematic measurement set-up). The rms noise is well below 1 nm. (CFFT is the Complex Fast Fourier Transform)
(c) The technology can be applied to various surfaces, e.g., radial bearings made of bronze (left), epoxy-coated (top) or anodised aluminum bearing pads (bottom), or radial-segment bearings (right; in this case, made of steel).

The parameters for the laser process are highly dependent on the material of the bearing and the desired nozzle diameter. The latter is defined by the design of the air bearing and ranges typically between 25 and 50 μm. The size of the nozzles is determined by measuring the air flow rate. During the laser-drilling process, it is checked on a regular basis and, if necessary, the process parameters are adjusted to keep the variations in the air flow as low as possible.

Except for the nozzles, the surface of the air bearing does not exhibit any holes or cavities which would form dead volume. Additionally, the surfaces are grinded to a roughness R_a below 0.2 μm to further minimise dead volume. This guarantees that the air bearings exhibit very low air bearing noise, as shown in Figure 2b. The z noise spectrum is recorded on a slider equipped with standard round air bearing pads (supply pressure of 5 bar), which are preloaded by vacuum in the centre of the slider. It can be seen that the noise level is below 1 nm for the whole measurement period of 2 sec.

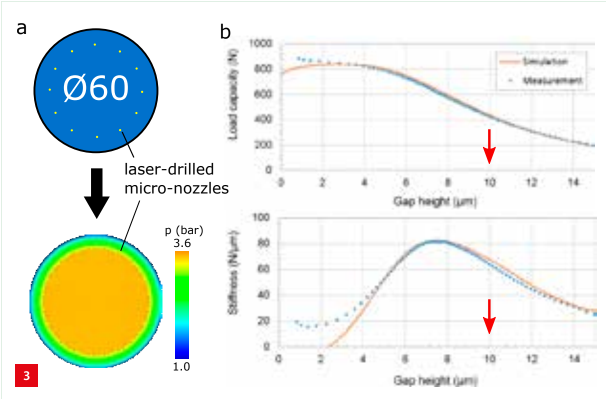
Besides minimising dead volume, additional measures are taken to avoid self-excited vibrations. The laser-drilling process is also used to create passive damping elements which are implemented into the bearing surface. These reduce the stiffness at intermediate frequencies and, hence, the ratio between dynamic stiffness at high and low frequencies is increased. As a result, the stability of the air bearing increases. Furthermore, with the help of these damping elements the dynamic properties of a bearing can be altered independently from the static properties, which is a unique feature of these air bearings.

As mentioned before, a great advantage of the micro-nozzle technology is the wide variety of materials which can be used to manufacture air bearings. Figure 2c shows a selection of bearings made from typical materials. Radial bearings for spindle applications, for example, are often made from bearing bronze. Air bearing pads for standard applications are usually fabricated from aluminum and either the surface is anodised or the bearing side coated with epoxy. In special cases, or for heavy load applications, stainless steel is used, either coated with epoxy or blank, like the radial segment shown in Figure 2c. The flexibility in the choice of materials also offers the possibility to meet extraordinary customer requirements. For example, an air bearing slider was fabricated from special stainless steel which can withstand hydrogen sulfide at temperatures of 350 °C.

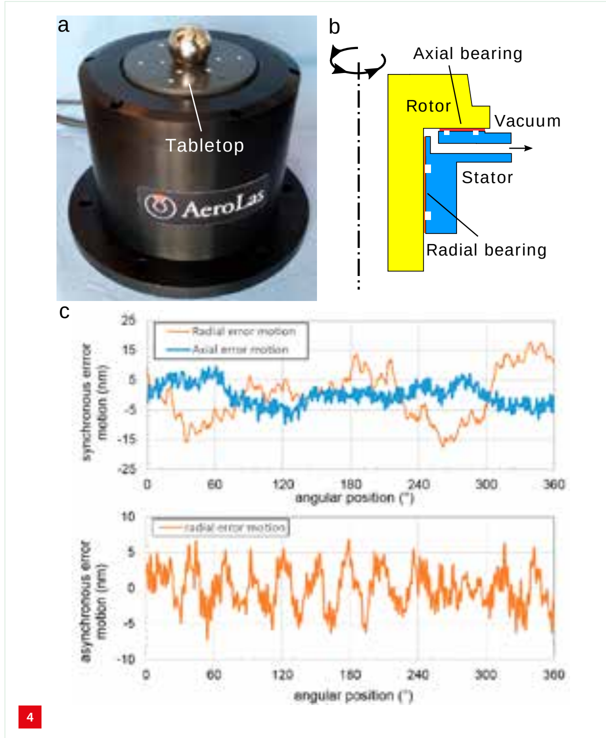
The technology of epoxy-coated air bearings, patented in [3], offers unique possibilities to create air bearing solutions with outstanding performance. One great benefit is that there is virtually no limit to the size of the active bearing surface. Additionally, vacuum pockets for preloading can be integrated simply by milling. Large, lightweight air bearing components with very high stiffness and load capacity can, therefore, be manufactured at a competitive price.

Simulation

The micro-nozzle technology necessitates a step during the development of a new air bearing where the number, size and positions of the nozzles are defined. For this purpose, a proprietary simulation tool is used which has been developed at AeroLas over the last twenty years. It allows the calculation of static and dynamic air bearing properties like load capacity, stiffness and flow rate for any bearing geometry. Also deformation of the bearing, e.g., due to the applied load, resulting in a change in the bearing surface, can be taken into account. The results of the simulations have been validated by numerous measurements. In most cases the accuracy of the simulation is within five percent. With the possibility to accurately simulate air bearings it is



3 *Simulation of a standard air bearing pad AL-60 HD (60 mm diameter) with a proprietary 2D simulation tool, at a supply pressure of 5 bar absolute.*
(a) Pressure distribution for a gap height of 6 µm.
(b) Curves displaying simulated and measured load capacity and stiffness versus gap height. The simulated load capacity curves have been calculated from the pressure distribution, as shown in (a), at the various gap heights. The stiffness curves were derived from the load capacity curves. The measurements have been performed at a test stand by applying an increasing load while measuring the gap height. The red arrow indicates the suggested working point.



4 *A high-precision rotary stage as an example for a typical air bearing application.*
(a) The stage with a tabletop diameter of 93 mm and an aperture of 20 mm.
(b) Schematic of the air bearing. The rotor is supported by a relatively long radial air bearing and a vacuum-preloaded axial bearing.
(c) Synchronous and asynchronous error motion. An eccentric position of the precision steel ball is compensated.

feasible to design air bearings which optimally fulfil the requirements of the application within reasonable time.

Figure 3a shows a typical output of the simulation for a standard round air bearing with a large number of micro-nozzles and a supply pressure of 5 bar absolute (ambient pressure is one bar absolute). The deformation of the bearing pad, which leads to a convex bearing surface, is taken into account. The bitmap represents the pressure distribution at a certain gap height. Within the ring of nozzles the pressure is very uniform and decreases rapidly to ambient pressure outside of the ring.

To obtain the load capacity of the bearing at the corresponding gap height, the pressure is summed up, representing one data point in the load capacity versus gap height curve in Figure 3b. The stiffness curve is calculated from the load capacity curve by differentiation with respect to gap height. Both diagrams present the simulated and a measured curve, showing excellent agreement down to a gap height of 4 µm. The discrepancy at lower gap heights originates from the fact that the bearing surface becomes convex.

Application example

Figure 4a shows a high-precision rotary stage as an example for a typical air bearing application. A few key parameters of the stage are listed in Table 1. The goal was to build a stage with minimal radial and axial error motion of the rotor for a given tabletop diameter. To that end, the air bearing system was designed for high stiffness in combination with low air flow. As a result a relatively long radial bearing was chosen and the axial air bearing is preloaded with vacuum. A schematic cross-section of the bearing system is depicted in Figure 4b. To prevent a negative influence of the motor on the performance, a brushless motor without any magnetic material in the coil unit was installed. Figure 4c shows diagrams for the synchronous error motion in axial and radial direction and the asynchronous error motion in radial direction. Both graphs were recorded at a rotation speed of 48 rpm. The error motions were measured with capacitive distance sensors pointing on a precise steel ball.

The Donaldson reversal method [4] was used to remove form errors of the steel ball from the radial error motion data. Both radial and axial synchronous error motion are below 20 nm (peak-peak). The asynchronous error motion is smaller than 10 nm (peak-peak). These are excellent values compared to those of rotary stages on the market. ■

Table 1. Selected parameters of the high-precision rotary stage.

Dimensions	Tabletop diameter	93 mm
	Housing diameter	155 mm
	Height	135 mm
Load (max.)	Axial	750 N
	Tilt	8.5 Nm
Measuring system	Signal	1 V_{pp}
	Line count	18,000 1/rev.
Motor	Continuous stall torque	0.14 Nm
Miscellaneous	Supply pressure	5 bar (relative)
	Air consumption	< 5.5 slm

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LEVITATING HIGH-PERFORMANCE MACHINING

Machine tools for ultra-precision machining generally feature a working precision in the submicron range, but at the same time suffer from limited machining speed and low productivity. In order to increase the performance of ultra-precision machining processes, an innovative feed axis based on electromagnetic levitation technology has been designed and constructed. After commissioning, the active guiding system demonstrated a decoupled control of its five degrees of freedom with submicron precision.

BEREND DENKENA, BENJAMIN BERGMANN AND RUDOLF KRÜGER

Introduction

Currently, ultra-precision machining with diamond tools allows for the mechanical manipulation of raw material with submicron precision. It features a variety of established process technologies as well as a wide range of compatible engineering materials for the manufacture of high-precision components with specific mechanical and optical surface properties [1] [2]. Thus, it has become an important driver for various industrial sectors, such as automotive, lighting, medical engineering, metrology and optics.

In view of recent research activities in the field of ultra-precision machining, two main objectives are apparent. On the one hand, the increase of the overall machining accuracy, and on the other hand, the production of increasingly complex workpiece and surface geometries. The aspect of manufacturing productivity in ultra-precision machining has been mostly neglected so far.

Hence, respective machining processes are usually characterised by disproportionately long machining times and limited economic applicability [2] [3]. Productivity restrictions can be traced back to the machine tools' feed axes, among other things, because they are designed to operate solely at low feed rates in order to ensure the highest degree of positioning precision [4]. Further challenges still remain with respect to the time-consuming workpiece and tool alignment.

Against this background, machine tool feed axes based on electromagnetic levitation technology present a promising approach to overcome existing restrictions. Electromagnetic linear guides offer friction-free motion, adaptive control of the guiding system's properties (such as stiffness and damping) as well as fine positioning of the levitating slide in five degrees of freedom (DoFs) [5]. In machining operations, these qualities allow for high feed rates and cutting speeds without sacrificing positioning precision or process stability. Moreover, the guiding system's functionality as a combined sensor and actuator offers additional benefits for an efficient process set-up by reducing the need for manual measurement and realignment of the workpiece and cutting tool.

To this day, known applications of electromagnetic guiding systems in manufacturing cover conventional high-speed machining [5] [6] or high-precision positioning (for testing or non-mechanical processing) [7]. However, an electromagnetic guiding system combining nanometer positioning capability and sufficient stiffness for ultra-precision cutting operations has not been presented yet. Consequently, a novel electromagnetic linear guide for ultra-precision high-performance machining was developed and constructed. This contribution introduces the functional prototype and presents initial results from the commissioning of the guiding system.

Concept

The functional basis of the electromagnetic guide is a set of reluctance force actuators, each consisting of an electromagnet and a back iron (to close the iron circuit). Since the electromagnets are only capable of applying attractive forces, two opposing magnets are required to form a bi-directional actuator. Therefore, twelve electromagnets in differential arrangement, as illustrated in Figure 1, control the guiding system's five DoFs.

AUTHORS' NOTE

This contribution was prepared by Rudolf Krüger while working on the project "Electromagnetic ultra-precision linear guide" within the DFG research group FOR 1845 at the Institute of Production Engineering and Machine Tools (IFW) in Hannover, Germany. The project is being supervised by Berend Denkena (head of the IFW) and Benjamin Bergmann (head of the IFW department for machine tools and controls).
The authors would like to thank the German Research Foundation (DFG) for funding the research group FOR 1845, "Ultra-Precision High Performance Cutting".

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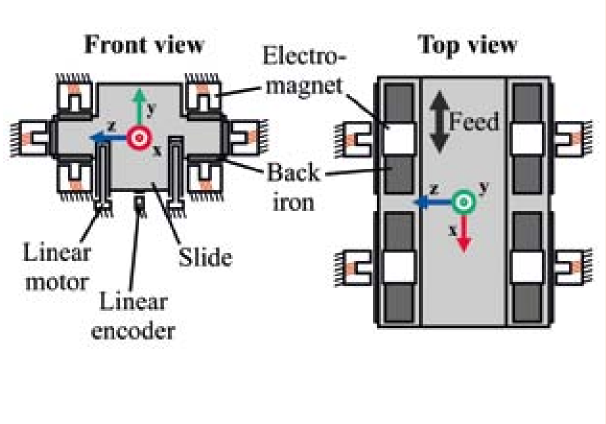

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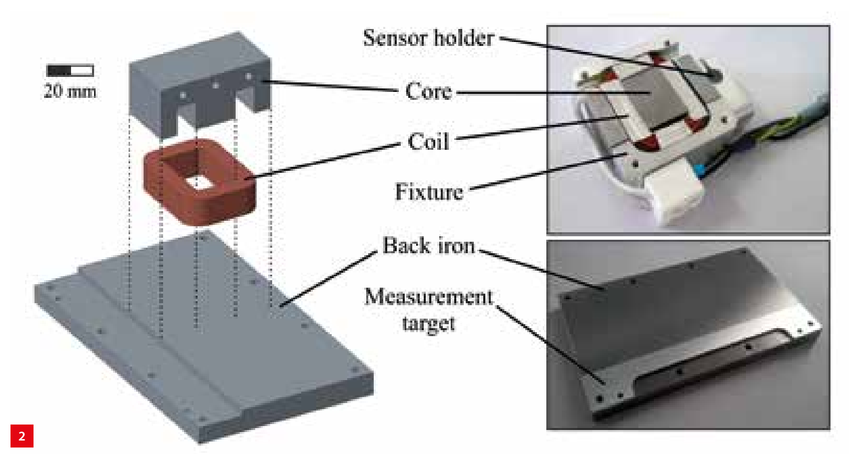


2

1 *Concept for the electromagnetic ultra-precision linear guide. (All figures © IFW)*

2 *Actuator design for the electromagnetic ultra-precision linear guide.*

Admittedly, the actuator design is inherently unstable due to its negative stiffness and requires constant monitoring of the air gap and appropriate adjustment of the coil current to maintain a given position. Hence, capacitive probes are attached to all electromagnets to measure the distance between the core's pole surface and the back iron. A pair of ironless linear motors drives the levitating slide in the feed direction (sixth DoF). An exposed linear encoder with nanometer resolution is used for position feedback in x-direction, respectively.

A substantial objective of the conceptual design phase was the minimisation of the guiding system's error budget. Thus, several measures were taken to reduce predominant disturbance effects. As a result, the electromagnetic guide's active components (i.e. electromagnets, coil units of the linear motors, capacitive measurement system and linear encoder) are mounted to the frame in order to avoid supply lines to the levitating slide as a source of non-linear friction. The electromagnets and linear motors are positioned near the slide's horizontal centre of gravity plane to minimise cantilevers and unwanted breakdown torques. Natural granite as the main construction material for the guiding system's structural components facilitates thermal stability and beneficial damping properties.

Prototype

Based on the initial concept, a functional electromagnetic guide prototype was designed and constructed. Special attention was given to the design of the electromagnetic actuators due to the impact of the attainable force dynamics on the guiding system's overall properties [8]. First, a basic concept for the electromagnets was developed using an analytical description of the iron circuit and the resulting reluctance force at the iron-air-transition. Then, a parametric finite-element model was used to optimise the geometry of the iron circuit in order to achieve an even flux-density distribution for a high power generation. Finally, a genetic algorithm was applied to adjust the field coil parameters for a favourable compromise between force dynamics, current ripple and power dissipation.

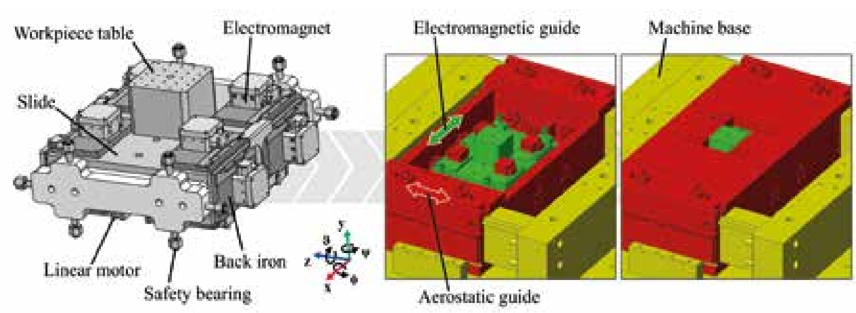
The result of the optimisation is a compact electromagnet design with an E-shaped core and an I-shaped back iron (Figure 2). Both the magnet core and the back iron are made of laminated sheet metal (M250-35A) in order to minimise eddy current losses in the iron circuit. Aluminium plates are integrated into each back iron to provide suitable measurement targets for the capacitive probes. Table 1 summarises the technical specification of the optimised electromagnets.

Table 1. Technical specification of the optimised magnet design.

Specification	Value
Core measurements [mm^3]	50.0 x 25.0 x 22.5
Pole surface [cm^2]	8.25
Air gap [mm]	0.2
Coil windings [-]	50
Coil inductivity [mH]	3.95
Coil resistance [Ω]	0.084
Coil current (maximum) [A]	12
Flux density (maximum) [T]	1.6
Magnet force (maximum) [N]	700

Movement in feed direction is achieved with two ironless linear direct drives in gantry configuration. With a combined maximum force of 600 N, the direct drives allow for a maximum acceleration of up to 15 m/s^2 (or 1.5 g) for a slide mass of 39.5 kg.

Since the machining of a workpiece surface requires at least two controlled feed axes, the guiding system was incorporated in a two-axis positioning stage. Figure 3a presents a detailed design study of the electromagnetic guide prototype (without the frame) as well as the integration of the guiding system in the two-axis stage.



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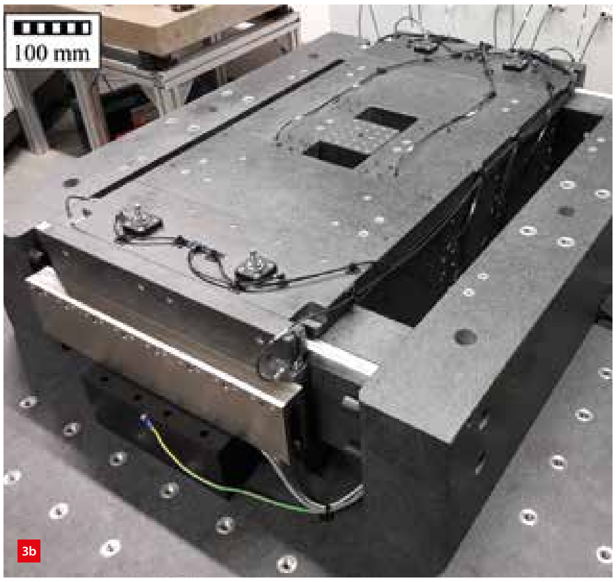


3b

3 *Electromagnetic guide for ultra-precision two-axis positioning stage.*
(a) Design study for the guide prototype and implementation in the stage.
(b) Realised two-axis stage prototype.

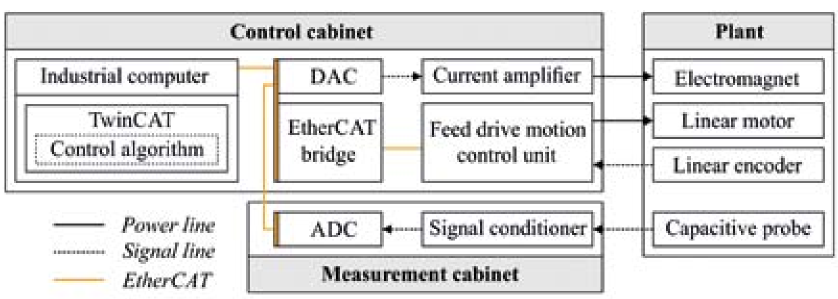
4 *Hardware structure of the control system.*

The secondary axis features aerostatic guideways, ironless linear motors in a gantry configuration with individual linear encoders and a box-in-a-box set-up to minimise the overall error budget of the stage. Figure 3b shows the final cross-table prototype.

Control environment

Due to its inherently unstable properties, the electromagnetic guide requires a control system consisting of a sensor system, a suitable control algorithm and power electronics for stable operation. A control cabinet was constructed, housing the electromagnets' current amplifiers, an industrial computer for the guiding system's control algorithm, and a separate feed drive motion control unit for the linear motors. The measurement electronics were placed in a separate cabinet to minimise possible impairment of the sensor signals by the power electronics.

The control algorithm for the electromagnetic guide was designed in MATLAB Simulink® and transferred to a real-time control environment (TwinCAT implemented in MS Visual Studio) on the industrial computer. The hardware connection was established via modular terminal systems based on an EtherCAT protocol with a maximum sample rate of 20 kHz. Figure 4 outlines the hardware structure for the control application at hand.



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Initial operation

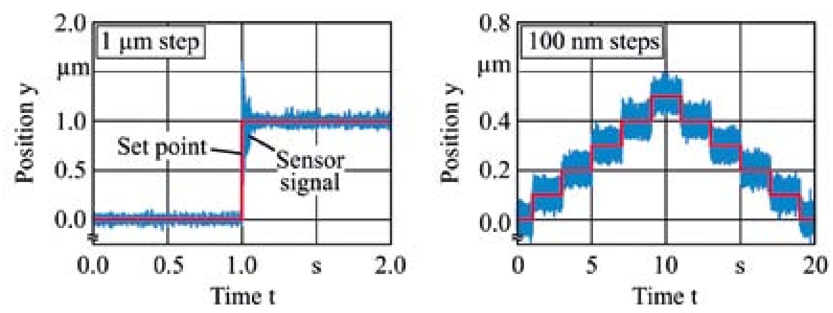
The overall complexity and the inherent instability of the system require a robust and practical approach for the initial operation. In this regard, the use of proportional-integral-derivative (PID) controllers presents a suitable solution for the commissioning and plant identification due to the simple design and implementation as well as the high practical relevance for industrial control applications.

In a first step, the functionality of the electromagnetic actuators was investigated. For this purpose, a PID feedback mechanism was used to control two opposing electromagnets (forming one bi-directional actuator) at a time with a control frequency of 10 kHz. Robust control parameters were calculated for an operating point with an air gap of 200 μm and a bias current of 5 A based on a linearisation of the electromagnets' characteristic diagram. In a second step, Jacobian matrices were used to decouple the slide's five DoFs. Accordingly, five individual PID controllers were implemented to manipulate the position and orientation of the levitating slide.

Control accuracy and robustness were evaluated through step response analysis. The position and orientation of the slide were monitored with the integrated capacitive probes. Besides the aliasing filters of the measurement electronics, no additional filters were used, to avoid any effects on the control loop's dynamic properties.

Measurement results

The use of PID feedback mechanisms presents an accessible solution for a robust position control of the electromagnetic actuators [9]. Figure 5 shows the actuators response to 1μm and 100nm control input steps. Notable overshoots occur at a step size of 1 μm but disappear completely for 100nm steps due to the control parameter optimisation for small



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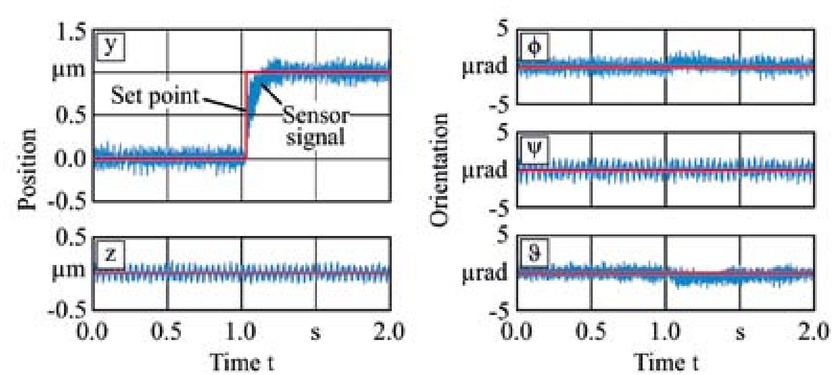
5 *Position control of a single bi-directional electromagnetic actuator.*

6 *Decoupled control of the slide's five DoFs for a step response in the y-direction.*

step sizes in the submicron range. Moreover, the electromagnets clearly interfere with the capacitive probes as soon as the power electronics are active. The derivative term of the PID controller additionally amplifies existing sensor noise; however, it is necessary to stabilise the closed control loop. In total, the noise level increases from 40 to 200 nm (peak-to-peak) when the position control of the electromagnets is in use.
Consequently, the existing sensor noise limits the achievable gain, stiffness and position accuracy of the electromagnetic actuators at this point.

Despite the given limitations of PID feedback mechanisms, decoupling the slide's five DoFs with Jacobian matrices and implementing individual PID controllers per DoF enables stable levitation. Figure 6 shows the position and orientation of the slide in generalised coordinates for a control input step response in the y-direction. The measurement results indicate a satisfactory decoupling of the five DoFs with only minor interdependencies for the rotational DoFs. Remaining coupling between the rotational DoFs occurs due to manufacturing and mounting tolerances, which lead to imperfect Jacobian matrices. Once again, the derivative term of the control algorithm



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compromises the noise level resulting in a position noise of approximately 450 nm and 4 µrad, respectively.

Summary and outlook

This work outlines the development and commissioning of a novel electromagnetic linear guide for ultra-precision high-performance cutting. The guiding system prototype was set up and integrated in a two-axis positioning stage. A suitable control environment was created to drive all the mechatronic systems of the stage. Decoupled control of the levitating slide's five DoFs was achieved with independent PID feedback mechanisms for an initial proof of functionality.

The initial results confirm a robust position control with submicron accuracy. At the same time, the commissioning of the system revealed the need for further optimisation regarding precise alignment of the guide's functional components and the implementation of the capacitive air gap measurement system. Therefore, the electromagnetic guide has been fully reassembled including precision alignment of actuators, sensors and measurement targets as well as a metrological investigation of the assembly.

Ongoing studies cover the implementation of the capacitive measurement system with a focus on electrical and thermal isolation. Future work includes the implementation of a previously developed state-space controller based on Kalman filtering with an updated state-space model, which presents a promising approach to reduce position noise and improve position accuracy of the active guiding system [10].

However, the pursued productivity increase in ultra-precision machining requires further research with regard to appropriate machine and process technologies to complement the newly developed guiding system. Accordingly, projects within the FOR 1845 research group, "Ultra-Precision High Performance Cutting", focus on technological research on wear and surface integrity in ultra-precision machining with increased cutting speed, ultra-precision milling with multiple diamond tools, balancing of high-speed air bearing spindles for ultra-precision applications as well as in-process-analysis and modelling of the dynamic behaviour of ultra-precision machine tools [11]. ■

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ASML, A COMPANY TO BE PROUD OF

Everybody knows ASML, but not everyone is familiar with the secrets of its success. The DSPE Precision-in-Business (PiB) day offered a good insight into the application of extremely short-wavelength radiation for the production of the chips that everyone uses in their computer, smartphone and washing machine. The ASML contribution to semiconductor production lies in the research and development of the lithography process and the manufacturing of the associated wafer steppers. These precision machines use lithography to project ultra-precise patterns onto silicon wafers.

FRANS ZUURVEEN

On the well-attended PiB day (see Figure 1), Cor Ottens from the ASML Opto-Mechanics department highlighted the latest trends in the dynamic world of integrated circuit manufacturing. The continuing race to fit more and more transistors onto a single chip is described by Moore's law: the doubling every two years of the number of transistors per surface area unit. From 500 transistors on one chip in 1970, to a nearly unimaginable estimated number of 10^{10} in 2020, the double-logarithmic representation of number of transistors vs. time can be depicted in an almost perfectly straight line. Keywords in the IC world are smaller, faster and cheaper.

1 *The DSPE Precision-in-Business day at ASML was well attended. (Photo: Annemarie Schrauwen)*

AUTHOR'S NOTE

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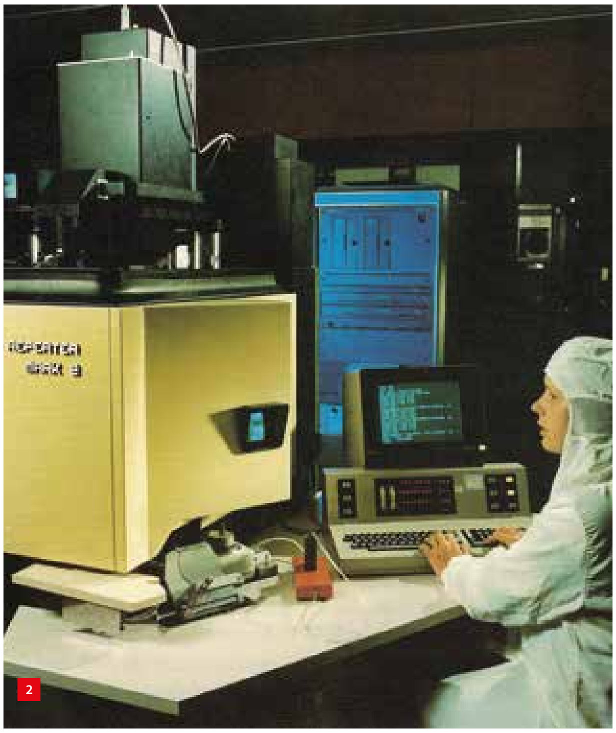


2 *The wafer stepper known as the Silicon Repeater, working with radiation with wavelengths of 405 and 436 nm. It resulted from research at Philips Electronics in 1983 and had a resolution of 1.25 µm. (Photo: Philips Technical Review)*

Moore's milestones

Several milestones can be distinguished in the historical transition of specialisation in wafer steppers, beginning at Philips Electronics in Eindhoven and leading to ASML in Veldhoven, in what is known as the Brainport region. The author's own experience of this can be found in an article published in 1983 in Philips Technical Review describing the Silicon Repeater (see Figure 2). This research instrument worked with violet radiation of about 400 nm from a high-pressure mercury light source. The Silicon Repeater could project details of minimum 1.25 µm onto a 4-inch wafer, thanks to a high-precision telecentric objective.

3 *The ASML TWINSCAN NXE wafer stepper working with extreme UV-radiation with a wavelength of 13.5 nm. It provides a resolution of 13 nm and an overlay accuracy of better than 2 nm in the projected patterns. (Picture: ASML)*

Although the Silicon Repeater was an advanced instrument for its time, it could be upgraded successively by applying radiation with lower wavelengths. Why and how? The Rayleigh criterion states that the smallest distance between two features that can still be distinguished as separate – called optical resolution – is proportional to the wavelength of the used radiation and inversely proportional to the numerical aperture of the objective. As more functions on a chip demand smaller dimensions of the transistor, consequently the application of radiation with ever smaller wavelengths is required.

This brings us to a second milestone contributing to progress according to Moore's law: the ASML TWINSCAN NXE (see Figure 3). This wafer stepper applies EUV radiation, which is extreme ultra-violet with a wavelength of no more than 13.5 nm. This advanced instrument handles wafers with a diameter of 300 mm, three times larger than the wafers in the Silicon Repeater. The huge machine is provided with a wafer stage comprising two wafer tables to enhance its throughput by enabling the preparation of a second wafer while the first one undergoes the repeated-projection process. When comparing this TWINSCAN with its early predecessor the Silicon Repeater, one difference is conspicuous: decreasing the applied wavelength results in a considerable enlargement of the machine.

How to make an IC?

During a tour of the ASML Experience Centre, the PiB attendants were able to watch the processes a wafer undergoes to become a large series of separate dies, each containing numerous integrated circuits (ICs), which then only have to be packaged. The silicon surface undergoes successive treatments like vapour deposition, magnetron sputtering, ion implantation or etching. These treatments, however, only need to be processed locally with high-resolution details. That's why the wafer is covered repeatedly with a UV-light-sensitive photoresist, which is radiated locally according to patterns fixed in successively applied reticles.

Thus every chip production cycle involves:

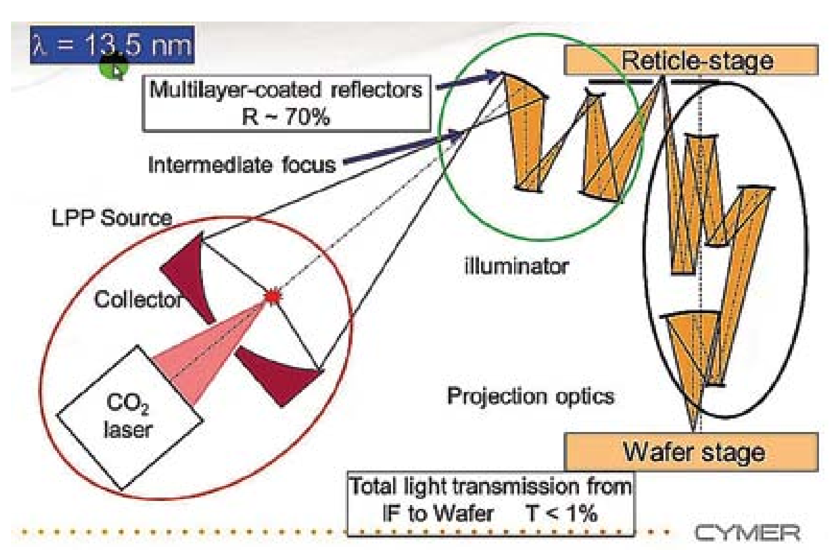
- step-wise locally exposing the photoresist in the wafer stepper;
- removing the wafer from the wafer stepper;
- developing the photoresist;
- treating the free-coming silicon surface parts with one of the described processes;
- removing the photoresist from the wafer;
- covering the wafer with a new layer of photoresist;
- putting the wafer in the wafer stepper again for a new EUV exposure cycle.

Needless to say that subsequent illuminations have to match each other dimensionally with nanometer precision, thanks to ultra-precise aligning marks. It will have become clear that after each step-wise exposure, the wafer moves so that a new part of the silicon surface is illuminated. It is not only the precision stage in which the wafer moves, however; the reticle also moves, in the opposite direction to make optimal use of the optical beam trajectory. In the older models, these stages are designed with slides on air bearings, driven by linear motors. The even more sophisticated stages in the TWINSCAN NXE move on magnetic bearings with integrated electromagnetic drives.

EUV optics

The ASML wafer stepper TWINSCAN NXT works with a 193nm wavelength Deep UV light source and an immersion objective with a record numerical aperture of 1.35. This chip-making machine is equipped with lenses and a gas-discharge DUV light source. As mentioned earlier, its successor, the TWINSCAN NXE, works with Extreme UV radiation with a 13.5 nm wavelength. Unfortunately, such radiation cannot pass through 'conventional' optical lenses made from glass or other refractive materials. The only method to focus such optical beams is by using ultraflat multi-layer mirrors.

For a wavelength of 13.5 nm, ASML covers mirrors with a Mo-Si multilayer coating. This enables the reflection of 13.5 nm EUV, but nearly extinguishes the reflection of nearby wavelengths according to Brag's interference principle. The transmission efficiency of one coated mirror amounts to only 70%, obviously rather poor but still workable with a total transmission from the first focus to the wafer of only 1%. Figure 4 shows the principles of the EUV light path in the TWINSCAN NXE.



4 *The principle of the EUV source, originally from Cymer, which was acquired by ASML in 2012, with an optical chain of multilayer-coated concave mirrors that project a reticle pattern in 13.5nm wavelength EUV onto a silicon wafer. (Picture: Cymer)*

The EUV source

Yet how to generate 13.5 nm EUV light? ASML owns the Cymer Technologies division in San Diego, USA, which designed a highly sophisticated 13.5 nm EUV source. ASML housed this source in a thermostatically water-cooled and vibration-isolated vacuum vessel, designed in the Eindhoven Brainport area.

A CO_2 laser beam hits droplets of liquid tin with some tens of μm diameter, thus heating the tin and eventually creating a plasma, consisting of tin ions and electrons. These tin ions emit all kinds of 'light', including 13.5 nm EUV photons. A first concave mirror concentrates the EUV beam in an intermediate point focus (Figure 4).

Figure 5 shows a specialised mechanic working at a TWINSCAN illumination system. For such assembling operations, ASML uses a high-grade cleanroom that, of course, conforms to stringent climate and particle-free standards.

Lecture and tour

It is not only the EUV optical path itself that asks for intelligent alignment procedures. Bas van Dorp, system architect at ASML, explained the problems associated with the alignment of the CO_2 laser beam with respect to the centre of the EUV source.

After his highly interesting lecture, the PiB day finished with a tour through the ASML test and measurement facilities. Here, several movement assemblies from the TWINSCAN machines are tested for durability and dynamics, making use of advanced high-speed cameras, for example.

One remarkable test was for a reticle stage, on which a pellicle is deposed to protect the very sensitive reticle from contamination. During the high-acceleration movement of the stage, the pellicle is excitated in its natural frequencies, causing various oscillation patterns. The test is aimed at helping to design measures to avoid these oscillations. All of these experimental set-ups help to increase the reliability and lifetime of ASML products.

5 *A specialised mechanic working on a TWINSCAN illumination system. (Photo: ASML)*

To conclude

The PiB day at ASML provided an excellent opportunity to make acquaintance with one the most prominent members of the Dutch precision engineering industry. It was also an extra stimulant for DSPE to organise more PiB days to show what the Dutch precision industry is bringing forth. ■

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BOTTLENECKS OR STANDARDS?

The measuring room can turn into a bottleneck within a manufacturing organisation; for example, products cannot be delivered because the measurement report is missing. This may be due to the lack of a sound measurement strategy. The Meten 2018 seminar, held in early February in Veldhoven, the Netherlands, and organised by Mikrocentrum, was devoted to the optimisation of industrial measuring processes. It covered trends in metrology practice, the operation of a measuring room, the management of measuring equipment, and calibration standards. The following is a brief report.

AUTHOR'S NOTE

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FRANS ZUURVEEN

The national metrology institute VSL is commissioned to manage the measurement standards in the Netherlands, not only for length, but also for mass, temperature and electrical and other quantities. In his introductory lecture to the Meten 2018 seminar, chairman of the day Jacob Jan de Boer, a consultant at VSL, explained that several trends may be observed in today's metrology practice, when differentiating between the old and new technological economy.

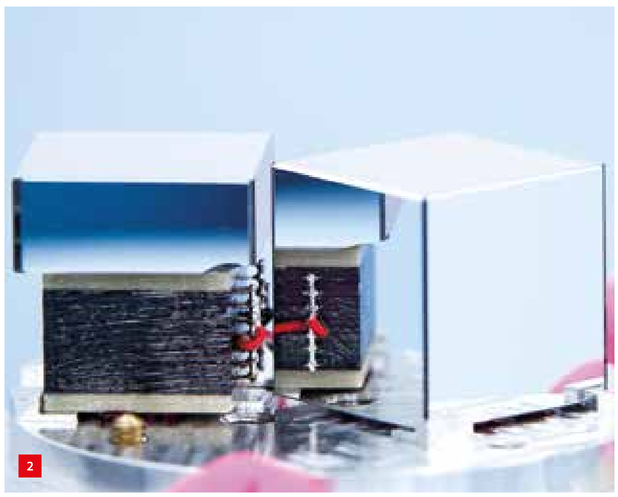
The old economy is based on mass production in large series, with Taylor-derived management of workforces.

1 *The AFM developed and assembled by VSL, the Dutch metrology institute, used as a reference tool for nanoscale measurements. (Photo: VSL)*

In the new technological economy, goods production is flexible, with lower serial quantities based on local demands, bringing a better and more human-friendly working climate. The ultimate goal is the "factory of the future", which is continuous in operation and where people are only necessary for supervision and flexible-production programming.

These trends also influence geometrical measuring practice. Smart sensors monitor production progress, and measuring and inspection take place during machining, avoiding the possibility that products are rejected at the end of an expensive production process. More advanced precision-measuring technologies are going to be introduced into work-shop practice, even atomic-force and interferometric measurements, resulting in nanometer accuracies.

Figure 1 shows the Atomic Force Microscope (AFM) developed by VSL. In such a measuring instrument, a tiny mechanical probe made from tungsten scans the contours of



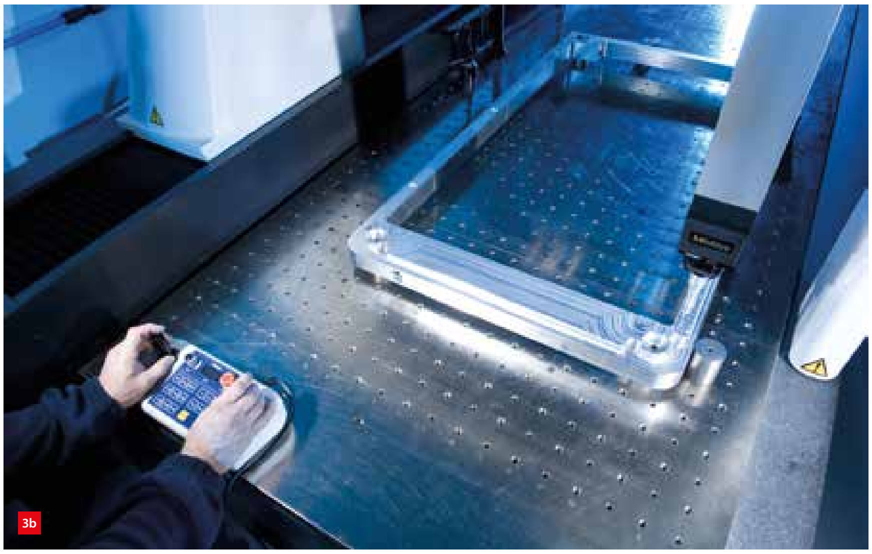
2 *Virtual standards with a tuneable pitch, developed by VSL for the calibration of AFMs [1]. They consist of highly linear, shear piezoelectric cubes, with a dimension of about 1 cm³. (Photo: VSL)*

a surface line-by-line, capturing the shape of the surface with potentially sub-nanometer accuracy. Figure 2 depicts the virtual standards developed by VSL for the calibration of AFMs. These standards have a tuneable pitch, specifically designed for the calibration of small scanning ranges. VSL has thus created a virtual pitch by periodically shifting the lateral position of an arbitrary surface over a well-known distance in the 10 nm range [1].

Measuring room a bottleneck?

Peter van Lierop is a team leader in the measuring room of the KMWE Group, which specialises in high-precision mechanical cutting. In his lecture, Van Lierop discussed the problem of how to transform a measuring room from a bottleneck into a success factor (see Figure 3).

Firstly, Van Lierop explained that abandoning measuring operations guarantees saving money in a production chain. In most cases, however, inspection and measuring are unavoidable steps in the production of high-precision components. When the capacity of a measuring room has not grown in parallel with the expansion of production facilities, the measuring room indeed becomes a bottleneck. A one-hour waiting time to fulfil the measuring specification demands of a finished workpiece very often means a standstill of one hour in the complete production process.



The solution to the described problems is to improve the organisation of factory routing and planning. A helpful work tool is ERP: Enterprise Resource Planning. This system helps to streamline processes and information exchange across the entire factory. The software also helps to synchronise reporting by production-chain staff. For example, sales orders automatically flow into the financial system, whereby measuring becomes a seamless finishing element in the production process.
Finally, statistical values such as *Cp* and *Cpk* can help to monitor the efficiency of the organisational changes being introduced. These quantities explain how the three-sigma values of the statistical spreading curves are situated in relation to the specified tolerance fields.

Measuring aeroplane parts

Roy Helmos' responsibility is the management of measurement equipment and processes at Fokker Aerostructures in Papendrecht, the Netherlands. This company is part of Fokker Aerospace, recently taken over by GKN Aerospace. The most interesting fact here is that Fokker Papendrecht makes lightweight components for aeroplanes from different materials, among them Glare.

3 *In the KMWE measuring room. (Photos: KMWE)*
(a) A Mitutoyo co-ordinate measuring machine, type Crysta-Apex, with a Y-axis range of 3,000 mm.
(b) Measuring an aluminium frame for ASML.

4 *Aircraft manufacturing is a complex, high-precision business.*
(a) Making a lightweight horizontal stabiliser for the Gulfstream G650 business jet. The photo shows the final drilling of holes by a robotic arm in the Fokker Aerostructures factory. (Photo: Fokker Aerospace)
(b) The giant Gulfstream assembly factory. (Photo: Gulfstream Aerospace)

5 *Overview of calibration activities at MetricControl. (Photos: MetricControl)*

This is a glass fibre-aluminium laminate that integrates light weight, high stiffness and high strength.

Aluminium and thermoplastic composites, however, are also included in the materials used in the modern aircraft components being made in Papendrecht, for example for the giant Airbus 380, the Dassault F7X and F5X, and the Gulfstream G650 (see Figure 4). The very stiff and strong torsion box of the horizontal stabiliser in Figure 4a is the result of co-operation between several companies, among them Airbus and Fokker, in the TAPAS project: Thermoplastic Affordable Primary Aircraft Structures.

Helmos explained that measuring huge parts is not at all easy. That's why this remnant of the famous Fokker history tries to avoid measuring workpieces by instead only measuring the tool, thus ensuring that its accuracy is carefully reproduced in the component. But when parts inspection is unavoidable, Fokker Aerostructures uses an AT901 laser-tracker system from Leica Geosystems, which was shown by Hexagon Manufacturing Intelligence during the seminar.

The Leica AT901 works according to an absolute interferometric principle, with two lasers in which the radiation intensity is doubled or extinguished, depending on the phase relation of the two interfering beams. Thus the system features multiples of laser-beam wavelengths. At short distances, accuracies of 10 μm are attainable, but for the long-range versions with measuring distances up to 30 m, an uncertainty factor taking the measuring distance into account has to be calculated.

Calibration

Gert de Bruin represents MetricControl in Hengelo (Ov), the Netherlands. This calibration institute has its origins in 1922 with the start of Hollandse Signaalapparaten (HSA), later becoming part of Philips Electronics. In 1990, HSA was taken over by the Thales Group. After some renaming and reorganising, MetricControl has become an independent institute with a workforce of 38 people working with elaborate equipment, not only for geometric calibrations, but also for the calibration of mass, electrical quantities, force, pressure, temperature and more (see Figure 5). MetricControl has been acknowledged by the Dutch Raad voor Accreditatie (Board of Accreditation), according to standard ISO/IEC 17025.

De Bruin explained that calibration implies the comparison of measurement results, from an instrument to be calibrated and from some kind of standard. The outcome is 'satisfactory' or 'not satisfactory'. The last verdict doesn't always mean the rejection of the instrument, because comparison with specifications may result in the instrument complying with less severe demands, while necessary modification of an instrument often brings about a second calibration.

MetricControl helps to install calibration management systems, determining regular calibration moments and respective registrations after agreed time intervals. Problems may arise when no norms are available for quantities to be calibrated. Norms for geometrical quantities are, however, in general excellently defined, as referred to when discussing Jan Hendrik van Swinden's activities (regarding the definition of the meter; see the next page).

To conclude

Many items discussed during the seminar seemed to be rather obvious, but nevertheless were worthy of reconsideration. Moreover, exhibitors like Mitutoyo, Faro, Bemet, GOM, Hexagon and MetricControl showed how their companies can help to solve difficult measuring problems. In any event, the interchange of ideas between measuring specialists was exceptionally useful.

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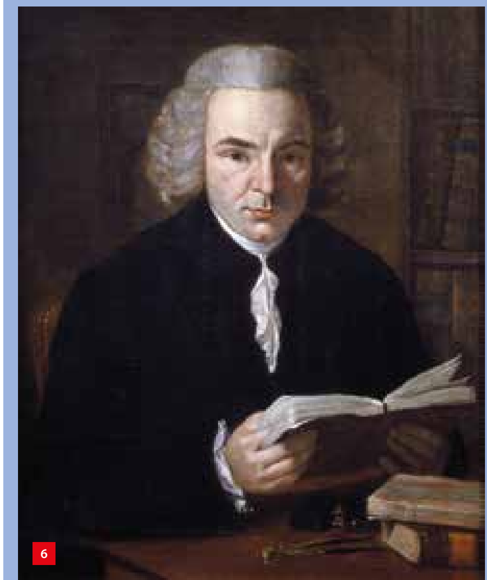
In Van Swinden's footsteps

Jacob Jan de Boer was the chairman of the Meten 2018 seminar in Veldhoven, held on 6 February. He is a consultant at VSL, the Dutch metrology institute, situated in Delft. The initials VSL stand for Van Swinden Laboratory, after mathematician and physicist Jan Hendrik van Swinden (1746-1823), who is historically important for the unification of length units and the development of geometrical measuring in the Netherlands.



6 *Mathematician and physicist Jan Hendrik van Swinden (1746-1823, artist unknown).*

On behalf of the Netherlands, Van Swinden (Figure 6) participated in the Conférence Générale des Poids et Mesures held in Paris from November 1798 to July 1799. This event resulted in the definition of the meter as the distance between two marks on a square-sectioned bar of platinum, of which Van Swinden could take home a copy with an accuracy of about 0.05 mm. This meter definition was based on measurements taken by Delambre and Méchain of the length of one earth quadrant, because the world unit standards should be based on constants in nature, thus defining one meter as 10^{-7} part of the quadrant length of 10,000 km.

After the signing of the Treaty of the Meter by seventeen countries on 20 May, 1875 in Paris, the meter was redefined as two marks on an X-formed bar of 90% platinum and 10% iridium, kept in Sèvre, a suburb of Paris. All contributing countries received a copy of this standard. This means that such a copy should still be somewhere in the basement of the VSL.

In 1802, Van Swinden published the article "Verhandeling over volmaakte maaten en gewigten" (Treatise on perfect measures and weights). He could not have imagined that about two centuries later 'his' definition of a meter would be replaced by a definition made in relation to the wavelength of the orange-red line in the spectrum of the krypton-86 isotope. Today, the meter definition is related to the speed of light, standardising the time necessary to propagate light across a distance of one meter exactly. According to Wikipedia, the accuracy of this last definition amounts to 0.1 nm.

MIKRONIEK **EDITORIAL BOARD** UPDATE

Since 2012, Mikroniek has had an editorial board in place in order to secure and refine Mikroniek's editorial policy, define new themes and topics, and review contributions. Over the years, editorial board members from companies and universities (of applied sciences) have contributed to further raising the bar for Mikroniek.

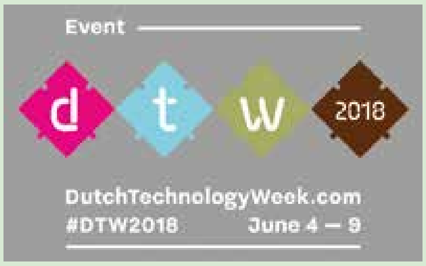
In recent years, a number of members have stepped down from the board: ir. Bart Dirkx (WittyWorX), ir. Jos Gunsing (MaromeTech), ir. Rob van Haendel (Philips Innovation Services), ir. Huub Janssen (Janssen Precision Engineering), ir. Henk Kiela (Opteq, Probotics, Fontys), ir. Casper Kruijer, MBI (Thermo Fisher Scientific), ir. Piet van Rens (Settels Savenije van Amelsfoort), ir. Herman Soemers (Philips Innovation Services), ir. Ad Vermeer (Cerescon, Adinsyde) and ir. Rini Zwikker (Saxion).

Their commitment has been highly appreciated. The current composition of the editorial board can be found on page 3.

Call for Martin van den Brink Award sponsors

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 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*.



The Martin van den Brink Award ceremony will be held on Thursday 7 June 2018, during the Dutch Technology Week.

Call for 2018 Ir. A. Davidson Award candidates

At the 2018 Precision Fair in November, another young and promising engineer will receive an award for her or his contribution to the precision engineering profession. The purpose of the Ir. A. Davidson Award is to encourage young talent by recognising the efforts of a precision engineer with 5-10 years of experience working at a company or institute and a proven performance record of outstanding precision designs that has been acknowledged internally and externally. Candidates must have a demonstrated enthusiasm for the field that produces a positive effect on young colleagues and the wider community, and contributes to a positive reputation of the profession.

The biennial prize, which was established in 2005, is named after an authority in the field of precision mechanics who worked at Philips in the 1950s and 1960s. The jury is searching for candidates. Please contact DSPE board member, Toon Hermans (*toon.hermans@demcon.nl*), if you know any young engineers that qualify.

The 2016 Ir. A. Davidson Award was presented to Wouter Aangenent of ASML (right). He received the award certificate from DSPE board member Toon Hermans. (Photo: Mikrocentrum)

READERS' SURVEY: **CALL FOR ACTION**

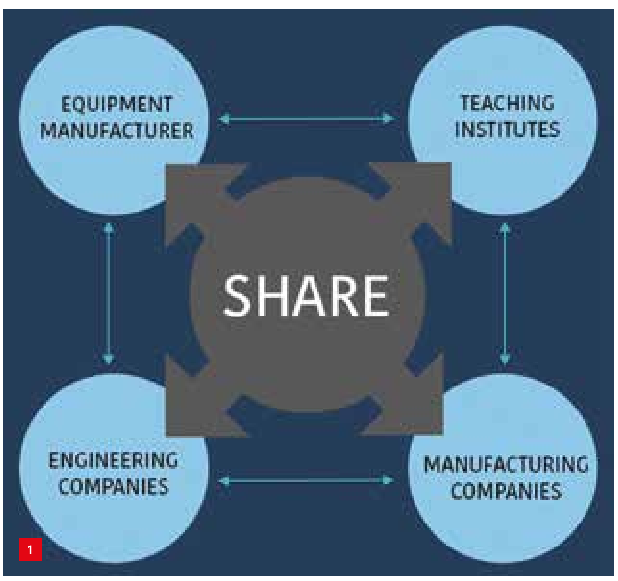
To gain insight into the reception of Mikroniek and further align Mikroniek's editorial focus and standard to the information needs and wishes of its (potential) readership, the editorial board has decided to conduct a readers' survey.
All Mikroniek readers are kindly invited to participate in this brief survey. It can be found on the DSPE website.

WWW.DSPE.NL/ABOUT-US/NEWS

PLATFORM FOR DESIGNERS AND MANUFACTURERS

The Knowledge Sharing Centre (KSC) is an independent, not-for-profit platform that promotes the sharing of engineering and manufacturing knowledge. KSC's goal is to empower continuous innovation by maximally aligning design and manufacturing processes. Its underlying ambition is to maintain and strengthen the global competitiveness of the high-tech systems industry in the greater Eindhoven region, i.e., the Netherlands, Belgium and (part of) Germany. As KSC initiator Arno Sprengers said, "The future belongs to knowledge sharing".

The ever-increasing complexity of products and systems, combined with the cost- and lead-time-driven global competition, puts pressure on the innovation process in the high-tech systems industry. Smart collaboration and knowledge sharing between Original Equipment Manufacturers (OEMs), educational institutions, engineering companies and manufacturing companies in the supply chain is required for successful innovation and new product introduction (Figure 1). Drawing upon a shared knowledge base, the right design decisions can be made to facilitate the most effective and efficient manufacturing processes. To this end, the initiative to found the Knowledge Sharing Centre (KSC) was taken in 2014.



1 *The Knowledge Sharing Centre wants to promote and facilitate collaboration and knowledge sharing between OEMs, educational institutions, engineering companies and manufacturing companies in the supply chain.*

Platform

The KSC is set up as both a physical and virtual platform that effectively combines the knowledge of the various chain partners. The philosophy behind the KSC is that, on average, 60 per cent of the knowledge present in a company is general knowledge not related to its core technology. The company can freely share this knowledge without compromising its competitive position. The other 40 per cent is related to the company's intellectual property (IP), whether patented or not, and can only be shared after proper arrangements such as or licensing agreements or other contracts.

Arno Sprengers (Figure 2), Team Leader Precision Mechanics at ASML, initiated the concept of the KSC after he had concluded a challenging project regarding a tribological problem in a wafer handler [1]. It took two years of hard work and perseverance to crack the problem, involving intensive collaboration between ASML representatives and suppliers, numerous experiments and a great deal of documentation.

Manufacturability and more

That project demonstrated the strength of collaboration, and as a 'by-product' it generated knowledge that had been collectively developed and shared. Also, it once again made clear that ASML was lacking manufacturability knowledge and manufacturing experience, especially within the younger generations of engineers. Sprengers, as a member of the ASML competence group on manufacturability and costs (one of the over 100 internal ASML competence groups), concluded that optimal collaboration and knowledge sharing would bring about project success.

2 *Initiator of the KSC, Arno Sprengers.*

It was evident that the collaboration should involve external partners, especially on the topic of manufacturability, e.g., regarding knowledge of the numerous manufacturing technologies and the impact of design constraints on manufacturing options and vice versa, including quality and cost price aspects. However, manufacturability is not the sole focus of the KSC. Its remit covers the full design lifecycle: engineering, cost pricing, manufacturing, measuring, and testing.

Marketing

Knowledge sharing is about giving and taking, Sprengers says. "Sharing also means profiling your knowledge in the market, something that a lot of suppliers are not accustomed to do. But now, via the KSC, they can for instance convince designers to use their manufacturing capabilities. The KSC will help participants in mapping and marketing their knowledge, to determine what is the 60 per cent general knowledge that they can freely share, and then what is the 40 per cent IP-related knowledge that they have to protect, but also can exploit."

Campus

The KSC can also take a physical shape, beyond the virtual platform of website and online database. First contact has been made with Brainport Industries Campus (BIC) [2], a "state-of-the-art working and learning environment for the next generation in high-tech manufacturing", which was created out of a broad alliance between suppliers, specialised companies and innovative educational and knowledge institutions in the Brainport (greater Eindhoven) region. "We have had a first handshake and concluded that our vision matches 100 per cent. In future, the KSC can have a spot on the BIC campus, where for instance workshops can be held with companies sharing their specific knowledge."

Education and training

The aim of the KSC is to get engineers enthusiastic about this approach to sharing and gaining knowledge on manufacturability as early as possible, i.e., at least in the early phase of individual projects, but ideally also early in their career, preferably already during their education. Hence, the KSC has contacted educational institutions, such as Eindhoven University of Technology, through their knowledge transfer unit, United Brains, and Fontys University of Applied Sciences. The idea is that, via the KSC, students can engage in projects at companies to gain multidisciplinary collaboration experience, which they can later on transfer to their employer.

Another educational objective of the KSC is to translate the results of (demonstration) projects to training materials that will help students learn about knowledge 'mining' and sharing. The project results can then also be used to secure internal knowledge of the participating companies. "Engineers generally are not exuberant communicators, but if you put a concrete product or piece of technology on the table, they will not stop talking about it," says Sprengers. This can help them disclose knowledge, which is very often of the implicit or tacit kind, and make it more explicitly available within the organisation.

Reference sources

While working on the start-up, the KSC came across multiple knowledge sources that are of interest to the initiative. Examples include the Precision Point, Janssen Precision Engineering's portal to precision engineering knowledge [3], and the DSPE Knowledge Base, featuring a publication database and the introductory Thermomechanics website [4]. The KSC foresees collaboration with parties like JPE and DSPE to possibly extend their databases and integrate them into the overall KSC platform. At ASML, the various competence groups can each assess their contribution to the platform. Eventually, the concept of competence groups can be extended to the KSC level, with representatives from relevant parties joining each group.

With its wide scope, the KSC is comparable only to a few initiatives in the US, such as CustomPart.Net and eFunda. CustomPart.Net is a resource for engineers, inventors and contract manufacturers to facilitate informed decision making during the product design and sourcing process [5]. eFunda, which stands for engineering Fundamentals, is an online destination where professionals can quickly find concise and reliable engineering information [6]. There are also more targeted platforms, e.g., restricted to materials selection such as Matmatch, which offers a large amount of material properties, including physical, chemical and thermal characteristics, and information on the applications and processing histories of materials [7].

3 *One of the KSC's initial projects involves the design and realisation of a demo system that combines a planetary gear system and a car differential. This project started as a learning project for promoting technology in the Brainport region. The plan is to produce five copies of the system, three of which will be handed over to educational institutions. (Photo: Jeroen van Schaik)*

KSC future

These first years have been devoted to spreading the message. Now, to ensure maximum acceptance and highest relevance, a wide range of partners will need to join the platform. A number of OEMs and educational institutions and a few dozen suppliers have already signed up, but many more are welcome. A provisional online database has been set up to present the concept, and two projects were organised to demonstrate the power of knowledge sharing (Figure 3).

The next step will be to build up a pilot environment for networking within the KSC framework to show how the combination of networking and knowledge sharing can work effectively, and to make more people enthusiastic about the KSC concept. After that, the 'real' platform will be constructed: a modern database (or perhaps a blockchain) using smart algorithms for knowledge sharing and matchmaking between partners. Here, care will take precedence over speed, Arno Sprengers says. "Knowledge sharing requires a culture change. This takes time and that's no problem as long as the platform will be there for the long haul. That's exactly my message to the readers of Mikroniek: the future belongs to knowledge sharing."

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Master's underpinning

In 2016, Anne Gommers finished her Master Supply Chain Management at Tilburg University in the Netherlands, with a thesis project on the Knowledge Sharing Centre. She explored how the KSC could stimulate collaboration through early supplier involvement, in order to improve manufacturability within new inter-company product development projects.

Results showed that early supplier involvement can have a positive impact on manufacturability, with some negatives. The platform can be used to create awareness of production process steps and design constraints earlier during the development process, and to find suitable suppliers for project participation.

The thesis also highlighted the importance of sharing, at the least, information regarding manufacturing processes, materials, the products, design/manufacturability and general company information on the platform or during bilateral contact between participants. Participants should feel safe concerning the financial basis and proprietary and confidential knowledge sharing.

INFORMATION
WWW.KNOWLEDGESHARINGCENTRE.COM

COLLABORATIVE ROBOTS ARE REALLY COMING INTO YOUR WORKSPACE

Developments in collaborative robotics are accelerating. Mechanics, position sensoring and localisation, mapping and vision technologies, and of course gripping are still improving and becoming more and more affordable in robotic applications, while artificial intelligence and deep learning are acting as technology drivers. Hence, collaborative robots will become much more adaptive, versatile and easier to use in areas such as the assembly and testing of complex precision equipment. This was the conclusion of the 10th International Expert Days on Service Robotics, titled "Smart Future with Cobots and Co-acts".

JOS GUNSING

The 10th International Expert Days on Service Robotics were organised between 28 February and 1 March, 2018, in Lauffen, Germany, by Schunk, the family-owned German company specialising in clamping and gripping, including robotic arms and grippers. Compared with the 8th edition of the event, which the author also attended, the 10th showed a significantly increased focus on the application of cobots. For example, three years ago Audi had begun experimenting with logistics functions for cobots, which involved bringing a wide variety of components to the automotive assembly worker. This year, BMW showed a broad selection of potential applications, which are already being introduced on a small scale.

The scope of the Expert Days' lecture subjects was another remarkable change, moving from an earlier focus on hardware (grippers, force/pressure sensing) and hardware/software to intelligence/behaviour and deep learning. From the author's point of view, we are very close to the introduction of the cobot in high-tech equipment assembly and testing. In an era where finding capable and skilled people for complex assembly tasks is difficult, we should aim to work intelligently.

The assembly engineer should be able to concentrate on their skilled tasks instead of 'wasting' time with logistics, e.g. picking up tools and components from the workbench. A next step could be a cobot that executes the routine tasks (and not necessarily just the simple ones) like bolt/washer/nut placement. Thus the assembly engineer is free to concentrate on the truly complex tasks. A further improvement would be if cobots could be designed so that the operator is able to teach and personalise their cobot. The technology is ready for this.

The only contributions that appeared to be missing were related to the issue of robot security in relation to interconnectivity/Internet of Things. This issue may very well be worth looking into in a time of DDoS and other hacker attacks on our software-based infrastructure.

Robotic revolutions

Dr. Bernd Liepert (KUKA) discussed the four robotic revolutions:

1. Robot-based automation:
   This started in the automotive industry some 50 years ago. Robots can be programmed, but are 'blind' and not flexible during the execution of their tasks.
   - Speed and repeatability of quality is high; flexibility during tasks is low.
2. Sensitive and safe robot-based automation:
   Involvement of sensorics, especially vision, in industrial robots. Robots can adjust their movements with respect to the end position to be reached or the path to be followed based on sensor information, in particular vision.
   - Speed may decrease, but repeatability of quality is still high; flexibility during task is increasing.
3. Mobile, sensitive and safe robot-based automation:
   Automatic guided vehicles (AGVs) combined with collaborative robotics (Figure 1).
   - Speed may decrease, repeatability of quality is still high; flexibility during task is high.

AUTHOR'S NOTE

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1 *Adaptive assembly, in this case connecting tubes to a manifold, is a promising collaborative robotics application. (Photo: KUKA)*

4. Cognitive, sensitive and safe robot-based automation: Involvement of augmented reality, self-learning, collective learning and deep learning.
   - Speed may decrease, repeatability of quality is high; flexibility during task is high; due to self-learning capabilities or exchange of learned patterns, systems can improve themselves.

Remark: the first robotic revolution coincided with the third industrial revolution; the second up to the fourth robotic revolution are part of the fourth industrial revolution (Industrie 4.0/Smart Industry).

Prof. Dr.-Ing. Torsten Kröger (Karlsruhe Institute of Technology) added an overview of Silicon Valley activities to these future perspectives. Several companies are, not surprisingly, active in artificial intelligence, deep learning, augmented and virtual reality, but many of them are still in stealth phase, i.e. not on the market with products and/or services. Kröger's opinion is that the future of mobile robotics is now; software and artificial intelligence will be the key enablers for this.

Automation/cobotisation in general

Prof. Dr.-Ing. Thomas Bauernhansl (Fraunhofer IPA) presented ten design rules/guidelines for optimisation and adding value in production. Although they are all interesting, only five will be mentioned here:

- Merging production and logistics into one value-adding system:
  - Avoid individual optimisation;
  - Production and logistics areas are integrated;
  - Changeable/flexible production and logistics structures.
- Realising a mobile and scalable set-up of processes and structures:
  - Output-oriented configuration of process modules, scalable automation;
  - Human-robot co-operation;
  - Scaling/adjustment of flow-oriented layout related to daily production schedule and availability of resources.
- Designing intelligent systems (see Figure 2):
  - Intelligence shifted from central to decentral level;
  - Plug and produce, systems elements communicate instantly even in complex systems;
  - Include self-healing capabilities, or robustness in the system, with the help of, e.g., cloud solutions.
  - Include self-optimising operation planning.
- Shifting process complexity to where it can be handled most efficiently:
  - Involve specialists for specific tasks in the value-adding system;
  - Ad hoc configuration of value chains (manufacturing as a service).
- Focusing the human role on design and optimisation:
  - Reverse Taylor's way of thinking by bringing engineering and production operation together on the work floor;
  - Automate repetitive and standard work ("dull, dangerous, dirty") for reasons of cost and quality (of product and life), keep people for complex tasks and interventions. People will move towards more complex tasks, requiring more (continuous) education, training and flexibility.
  - The relationship between human operators and their work environment is changing.

2 *Designing intelligent systems – one of the design rules/guidelines for optimisation and adding value in production, as presented by Prof. Dr.-Ing. Thomas Bauernhansl (Fraunhofer IPA).*

3 *Søren Peter Johansen of DTI advises avoiding full automation. Here, components previously placed on the table by an operator are picked up by a vision-driven collaborative robot for assembly. (Photos: DTI)*

Søren Peter Johansen (Danish Technological Institute, DTI) held an enthusiastic lecture on how to activate companies and employees to work with robots. He is a strong advocate for down-to-earth automation and robotisation and offered good examples. In order to obtain results in a company, he advises avoiding full automation; instead, by applying the 80-20 rule, he recommends distributing work between operators and robots in shared workplaces. This requires flexible tools (see Figure 3). The application of safe robots and safe tools (often self-designed) is, of course, a must. Strong co-operation between employees, employers, unions and government is beneficial in creating an atmosphere in which robotics can be applied for the benefit of a wide range of stakeholders.

Yvonne Straube (BMW) showed how, starting with careful experiments, it took approximately five years for the full-blown introduction of collaborative robots into automotive assembly to be realised. In 2017, the roll-out of ten applications was started. Robots can be of significant help, especially in combining complex components. Also, having the robots carry heavy windows or sunroofs simplifies the life of the operator. She used the example of a remarkable but very logical application of exo-skeletons: operators employing a shoulder exoskeleton to help hold their electric tools when working overhead, e.g. for the assembly of the drive line and suspension components underneath the car. For making dedicated assembly tools, e.g. for positioning or holding products or components, additive manufacturing was introduced on the work floor. This is also an example of bringing engineering to the production environment.

Dr. Andreas Bihlmaier (robodev) started his presentation with Amdahl's Law of Automation (defining limits with respect to the degree of processing-time reduction in automation processes) and made a strong plea for keeping the introduction of robots very much down-to-earth, instead of sophisticated, by involving non-engineers at a very early stage. Low-cost intelligent automation, rather than high-cost top performance, will enable a gradual growth of automation/robotisation. That is, keep things simple and cheap. Robodev has developed a lot of hardware and software components for automation that can very easily be combined (self-configuring and self-updating) and can also be used with third-party robotic controls. In this way, a gradual change from manual work to a hybrid situation and then to full automation can be made, avoiding big investments during this route.

Automation of logistics

Dr. Irma Lindt (DHL Innovation Centre) showed that there is still a lot of manual work in the total chain of post and parcel logistics. Many tasks such as picking up, packing, labelling, loading and delivery are not very ergonomic and include a lot of repetition. For DHL, increasing volumes/numbers and higher customer expectations, together with an ageing population and declining workforce, are the main drivers for looking deeply into robotising opportunities. Fortunately, falling sensor prices and rapidly improving SLAM (simultaneous localisation and mapping) technologies are enabling a rapid increase in the range of robotising opportunities.

Melonee Wise (Fetch Robotics) and Frederik Brantner (Magazino) are both involved in the design and development of logistics robotics, including the total software infrastructure. They emphasised the importance of working in the cloud, thus increasing system robustness and adaptability (robots sharing actual map information, for example). Also, systems become scalable and can follow customer needs in up- and downturns. The collection of data and the interpretation of these data sets will also offer many optimisation opportunities and are still to be explored.

Christopher Parlitz (Robert Bosch Start-up) presented the development of a high-precision (< 10 mm) Laser SLAM device through which mobile robots/AGVs and autonomous forklift trucks can find their way without an initial site survey or the necessity of markings (visual or magnetic).

Grasping and gripping

Adaptive 'hands' are crucial to the operation of robots. Over the years, a new class of adaptive robot hands has emerged (see Figure 4). The work on grasping and gripping by Dr. Minas Liarokapis (New Dexterity, University of Auckland) is based on thorough studies of the hand. A bio-inspired/biomimicry approach was applied when making steps towards the design for a hand. Both fully actuated adaptive robot hands and underactuated hands were designed, built and tested. Not surprisingly, the underactuated hands are much cheaper both in terms of hardware (number of actuators) and control. However, they come with a limited dexterity. Liarokapis has investigated how to apply (and to overcome) this limited dexterity in handling objects across a wide range of sizes, flexibility and mass.

Conclusions

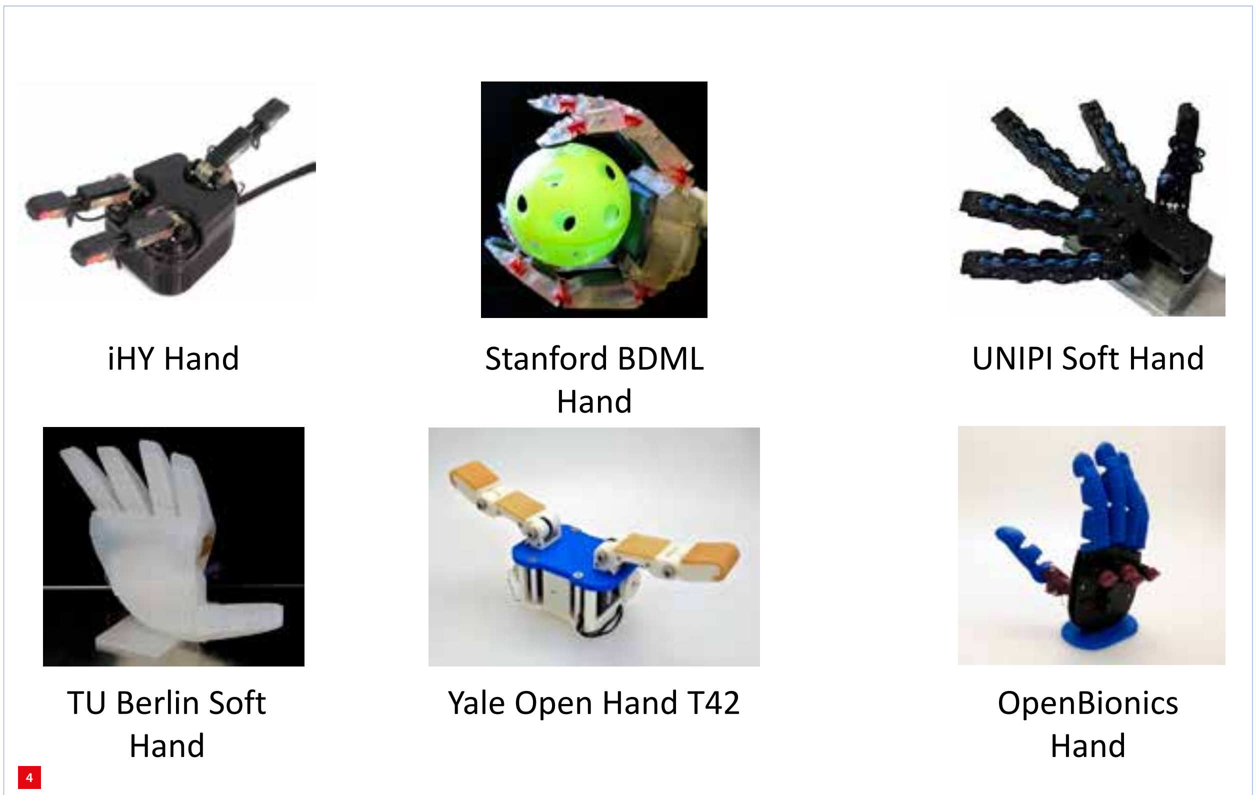
It is clear that the developments in collaborative robotics are accelerating. The technologies are becoming more and more available at affordable prices, and the trend is towards artificial intelligence and deep learning being the technology drivers for the near future. Mechanics, position sensoring and localisation, mapping and vision technologies, and gripping are still improving. Thus, collaborative robots will become much more adaptive, versatile and easier to use, such that in the near future many of them will be actively applied in the assembly and testing of complex precision equipment, working together with highly skilled assembly engineers who will teach and train their robot buddies themselves.

Too farfetched? Dr. Hubert Zitt, the last speaker at Expert Days, gave an entertaining overview of inventions in Star Trek, the American science-fiction television programmes and films that have been made over the last 50 or so years, set in a distant future. He showed that many functions/devices that were fictitious in the series/films have already become a reality. So, the message is: dare to dream and realise it. ■

INFORMATION

The 11th Expert Days on Service Robotics will be held on 27-28 February 2019 in Odense, Denmark.

WWW.EXPERTDAYS.SCHUNK.COM



4 *A new class of adaptive robot hands. Characteristics: underactuated, compliant, robust, cheap and lightweight. (Source: presentation of Dr. Minas Liarokapis)*

HIGH-TECH SYSTEMS 2018: BETWEEN ALGORITHMISATION AND MICRO-MECHATRONICS

The High-Tech Systems 2018 event, organised by Techwatch on 22 March 2018, in Eindhoven, the Netherlands, focussed on high-end system engineering and disruptive mechatronics. The conference themes included the industrial Internet of Things, cobotics and design for additive manufacturing.

The conference programme was sandwiched between two keynotes. Opening the day was the industrial keynote by Jim Stolze, tech entrepreneur and founder of Aigency, who tried to answer the question, "What's next for digital and blockchain?". He did this in an informal and entertaining way, including a quiz to assess the ICT knowledge of his audience. According to Stolze, the next step in digitalisation is 'algorithmisation'. Smart algorithms, including transactional algorithms such as blockchain, are required to make sense of the big data collected by modern multi-sensor systems. He showed how artificial intelligence and blockchain technology can offer new opportunities for the manufacturing industry.

The closing, scientific, keynote was delivered by Prof. Yves Perriard of the Integrated Actuators Laboratory, École Polytechnique Fédérale de Lausanne (EPFL), Switzerland, who was given an extensive introduction by Prof. Elena Lomonova, Chair of Electromechanics and Power Electronics Group, Eindhoven University of Technology. Perriard – "I'm sorry, no quiz" – discussed the field of micro-mechatronics, which builds on Swiss watchmaking heritage.

The evolution of micro-mechatronic systems is continuing with the steadily increasing numbers of actuators and sensors in systems, the progress in miniaturisation and the potential for autonomy by means of smart electronics. One of the key issues here is energy saving, which strongly depends on device efficiency, even in the case of low power consumption. Other challenges are function integration, high precision, reliability and robustness, and eventually mass production. Hence, multidisciplinary innovation is required, including material science and information technology.

Regarding the issue of miniaturisation, Perriard dwelled upon the scaling laws that apply. He demonstrated that, contrary to intuition, current density can be increased when downsizing a system. Inspiring examples included an electro-active polymer actuator for a blood pump and the use of magnetorheological fluids in 'smart' shoes for diabetic patients, to prevent harmful pressure spots.

In between the two keynotes, topics such as smart industry and maintenance, design for 3D, and robots, drones and exoskeletons hit the stage at the Van der Valk hotel in Eindhoven. A thought-provoking contribution was delivered by Prof. Herman Bruyninckx, Section of Production Engineering, Machine Design and Automation, Department of Mechanical Engineering, KU Leuven, Belgium. The title of his lecture was "Behavioural-full complex system design: domain knowledge beats agility". He discussed concrete examples of formal models of robotics, in particular regarding discrete and continuous control and perception, and stated that, fundamentally, nothing new has arisen in this field in the last 25 years. According to Bruyninckx, domain knowledge should drive the development process in robotics.

■ *Prof. Yves Perriard talked about the evolution of micro-mechatronic systems. (Source: EPFL)*

WWW.HIGHTECHSYSTEMS.EU
WWW.JIMSTOLZE.NL
LAI.EPFL.CH
PEOPLE.MECH.KULEUVEN.BE/~BRUYNINC

DYNAMICS FOR PRECISION ENGINEERING:
FROM MACRO TO MICRO

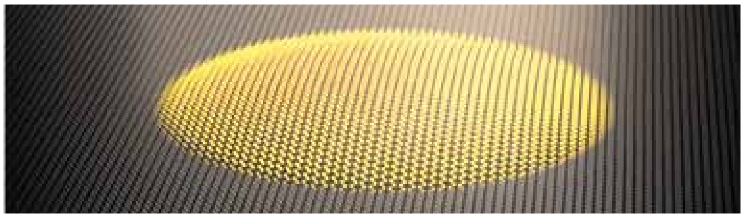
Mikrocentrum organised the Dynamics for Precision Engineering workshop on 29 March 2018, with the support of Delft University of Technology (TU Delft) and DSPE. The event provided an overview of the challenges and solutions involving dynamics and control in precision engineering at all length scales.

■ *Prof. Peter Steeneken, chair of Dynamics of Micro and Nanosystems, in his lab at TU Delft. (Photo: TU Delft)*

Chairman for the day, Prof. Peter Steeneken, chair of Dynamics of Micro and Nanosystems at TU Delft, introduced the fields of dynamics and precision engineering and the interplay between them. Modern high-tech applications require both high speed and high precision; however, dynamic effects usually degrade precision.
The contributions from both industry and academia came under three headings: dynamics of nano/microscale systems; vibration isolation and transfer path analysis; and prediction of shock- and dynamics-induced damage. The application fields included medical imaging, electron microscopy, lithography, space instrumentation and automotive.

At the sub-atomic level, the presentation by Ab Visscher, senior expert dynamics and construction at Thermo Fisher Scientific in Eindhoven, was concerned with tackling a picometer-scale vibration problem. In electron microscopes, the local identification of materials down to individual atoms using energy-dispersive X-ray spectrometry requires detectors that are cooled to cryogenic temperatures. It was discovered that the boiling of liquid nitrogen in the cooling vessel induces vibrations. While these were measured to be only 10 pm at 270 Hz, they are still enough to disturb image quality. Visscher discussed the measurement of these sub-atomic vibrations and the design solutions to reduce the problem. These solutions include the application of light-but-stiff friction brakes placed in parallel over the plastic leafspring support of the vibrating base that carries the X-ray sensors, and the use of slits in this same aluminium base to reduce the eddy currents that induce the beam deflection.

Also at the lower extreme of the length scale, Steeneken discussed graphene, the new wonder material known for its exceptional mechanical, electrical and optical properties. Measurement of graphene dynamics using optical interferometry is challenging because of the small amplitudes (< 1 nm) and high frequencies (> 10 MHz) involved, and also because atomic-scale physics and thermodynamics introduce phenomena that are unique to the nanoscale.
As an example, Steeneken demonstrated how a modulated laser beam can be used for the parametric excitation of a graphene membrane. The dynamic properties of graphene enable new sensor and actuator concepts, such as squeeze-film pressure sensors, light pixels (see the figure on the right), nonlinear material characterisation methods, and graphene pumps.



■ *A 'mechanical pixel' of double-layered graphene on a silicon oxide substrate oscillates under the influence of pressure changes underneath the pixel. Accordingly, the colour of the light reflected by the pixel changes. (Ref.: S.J. Cartamil-Bueno et al., "Graphene mechanical pixels for Interferometric MOdulator Displays (GIMOD)", arxiv.org/abs/1803.01883)*

Steeneken concluded that graphene is a material with interesting properties. It is sensitive, tuneable and strong, can be operated at high frequencies and behaves differently from conventional materials. Realising the promising applications of graphene will require precision engineering and dynamics for fabrication, characterisation and dynamic modelling.

Rob Fey from TU/e, in a collaboration with Philips, showed how dynamic models are essential for simulating a new generation of ultrasound imagers. At larger scales, Maarten van der Seijs from VIBES technology discussed methods for predicting vibrations in cars based on combinations of numerical simulations and experimental dynamics. Bert Roozen from NOVIC gave an insight into how vibrations that are due to acoustic sources can be simulated and prevented. Ronald Ruimerman showed how earthquake damage on ASML steppers might be prevented by simulations and predictive measures. Finally, Floris van Kempen from TNO closed the day's programme with a discussion on a numerical optimisation approach to minimising both weight and vibrations in detectors in environmental monitoring satellites.

WWW.MIKROCENTRUM.NL
WWW.FEI.COM
WWW.PME.TUDELFT.NL/DMN

MetaQuip – laser solutions for engraving, marking, cutting and welding

MetaQuip is a supplier, developer and manufacturer of laser machines and high-tech solutions for laser-engraving, laser-marking and laser-cutting applications for metals, plastics and a wide variety of other materials. In the development of new products, MetaQuip creates practical solutions for new applications using laser technology with possibilities for integration into fully-automated production lines.

MetaQuip, based in Maarheeze, the Netherlands, is an expert in the field of laser technology and is active in supplying and developing laser products and solutions like CO_2 lasers for laser cutting or laser engraving of organic materials, fibre lasers for cutting, engraving and marking metals, and UV lasers for engraving plastics and laser-welding solutions. MetaQuip has a range of standard laser systems and also creates custom solutions whenever this is required by the application.

Competences

- Laser cutting
- Laser engraving
- Laser marking
- Laser safety and certification
- Cost-effective production
- System architecture / system design
- Mechatronics
- Electronics
- Software and industrial automation
- Process control and optimisation

New and flexible production tools

Laser technology offers enormous benefits in clean, fast and flexible production of small and large series without further post-processing. Most mechanical solutions show wear and tear of tools over time, a drawback laser processing does not have as it is fully contactless. MetaQuip brings these solutions to market in a cost-effective way, making the technology accessible for a wide audience.

1 *The use of fibre lasers for cutting metals is one of MetaQuip's expertises.*

2 *Smart Industry generates a growing interest in the marking of unique identifications and barcodes.*

Knowledge partner

MetaQuip has grown in recent years into a company with in-depth knowhow of laser technology, laser machines and development of solutions for new applications using lasers. Besides offering quality solutions that are safe at all times, MetaQuip aims to be a trusted partner for the long term, delivering what it promises, based on open and honest relations.

New applications

MetaQuip can quickly assess whether laser technology is feasible and delivers the benefits the customer envisions. Companies are invited to explain their needs, show their applications and bring materials so that MetaQuip can test what wavelength, power and settings are needed to create the best results. With the recent trend of Smart Industry, a growing interest is observed in the marking of unique, permanent identifications and barcodes on metal (sub) assemblies and products in production lines.

INFORMATION
INFO@METAQUIP.NL
WWW.METAQUIP.NL

UPCOMING **EVENTS**

30 May 2018, Den Bosch (NL)
National Contamination Control Symposium
Event, organised by VCCN, comprises a parallel lecture programme and an exhibition. One of the sessions is devoted to measurement techniques for nanoparticles.

WWW.VCCN.NL

30-31 May 2018, Veldhoven (NL)
Materials 2018
Trade fair, with exhibition and lecture programme, targeted at product developers, constructors and engineers. The focus is on materials - analyses - surfaces - connections.

WWW.MATERIALS.NL

4-8 June 2018, Venice (IT)
Euspen's 18th International Conference & Exhibition
This event will once again showcase the latest advances in traditional precision engineering fields such as metrology, ultra-precision machining, additive and replication processes, precision mechatronic systems & control and precision cutting processes. Furthermore, new topics will be addressed covering robotics and automation, and Industry 4.0 for precision manufacturing.

WWW.EUSPEN.EU

5-7 June 2018, Erfurt (DE)
Rapid.Tech + FabCon 3.D
International trade show and conference for additive manufacturing.

WWW.RAPIDTECH-FABCON.DE

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 2018, the Martin van den Brink Award, for the best system architect in precision engineering, will be handed out for the third time.

WWW.DSPE.NL

14 June 2018, Den Bosch (NL)
Dutch System Architecting Conference
This year's edition is especially targeted at exchanging experiences from the worlds of civil engineering, transport and high-tech.

WWW.SYSARCH.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
WWW.WORLDTECHNOLOGYMAPPINGFORUM.ORG

20-22 June 2018, Delft (NL)
ReMAR 2018
Fourth edition of the IEEE/IFToMM International conference on Reconfigurable Mechanisms and Robots.

WWW.REMAR2018.ORG

22-25 July 2018, Berkely (CA, USA)
2018 Summer Topical Meeting: Advancing Precision in Additive Manufacturing
The 5th in a series of joint Special Interest Group meetings between ASPE and euspen on dimensional accuracy and surface finish in additive manufacturing.

WWW.EUSPEN.EU

4-5 September 2018, Sint-Michielsgestel (NL)
DSPE Conference on Precision Mechatronics 2018
Fourth edition of conference on precision mechatronics, organised by DSPE. 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

23-26 September 2018, The Hague (NL)
ISCC'18
Every two years a member society of the ICCCS (International Confederation of Contamination Control Societies) organises the International Symposium on Contamination Control (ISCC). This year, the Netherlands Contamination Control Society VCCN will be the host. The event comprises a 2-day conference, workshops, tutorials and technical tours.

WWW.ISCC2018.COM

8-12 October 2018, Delft (NL)
European Optical Society Biennial Meeting 2018
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

4-9 November 2018, Las Vegas (NV, USA)
33th ASPE Annual Meeting
Meeting of the American Society for Precision Engineering, introducing new concepts, processes, equipment, and products while highlighting recent advances in precision measurement, design, control, and fabrication.

ASPE.NET

ECP² COURSE CALENDAR

COURSE (content partner)	ECP² points	Provider	Starting date
FOUNDATION			
Mechatronics System Design - part 1 (MA)	5	HTI	8 October 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	4 June 2018
Design Principles for Precision Engineering (MA)	5	HTI	18 June 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	3 September 2018
RF1 Life Data Analysis and Reliability Testing	3	HI	5 November 2018
SPECIFIC			
Applied Optics (T2Prof)	6.5	HTI	to be planned (Q4 2018)
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	30 October 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	10 October 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)

New bearing solutions from LAB Motion Systems

LAB Motion Systems, the Leuven (Belgium) based specialist in the development of machines that require advanced motion performance, has introduced new bearing solutions.

The new RT075S is the most compact member of LAB's RT-S series of rotary air bearing stages. They provide excellent error motion performance (axial and radial error motion < 50 and 100 nm LSC (least-squares circle), respectively), high stiffness (25 N/µm radially and 68 N/µm axially) and high load-carrying capacity (137 N axially and 51 N radially). The low-profile design of the RT-S series houses an air bearing, motor and encoder for excellent angular positioning and velocity stability. A large through hole facilitates slip-ring integration and optical or other feedthrough for specific applications such as X-ray and optical inspection.

The new RT100B ball bearing rotary stage has the exact same footprint as its air bearing counterpart (RT100S). The RT-B series features robust rotary stages, without the need for a conditioned air supply. These ball bearing stages combine a high load-carrying capacity with a compact design; maximum load is 300 N (axial) and 500 N (radial), stiffness is 100 N/µm (axial) and 200 N/µm (radial). High-quality ball bearings ensure that both the radial and axial error motions remain below 2 µm. The angular accuracy is 10.3 arcsec.

All rotary stages can be supplied with motion driver and software. The software offers an easily programmable positioning loop, automatic homing procedure and communication with the machine interface. An emergency procedure to generate a safe stop when pressure supply fails is integrated. Additionally, a graphical user interface decreases the set-up time to a minimum.

LAB Motion Systems' new rotary stages, RT75S (left) and RT100B.

WWW.LABMOTIONSYSTEMS.COM

Digital monitoring with bearings

The Schaeffler Group, a global automotive and industrial supplier, makes getting started in digitalisation easy, e.g., with its sensor-bearing solutions. FAG VarioSense bearings, a combination of a standard rolling bearing and a sensor cluster, provide several sensor signals for monitoring machines and processes in one compact unit. Up to four different sensors can record data at the same time. This solution which is based on standard FAG bearings integrates several sensor elements into a ring-shaped housing that is just 7 mm high and requires no additional radial design envelope.

The range of values which can be measured is currently –40 to +125 °C temperature, up to 17,000 rpm speed, and 56-96 impulses per revolution, while vibration signals can be measered for long-term trending. Measuring the radial shaft displacement in the bearing, to a resolution of 1 μm, allows the radial bearing force on the sensor bearing to be determined through interactions recognised by the computer. If the specific powertrain is already present in the Schaeffler cloud as an algorithm in the Bearinx calculation software, the forces and displacements at the other bearings and machine elements, such as the gears, can also be determined from this data, as can the torque.

Variosense: a combination of a rolling bearing and a just 7 mm wide sensor-cluster.

With the innovative thin-film sensor technology Sensotect, Schaeffler is introducing intelligent coating systems into the automotive and industrial sectors. Sensotect allows, with neutral effect on design envelope and in real time, measurement of the load condition at locations where classic sensors such as adhesively bonded strain gauges cannot be used. The functionality is achieved by means of a strain-sensitive metal coating, with a thickness in the submicrometer range, that is structured by micro-processing. This allows continuous measurement of force and torque during operation.

So, the component becomes a sensor and the sensor becomes a component. Due to this measurement technology, it is possible, for example, to determine the torque of drive shafts or in vehicle gearboxes very quickly and precisely. Advantages and benefits include very precise measurement of force and torque on functional components where the possibilities associated with conventional methods are limited; measurement on 2D and 3D geometries; and high sensitivity with very little deviation in hysteresis and linearity.

Automotive wheel bearing, provided with Sensotect sensor layer.

WWW.SCHAEFFLER.COM

High-performance control for precision air bearing positioning systems

Air bearing positioning stages have proven themselves in a large number of applications; for instance in metrology, when aligning optical fibres, in semiconductor manufacturing and wafer inspection, in precision scanning applications or positioning tasks in cleanrooms. The air bearings have a number of advantages compared to mechanical bearings. They operate without friction, there is no abrasion, the speed of vibration-free motion can be controlled exactly and repeatability is possible in the nanometer range.

PI (Physik Instrumente) now offers modular high-performance motion controllers suitable for four, six or eight axes for the PIglide air bearing positioning stages, which work with linear or rotary servo motors with direct drive and high-resolution encoders. The multi-axis controllers are based on hardware from ACS, an international manufacturer of modern multi-axis motion controllers, who has been a part of the PI Group since 2017. The controllers therefore support the ACS ServoBoost algorithm that allows extremely stable servo-control that is insensitive to noise or changes in the system.

PI now offers modular high-performance motion controllers suitable for four, six or eight axes for the PIglide air bearing positioning stages, such as in this planar scanner.

WWW.PI.WS

Crossed-roller bearing ball-screw linear stages

Aerotech's ATX series linear positioning stages combine the performance capabilities of a high-precision crossed-roller-bearing positioner with the convenience and simplicity of a ball-screw drive mechanism. Featuring anti-creep crossed-roller bearings and a precision-ground, fine-pitch ball-screw, the ATX series boasts excellent geometric performance and minimal angular error motion. With up to 250 mm of nominal travel, these linear stages offer superior minimum incremental step size and in-position stability compared to other stages that utilise recirculating ball bearings. This makes the ATX series ideal for high-precision tasks such as vertical positioning of sensors and cameras, optics focusing, and beamline measurement and manipulation applications.

ATX stages offer an integral centre-mounted linear encoder to provide direct position measurement at the stage's moving carriage. The typical effects of backlash commonly associated with screw drives are virtually eliminated when using the linear encoder as a position feedback device. Brushless, slotless servomotors, with or without a holding brake, as well as stepper motors are available. The ATX series can be equipped with an optional motor foldback kit in order to reduce the overall length of the stage. This is particularly useful in vertical-axis applications where space is limited. Vacuum- and cleanroom-compatible variants are also offered.

Temperature changes and thermal effects due to, e.g., friction-induced self-heating are often the most detrimental sources of error in precision machines, and screw drives are particularly susceptible. All ATX-series stages are available with Aerotech's integrated temperature compensation solution that delivers accurate and dependable positioning performance in the presence of thermal disturbances.

WWW.AEROTECH.COM

A new approach to 5-axis measuring technology

Renishaw's REVO system scanning a valve.

Measurement is an essential part of manufacturing, used to control processes and verify products. However, measurement time is often viewed as non-productive, causing unwanted bottlenecks and putting pressure on manufacturers' operating margins. Renishaw claims its REVO 5-axis measurement product range for coordinate measuring machines (CMMs) to be a step-change in measurement capability for industrial metrology overcoming these challenges.

The need to retain accuracy has historically compromised the ultimate speed of the measuring process due to the characteristics of a CMM's structure. The nonlinear motion of a Cartesian CMM induces accelerations and decelerations that twist and deflect the machine structure, and result in measurement errors that increase with speed and acceleration.

CMM manufacturers work relentlessly on software and machine improvements to overcome those limitations, but ultimately the physical nature of the CMM structure constrains further improvement.
REVO® 5-axis systems approach this challenge from an entirely different perspective, minimising CMM accelerations whilst moving the stylus very rapidly over the component surface through the simultaneous control of the three machine and two probe head axes (X, Y, Z and A, B).

Additionally, the REVO system offers five different probe families, each specifically designed to maximise the advantages of 5-axis motion and infinite positioning. The probes are automatically interchangeable and include tactile scanning, touch-trigger, surface finish and non-contact vision probes. All are used within a common coordinate reference frame and provide the choice of an optimum tool to measure multiple features all on a single CMM platform.

WWW.RENISHAW.COM

25 years of IBS Precision Engineering

In 1993, Henny Spaan started a small precision engineering company in Eindhoven, the Netherlands, with a big mission: to create measurement solutions which would help companies and research institutes achieve the precision they needed in their most challenging machines or processes. He started with software-based solutions and won his first contract in the Netherlands with international company Océ – where he created software which improved the accuracy of cylinders manufactured for large printing machines. By customer two he went international, and was improving the rollers for the paper industry.

IBS Precision Engineering started developing into a full-solution provider, adding measurement modules and machines to their portfolio. The late 90s saw solutions developed for the disk-drive industry, enhancing the spindle accuracy of the mastering machines, to support improvements in the storage density. Today, more than 90% of disks produced world-wide are produced on machines employing this technology. For the pick & place industry, calibration machines were developed for the vision systems they employed. For CERN, software was developed for the assembly machine for the ALICE detector.

As the new millennium began, IBS expanded with offices in France and then Germany. For the semicon industry modules were developed not only to measure the product but as precision parts within the product itself. Partnerships were established with volume manufacturers to enable IBS precision engineering designs to be supplied to the end customer in the most effective way including training and tool making. A patent in 2003 for the measurement of machine tools led IBS to develop a portfolio of products which are today transforming the way machine calibration is implemented in the aviation and medical industries for the delivery of complex freeform parts.

In 2010, IBS Precision Engineering was responsible for the ISARA 400, recognised to be within the top three of most accurate coordinate measuring machines in the world. It has a traceable measurement uncertainty of 11 nm and has been engaged in round-robin activities to establish norms for freeform measurement. IBS is currently engaged in the next generation of this machine, to measure mirrors for the semicon industry with accuracies down to tens of picometers.

From the beginning, IBS has provided solutions to research institutes and facilities – from those developing next-generation manufacturing techniques to the precision engineering or measurement needs of synchrotrons. IBS is active in leading European research programmes and have led multiple EU and national funded projects. They are also active in key standardisation bodies.

In 2015, IBS together with ASML were founding partners responsible for the launch of the Advanced Thermal Control Consortium; a first of its kind industrial body funding next-generation modeling, simulation and control technologies for precision systems. In 2016, CERN awarded IBS with the largest order ever given to a Dutch company for the development and realisation of the next-generation ALICE detector assembly machines. Machines have since been shipped to eight locations globally.

In 2013, IBS managing director Henny Spaan received the Rien Koster Award for his significant contribution to the field of mechatronics and precision engineering in the Netherlands. Today, 25 years on from his initial vision, IBS exports to 36 countries world-wide. Customers include Rolls-Royce, Mercedes-Benz, Johnson & Johnson, Applied Materials and the ESRF. But also smaller companies and research groups whose vision, like Spaan's all those years ago, demands the ultimate in precision engineering and measurement.

WWW.IBSPE.COM

Last month, IBS Precision Engineering celebrated its 25th anniversary with a reception held at headquarters in Eindhoven, where technology demonstrations and engineering milestones were complemented with an inspiring presentation on gravitational waves by the famous German scientist, Prof. Karsten Danzmann, director at the Max Planck Institute for Gravitational Physics (left). On the right IBS founder, Henny Spaan. (Photo: Nicole Minneboo)

Nanosecond fibre lasers from Jenoptik

Te Lintelo Systems in Zevenaar, the Netherlands, now supplies the Benelux market with the JenLas® fibre ns 25-105 laser product family from Jenoptik, which opens up a wealth of possibilities for laser material processing applications. The pulsed nanosecond fibre lasers are suitable for labeling, marking, and cutting different materials, as well as for structuring surfaces. They are specially designed for integration in industrial plants, but can also be operated separately as modules.

The lasers are available with 20 to 100 W power, based on reliable, industry-tested fibre laser technology. The lasers are air-cooled, offer pulse duration settings ranging from 190 to 250 ns, and reach peak pulse powers of up to 8 kilowatts. The lasers' immunity to back reflections has been significantly improved through optical isolators, which are built-in as standard. Directly adaptable collimator modules can be provided for different beam diameters, as well as a wide range of accessories for optical beam guidance systems in the form of variable beam expanders, F-theta lenses and telecentric lenses, through to entire optical subsystems for integration in machinery.

Areas of application cover micromaterials processing (labeling, marking, cutting, removing, and creating surface structures on plastics and metals), electronics (trimming resistors and conductors, marking ceramic substrates, and removing thin layers on transparent substrates) and metal processing (adhesive preparation, metal surface cleaning).

WWW.TLSBV.NL

WWW.JENOPTIK.COM

Purpose-designed water-based cleaning systems

For the most exacting cleaning specifications, UCM, part of the SBS Ecoclean Group, develops cleaning processes and ultrasound-based ultrafine cleaning equipment to match a given part geometry, material, contamination type and cleanliness standard. (Photo: Ecoclean)

The application fields of part cleaning processes using aqueous media range from coarse through intermediate to fine and ultrafine cleaning. Ecoclean addresses the aspects of cleaning quality, throughput, cycle times, process stability and cost efficiency via different machine concepts adapted to the respective industries and tasks.

Water-based cleaning with alkaline, neutral and acidic media is the technology most frequently employed in industry. True to the principle of 'like dissolves like', it enters the field whenever water-based (polar) contamination – e.g. coolant and lubricant emulsions, polishing pastes, particles, abrasive materials, salts or fingerprints – need to be removed.

Short cycle times and high flexibility have made robot cells an indispensable item of production equipment when it comes to cleaning engine and transmission parts such as cylinder heads and crankcases in automotive manufacturing. Ecoclean offers the EcoCflex 3M/3L cleaning system, which has a SCARA manipulator developed specifically for use in cleaning equipment. The assembly can be operated conveniently via the CNC controller of the cleaning machine; no separate robot PLC controller needed. The EcoCflex 3 can provide high- and low-pressure processes as well as injection flood washing flexibly in one cleaning station.

The many and diverse tasks related to degreasing, intermediate and fine-cleaning of parts across a broad range of general industry applications are covered with a range of different water-based cleaning systems. The EcoCcube compact unit can be integrated into a manufacturing line easily and in minimum time. The EcoCwave with its vacuum-tight work chamber is designed for immersion and spray processes ranging from coarse to ultra-fine cleaning. The EcoCmax, a single-chamber system for three-stage cleaning processes plus drying, features full-flow filtration in the work chamber filling and draining circuit as well as continuous bypass filtration on all flood tanks for reconditioning the rinsing baths.

Part cleanliness specifications limiting particulates to the single-digit micrometer range and below, combined with ultra-exacting thresholds for film-type contaminants, are the domain of UCM, the precision applications business unit of the SBS Ecoclean Group. Starting out from a specific part geometry, material, contamination and cleanliness requirement, the company develops made-to-measure cleaning processes and corresponding ultrafine cleaning equipment comprising ultrasound technology and equipped with UCM's proprietary four-sided overflow system.

WWW.ECOCLEAN-GROUP.NET

First ELT main mirror segments successfully cast

The first six hexagonal segments for the main mirror of ESO's Extremely Large Telescope (ELT) have been successfully cast by the German company Schott at their facility in Mainz, European astronomy organisation ESO reported earlier this year. These segments will form parts of the ELT's 39-meter main mirror, which will have 798 segments in total when completed. The ELT, to be built in Chile, will be the largest optical telescope in the world when it sees first light in 2024.

The ELT's primary mirror is much too large to be made from a single piece of glass, so it will consist of 798 individual hexagonal segments, each measuring 1.4 m across and about 5 cm thick. The segments will work together as a single huge mirror to collect tens of millions of times as much light as the human eye.

As with the telescope's secondary mirror blank, the ELT main mirror segments are made from the low-expansion ceramic material Zerodur© from Schott. ESO has awarded this German company with contracts to manufacture the blanks of the first four ELT mirrors (known as M1 to M4, with M1 being the primary mirror). The first segment castings are important as they allow the engineers at Schott to validate and optimise the manufacturing process and the associated tools and procedures.

The casting of the first six segments is a major milestone, but the road ahead is long — in total more than 900 segments will need to be cast and polished (798 for the main mirror itself, plus a spare set of 133). When fully up to speed, the production rate will be about one segment per day. After casting, the mirror segment blanks will go through a slow cooling and heat treatment sequence and will then be ground to the right shape and polished to a precision of 15 nm across the entire optical surface. The shaping and polishing will be performed by the French company Safran Reosc, which will also be responsible for additional testing

Zerodur was originally developed for astronomical telescopes in the late 1960s. It has an extremely low coefficient of thermal expansion, meaning that even in the case of large temperature fluctuations, the material does not expand. Chemically, Zerodur is very resistant and can be polished to a high standard of finish. The actual reflective layer, made of aluminium or silver, is usually vaporised onto the extremely smooth surface shortly before a telescope is put into operation and at regular intervals afterwards. Many well-known telescopes with Zerodur mirrors have been operating reliably for decades, including ESO's Very Large Telescope in Chile.

WWW.ESO.ORG/ELT
WWW.SCHOTT.DE
WWW.SAFRAN-REOSC.COM

■ A rendering of the internal structure of the 39-meter ELT, showing the segmented primary mirror. (Source: ESO/ Dorling Kindersley)

■ The first hexagonal segments for the primary mirror of ESO's Extremely Large Telescope have been successfully cast by Schott. (Photo: Schott/ESO)

Delft researcher Nima Tolou wins Prins Friso Engineering Award

Nima Tolou, researcher at the Department of Precision and Microsystems Engineering, Delft University of Technology, the Netherlands, and co-founder of Flexous and Kinergizer, has been named the 2018 Engineer of the Year. Last month, he received the Prins Friso Engineering Award at the University of Groningen's Engineering Center in the presence of Princess Beatrix and Princess Mabel. The Royal Netherlands Society of Engineers (KIVI) gives the award annually to the engineer who distinguishes him- or herself in terms of expertise, innovative capability, social impact and entrepreneurship.
"The modern engineer is capable of addressing social challenges in a scientific way and turning them into breakthrough technologies. Nima Tolou has this capability. He sees challenges and integrates them into engaging research that helps to make the world a bit of a better place", said jury chair Micaela dos Ramos, director of KIVI.

Tolou (1982) used his knowledge of elastic mechanisms and micro-electromagnetic systems (MEMS) to develop a watch with a completely new movement in an integrated team with the LVMH Watch Division (TAG Heuer/Zenith) and Flexous (see also the News item in the October 2017 issue of Mikroniek). In the process, he has revolutionised a technique that has been used in watches for 350 years. The oscillator that he has developed, which replaces the traditional hairspring mechanism in watches, can be used for other applications as well. In a watch, the oscillator converts energy into movement, but the opposite – converting movement into energy – appears to be possible as well.

This principle has given Nima Tolou the key to developing battery-free sensors and other microwatt devices that can derive their energy from their environment. The range of applications is huge: from the Internet of Things to the healthcare sector, where batteries can be used in pacemakers that can be charged by the movement of the heart itself, for example.

Winner of the Prins Friso Engineering Award, Nima Tolou, flanked by Princess Beatrix (left) and Princess Mabel: "I'm a designer, but definitely also a maker." (Photo: KIVI)

WWW.PME.TUDELFT.NL

WWW.KIVI.NL

MATLAB and Simulink Release 2018a

Last month, MathWorks, a leading developer of mathematical computing software, introduced Release 2018a (R2018a) with a range of new capabilities in MATLAB and Simulink. MATLAB is a programming environment for algorithm development, data analysis, visualisation, and numeric computation. Simulink is a graphical environment for simulation and model-based design for multi-domain dynamic and embedded systems.

R2018a includes, besides updates and bug fixes, two new products: Predictive Maintenance Toolbox for designing and testing condition monitoring and predictive maintenance algorithms, and Vehicle Dynamics Blockset for modeling and simulating vehicle dynamics in a virtual 3D environment.

WWW.MATHWORKS.COM

New positioner for ultra-high-stability applications

Many cryogenic experiments such as super-resolution microscopy or open-cavity QED (quantum electrodynamics) are becoming increasingly complex. Frequently, multiple-axis nanopositioning systems are used in these set-ups. The increased weight however leads to lower resonance frequencies of the configuration and hence increased sensitivity to external vibrations.

Attocube introduces a solution to this challenge. The new, ultra-stable ANPx312 piezo stage offers enhanced stiffness of up to 300% compared to similar cryogenic positioners leading to an unmatched resonance frequency of 4 kHz. As all attocube stages, it is compatible with other positioners to achieve multi-degree-of-freedom motion devices offering up to six movement axes. The ANPx312 is available in both an open- and closed-loop version with integrated resistive encoders.

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