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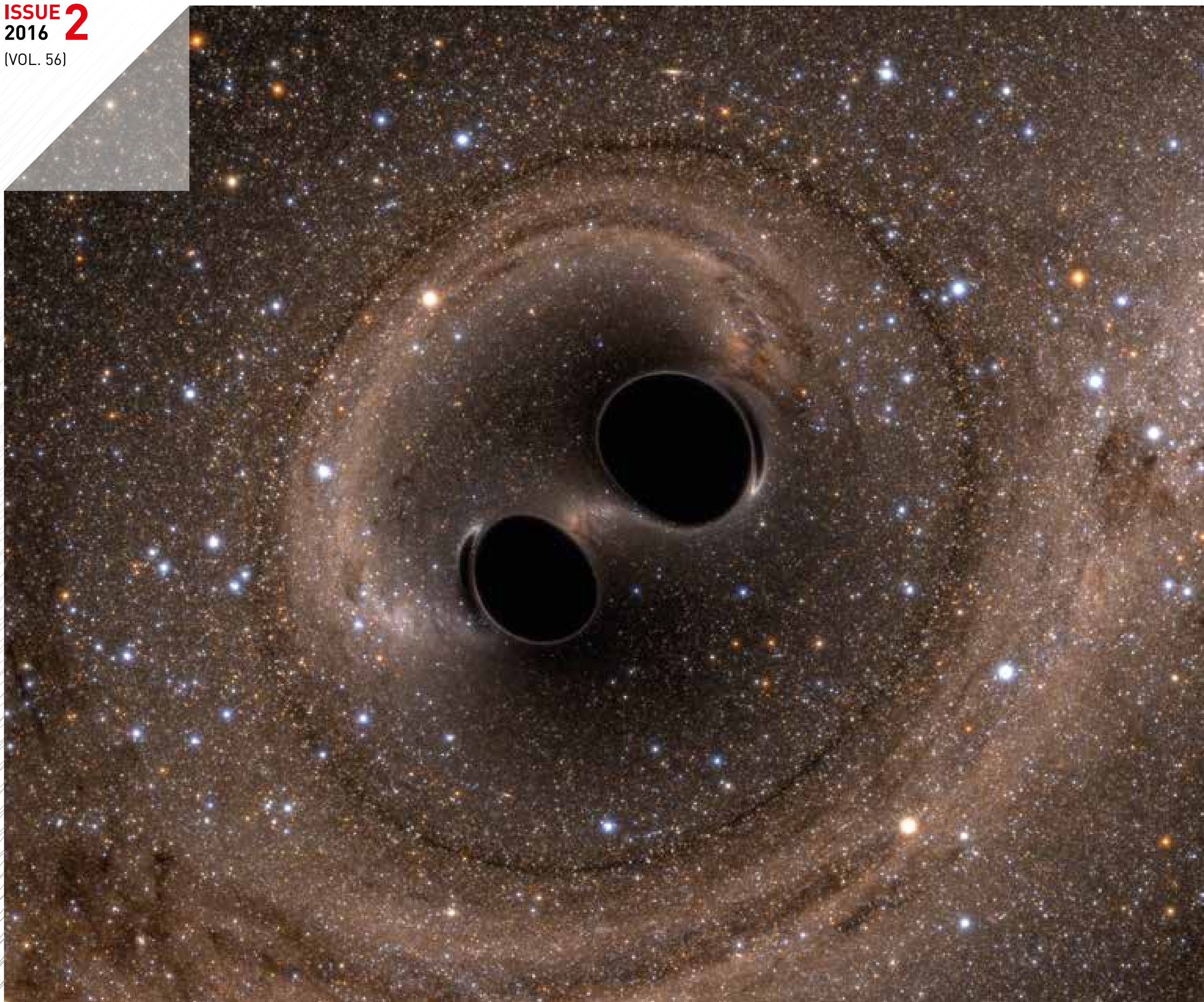
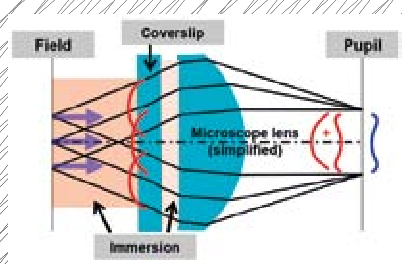


■ CAUGHT: EINSTEIN'S **GRAVITATIONAL WAVE** ■ SMART **OPTICAL SYSTEMS**
■ ADVANCED **THERMAL CONTROL** ■ **3D PRINTING** OF METAL VACUUM SEALS



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

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The main cover photo (featuring the simulation of a black holes collision) is courtesy of SXS, the Simulating eXtreme Spacetimes project (www.black-holes.org). Read the article on page 16 ff.

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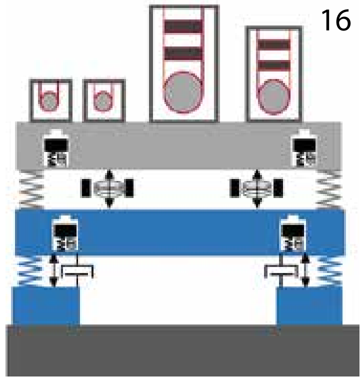

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FEATURES

THE RIGHT TEMPERATURE FOR COLLABORATION

In precision systems, thermal effects have a large influence on the desired accuracy and throughput. In machine tools, heat generated by driving motors and processes leads to deformations that reduce accuracy. In semiconductor lithography tools, extreme thermal conditioning and control is needed to achieve nanometer overlay precision. In tools for nanoscience, thermal drift on a nanometer scale can limit an application. For instance, in the latest generation of transmission electron microscopes, sub-Ångström imaging resolution can only be achieved with corresponding small drift rates. Such microscopes are at the vanguard of developments in structural biology.

In 2007, as Chief Executive of euspen (European Society for Precision Engineering & Nanotechnology), I received a request from the then CTO of Philips Centre for Industrial Technology (CFT), Prof. Jan van Eijk, to initiate a Special Interest Group on 'Thermal Effects in Precision Systems'. We held a first meeting, in Maastricht, which was attended by over 100 delegates from 20 countries and brought to the table challenges and developments from applications ranging from machine tools, space optics and synchrotrons to lithography systems and printers. Subsequent meetings continued to reinforce the importance of the topic and breadth of the impact. In simple terms, standard methodologies, such as are applied for the mechanics, positioning and control, are an outstanding need for thermal problems.

Jump forward to 2012 and, coming from the UK, I am newly living in Eindhoven. Thermal issues have been highlighted by the local precision engineering community as a common problem. With no government funding on the horizon, Hans Vermeulen of ASML and Henny Spaan of IBS wondered if it would be possible to put together an industrial consortium to fund work on this area. I volunteered to see if we could find interested parties and together shape both a program of work and a structure for collaboration. In my search, I could also practice driving on the 'other side' of the road. In the event, together with our potential partners, we covered many miles – many cups of coffee were drunk, IP issues and collaborative structures discussed. Thanks to all their efforts, a consortium agreement was signed in September 2015.

For the first time these partners (ASML, IBS Precision Engineering, FEI Electron Optics, Philips Electronics Nederland, VDL Enabling Technologies and Segula Technologies Nederland) had come together to conduct shared development in a new innovation forum.

The Advanced Thermal Control Consortium has been brought together to cover the common needs of the Dutch high-tech industry, addressed by leading Dutch research institutes TU Eindhoven and TU Delft. It will deliver a step change for products within multiple markets, including life sciences & health, semicon and automotive. And it is open to new industrial members – Interested? *De koffie is bruin* (coffee's ready).

Dr Theresa Spaan-Burke
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A HOT KICK-OFF

In the development of precision systems and machines, thermal effects can play a critical role. As accuracy, productivity and optimisation demands increase, the challenge to further improve performance from the perspective of improved thermal control is of growing importance to markets, ranging from inkjet printing to automotive to lithography systems. On 25 February 2016, the kick-off of a consortium concerned with advanced thermal control was held at the High Tech Campus Eindhoven, the Netherlands.

1 *The ATCC kick-off took place in the Conference Center in The Strip, at the High Tech Campus Eindhoven.*

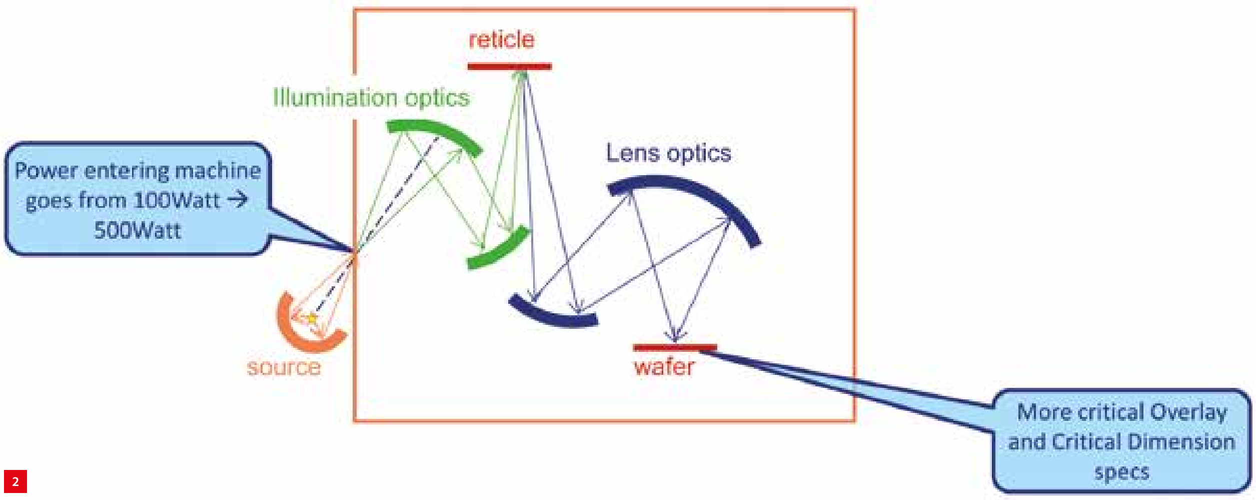
IBS Precision Engineering and ASML were the main advocates of forming an industrial consortium of leading companies from the Dutch high-tech sector to address the topic of thermal control. The members of the consortium are ASML, FEI, IBS, Philips, VDL and Segula. The consortium aims to advance the theoretical and applied approaches to design, simulation, measurement and compensation techniques essential for the development of precision modules/systems subject to internal or external thermal loads.

The kick-off of the Advanced Thermal Control Consortium (ATCC) in the Conference Center at the High Tech Campus Eindhoven (Figure 1) attracted a decent crowd. This confirmed that 'thermal effects in high-precision systems' is a hot topic. The temperature rose in the crowded conference room during the meeting, which featured a short introduction on behalf of the initiators and presentations from the academic and industrial partners as well as pitches from non-consortium partners.

Research scope

The consortium will fund Ph.D. projects, in collaboration with both Eindhoven University of Technology and Delft University of Technology, covering:

- Design rules and optimisation tools that enable the module designer to effectively account for transient thermomechanical performance and optimisation for systems under feedback control.
- Advanced methods for experimental modelling (i.e. identification) and feedback control for thermal problems.
- Model reduction including next-generation techniques for complex systems.
- Multivariable feedback control for thermal applications and controller design methods.
- Systematic and effective tools for observer design.
- Thermal management of optical systems.



2 *Thermal challenges in ASML's new EUV lithography machines.*

In her introduction, Theresa Spaan-Burke, IBS innovation director, recollected how first explorations started in 2012, with interest from high-tech companies, but no available government funding. The consortium will work with a spirit of open innovation, finding the right balance between IP protection and sharing. The aim is to develop a satellite network body of international expertise and interest in the field. The consortium will provide this body with full insight on developments within the generic research of the consortium and a forum for sharing industry perspectives and academic developments.

Academic partners

The first speaker at the kick-off representing the academic partners of the consortium was Fred van Keulen, professor of Structural Optimization and Mechanics (SOM) in the Department of Precision and Microsystems Engineering at Delft University of Technology. He talked about thermal topology optimisation for precision applications. Topology optimisation can be used for improving the performance of systems. The extensive design freedom offered by this method may result in complex geometries that can only be realised with additive manufacturing (AM) techniques. When thermal performance is included in the optimisation, AM-only cooling channels can be integrated into the design of a precision system.

Maarten Steinbuch, professor of Control Systems Technology in the Department of Mechanical Engineering at Eindhoven University of Technology (TU/e), started off by offering his congratulations to the ATCC initiators. His contribution included an overview of applications with thermal control issues covered by his research group, ranging from density control in a plasma fusion reactor to waste heat recovery from diesel engines and motion control in scanners and printers. He concluded that the integration of modelling and control is key when dealing with thermal issues, combining data-based and model-based approaches. Steinbuch stressed that thermal control cannot be copied from dynamic control as there is a difference in mathematical formulation (partial vs ordinary differential equations) and in time scale ('thermo' is slower, except on the nanoscale).

Technology trends lead to an abundant availability of (cheap) sensing, computation and communication. This encourages the use of discrete (finite-element) models for real-time monitoring and optimisation of systems. However, to keep the computational effort in hand, such models have to be reduced. Siep Weiland, professor of Control Systems in the Department of Electrical Engineering at TU/e, discussed the need for control-relevant model reduction, preserving the physical relevance of the model, for thermal control. As an example, he presented the case of thermal control in an AM process.

Industrial partners

As co-initiator of the consortium, ASML was the first industrial partner to deliver a presentation. Wim Symens, in charge of Mechatronics & Control Technology Development at ASML Research, gave an overview of the challenges facing advanced thermal control at ASML. He showed that the evolution in lithography machine design leads to a larger impact of thermal loads on deformations. This can be ascribed to the increase of light source power that enters the machine, the more stringent overlay and focus requirements (Moore's law) and the increase of machine dimensions (Figure 2). "The importance of the Joules to nanometers impact will increase for ASML."

Symens also stated that thermomechanics is not equal to structural mechanics/dynamics, but that there are opportunities to build on the vast experience that has already been built up with motion control in the latter area.

Jeroen de Boeij, mechatronics architect at FEI, discussed the same issues for electron microscopy systems and applications. He presented a general design approach for systems working under cryogenic conditions (< 100 K). This includes preventing heat from the environment reaching the sample, providing a good thermal connection from the sample to a Dewar, keeping heat loads as constant as possible, and realising a vacuum around the sample to avoid convection.

The next speaker was Henny Spaan, CEO of IBS, the company that specialises in metrology machines and metrology solutions for machine tools. Spaan showed how dealing with thermal behaviour in the design of a metrology machine involved not only the use of a metrology frame, but also the exclusion of thermal sources, the careful selection of 'thermo-insensitive' materials, such as SiC and Zerodur, and passive thermal shielding. In machine tools, thermal drift is a big issue. IBS partners up with organisations such as Fraunhofer to research advanced thermal models of machine tools.

Rob van Gils, thermal technologist at Philips Innovation Services, gave an overview of the challenges facing Philips when addressing thermal effects in mechatronic systems: model reduction, system identification and advanced thermal control design. Patrick Smulders, director of System Architecture at Segula Technologies, highlighted the Segula approach of thermal control in thermal & flow systems: model-based design which involves modelling on different system levels, designing with different types of models, and verification with measurements.

Non-consortium organisations

The kick-off was concluded with pitches made by interested non-consortium partners. Jan Bienstman talked about thermal management research at Flanders Make, the Flanders strategic research centre for the manufacturing industry. He stressed that thermal effects limit the performance of systems, vehicles, etc., and showed examples of advanced thermal control in 3D-printing processes and in the cooling of power electronics and integrated drivetrains.

Jens Flügge from the Department of Dimensional Nanometrology at the German National Metrology Institute (PTB) discussed the need for thermal control in order to obtain homogenous temperature fields in measurement machines, such as for the calibration of length artefacts. Ruud Börger demonstrated the accurate thermal modelling capabilities of COMSOL simulation software. Matěj Sulitka from the Research Center of Manufacturing Technology at the Czech Technical University in Prague (Czech Republic) talked about advanced techniques for modelling and compensation of thermal errors, and their industrial implementation in machine tools.

Maurice Limpens from TNO discussed the combination of dedicated analysis and manufacturing techniques for performance optimisation of precision systems. He showed the use of (patented) micro-fin structures for liquid evaporation-based cooling, which is capable of removing significant heat fluxes while using very small (water) flows. Another example was adaptive surface cooling/heating of individual 'pixels' in a (wafer) table using complex 3D-printed structures (Figure 3).

These pitches illustrated the wide range of thermal control issues. Anticipating a demand for thermal control engineers, Jan-Jaap Koning of TU/e introduced a two-year PDEng programme on the subject of thermal control (PDEng is a Professional Doctorate in Engineering).

On the road

The Advanced Thermal Control Consortium (ATCC) kick-off ended with a reception offering participants the opportunity to cool down, meet consortium members and consider registration as a partner. The ATCC offers workshops, reports, preferred supplier status regarding the research, and access to roadmapping activities. Thermal control has hit the road! ■

INFORMATION
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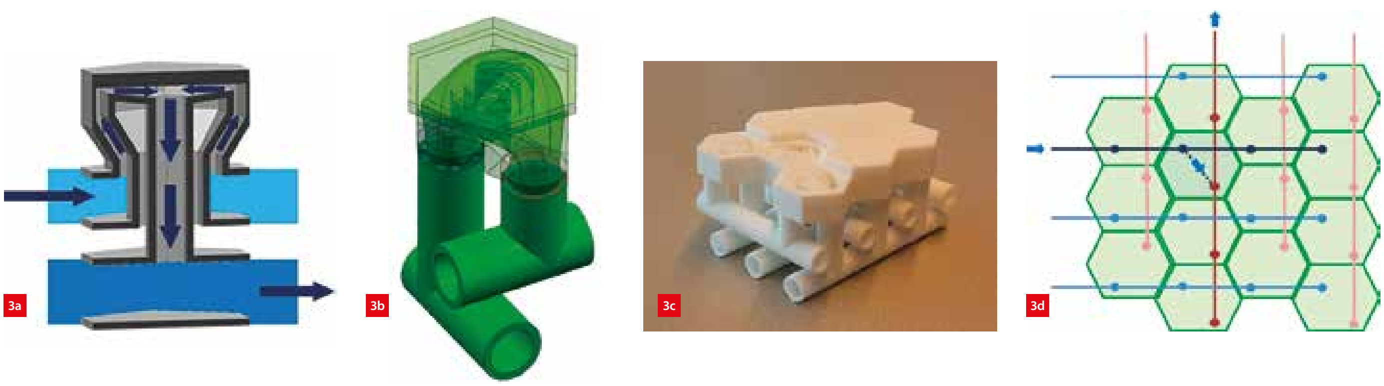
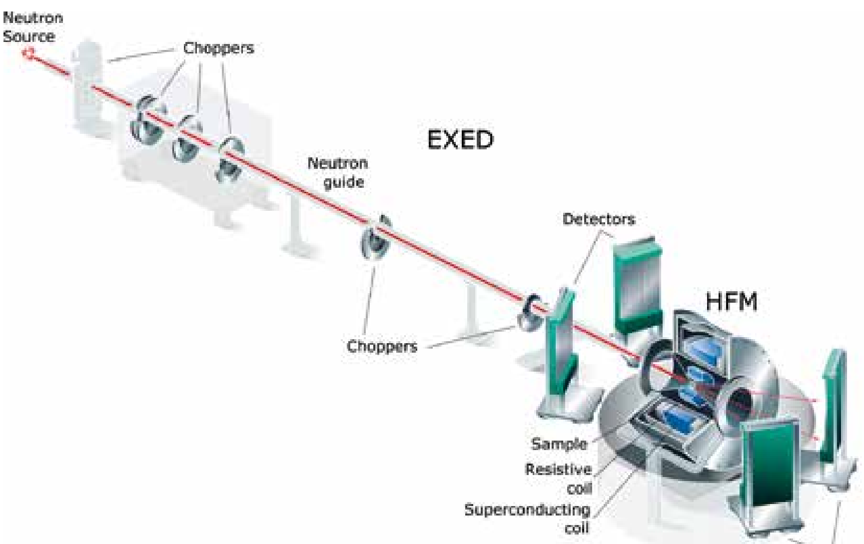


3 *Thermal pixel development (reprinted from Mikroniek 2014, no. 6).*
(a) Basic idea starting point.
(b) One of the design concepts.
(c) Printed sample with multiple thermal pixels.
(d) Possible supply and return channels to feed each thermal pixel with cooling flow.

DESIGN FOR HIGH MAGNETIC FIELD COMPATIBILITY

Janssen Precision Engineering has developed a sample rotation instrument for use in very high magnetic fields for the Helmholtz-Zentrum Berlin (HZB). This magnetic field sample rotator will be used under cryogenic conditions (0.5 K) in HZB's High Magnetic Field Facility for Neutron Scattering. The mechanical design required knowledge of cryogenic design and material behaviour in a combined cryogenic and high magnetic field environment.

BART VAN BREE



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1 *The High Magnetic Field Facility for Neutron Scattering at the Helmholtz-Zentrum Berlin. (Source: HZB)*
2 *The high field magnet with the sample position in the middle. (Source: HZB)*

AUTHOR'S NOTE

Bart van Bree is a system engineer at Janssen Precision Engineering (JPE) in Maastricht, the Netherlands. He would like to acknowledge the contributions made by Maurice Teuwen and Huub Janssen of JPE. For project information, refer to [1].

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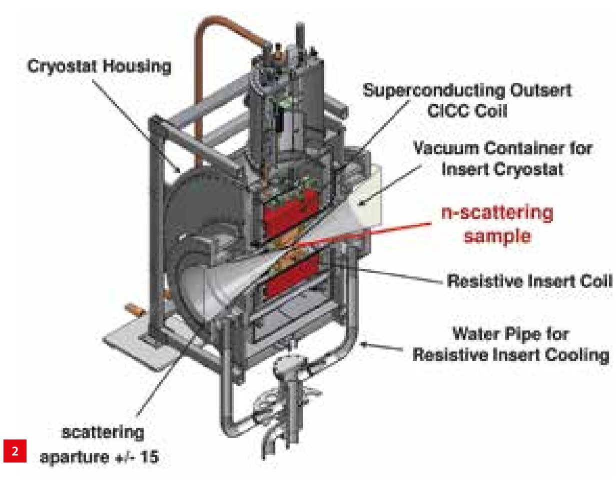
A key part of the High Magnetic Field Facility (Figure 1) at the Helmholz-Zentrum Berlin (HZB) [2] in Berlin, Germany, is the high field magnet (HFM, Figure 2) [3]. It produces a horizontal magnetic field of 26 Tesla, which is a million times stronger than the earth's magnetic field, making it by far the strongest continuous magnet for neutron scattering experiments worldwide. This magnetic field is generated by a large-bore 13 T superconducting coil and a resistive 13 T coil placed inside the bore. The HFM is 5 m in height, weighs 25 tonnes and has an operating current of 20,000 A.

The sample to be investigated is placed in the middle of the HFM and bombarded with neutrons produced in the on-site nuclear plant. Neutrons are scattered by the sample and hit the detectors. Typical applications can be found in the study of:
- Quantum magnets and quantum phase transitions
- Superconductivity
- Correlated electrons in 3d, 4f and 5f metal compounds
- Spin, charge and lattice degrees of freedom in transition metal oxides
- Frustrated magnets
- Novel states of matter



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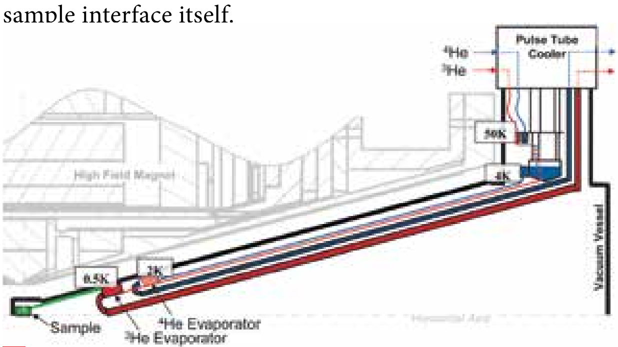
To make the outer coil superconducting, it is placed in a cryostat – basically a refrigerated vacuum vessel – and helium-cooled to 4 K. The resistive coils are water-cooled using cooling towers, chillers and a 300 m³ water storage tank. The sample area is temperature-controlled separately and positioned inside a cone-shaped cryostat running through the bore of the resistive coil. A first thermal shield lines the inside of the cryostat vacuum vessel and is cooled to 50 K, followed by a secondary shield which is cooled to 2 K and finally a direct 0.5 K link is made to the sample interface itself.



3 *Sample in the central cone-shaped cryostat. (Source: HZB)*

Sample rotation mechanism

To expand the scope of measurements, a rotation of the sample with a vertical axis of rotation is ideal. HZB commissioned Janssen Precision Engineering (JPE) to design the magnetic field sample rotator (MFSR). Any interaction of both the primary and the scattered neutron beams with anything other than the sample must be avoided. Opening angles up to 30° starting from the sample facilitate this. The only feasible location for the MFSR is below the primary beam. Figure 4 shows the neutron beam and the sample in the cryostat. Table 1 lists the specifications for the MFSR design.

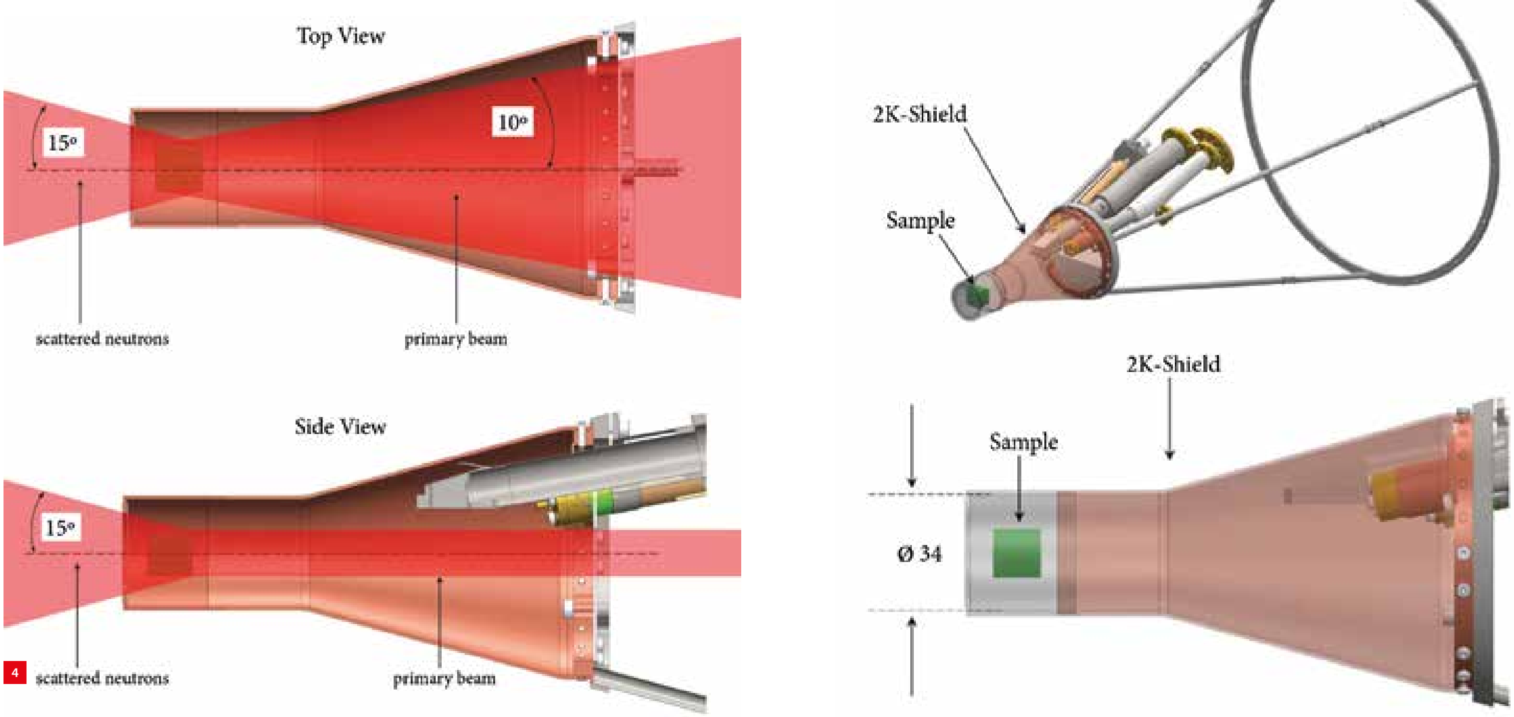
Table 1. Specifications for the MFSR design.

Magnetic field	26 T
Temperature range	0.5-300 K
Pressure	10^{-6} mbar
Mechanism volume	Below the primary beam, no blocking of the neutron beams
Sample size	1 cm³
Total angle of rotation	> 180°
Sample forces	0.1 Nm as a result of magnetic field with random orientation
Holding torque	0.1 Nm
Driving torque	0.01 Nm
Speed	0.1°/s
Encoder resolution	0.01°
Sample mounting	Play-free
Actuation	Play-free

Material selection

The extremely high magnetic field limits the range of acceptable materials. For instance, stainless steel AISI316L is generally used as a non-magnetic material, but for this application it is not acceptable as 'non-magnetic', not even in miniature parts like M1 set screws.

Another issue is thermal expansion. A thermal expansion coefficient of $15 \cdot 10^{-6}$ K^{-1} over a length of 100 mm for a temperature drop of 300 K will result in a 450 µm error. Therefore, critical alignments will typically not survive when dropped to cryogenic temperatures and fits will become either too tight or loose. Non-identical materials in contact should be carefully matched or expansion-compensated so that the desired dimension or fit is reached



4 *Neutron beam (left) and sample (right) in the cryostat. (Source: HZB)*

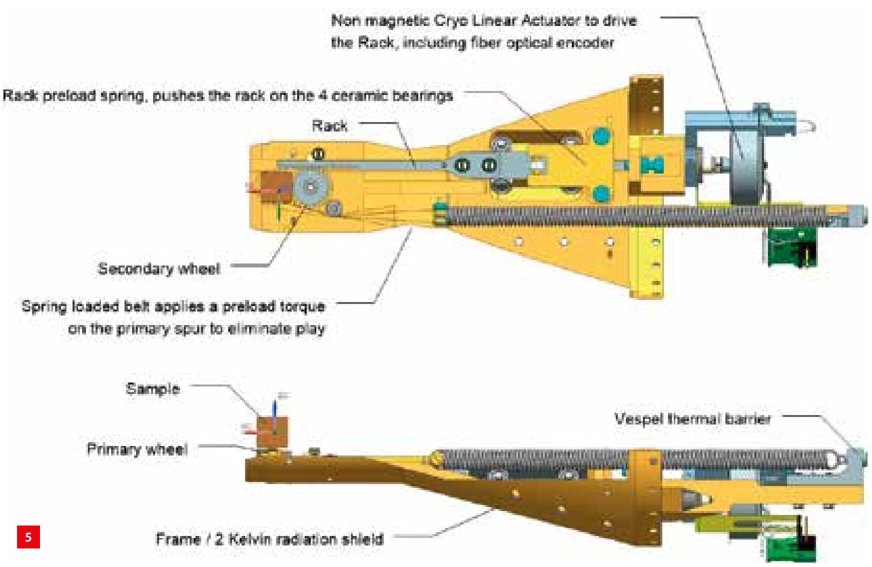
in operational conditions. However, the effectiveness of this approach is limited by the availability of material data and the temperature homogeneity of the instrument.

Electrical superconductivity is another consideration. This phenomenon is required for the functioning of the magnet, but should be avoided in other construction elements because when materials become superconductive they become very poor thermal conductors. This is typically an undesired disruptive factor for predictable thermal behaviour. It rules out the use of, for instance, aluminium alloys, which become superconductive in the 1-2 K range.

Adhesive bonding must be carefully designed to prevent breakage by thermal stress. Lubricants cannot be used either because they become solid at low temperatures.

Taking all of these considerations into account, a list of acceptable materials has been compiled, for various usages:

- Oxygen-free high-conductivity copper (OFHC)
  Construction material for low-stressed parts with very high thermal conductivity.
- Phosphor bronze
  For springs and other stressed parts with high thermal conductivity and thermal expansion close to OFHC.
- Titanium Ti-6Al-4V
  For highly stressed parts with low thermal conductivity; material becomes electrically superconductive at 400 mK.
- ZrO_2 ceramic
  For roller bearings with low thermal conductivity and thermal expansion close to Ti-6Al-4V.
- Vespel
  A plastic that can be used in cryogenics, with reasonable mechanical properties and very low thermal conductivity.



5 Concept of the MFSR (see text for explanation), top view (above) and side view (below).

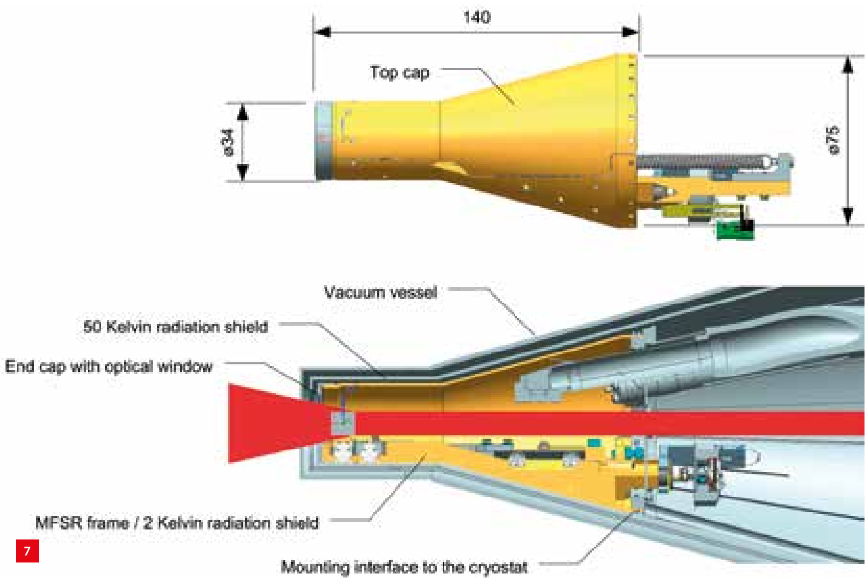
Mechanism

The concept of the MFSR is shown in Figure 5. To optimise the use of the available volume, it was decided to make the frame of the instrument part of the 2 K thermal shield. As such, it is made of OFHC. The semicircular flange on the right (the wide end of the cone) attaches it to the rest of the 2 K shield.

The rotation is realised via a linear toothed rack driving two toothed wheels in sequence. The sample is placed on the primary wheel and can be rotated a little over ±90°. A single-wheel concept was preferred but not possible because the rack would exit the left side of the mechanism at full stroke. A worm gear drive was also considered, but proved unfeasible in the volume as it would interfere with the neutron beam. The rack translation range of ±9 mm is realised by running it through four ZrO_2 bearings in a V-shape configuration, preloaded with a phosphor bronze leaf spring.

The rack translation is actuated using JPE's cryo linear actuator, the 'PiezoKnob' [4] (Figure 6). This is essentially a torque pulse generator that drives a spindle for use below 1 K. It delivers forces of up to 50 N, can take nanometer steps, is easy to modify for ±9 mm stroke, is available in a non-magnetic variant and can be fitted with JPE's non-magnetic, cryogenic-compatible fibre-optic encoder. The fibre-optic encoder outputs 800 pulses per revolution, which translates to 313 Nm of detectable output of the spindle or 0.0036° rotation of the primary wheel.

6 Two views of JPE's non-magnetic cryo linear actuator with fibre-optic encoder, which is used to drive the MFSR.



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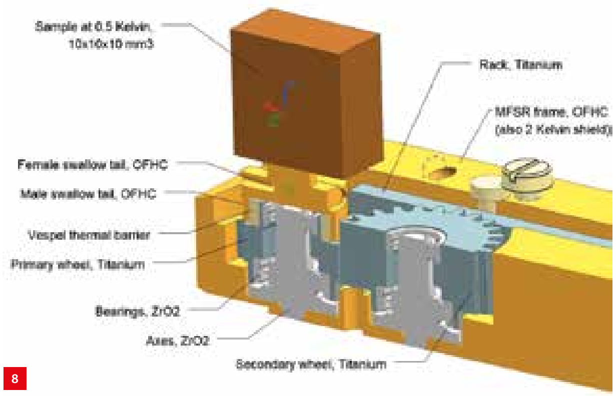

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Available alternatives like cryogenic-compatible stick-slip motors or stepper motors have been evaluated, but simply cannot deliver the required force or torque or are incompatible with the magnetic field.

Closing the 2 K shield requires mounting a top cap and end caps (Figure 7) with optical windows, which allow the scattered neutrons to pass. The system is mounted onto the cryostat via a flange on the right-hand side of the MFSR.

During the measurement, magnetic loads of up to 0.1 Nm can be exerted on the sample in any direction. This can cause play between rack and wheels to become visible in the sample rotation. As such, the primary wheel holding the sample is preloaded via a low-stiffness tension spring. The spring force is transmitted to the primary wheel via a double-layered belt of 0.05 mm thick phosphor bronze foil, wrapped around the primary wheel. The double-belt configuration was required because a single belt could not safely withstand the 33 N preload force, equivalent to 0.1 Nm, given that a thicker foil is incompatible with the desired bending radius.

The sample to be investigated is glued on a swallowtail interface that makes it easier to swap samples between experiments. The swallowtail is secured with a set screw to eliminate play.

Thermal isolation

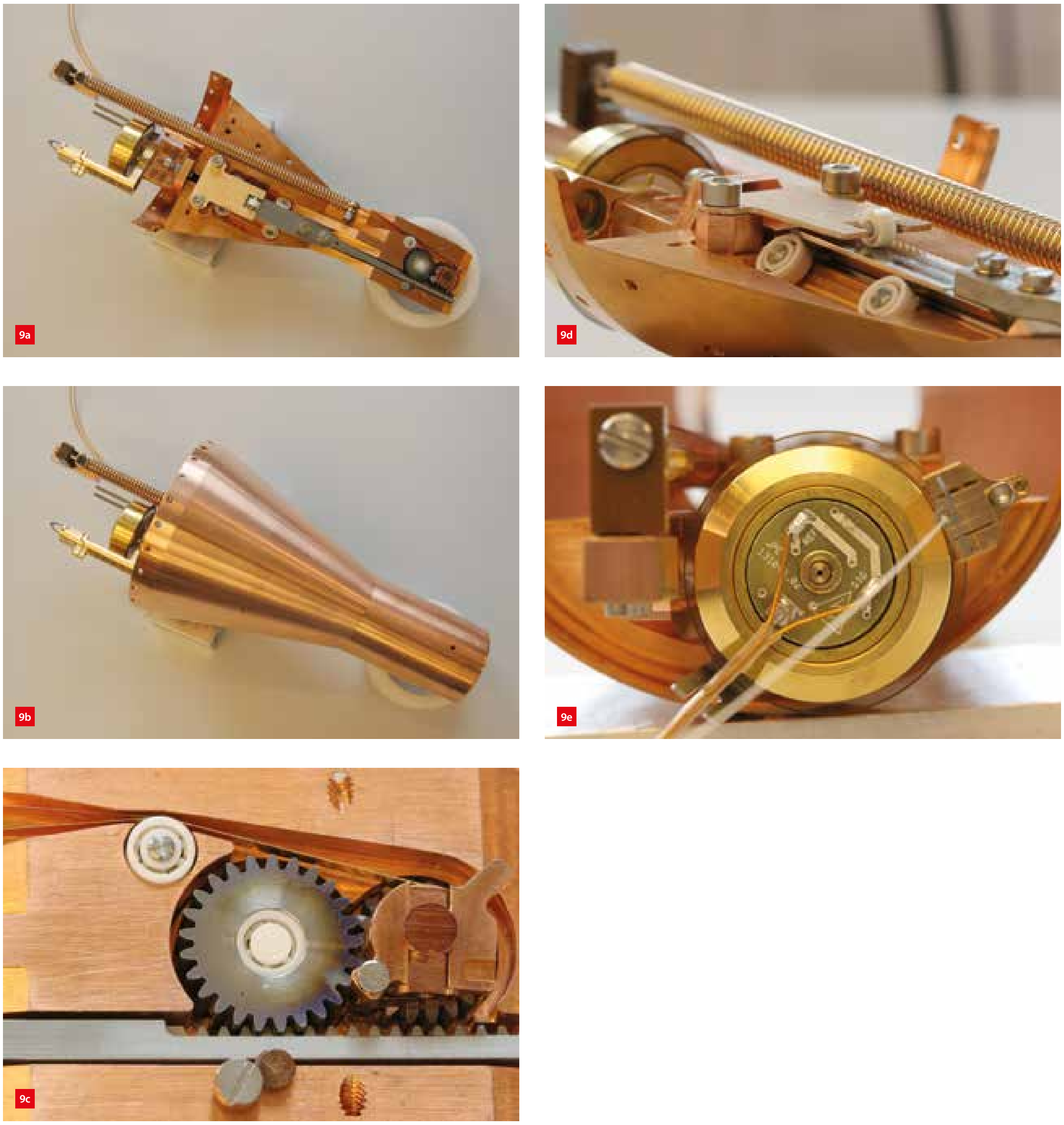
The sample must be thermally isolated from the 2 K frame to allow it to be separately cooled to 0.5 K (Figure 8). As such, the bearings and axes are made of ZrO_2 ceramic, which has low thermal conductivity. The wheels are made of Ti-6Al-4V, combining high load capacity, low thermal conductivity and a thermal expansion that matches ZrO_2 quite well. To enhance the thermal isolation of the sample, a Vespel ring is mounted between the primary wheel and the sample.

Moreover, sample play in any other direction than the rotational direction of the wheels needed to be limited to a few µm. Ideally, spring-preloaded ceramic angular contact bearings would be used, but these could not be found in small enough sizes. As an alternative, ceramic deep-groove roller bearings with reduced internal radial play were selected. With these bearings, the prevention of excessive compressive fits is important, as this causes bad running characteristics.

An analysis was carried out to find appropriate bearing fits, so that the play at cryogenic temperatures would reach the desired value. This did not prove feasible. Not only did it require sub-micron machining tolerances, but the tolerances on the bearings themselves were too great to guarantee the prevention of excessive bearing compression. Instead, it was decided to use under- and oversized fits and fill the resulting gaps with a capillary adhesive, which eliminates play completely. The residual expansion mismatch between bearing and wheel in the order of 1.5 µm will be compressive and is acceptable for the bearings. Furthermore, the low-stiffness adhesive reduces the stress levels.

Similarly, the Ti-6Al-4V rack on ZrO_2 bearings in a V-shape configuration prevents a thermal load from the 2 K frame to the sample via the drive train. Finally, a Vespel part is used as a thermal barrier on the right-hand side of the tension preload spring. This prevents a thermal load from the 2 K frame into this spring, through the belt into the primary wheel.

7 *Magnetic field sample rotator with caps in the cryostat.*
8 *Thermal decoupling of the sample from the environment.*



9 *Realised MFSR.*
(a) Without caps.
(b) With caps.
(c) The secondary (left) and the primary wheel.
(d) The rack running through ceramic (ZrO_2) bearings in a V-shape configuration, with the rack preload spring on top; in the background the tension spring which preloads the primary wheel.
(e) The PiezoKnob actuator with fibre-optic encoder.

Figure 9 shows the realised sample rotation instrument, the MFSR (magnetic field sample rotator), delivered to HZB.

Conclusion

JPE, in close cooperation with HZB, has successfully developed the MFSR sample rotation mechanism for integration in the High Magnetic Field Facility for Neutron Scattering at HZB. Strict specifications in terms of volume, magnetic field and temperature have been successfully achieved. Thermal isolation of the sample with respect to the rest of the structure allows the sample to reach temperatures of 0.5 K or even to be locally heated via a miniature heater element on the sample holder. The mechanical design and thermal behaviour are heavily connected and to successfully complete the project required extensive knowledge of cryogenic design and material behaviour in a combined cryogenic and high magnetic field environment.

The MFSR will open up new possibilities for users of the High Magnetic Field Facility for Neutron Scattering and allow them to do exciting new research. ■

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Punch Powertrain – New developments for automatic transmissions, electrical drives and hybrids

Punch Powertrain is an independent developer and manufacturer of automatic transmissions, electric and hybrid power-trains for passenger cars. In the development of new product lines, Punch Powertrain prioritises minimal fuel consumption and low emissions. Furthermore, driving pleasure and performance remain the key elements.

Worldwide, Punch Powertrain employs about 1.200 people. Headquarters are situated in Sint-Truiden, Belgium, where the high-tech components of the CVT (Continuously Variable Transmission) are being produced. Punch Powertrain also runs an assembly factory in Nanjing (China). R&D is performed in Sint-Truiden (including coordination), Eindhoven and Nanjing, China. Last month, it was announced that the Chinese Yinyi Group was to acquire 100% of the shares of Punch Powertrain. Within Punch Powertrain a culture dominates where an "open-minded, can do" attitude is appreciated and encouraged. The engineers have a single clear goal in mind: thinking together with the customer in order to jointly deliver the best product.

Eindhoven

Since 2013, the Eindhoven branch in the Netherlands has become part of Punch Powertrain. In 2003, the current Punch Powertrain Eindhoven was founded as Drivetrain Innovations (DTI). DTI designed and developed innovative drive engineering concepts and had built up quite a significant patent portfolio. Before the merger with Punch Powertrain, there had already been an intensive synergy between both companies for several projects.

Meanwhile, Punch Powertrain Eindhoven has been fully integrated in the R&D organisation of Punch Powertrain. Thanks to the R&D satellite in Eindhoven, Punch Powertrain has been able to strongly increase the R&D capacity which enables better access to innovative talent in the Eindhoven area. At the same time, Punch Powertrain Eindhoven can offer a stimulating work environment filled with innovative challenges to that same automotive talent. 'Eindhoven' currently employs approximately 50 people working in various competences such as system engineering, controls, testing and mechanics.

Products and technologies

Punch Powertrain has been producing and developing Continuously Variable Transmissions for over forty years. It started for DAF with the rubber drive belt CVT but nowadays Punch Powertrain mainly produces for Asian clients. In the recent past, there have been new developments for automatic transmissions, such as double-clutch transmissions, but also for hybrid and completely electrical drives. This resulted in a strong growth, and this is confirmed by the start of a 5-year investment plan that will increase the current capacity at the plants in China and Europe from 300.000 to 1.3 million units. Punch Powertrain is also continuing to pursue innovations, and for this its R&D department will be growing from almost 300 to over 700 employees in the coming five years. ■

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MODELLING, MEASUREMENT, CORRECTION, COMPENSATION AND **CONTROL**

Last month, the Thermal Issues Special Interest Group of euspen held a meeting in Prague. Global leading expertise was brought together to an open forum for focused presentations and discussions on thermal issues. The meeting attracted approximately sixty participants. Dutch precision engineering was well represented, with two of the four keynotes and four out of eighteen presentations.

Thermal effects are regarded as a major contributor to errors on machine tools, on measuring equipment and on workpieces. Measurement of thermal effects is becoming even more important as workpiece tolerances decrease, as thermal effects not only use a larger part of the tolerances, but also influence repeatability and long-term stability of machine tools and measuring equipment. The intensive on-going work of several research groups and industries in this area led euspen to bring together an international meeting. The Thermal Issues Special Interest Group Meeting took place on 16-18 March 2016 at the Jurys Inn Hotel in Prague, Czech Republic, and featured a number of interesting sessions as well as two company tours.

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Company tours

A first company tour was made to Kovosvit MAS, based in Sezimovo Ùsti (Czech Republic). This company developed several new prototype machine tools with the goal of minimising thermal errors, including compensation models, thermal machine tool structure optimisation and advanced cooling systems. The MCU 1100 machining center was shown (Figure 1), with a thermally optimised machine tool structure (finite-element method based) and an advanced compensation algorithm for thermal errors based on transfer functions.

The second tour was to the Research Centre of Manufacturing Technology (RCMT), established in 2000 as an institute of the Faculty of Mechanical Engineering of the Czech Technical University in Prague. The RCMT is a highly professional and well-equipped educational and training facility and a research base for the Czech machine tool industry (Figure 2).

1 *MCU 1100 five-axis vertical machine center.*
2 *Impression of the RCMT.*

Temperature Measurement & Control

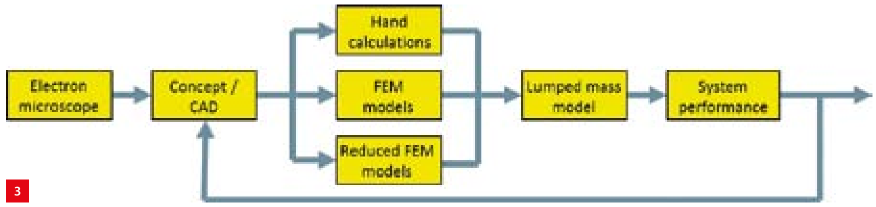
The session keynote was given by Christof Gaiser (PTB) on dielectric-constant gas thermometry. In the newly revised SI system, the base unit Kelvin will be defined in terms of a fixed numerical value of the Boltzmann constant. Many projects are underway to measure independently the value of the Boltzmann constant at the triple point of water. At PTB the recently established dielectric-constant gas-thermometry set-up is used. The basic idea is to replace the density in the state equation of a gas by the dielectric constant, and to measure the dielectric constant via the capacitance change of a capacitor filled with gas at different pressures and constant temperature (measurement of isotherms).

Presentations were given on active control of thermal aberrations in projection optics for EUV lithography (ASML), characterising the temperature measuring capabilities at the PTB sphere interferometer (PTB) and the energy balance investigation of an inductively coupled plasma torch for plasma figuring (Cranfield University).

Modelling Techniques & Model Reduction Techniques

Keynote speaker Jeroen de Boeij (FEI) talked about the thermal challenges in electron microscopy systems and applications. Making images with a few tenths of a nanometer resolution under cryogenic conditions poses many challenges in the mechatronic design and thermal management of the entire workflow in general and transmission electron microscopy (TEM) in particular. One of the main challenges in cryogenic TEM is to keep the sample at < 100 K while dissipating > 1 kW in the coils around the sample with < 1 nm/min drift between beam and sample. The author of this article presented an approach on the thermal-elastic modelling of such a complex system, in which different modelling techniques are combined (Figure 3).

Presentations featured the influence of the machine housing on tool centre tip displacement (IWF ETH), easy thermal transient modelling of large components during inspection (WZL RWTH), calibration and validation of an opto-thermo-mechanical model for thermal aberration predictions in EUV lithography (TU Eindhoven), robust prediction of machine tool errors (University of Huddersfield), macro-models for modelling cooled spindles (IWF ETH) and reducing thermal errors with topology optimisation and distributed cooling (TU Delft).



3 *Effective thermal-elastic system modelling approach.*

Correction & Compensation Strategies

Hans Vermeulen (ASML) discussed in his keynote the thermal challenges for next-generation EUV lithography systems. For further enhancement of resolution in optical lithography, ASML is currently studying feasibility of an EUV system with improved numerical aperture. As a result of higher throughput requirements and increasing dose for better imaging performance in future resist, source power increase from about 100 W to 500 W at intermediate focus will be needed. In combination with improved overlay and focus requirements (Moore's law), this implies very significant thermal challenges on next generation EUV systems, specifically the optics, and at the wafer and reticle level.

Subsequent presentations dealth with alternative, two-phase cooling fluids (Carl Zeiss SMT), compensation of thermal errors in machine tools including the use of temperature field observers and structural strain measurements (IK4-IDEKO et al.), and the influence of the cutting process on thermal errors (RCMT).

Thermal Control Strategies

In his keynote, Nick Jones (Renishaw) discussed the thermal issues in additive manufacturing. In the Laser Powder Bed Fusion process layers of metal powder are deposited and selectively fused using one or more lasers. Thermal system issues are the need to control the relative alignment and position of optical elements which are necessarily remote from the powder bed and to maintain the laser position(s) on that surface. From a process perspective, the thermal issues relate mainly to the control of part residual stresses & microstructural changes induced by the temperature gradients and rapid cooling inherent to the process, as well as the dissipation of waste heat.

Presentations were given on cooling a machine tool spindle using lamellar heat exchangers (IFW Hannover) and feedback control of thermal systems using heat flux sensors (TU Ilmenau).

Conclusion

Significant progress has been made to tackle thermal issues in a wide variety of precision systems in many novel ways, ranging from cooling fluids to artificial neural networks to observer-based temperature field reconstruction. ■

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CAUGHT 1.3 BILLION YEARS AFTER THE ACT: EINSTEIN'S **GRAVITATIONAL WAVE**

On the 14th of September 2015, the two US-based LIGO interferometers recorded the detection of a gravitational wave – the phenomenon predicted by Albert Einstein 100 years ago – emitted by the merger of a binary black holes system. The Advanced LIGO detectors required isolation systems designed to perform beyond traditional requirements. Moreover, they also had to be engineered to sustain volume production for the construction phase of the project, and to guarantee high duty cycle (uptime) during the phase of operation.

FABRICE MATICHARD

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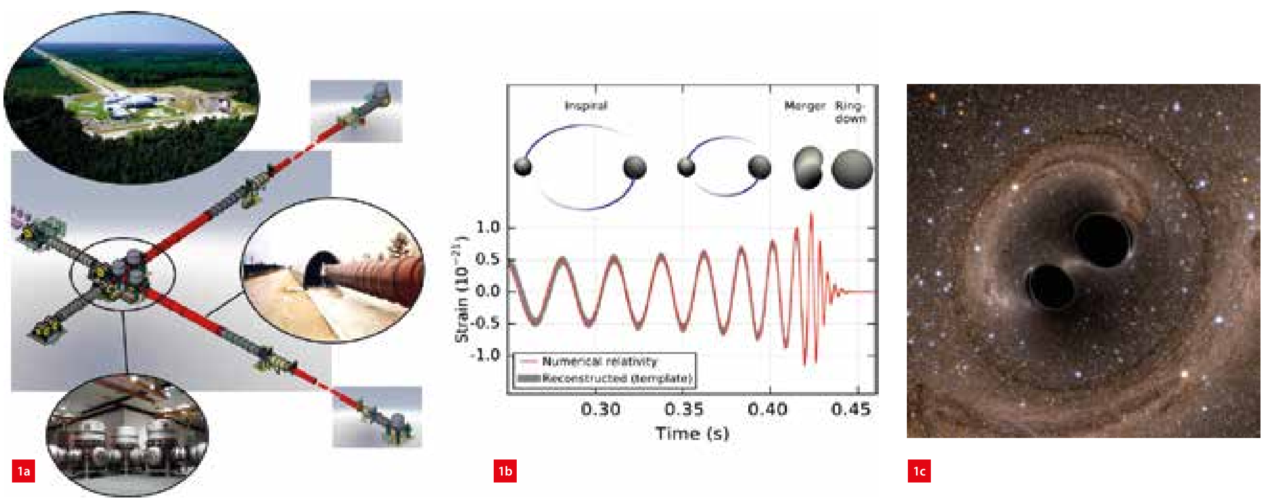
Introduction

The Laser Interferometer Gravitational-Wave Observatory (LIGO) runs a large-scale physics experiment that measures gravitational waves emitted by astrophysical sources. The level of sensitivity and the complexity of the system used to achieve these measurements relies on many decades of engineering development. In particular, the Advanced LIGO detectors required isolation systems that not only perform beyond traditional requirements, but also had to be engineered for volume production. They were also required to guarantee high duty cycle during the phase of operation.

This article describes the strategy chosen for Advanced LIGO, and how it has been engineered to meet all these objectives.

The two LIGO detectors located in Hanford, WA, and Livingston, LA, house 4 km long interferometers designed to measure gravitational waves. In the past five years, the new generation of instruments called Advanced LIGO was constructed and installed in the vacuum envelope of the two observatories [1]. Figure 1a shows an aerial view of the Livingston observatory and its 4 km long vacuum envelope.



1a 1b 1c

1 LIGO detector and signal (source).
(a) One of two LIGO detectors (aerial view of the Livingston site and pictures of the vacuum system housing the 4 km interferometer).
(b) The gravitational signal emitted by the binary black holes merger detected by the LIGO detectors on September 14, 2015 [2]. The strain of the wave (10^{-21}) induced a relative motion on the order of 10^{-18} m between the test masses of the 4 km long interferometers.
(c) Computer simulation of the collision/merger of two black holes. (Image courtesy of SXS, the Simulating eXtreme Spacetimes project, www.black-holes.org)

On the 14th of September 2015, the two LIGO interferometers recorded the detection (see the strain waveform in Figure 1b) of a gravitational wave emitted by the merger of a binary black holes system [2], see Figure 1c. The relative motion measured between the test masses of the 4 km long interferometer is on the order of 10^{-18} m. To perform such sensitive measurements twenty active platforms and several tens of passive suspensions are used on each site to isolate the optical components from ground motion.

This article describes how the vibration isolation sub-systems have been engineered not only to provide tremendous isolation performance, but also to meet all the project requirements of the construction (schedule, budget, integration) and operation phases (stability, robustness, operability).

System overview

A gravitational wave is a transverse wave which compresses one direction of space orthogonal to the direction of propagation while it elongates the other orthogonal direction, and vice versa as the wave passes by. Interferometric detectors are based on a Michelson configuration to measure the differential change of length between the two directions orthogonal to the wave propagation. The amplitude of the strain wave produced by astrophysical events can be gigantic at the source but it is expected to be minuscule by the time it reaches earth. The interferometers must be extremely sensitive in order to detect the wave.

A simplified schematic of the Advanced LIGO optical layout is shown in Figure 2. To reach the required level of sensitivity, the detectors use: a 4 km Michelson baseline; two test masses in each arm to form Fabry-Perot cavities; mode cleaners and recycling cavities on the input and output sides of the interferometer.

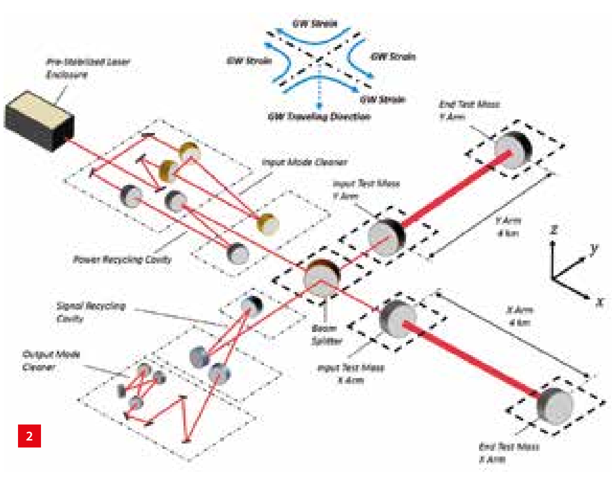
A very high level of vibration isolation is needed to lock the interferometers and cavities on their operating point, and to lower the test masses motion below the amplitude of the gravitational waves. About three orders of magnitude of isolation is required at 1 Hz to lock the interferometers, and more than ten orders of magnitude above 10 Hz to detect the signals (RMS residual motion between the test masses on the order of 1 to 3 μm before locking the interferometer, and on the order of 10 fm once it is locked).

Like most high-performance isolation systems, the isolation strategy requires the use of multiple layers of filtering, and a subtle combination of passive and active components to obtain adequate seismic noise attenuation over a large bandwidth. The design of such distributed isolation systems is complicated. Trade-offs must be made between cut-off frequencies and number of layers of isolation, while accounting for cost, schedule constraints, and robustness of operation. The next section gives an overview of the strategy used in Advanced LIGO.

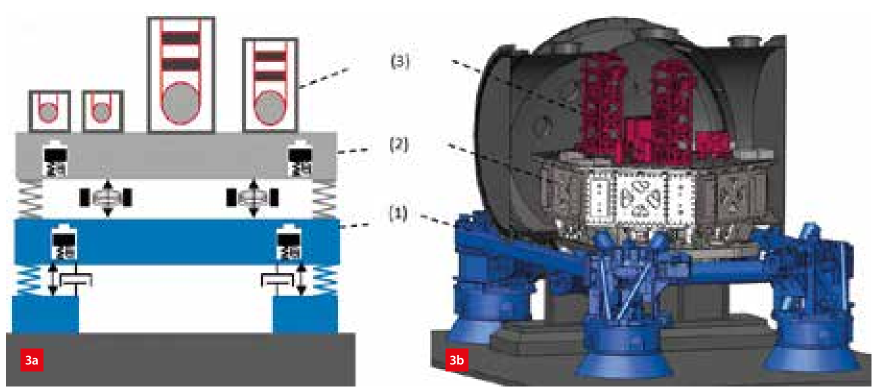
Vibration isolation strategy

Advanced LIGO detectors are very complex systems which use hundreds of optical components and servo-control loops. They require not only very high vibration isolation, but also high robustness and duty cycle. To achieve the objectives, the isolation strategy is based on the use of active isolation platforms instrumented with very-low-noise inertial sensors, and featuring the large optical tables on which the passive suspensions holding the optics are mounted.

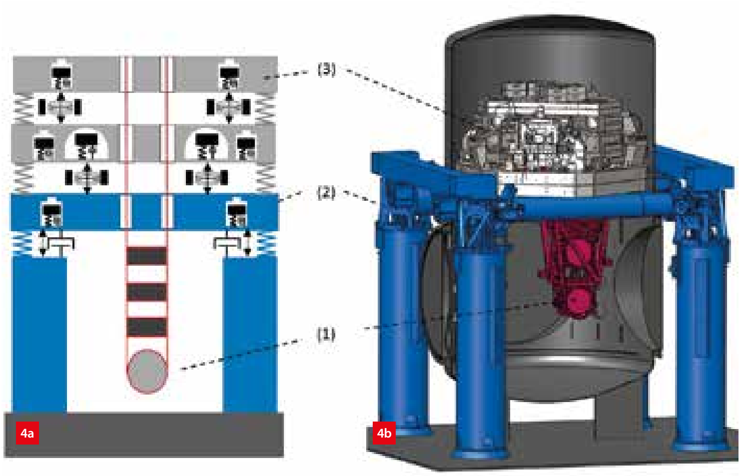
The active platforms provide the low-frequency isolation, from about 100 mHz to 10 Hz. They combine relative sensors for the quasi-DC positioning, and inertial sensors for the vibration isolation. The inertial active approach avoids the need for soft springs to provide low-frequency

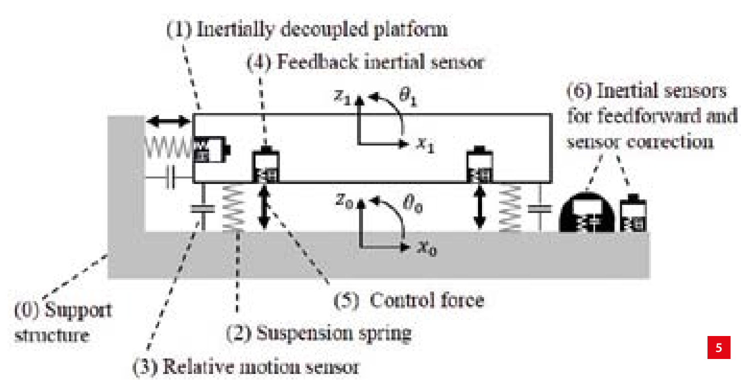


2 *Advanced LIGO simplified optical layout. The core optics (beam splitter and test masses) make up the main Michelson and Fabry-Perot cavities. The auxiliary optics provide the mode cleaners and recycling cavities.*



3 *The layers of isolation used for the auxiliary optics of Advanced LIGO.*
(a) Concept.
(b) CAD drawing.





isolation. Relatively rigid springs are used to suspend the platforms. The rigid-body modes are in the range of 1 Hz to 10 Hz. By comparison with soft platforms, this approach significantly improves the construction, balancing and tuning process.

Passive suspensions are used to hold the optics and provide the high-frequency isolation (> 1 Hz). Between one and four layers of passive isolation are used depending on the requirements for each optic. Compact actuator-sensor pairs are used to actively damp the rigid-body modes of the suspended stages.

As the sensors measure the differential motion between the frame and the stage (unlike the inertial sensors of the active platforms), the damping must be carefully tuned to not compromise the passive isolation with sensor noise and/or recoupling of the stage with the frame. Since the suspensions are mounted on very quiet inertial active platforms, only light damping is required to reduce the amplitude of motion at the suspension resonance. This relaxes the noise requirements for the sensors used to provide active damping and preserves the passive isolation.

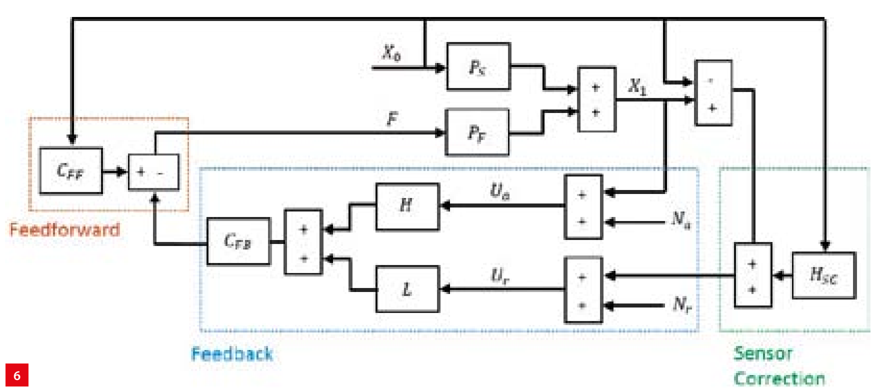
The schematics in Figure 3 and Figure 4 illustrate the combination of active and passive systems used for the auxiliary and core optics, respectively. Though they provide differing amounts of isolation, they rely on the same strategy:

1. An active stage located outside the vacuum system provides pre-isolation from approximately 0.1 Hz to 10 Hz. This hydraulic system provides a robust base for the subsequent layers of isolation. This system is used for the auxiliary and core chambers.
2. An active platform features an optical table about 2 m wide on which the components of the interferometers are mounted. This system is instrumented with the large and heavy low-noise inertial sensors. A single-stage active isolator is used for the auxiliary optics, while a two-stage system is used for the core optics.
3. The optics are suspended passively using multiple pendulums. Up to three layers of passive isolation are used for the auxiliary optics, while four layers are necessary for the core optics.

The next section gives a presentation of the active isolation platforms.

Active platforms

The schematic in Figure 5 illustrates the strategy used for all the active isolation platforms. The motion of the support structure (1) is decoupled from the motion of the support structure (0) using metal springs (2). Relative motion sensors (3) are used for the low-frequency longitudinal and angular control of the platform. Inertial sensors (4) are used for the active vibration isolation in a feedback control scheme. A set of actuators (5) is used to position and isolate the platform in all directions of translation and rotation. Inertial sensors mounted either on the ground or the support structure are used to provide additional isolation in a feedforward control scheme. A detailed presentation of each of the three types of platforms used in Advanced LIGO is given in [3].



4 The layers of isolation used for the core optics of Advanced LIGO.
(a) Concept.
(b) CAD drawing.

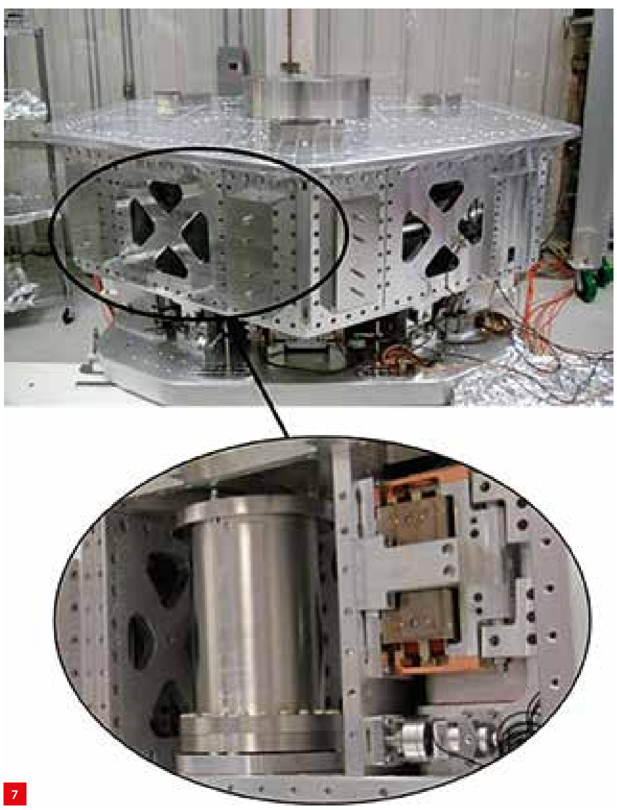
5 Schematic representation of the active platform architecture.

6 A block diagram representation of the active control scheme.

The platforms are designed to minimise the cross-couplings between the six degrees of freedom of a platform, so that the motion in each direction can be controlled independently. The control approach for one direction is summarised by the block diagram in Figure 6.

The input motion disturbance (X_0) induces the platform motion (X_1) via the seismic path (P_S). The platform motion is controlled with the force (F) which induces motion via the force path (P_F). The feedback block is the central part of the control strategy. The motion of the platform is measured with the inertial sensor which produces the inertial (absolute) motion signal (U_a). The signal contains sensor noise (N_a). Since the sensitivity of inertial sensors decreases at low frequency, the signal is filtered with a high-pass (H) to avoid sensor noise injection.

To complement the control at low frequency, the position sensors provide the differential motion signal (U_r) between the platform and input motion. This signal includes sensor noise (N_r). The signal is low-pass filtered (L) to dominate the control loop at low frequency, and to not compromise the active isolation at high frequency. The combined signal is sent to a compensator (C_{FB}) which drives the control force.



Additional isolation is obtained using measurements of the ground motion in a sensor correction scheme at low frequency (H_{SC}), and in a feedforward scheme at high frequency (C_{FF}). Further details regarding the control strategy and tuning of the control filters to optimise the performance can be found in [3].

Figure 7 shows one of three types of active isolators. The system is designed to operate in ultra-high vacuum. The inertial sensors are podded in sealed chambers for vacuum compatibility. Capacitive position sensors are used for the relative positioning. Magnetic actuators are used for the drive. The systems are assembled and tested in clean rooms. Fifteen platforms like the one shown in this picture were constructed for Advanced LIGO, on budget and schedule. Engineering details regarding the two-stage isolator are presented in [4-5]. The next section gives an overview of the passive components mounted on the active platforms.

Passive suspensions

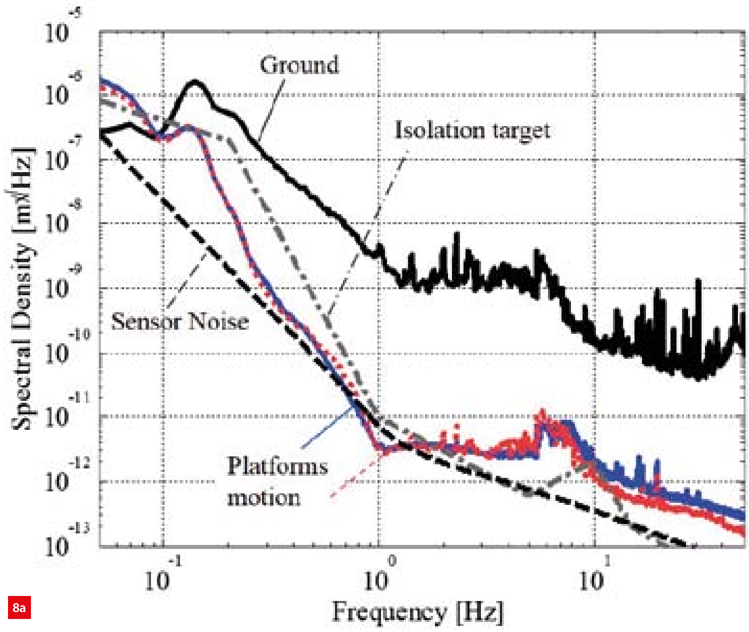
Figure 3 and 4 show the passive suspensions. These systems feature up to four stages of isolation, the bottom mass is the cavity optic. The surrounding welded frame supports the cantilever springs used to provide vertical isolation. Metal wires are used to suspend the stages, providing the horizontal isolation. For the core optics, silica wires are used to reduce the thermal noise within the observational frequency band [6]. Low-noise compact and collocated actuator-sensor pairs are used to provide light relative damping of the resonances. Vibration absorbers are used to damp the modes of the surrounding structure and reduce coupling with the active platform on which it is mounted.

Performance

Figure 8a shows an example of isolation results obtained with the two-stage active platforms. The black curve shows the input ground motion. The red and blue curves show the motion of two of the active platforms, which provide very similar isolation.

In Figure 8b the measurements of the six degrees of freedom of the active platform are combined to estimate the longitudinal motion at the input point of the suspension. In the red curve, this motion is combined with a model of the isolation provided by the suspension. Below 10 Hz, the residual motion is sufficiently low to lock the 4 km long interferometer. Above 10 Hz, the residual is sufficiently low to permit gravitational wave detection. As shown in this example, only light damping of the resonance is needed. The combined active and passive isolation permits bringing the optic motion under 10^{-19} m/√Hz above 10 Hz.

7 The vacuum-compatible single-stage active isolator. The bottom picture shows the sealed pod containing the inertial sensor, the magnetic actuator and the capacitive position sensors.



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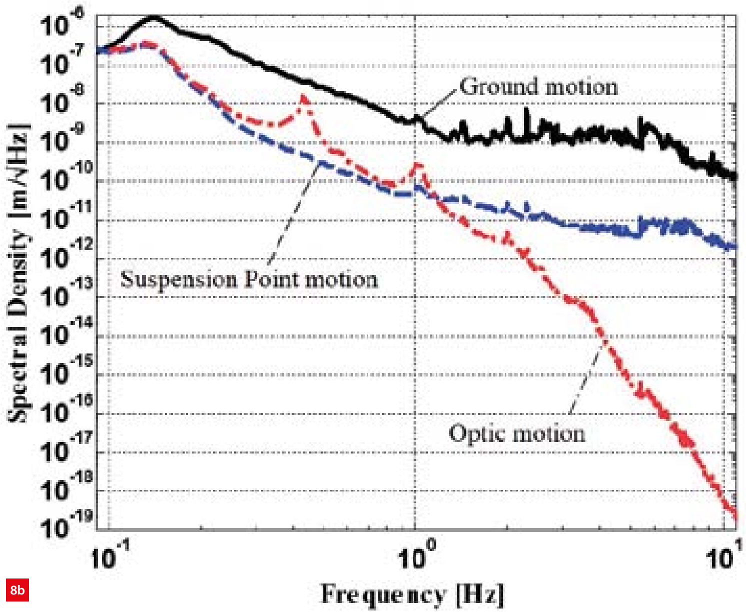

8b

Conclusion

The combined active-passive isolation approach developed for Advanced LIGO proved to be very effective. On each site, eleven active pre-isolators, five single-stage and five two-stage active isolators were constructed, installed and tuned, on budget and on schedule. All isolators perform at design sensitivity and robustly support the passive suspension holding the optics of the interferometers. The on-time schedule commissioning of both advanced LIGO detectors was possible due to the exceptional performance provided by the vibration isolation systems [7]. This achievement proved that not only these isolators provide remarkable isolation, but they also are engineered to sustain volume production and operational robustness required in other fields of research and precision engineering.

Acknowledgements

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This paper carries LIGO Document Number P1600103. ■

8 *Isolation performance.*
(a) Active isolation platform: the black curve shows the spectral density of the ground motion; the blue and red curves show the horizontal motion of the platforms supporting the intput test masses.
(b) Motion at the input (blue curve) and output points (red curve) of the suspension.

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Festo – technology partner in high-end electrical and pneumatical automation

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  - Front End
  - Back End
  - Flat Panel & Solar

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WITHOUT MONITORING, NO CONTROL

All smart systems need to go through monitoring, control and optimisation. Although optimising optical performance by controlling the adaptive optical elements is a well-known step in the process, adaptive elements alone cannot make systems smart. One major obstacle for smart systems is the first step in the overall process, namely monitoring. Monitoring is required to gather all the necessary information in order to control system performance. This article discusses two distinct applications – the human vision system and tissue imaging in microscopy – to illustrate this matter.

WOLFGANG SINGER

Adaptive optical elements have been available to buy and widely used for several years now. Examples range from lithography lenses with many adaptive elements, which compensate such things as the aberrations introduced by the thermal heating of the lenses, to auto-focus and active shock stabilisation in low-cost photo lenses.

Adaptive optical means are required for smart optical systems, which adapt their optical properties or behaviour depending on environmental changes or different requirements induced by the object to be imaged. This results in improved imaging performance, ensuring higher imaging contrast or larger penetration depths in tissue imaging, among other things.

However, the commercial breakthrough of adaptive optical systems has not happened yet for many applications. One reason for this is the lack of information about the status and the task – essential to be able to control the adaptive optical means. The distance of an object to 'smart eyeglasses' or the refractive index distribution of tissue are just two examples of this. Although there is a wide range of adaptive optical means available, the introduction of smart optical systems is often hindered by the most fundamental prerequisite of smart systems: monitoring and as such providing information about the status or task.

In general, monitoring capability is the fundamental requirement for smart products [1]. If a monitoring signal is available, control and optimisation seem to be relatively easy tasks. Autonomy is classified as the fourth decisive level of smart products. There is a huge number of technical devices with variable functions available, and optimisation strategies and algorithms do not seem to pose a challenge. However, without monitoring there is no control, no optimisation and no autonomy. One of the most frequent reasons a system isn't smart is because of the lack of monitoring that would provide the required status or task information as a basis for a control signal.

The problem isn't a lack of technical solutions for the monitoring task; in most cases, it's because the monitoring is either too slow, too costly or simply too inconvenient. It's often not technical limits that are the issue, but rather that the limits are more practical in nature. The following two examples will illustrate this.

First example: the eye

The eye is an example of a smart optical system, in terms of function; it monitors, controls, optimises and – in a certain sense – has autonomy. Of course, it is not connected in the same way smart products are, but nevertheless this example highlights the difficulty adaptive optical systems

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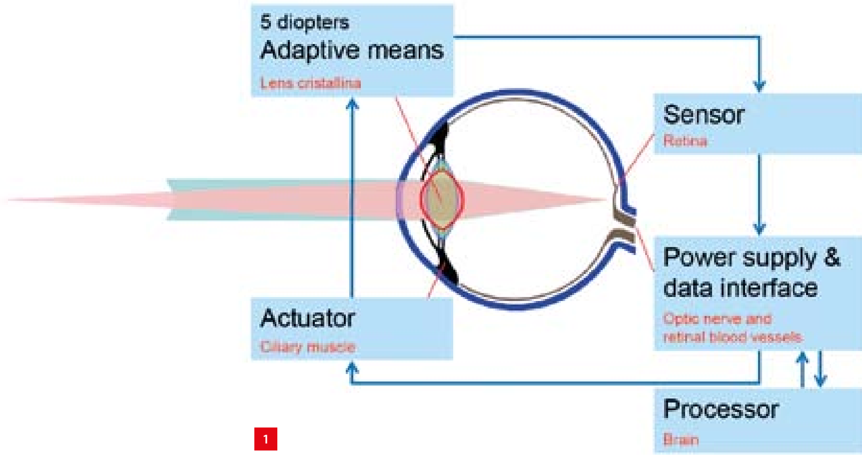

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are confronted with. We usually do not realise the power and action of our visual system and tend to expect a similar behaviour from technical systems. For instance, the autofocus function of modern digital cameras is often criticised because it is too slow and the camera focuses on the wrong detail in the imaging frame. A healthy human visual system has no problem with being able to do this.

According to the widely accepted Helmholtz theory, in the case of normal vision, the eye focuses by adjusting through deformation of the crystalline lens, actuated by the ciliary muscle. As such, the adaptive means is simply a deformable lens, deformed by a length-changing actuator. Although there may be other mechanisms involved in controlling accommodation, the information about proper focusing can be obtained in a direct feedback loop from the retina as sensor (see Figure 1) and the neural processing apparatus.

The difficulty arises when the crystalline lens loses its elasticity or develops scattering crystallites and cataractous opacification requires replacement of the crystalline lens. Although adaptive (accommodative) optical lenses will probably be available in many variations – such as deformable lenses or switchable lenses, liquid crystal devices or Alvarez plates – over the next few years, intraocular lenses (IOLs), which are currently available, do not allow focus control, the problem here being the lack of a reliable control signal. Control signal and power transmission would require head-mounted electrical devices.

Some work is being done to use the interpupillary distance (IPD) as a signal in this case. The IPD is linked to accommodation, because for near distances the eyes converge to manage the disparity mismatch between both eyes. The IPD changes 2-3° per diopter, so assuming an accuracy of 0.25 diopters as current glasses have, a measurement precision of approx. 0.2 mm is required.

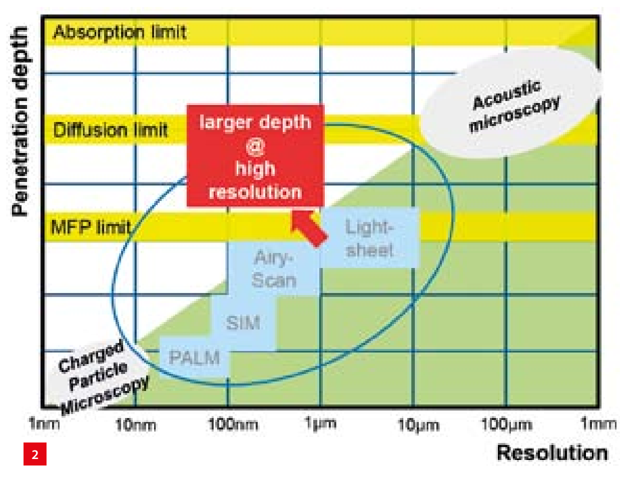
Measuring the IPD would require a head-mounted monitoring system, like the ones available in a head-mounted display.

Unless IOLs adhere to the ciliary muscle, they are very likely to remain static devices. The major problem is the lack of a control signal – or the monitoring capability. Even if power supply and actuation could be managed conveniently, the lack of a control signal is the largest obstacle for active IOLs or, in general, active glasses. Active IOLs or glasses should receive direct sensor information from the retina as well as information about what the user wants to see in focus. Currently, it is preferable to swap glasses that have different strengths.

Second example: tissue imaging

Tissue imaging is a challenge for optics. To examine the structure and function of biological tissue, microscopic imaging techniques are used. However, because tissue mostly has an unknown refractive index distribution that limits resolution and increases scattering inside the tissue, there is a limit to the penetration depth that can be achieved. Techniques to increase resolution in clear media are commercially available and various scientific publications have demonstrated the advantages of adaptive optical devices for deep tissue imaging.

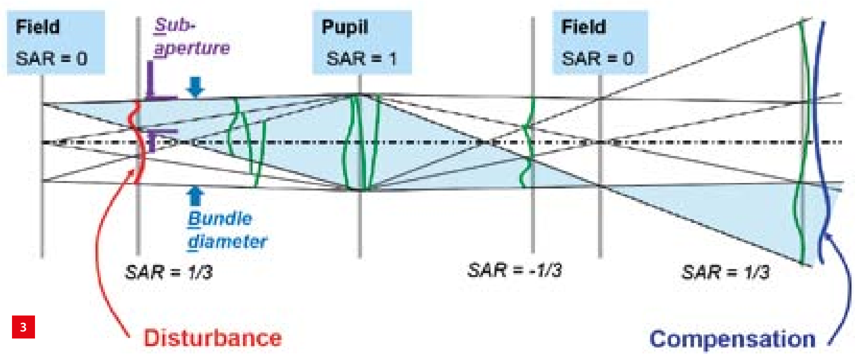
However, the strategies to increase penetration depth by adaptive optics still have a major problem, namely the ability to acquire enough information about the probe to generate a driving signal without destroying the probe. Living cells are sensitive to light, and the more aberrations are compensated, the more degrees of freedom (DoFs) of an adaptive optical element must be determined and the more measurements with light have to be made. Once again, it is the 'monitoring' capability that limits smart optical microscopes.



2

1 The 'smart' eye: the actuator – the ciliary muscle – drives the diopter adjustment of the imaging lens. Control and power supply is obtained by a 'sensor feedback loop'.

2 Resolution and penetration depth in tissue imaging. The MFP, diffusion and absorption limit are shown for optical imaging. The objective is to increase the penetration depth of high-resolution imaging.



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3 Sub-aperture ratios (SARs) at different planes or intersections in an imaging system. Disturbances introduced at a specific SAR value generate a specific field dependency of imaging aberrations, which can only be compensated at a conjugate plane of an identical SAR.

4 The challenge of wavefront compensation.
(a) The wavefront aberrations, generated at a plane of a specific SAR, deviate for different field points and are not identical at planes with a different SAR.
(b) Wavefront compensation with adaptive optics at a single plane is typically limited to either small areas or low-frequency disturbances

Before we discuss this limitation in more detail, it's worth looking at the problem: compensation of tissue-induced aberrations. If the sample is not clear, the resolution of tissue imaging is continuously degraded with penetration depth (see Figure 2). The highest resolution is only obtained using thin samples or surfaces. At a depth corresponding to the mean free path length (MFP), imaging resolution is degraded because, on average, each photon is diffracted at least once. At the diffusion limit, photons lose orientation completely. The MFP and diffusion limit typically increase with longer wavelengths or with acoustic waves instead of photons. A resolution below 1 µm, however, is only obtained with optical or particle microscopy. As such, the desire in tissue imaging is to increase penetration depth beyond the MFP limit, e.g. by adaptive compensation of the tissue-induced aberrations.

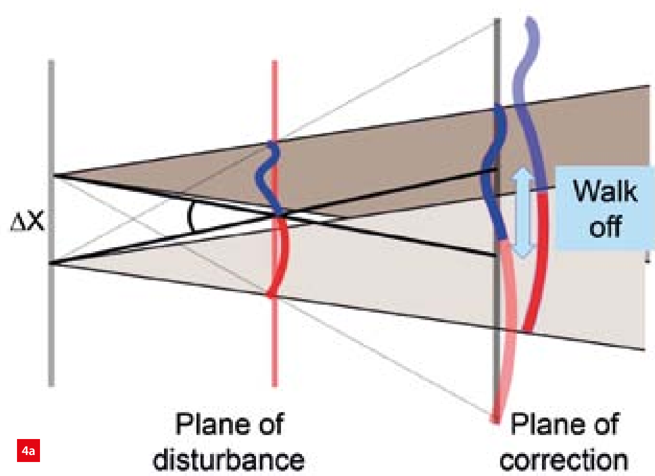
In general, the question of which aberrations can be compensated can be understood by analysing the sub-aperture ratios (SARs) of imaging optical systems (see Figure 3). At every surface, the ratio of an aperture bundle corresponding to an individual field point with respect to the clear aperture, defined by the total bundle of rays to all field points, gives the SAR. Any disturbance introduced at a plane with a specific SAR can only be compensated at an interface of identical SAR. Thus, with a single adaptive optical device, only aberrations introduced with an identical SAR can be compensated. Sometimes such geometry is called eggshell geometry with 'optical memory effect' [2].

Any efforts to correct disturbances with a different SAR, as addressed by the adaptive optical means, limit the imaging field of correction (see Figure 4). The wavefronts deviate for different field points, limiting the area of correction as well as the spatial frequencies of disturbances. Typically, only low-order Zernikes are corrected within a field size reduced by an order of magnitude [3].

Adaptive optics in the lens pupil and Corr Lenses

As an example, adaptive optical means located in a pupil plane with SAR = 1 are only capable of compensating field-invariant disturbances. As such, the compensation of tissue-induced aberrations should not be possible. There are, however, various examples demonstrating major improvements in imaging quality with adaptive optical elements at the lens pupil. How can this be?

There is one exception to the above-mentioned visual interpretation of field-variant disturbances. If the disturbance is identical for all field bundles, compensation in the pupil is possible (see Figure 5). In order to be field-invariant, the disturbances must be identical for all field bundles. For telecentric bundles, identical disturbances may only occur at planar interfaces. A deviation of the refractive index limited by a planar interface or a position variation of a planar interface will only cause defocusing and a field-invariant spherical aberration. A tilt of a planar interface may also introduce constant coma and astigmatism.



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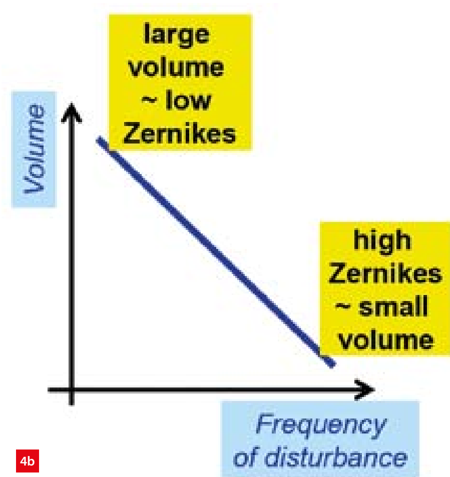

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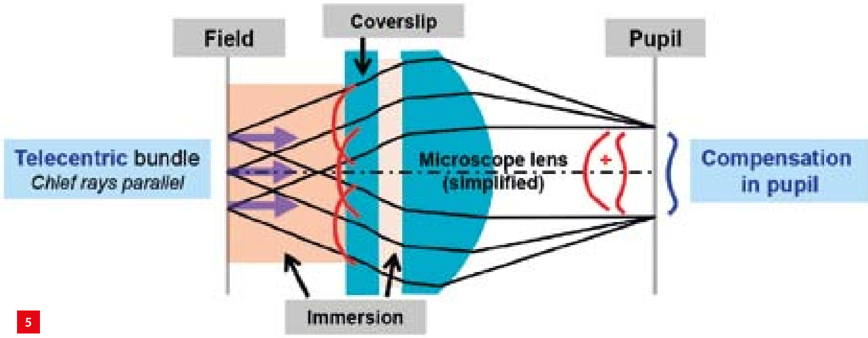
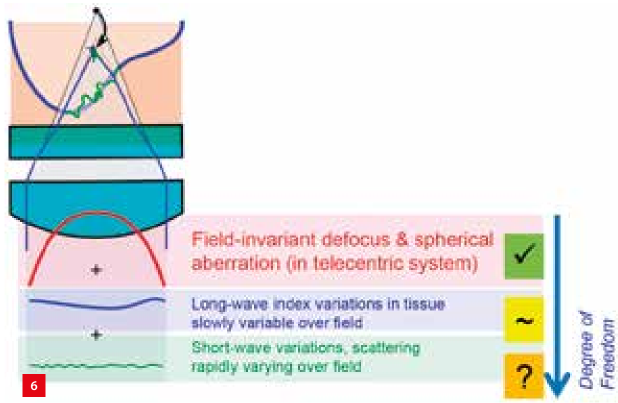




5 *Identical disturbances in telecentric bundles can be compensated at the lens pupil. For example, an improper refractive index change or the wrong position of a planar interface may introduce field-invariant aberrations which can be compensated in the pupil plane with SAR = 1.*

6 *With an increasing frequency of aberrations and increasing field size, the number of DoFs to be controlled increases. As such, a larger number of DoFs have to be determined by an increasing number of measurements.*

Thus, adaptive optical means such as deformable mirrors or spatial light modulators located in a pupil plane will predominantly serve to compensate field-invariant aberrations introduced by coverslips and refractive index deviations of immersion liquids.

Since the pupil of microscopic lenses is typically inaccessible, adaptive elements located in a pupil plane require a pupil relay. The more general elements in reflection also require a beam folding, thus introducing different types of parasitic aberrations. Furthermore, mirrors suffer from reflection losses. However, the correction of constant spherical aberration can also be achieved using specially designed lenses with movable elements, i.e. Corr Lenses [4]. Corr Lenses enable the adaption of the microscope lens to the imaging conditions depending on the cover glass thickness, the refractive index of immersion liquids or different temperatures. With manually adjustable lenses, the aberration optimisation can be done under visual control.

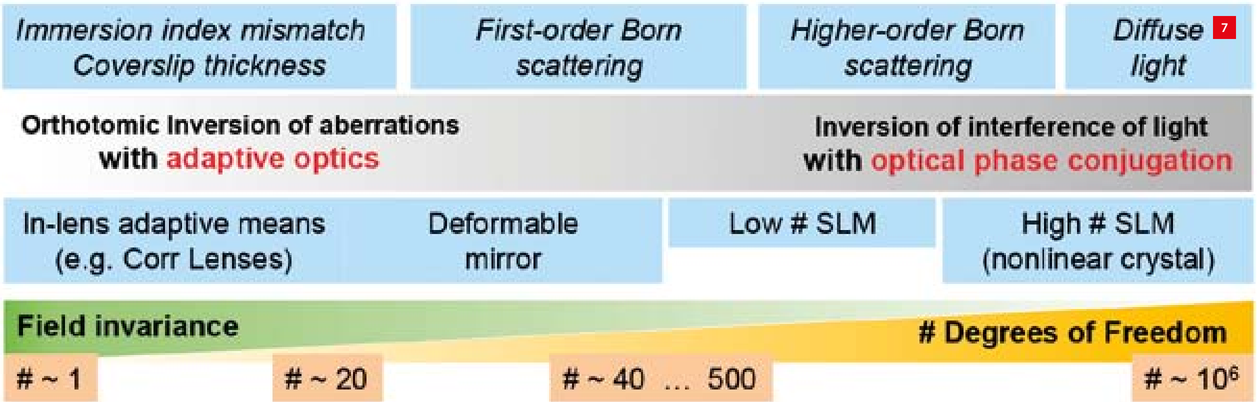
However, the number of aberrations induced by the coverslip or incorrect refractive index of the immersion liquid depends on the imaging depth [5]. While performing z-stacks within tissue, the amount of spherical aberration or coma, for instance, increases linearly in depth and as such compensation must be z-dependent. To address this, fast in-lens actuated lenses for the compensation of different aberrations, including higher orders, as introduced by index changes in immersion liquids or tissue, could be used. It is sufficient to measure these aberrations once in at least two planes in order to be able to extrapolate aberrations throughout the volume. A first ‘smart’ microscope could work with new lens designs with active lenses, which actively monitor and control aberrations introduced by coverslips and immersion liquids.

In terms of lithography lenses, it is well known that field-variant aberrations can also be compensated by in-lens actuators. In-lens actuators typically work by either axial or radial displacement or tilt of lenses. With these operations, the lowest order of aberrations following a double Zernike expansion of field-dependent pupil aberrations is introduced [6]. While this principle is well known in relation to the set-up and adjustment of lenses, it is also applied to active in-lens actuation in order to compensate or introduce specific amounts of these field-dependent aberrations of the lowest order.

The challenge to introduce these in-lens active manipulators in microscopy is, of course, the limited space and the cost structure of typical microscope lenses. Lithography lenses are about 20 times bigger than microscope lenses, allowing more space for mechanical guiding and actuation principles. However, since the effects scale with the wavelength, the precision requirements on a microscopy in-lens actuator are comparable to lithography lens actuation. The affordability of smart microscope in-lens actuation must compete with the price of more expensive coverslips and better control of immersion liquids.

Aberrations introduced by the index differences in tissue will most likely not be limited to one plane within the tissue. As illustrated above, only aberrations introduced in planes with a SAR identical to that of the compensator plane can be compensated for the whole imaging field. A compensation of aberrations in a volume however would require a volume compensator [7]. Although such a compensator might be technically possible, it would be very challenging. Therefore, in order to compensate tissue aberrations, the current approach is to restrict the object field to small fields of view [3]. As discussed above, there is a relationship between field patch size and the order of aberrations that can be compensated for one patch.

The real challenge of tissue imaging, however, is similar for both solutions: in order to compensate the many different field-dependent aberrations of tissue, the DoFs of the



7 *Simplified illustration of sources of aberrations, adaptive optics and optical phase conjugation.*

compensator must increase (see Figure 6). For each of the small patches of the object field, the local aberrations have to be determined individually, whereas for the volume compensator the information to control the compensator is required at once.

Figure 7 gives a simplified overview of sources of aberrations, the typical adaptive optical means and the DoFs involved. Geometrical aberrations of low spatial frequency, leading to reversible geometrical ray paths, can be compensated by geometrical optical means such as active lenses or deformable mirrors. Only the lowest orders, e.g. the lowest-order spherical aberration, are thereby field-invariant. Up to the first-order Born regime, light interaction in tissue is uniquely reversible – with an increasing number of DoFs. Especially in the higher-order scattering regimes, geometrical optical compensation fails and diffractive optical compensation elements with a large number of DoFs are then required. Perfectly diffuse light requires a number of DoFs comparable to the space bandwidth product of the optical system. As the number of DoFs increases, the field size of correction decreases.

The increasing spatial frequency of the aberrations introduced by tissue means there is a large number of DoFs for the compensator and each DoF has to be determined. This compensation again requires a major effort to obtain the required information to control the actuators, representing – in the nomenclature of Porter & Heppelmann [1] – the lowest step of monitoring. As long as there is no way to determine the probe disturbance, i.e. to perform the monitoring task with low probe load, the role of adaptive optics in tissue imaging will remain limited to the low orders or the aberrations introduced at the coverslip.

In conclusion

According to [1], monitoring capability is the fundamental requirement for smart products. Without monitoring, smart optical systems are not possible. In the above example of the visual system, only one DoF needs to be determined – the distance to the object within the 'focus' of the observer. Although it is technically possible to determine all technical parameters, smart eyeglasses would still require information about the wearer's intention. Therefore, such glasses do not currently seem feasible. The basis for smart optical systems, i.e. a monitoring capability, remains lacking.

There is a similar situation in terms of tissue microscopy. An autonomous correction of aberrations introduced by the coverslip and immersion with a low number of DoFs seems obvious for future smart microscopes. However, the challenge for tissue is the large number of DoFs of the introduced aberrations. Unless monitoring can be done without damaging the probes, smart tissue microscopes will continue to be limited to niche applications. Beyond this, real tissue aberrations will require either a volume compensator or a restriction to small imaging patches. ■

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UPCOMING **EVENTS**

25 May 2016, Eindhoven (NL)
Software-Centric Systems Conference
Conference devoted to complex software development, featuring software engineering trends, automatic testing, zero-defect software, dynamic reconfigurable software architectures, etc. The keynotes are on software development towards autonomous cars and software engineering in Ferrari F1.

SOFTWARECENTRICSYSTEMS.COM

[SC]²

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30 May - 3 June 2016, Nottingham (UK)
Euspen's 16th 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 precision engineering for aerospace and applications of precision in biological sciences.

WWW.EUSPEN.EU

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31 May - 2 June 2016, Stuttgart (DE)
Parts2clean 2016
International trade fair for industrial parts and surface cleaning.

WWW.PARTS2CLEAN.COM

1-2 June 2016, Veldhoven (NL)
Vision, Robotics & Mechatronics 2016 / Photonics 2016
Combination of two events organised by Mikrocentrum.

WWW.VISION-ROBOTICS.NL
WWW.PHOTONICS-EVENT.NL

14-16 June 2016, Erfurt (DE)
Rapid.Tech
International trade fair and users' conference on rapid technologies.

WWW.RAPIDTECH.DE

27-30 June 2016, Raleigh (NC, USA)
2016 Summer Topical Meeting
Meeting on the topic of dimensional accuracy and surface finish in additive manufacturing.

ASPE.NET

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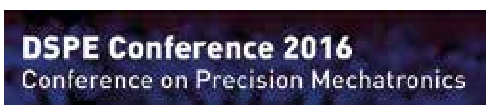
28 September 2016, Den Bosch (NL)
Bits&Chips Smart Systems 2016
Third edition of the annual event on embedded systems and software, focused on the development of networked technical information systems.

WWW.BC-SMARTSYSTEMS.NL

4-5 October 2016, Sint-Michielsgestel (NL)
DSPE Conference on Precision Mechatronics
Third edition of conference on precision mechatronics, organised by DSPE. The target group includes technologists, designers and architects in precision mechatronics, who are connected to DSPE, Brainport Industries, the mechatronics contact groups MCG/MSKE or selected companies or educational institutes. This year's theme is 'Farmers, Pioneers and Precision Engineers', inspired by the discussion about sustainable business and prosperity generated from precision engineering know-how and the role that (new) application areas play.

WWW.DSPE-CONFERENCE.NL



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12 October 2016, Bussum (NL)
14th National Cleanroom Day
Event for cleanroom technology users and suppliers in the fields of micro/nano electronics, healthcare, pharma and food, organised by the Dutch Contamination Control Society, VCCN.

WWW.VCCN.NL

23-28 October 2016, Portland (OR, USA)
31th ASPE Annual Meeting
Meeting of the American Society for Precision Engineering, introducing new concepts, processes, equipment, and products while highlighting recent advances in precision measurement, design, control, and fabrication.

ASPE.NET

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26 October 2016, London (UK)
The Future of Precision Engineering
The last outreach meeting of the EPSRC Centre in Ultra Precision. The activities over the past five years will be briefly reviewed and the majority of the event will focus on where precision and ultraprecision manufacturing is heading.

WWW.ULTRAPRECISION.ORG/NEWS/EVENTS

7-11 November 2016, Leiden (NL)
LiS Academy Summer School Manufacturability
Summer school targeted at young professional engineers with a limited knowledge of and experiences with manufacturing technologies and associated manufacturability aspects.

WWW.LISACADEMY.NL

16-17 November 2016, Veldhoven (NL)
Precision Fair 2015
Sixteenth edition of the Benelux premier trade fair and conference on precision engineering, organised by Mikrocentrum.

WWW.PRECISIEBEURS.NL

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30 November 2016, Utrecht (NL)
Dutch Industrial Suppliers & Customer Awards 2016
Event organised by Link Magazine, with awards for best knowledge supplier and best logistics supplier, and the Best Customer Award.

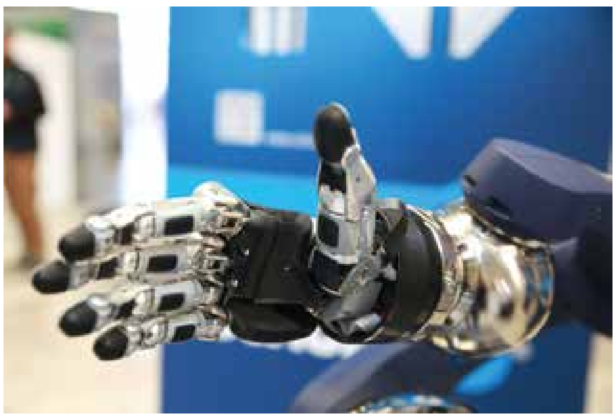
WWW.LINKMAGAZINE.NL

ROBOTS MATURE AND MOVING INTO SOCIETY

The theme of the 6th European Robotics Forum (ERF) was "Robotics for Europeans". This reflects the fact that robotics technology and industry are really maturing. In many of the event's workshops, advanced technology and market requirements were merged well. Academia and industry still speak different languages, but they try to understand each other and find common interests. Both stress subjects such as legislation, standardisation, robustness, modularity and user-centred design.

RINI ZWIKKER

This year the ERF was held in Ljubljana, Slovenia, from 21-23 March. With over 700 participants it was even larger than last year's event in Vienna [3]. Besides the general assembly meeting (Figure 1), there were eleven 1.5 hour time slots each with five parallel workshops. Some focused on specific EU-projects, others on funding, technologies or applications. A number were organised by euRobotics Topic Groups (see text box) to present their progress. Each workshop generally consisted of a series of short presentations, plus time for questions and discussion. In between the workshops and during the welcome reception and conference dinner, there was sufficient time for networking, or visiting the exhibition (Figure 2).



With this report, the author offers a selection of personal highlights and observations, focusing on four subjects: effects on society, user-centred design, knowledge transfer and robot ontologies.

Effects of robotics on society

Building on the 2016 theme "Robotics for Europeans", this subject was addressed by several speakers during the opening session plus panel discussion. Bernd Liepert, president of euRobotics (and chairman of KUKA) posed the questions: "What is pushing robotics?" and "What is the added value for the people?" Examples that he mentioned were elderly care and global warming. "We should focus on the use scenarios, then technology will follow."

Zoran Stančič, head of the EC representation in Slovenia, emphasised that it is not only a technical innovation but also a social one. Jasper Wesseling, manager of Innovation and Knowledge at the Dutch Ministry of Economic Affairs, stated that the highest impact of robotics would be on non-traditional sectors like agriculture and jurisdiction.

Mady Delvaux from the European Parliament acknowledged that legal barriers block opportunities, but that a legal framework is needed: "In Parliament, we are slow." And looking at the rest of the panel and audience she concluded that more women are needed in robotics: "We

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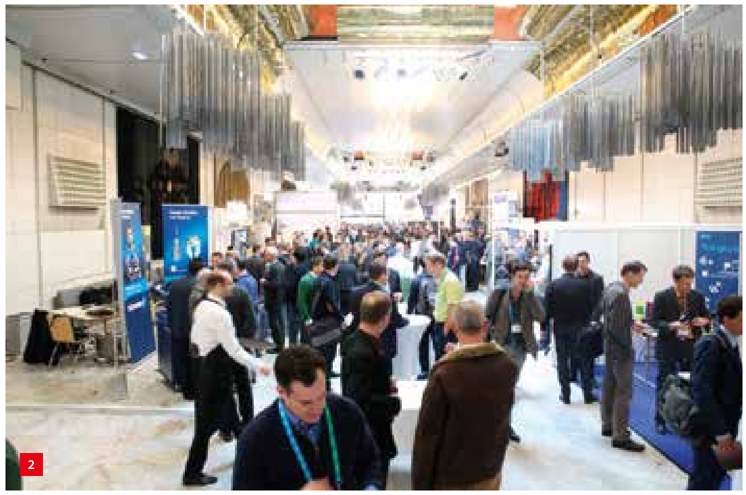

1 *Voting during the general assembly meeting of euRobotics. (All photos by Matic Bajželj)*
2 *Exhibition and meeting area at the Ljubljana convention centre.*

miss half the population." Markku Markkula, president of the European Committee of the Regions, gave an overview of many local initiatives for smart regions and cities, supported by EU projects.

User-centred design

The subject of user-centred design was not only addressed in the opening session, but also in a number of workshops. One was titled "Guidelines, methods and evaluation infrastructures for the market deployment of companion robots".

Professor Paolo Dario from the BioRobotics Institute of Scuola Superiore Sant'Anna in Pisa, Italy, gave an interesting overview of twenty years of testing robotic applications in real-life scenarios by his institute. Based on a study by the Japan Robotic Association, he sees a fast growing market for personal and service robots, calling it 'the new car industry' – if they add real value then people would be prepared to pay €10-20K for one.

In the recently completed European Framework Programme 7 (FP7) project 'Robot Era' [4], long-term experiments were carried out in a small town in Italy called Peccioli. Three different yet cooperating robots were used: Doro, Coro and Oro, and they provided indoor and outdoor services for the elderly. Professor Dario emphasised that these robots do not contain the most advanced technology, because the project aimed at developing standards to measure the acceptability. A quantitative 'system usability scale' was developed, but qualitative data was also collected. Overall, 95% of the 155 users were happy with the service of the robots in the three tested use scenarios.

Dominik Bösl from KUKA held a presentation about use case-based requirements engineering in robotics. He distinguished four robotic revolutions:
1. Robot-based automation solutions
2. Sensitive and safe robot-based automation solutions
3. Mobile, sensitive and safe robot-based automation solutions
4 Cognitive, mobile, sensitive and safe robot-based automation solutions

Robots will become more and more autonomous. To address and guide the ethical, juridical, social and political challenges, we will need robotic governance.

Bösl's colleague Tim Guhl presented the KUKA TecCamp initiative. It aims to let average citizens experience human-

euRobotics and SPARC

The European Robotics Forum (ERF) [1] is the annual meeting of EU Robotics AISBL [2]. This is a network organisation with members from academia and industry working together to develop and exchange knowledge on robotic technology and applications. It aims to bridge the well-known gap between academic research and the needs of both the robotic industry and the increasing diversity of sectors in society where robotic devices are used. There are currently 250 members and that number is steadily increasing. The ratio between academia and industry is shifting slightly towards academia, now at 7:3. A call was made at the ERF to attract more members from industry.

Together with the European Commission, the euRobotics Association has formed the public-private partnership SPARC. One of the aims of SPARC is to develop and implement a Strategic Research Agenda (SRA), leading to a Multi-Annual Roadmap (MAR). This MAR is referenced in the H2020 programme.

Thirty Topic Groups, formed by members from euRobotics, contribute to specific subjects of the SRA and MAR. They range from Agricultural Robots and Healthcare to Systems Engineering and Standardisation. The SRA, MAR and Topic Group list can be found on the website [2].

robot cooperation (HRC): how to introduce robots to 'John Smith'? The TecCamp may be used by companies interested in HRC as a platform for discussions with normal users, and for studies. KUKA wants to build these centres all over the world but financing must come from municipalities and other subsidy schemes.

Andrea Bertolini, a lawyer and researcher at the Institute of Law at the Scuola Superiore Sant'Anna, presented a legal analysis of robot companions. He distinguished five aspects. One of these raised the question if we can consider robot companions as products. He compared two situations: the robot's weak and strong autonomy. With weak autonomy, the robot is still a thing, which for a given situation follows the rules that are programmed in by its makers. Strong autonomy, however, entails from a philosophical point of view the ability to set one's goals and decide freely. This would justify treating the robot as a (physical) person, which has interesting legal consequences. Bertolini aims to define a fitting legal personhood for such robots. He has already contributed to the FP7 project RoboLaw [8], which was completed in 2014, giving some guidelines on regulating robotics as suggestions to the EC.

Knowledge transfer to SMEs

A workshop with some very interesting presentations was titled "Robotics for European SMEs in the context of Industry 4.0". Its main question was: how to bring innovations from large companies to SMEs?

Mariusz Baldyga, programme officer of Robotics at the EC, sketched the big picture. The three dimensions of digitisation are: innovations in products, transformations of processes, and changes in business models. The driving technologies are: the Internet of Things, big data, 3D printing and of course, robotics. But at the moment, only 2% of SMEs use these advanced digital technologies.

Jeremy Hadall represented the Manufacturing Technology Centre in Coventry, UK, a non-profit institute founded in 2010 by a group of research institutes. It appears to be very successful as it now employs 460 people, and has support from 85+ industry members. It supports SMEs by providing knowledge and resources, and can assist in accessing UK funds via the Catapult High Tech Manufacturing programme. With this, it can help to develop and build technology demonstrators for SMEs.

Ramez Awad from Fraunhofer IPA presented the very promising project ReApp: "Reusable Applications for flexible robot-based automation systems based on ROS-industrial". The aim of this project is to provide an app store for robotics, comparable to Google Play, to be used by both system integrators and software programmers. A workbench development environment is provided for composing apps in order to create solutions. ReApp is said to create all interfaces between the software modules. The project is now in its third year, and from this April, the first apps can be downloaded.

Björn Kahl from GPS presented the related project SME Robotics [5], with 25 partners from seven countries. Its aim is to strengthen the competiveness of SMEs in manufacturing by integrating aspects of cognitive systems. It does so by making the shift from explicit robot programming to skill-based instructions. These skills are combinable, executable modules containing encapsulated sensor/motor capabilities. Skills can be used to program a task, with a natural-language-coded task description. Another workshop focused entirely on this language-based programming using 'robot ontologies'.

Robot ontologies

The author of this report barely knew what an ontology was, but a sentence in the announcement of the workshop ("Making use of semantically meaningful information in robotics") aroused curiosity. Can we, as home users, program a robot by speech in the future? Well, not quite (yet): it still requires a formal language. An ontology in information science is a formal method for defining properties and relationships of entities in a particular domain. It is sometimes called the theory of categorisation. An example from nature is the taxonomy of flora and fauna.

The ontological approach is now applied to robot programming as well. There is much interest and research activity in this field. Programming a robot by using ontologies differs from the traditional way of writing new APIs for every specific action. With ontologies, only the task's goal is defined, and the robot itself will generate the actions needed to achieve that, using semantic information from data structures and/or the web.

Michael Beetz from the University of Bremen presented the openEASE project. He gave the simple example of the rotating action required to fasten a screw: the robot derives this itself from the information on Wikipedia for the lemma 'screw'.

ABB representative Mikael Hedelind described the prospects of ontologies in industrial robotics. In the FP7 project "Rosetta" [6], 'human-centric' technology for industrial robots was developed to enable programming in an intuitive and efficient manner, making it easier for them to adapt to new tasks, and cooperate with workers.

3 *A Robird is a remotely controlled robotic bird of prey, with the realistic appearance and weight of its living counterparts. Combined with other proven techniques, the Robird is the most effective way of bird control.*

4 *Prize winners: fourth and fifth from the left are Nico Nijenhuis (CFS) and Prof. Stefano Stramigioli (UT).*

However, there is still a trade-off to be made between robustness and task flexibility, compared to the traditional programming methods.

Jürgen Bock from KUKA took it one step further in the recently started (German Ministry funded) project ProDok 4.0, with the robot as a component in a cyber-physical production system. Industry 4.0 components communicate with each other autonomously, enabling self-description, self-configuration, self-optimisation, self-healing, self-x, ..., etc. One of the challenges in the project will be to agree on the reuse of existing vocabularies/ontologies. OPC UA appears to be the upcoming Industry 4.0 communication standard in this field.

Then, Nadia Ahmed from Karlsruhe Institute of Technology, Germany, presented the structure in which ontologies are used in the ReApp project. She distinguished four types of ontologies: domain, hardware, software and capability. Finally, Tamás Haidegger from Óbuda University, Hungary, made it clear that ontologies for robots will become a standard way of working – he is member of an IEEE Standards working group, defining Core Ontologies for Robotics & Automation (CORA) [7]. This is intended as a reference for knowledge representation and reasoning in robots, as well as for communicating knowledge between robots and humans.

Dutch success

The winner of the 2016 euRobotics Technology Transfer Award, seen as one of the ERF's most prominent activities, was the project "Robirds: from an idea to an animal-friendly revolution in bird control" (Figure 3). This started as a research activity in the Robotics and Mechatronics group at the University of Twente (UT). Now, it is a successful start-up company, Clear Flight Solutions (CFS) in Enschede. UT professor Stefano Stramigioli and Nico Nijenhuis from CFS were present to receive the prize (Figure 4).

Concluding remarks

ERF 2016 proved once again that there is a lot of activity in Europe within the field of robotics; this report could easily have been twice as long. The author also attended workshops on socially intelligent robotics, safety standardisation, cognitive robotics, wearable robotics and vision. And developments are moving fast. It is a challenging task for Dutch academia, applied sciences and industry to keep up with the pace on at least a number of these subjects, and convert knowledge into successful products before others do. ■

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EXPLORING THE 3D PRINTING OF METAL VACUUM SEALS

3D printing has been on the rise for some time now. Anything from plastic jewellery and car bodywork to biomaterial tissue and organs can now be printed, with industry experts continually learning about how to optimise materials, machinery, processes and procedures. The 3D printing of metal products for high-tech industrial applications remains quite the challenge however, with very demanding specifications in terms of accuracy, tolerances, surface finish, strength, etc. KMWE 3DP joined forces with Settels Savenije to build up experience in the 3D printing of metal vacuum seals.

ARNO GRAMSMA AND DORINE LAHEIJ

Research scope

The KMWE 3DP business unit is researching the additive manufacturing, popularly known as 3D printing, of metals (titanium and stainless steel) in collaboration with eight partners in the AddLab consortium. AddLab (www.addlab.com) is the first 3D printing pilot factory for the production of industrial metal parts in Eindhoven, and it is here that KMWE works on manufacturing-for-design, parameter optimisation, support strategy, material research and integration with existing technologies to make world-class additively manufactured parts.

The Research & Feasibility team of Settels Savenije's development department took part in AddLab's Design Challenge 2015 with a self-sealing vacuum seal designed for reducing construction space in high-tech vacuum systems for semicon-related and process industries.

After meeting during the Design Challenge finals, KMWE 3DP and Settels started working together to bring this design to market. KMWE is eager to learn about printing industrial products in stainless steel and titanium, while Settels is exploring the opportunities to issue a new standard for vacuum seals.

To kick off the research, a print job was built using the original seal design, printed in an upright position and supported by a so-called tree structure. This position was chosen to minimise the total amount of supports and material required. Reducing the machining effort for

1 *Single seal printed in an upright position supported by the so-called tree structures. In the back, the same seal can be seen printed with full supports. For this last type of support, note the undesirable amount of printing powder that remains after cleaning.*

AUTHORS' NOTE

Arno Gramsma is a director at KMWE 3DP, based in Eindhoven, the Netherlands, and Dorine Laheij is a technical consultant at Settels Savenije, also in Eindhoven. The authors acknowledge contributions by Pim van der Weijden, a trainee at Fontys University of Applied Sciences, Eindhoven, and Piet van Rens, a senior technical consultant at Wienes Product Development in Asten, the Netherlands.

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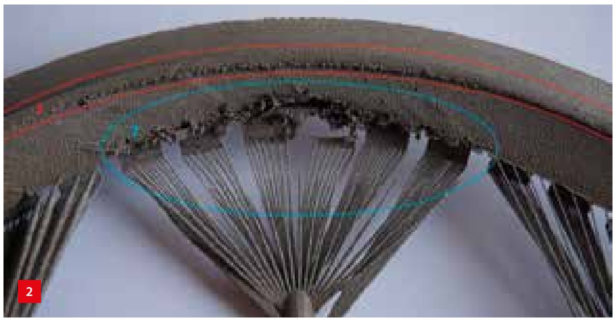
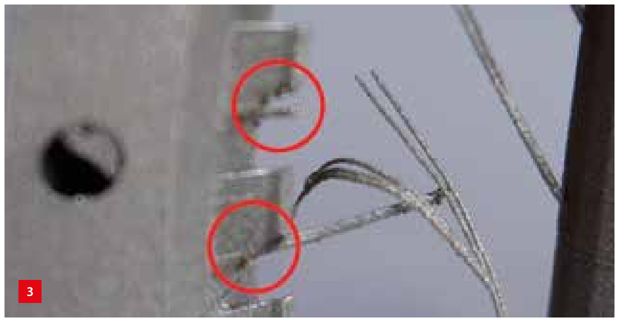




2 *The marked surfaces illustrate the effect of printing small surfaces without support.*
3 *Clamp fingers with defects due to a (3D-printing-specific) mismatch of length-to-width ratio.*
4 *Result of the second print job, with optimised support structures and adjusted seal design.*

removing the structures is an added benefit. Figure 1 shows the single seal on the printer after the 3D printing process has finished and most of the printing powder has been removed.

The prototypes made during this first print job demonstrate the difficulty of printing this design and the bad manufacturing because of the choice of support structures (see Figure 1). The following observations can be made.
A full structure support leads to:
1. Printing powder remaining in the structure.
2. A lot of post-processing time needed to remove structures and clean up the part.

A tree structure leads to:
1. A rough surface finish because of the absence of support structures (see area marked 1 (red) in Figure 2) or support structures that are too fragile (see area marked 2 (blue) in Figure 2). A low thermal conductivity in these areas causes the surfaces to erode.
2. Fragile branches in the tree structure which have unfortunately snapped (see Figure 3).

Partners: KMWE and Settels Savenije

KMWE / DutchAero is a Dutch company based in Eindhoven, operating as both a supplier to and partner for the high-tech equipment industry and aerospace sector. The company specialises in high-mix, low-volume, high-complexity machining. It develops and delivers a wide range of complex, function-critical components and high-quality (cleanroom) assembled mechatronic modules and systems to meet the demands of customers in the medical, semiconductor, aerospace and industrial automation sectors.

Settels Savenije is a group of companies that combines high-level technology with a passion for people. The group invents, designs, manufactures, assembles and tests high-tech products, modules, tools and equipment. Their international customers serve the display, semiconductor, medical, aerospace and sensor markets.

www.kmwe.com
www.sttls.com

Redesign of support structures

The vacuum seal design was optimised for 3D printing using the lessons learned from the first print job. The following principles were applied for this new design:
1. The product is placed at an angle of 5° off the normal (upright) orientation with respect to the baseplate to avoid having to use vertical supports.
2. Perforations are incorporated into the support structures, so the structures can be removed easily.
3. The support strategy changed from tree supports to reinforced supports, as these can be removed more easily (post-processing). Changing from a closed to an open support structure means less material is needed.

During a discussion with the seal's designers, it was decided to also optimise the seal design itself for printing. When a hole is required, most mechanical engineers will almost subconsciously choose a circular shape, as this can be easily made by machining on a lathe or a milling machine. Different rules apply for 3D printing however. A vertical printed circular hole requires a support structure, while a cat eye hole does not. As such, a cat eye hole is cheaper and quicker to create using 3D printing than conventional machining. Other concessions were made by reducing the amount of features, while still applying the learnings, e.g.

reducing the number of 'clamp fingers' (see Figure 3). This new support strategy combined with an adjusted seal design provided the basis for optimising the vacuum seal. The result of this print job can be seen in Figure 4.

This second print job provided additional lessons on 3D printing practice. Despite the new support structures, there were still some areas with a rough surface (see the marked areas in Figure 4). The reinforced support could be easily removed with the help of the perforations. There were a sufficient number of perforations and no further optimisation was required.

Another point that needed addressing was the discolouring of the material. At certain heights, the material seemed corroded. After investigating the complete print job, it became clear that the printing speed and breaks in the printing process were what caused this. Finally, it should be noted that supporting structures were still found in the cat eye holes, so the height-to-width ratio had to be optimised.

Redesign phase 2

To prevent the rough surface on the top of the seal, the outer radius was thickened. To further reduce the amount of support structure, a suggestion was made to nest seals with different sizes in one print job. The structure needed in the inner diameter was optimised to further reduce the amount of material required for the support structure (see Figure 5).

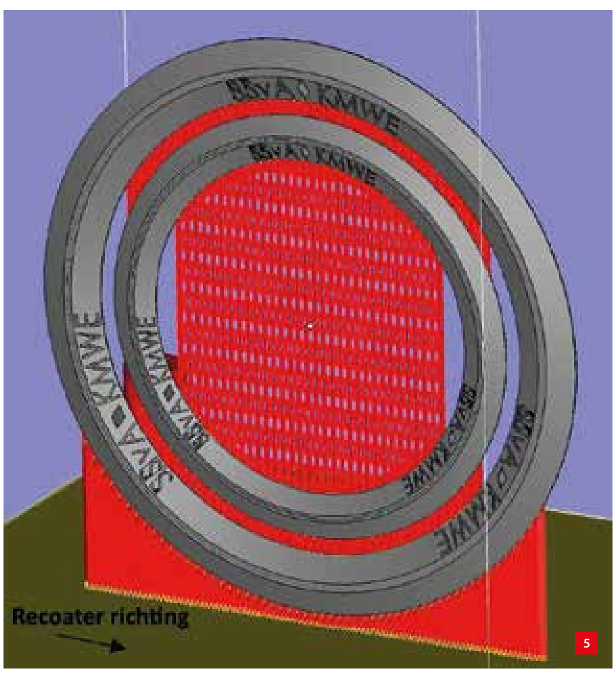
Evaluation of the results

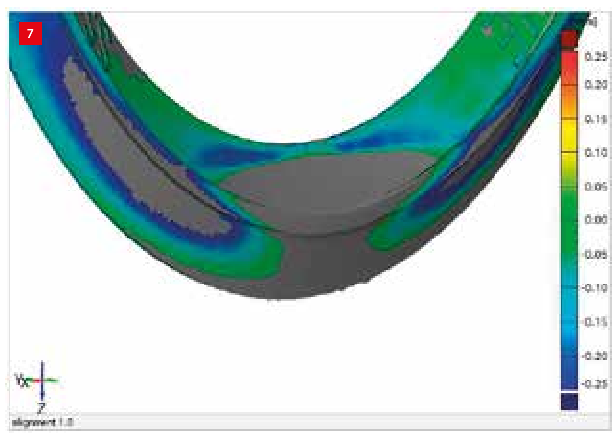
The initial appearance of the seal was very satisfying, as the surface looked smooth and clean. On closer inspection, however, it was clear that other issues would need addressing:

1. There was some deformation on the bottom of both seals (see the area marked in blue in Figure 6, and Figure 7). A cause could not be determined immediately, although shrinkage of the material was suspected. After analysing the print job, the new slicer and its new parameters were found to be the cause. Slicer software is normally used to partition the product in thin layers that are printed sequentially.
2. Discolouring (see the areas marked in green in Figure 6) occurred in two places for two different reasons. The discolouring at the bottom appears at the level where all other parts in the print job were finished. We suspect that the heat supply increased on the seal at this level. The discolouring at the top was probably caused by a break during the printing process.
3. The support has separated from the seal due to thermal stress (see Figure 8). As such, the support should be optimised and reinforced (see marked area).

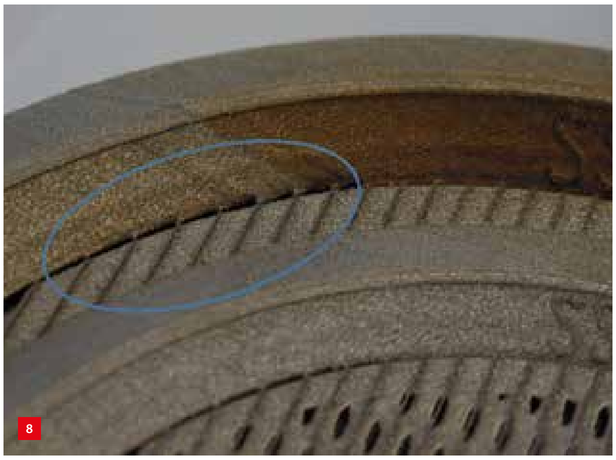
Final results

After 3D printing most parts require post-processing. The types of support used for this seal can be easily removed and polished with a handheld tool. Figure 9 shows some final results.





6 *Result of the third print job.*
7 *Measurement data (using the CAD model as a reference) showing the deformation of the lower side of the seal.*
5 *CAD design of the third print job.*



8 *Detail of the third print job: supports (at the bottom) loosened from the seal (shown in the marked areas) due to thermal stress, which in turn further hampers optimal thermal conditioning.*
9 *Final results of the research carried out on the seal.*

Settels Savenije is very happy with the progress made. The surface quality and overall finishing of the final products is currently at a level that the products can be tested on mechanical performance. A company that will apply a vacuum-compatible elastomer layer on the seal has been contacted and preparations are being made for vacuum testing. Further research has to be done on the internal stiffness of a seal made from this printed material. The tensile strength and other material properties of printed materials differ from those of traditional machined material, so tests and calculations have to be done.

KMWE learned that design and manufacturing have to work more closely together to create world-class additively manufactured parts. The orientation of the parts, parameter selection and support strategy have to be reviewed by the designers and engineers together to achieve the required quality of the product. Traditional manufacturing does not require such intense cooperation, since conventional technologies are common knowledge and have been further developed.

Settels and KMWE continue to work together on improving the 3D printing of metal vacuum seals. ■

IMPRESSIONS FROM KUALA LUMPUR

The International Congress on Design Engineering and Science (ICDES) 2016 was held on 27-29 February at the University of Malaya in Kuala Lumpur, Malaysia. The event provided the ideal opportunity to share opinions on technical matters, network and, last but not least, enjoy an all too short stay in a different culture.

JOS GUNSING

AUTHOR'S NOTE

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ICDES 2016 was organised by the Hong Kong Society of Mechanical Engineers. The idea of ICDES conferences is for scientists, scholars, engineers and students from around the world to present ongoing research activities, and thereby foster research relationships between universities and industry.

My overall view of the congress is that a very wide range of subjects was presented within the field of engineering and design. It was not a specialist, dedicated congress, which I usually prefer. There was a limited number of delegates, with almost everyone giving a presentation. Most of the presentations were very specialised, typically part of Ph.D. work. What also struck me is that many of the presentations did not have any experimental results or share any views on the set-up of an experiment; they mainly focussed on analytical matters.

Topics ranged from mathematical design optimisation processes (both for airplanes as well as for the construction of cranes or bridges) and plant organisation based on the behaviour of ants to corrosion measurement & prediction for off- and onshore pipelines and predicting the performance of PCB-based antenna shapes. In my view, the most interesting topics came from the Okayama University of Science in Japan. Delegates from this university presented on interesting pneumatic actuators for a pipe inspection robot and also a wrist mechanism for a rehabilitation robot.

1 *ICDES 2016 delegates. (Photo by Lyn Lee)*

Several professors gave informative systems-oriented presentations, providing an overview of their research work. Prof. Ruxu Du of the Chinese University of Hong Kong reviewed both theoretical and experimental studies related to systems design/under-actuated flexible wire-driven robot arms. He gave indications for several potential applications and spent a lot of time talking about a robot fish development based on the aforementioned principles. The wire-driven robot fish has an 80% efficiency in terms of converting electrical energy to hydraulic propulsion energy, which is high and cannot be derived with propeller-type drive mechanisms.

Prof. Cees de Bont (of the Hong Kong Polytechnic University since 2011, but formerly of Philips and Delft University of Technology) presented an overview of the evolution in industrial design thinking over the past 30 years:

Design	functional aesthetics, ergonomics
Experience	interface, feelings & emotions
Strategy	design thinking, design-driven innovation
Exploration	innovation & selection, collaborative design, stakeholder engagement

Given the breadth of the engineering & design field, this type of evolution is very much in line with the multidisciplinary thinking which is so integral to systems engineering nowadays (e.g. CAFCR model, Prof. Gerrit Muller).

The presentation given by Prof. Lucienne Blessing (only recently of the Singapore University of Technology and Design, but previously of the University of Luxemburg) was very much aimed at university-industry partnerships. The research conducted in such partnerships should be inquisitive, methodical, communicable and purposeful.

Prof. Jan Detand of Ghent University in Belgium also talked about industrial design projects in collaboration with industry, with a lot of emphasis on what he called ‘transdisciplinary’ research and innovation. In these projects, design thinking, creativity and prototyping are being combined in order to present all stakeholders with a product design and promote interaction at an early stage of the process.

University of Technology of Malaysia (UTM) professor Mohd Hamdi Bin Abd Shukor gave a lecture on spot welding of PET and aluminium. A lot of work has gone into modelling an experiment with the material and process parameters, especially looking at bubble formation during the spot welding process, since the bubbles may potentially cause cracks which affect fatigue strength. Prof. Mohd Nasit Tamin, also from UTM, focussed on such things as brazing processes and the properties of connection. Optimisation possibilities directed towards better mechanical (fatigue) properties have been investigated.

2 *Prof. Ruxu Du lecturing on wire-driven mechanisms. (Photo by Lyn Lee)*

Dr Mojtaba Ahmadi of Carleton University in Canada gave a presentation on his work in care robotics. He, of course, emphasised the combination of human-centred design, safety, dealing with uncertainties, ethics and certification. His most successful project is a robot development that helps patients get up out of bed and supports their recovery after knee or hip operations for instance.

An overview of papers will be available online in due course. The next ICDES conference may be hosted by Ghent University next year. ■

Impression of Kuala Lumpur

Kuala Lumpur is a melting pot of cultures, but unfortunately the city has some problems because of legally enforced inequalities between ethnic groups. Although there is a wide range of prosperity in Kuala Lumpur, there is no visible extreme poverty. Must-see places include the Petronas Towers, the old town, Chinatown and Little India. It’s striking that there are no bikes on the streets of the relatively flat Kuala Lumpur, but thankfully public transport is good.

3 *Giant opposites meet. (Photos by Jos Gunsing)*
(a) The Batu Caves with the statue of Hindu god Murugan.
(b) One of the Petronas Towers (viewed from the other tower). These towers were the tallest buildings in the world from 1998 to 2004.

INFORMATION
WWW.ICDES.ORG

CPE COURSE CALENDAR

The DSPE Certification Program has been incorporated in ECP², the European Certified Precision Engineering Course Program. See ecp2eu.wpengine.com

COURSE (content partner)	CPE points	Provider	Starting date (location, if not Eindhoven)
BASIC			
Mechatronics System Design - part 1 (MA)	5	HTI	6 June 2016
Mechatronics System Design - part 2 (MA)	5	HTI	31 October 2016
Design Principles	3	MC	26 September 2016
System Architecting (Sioux)	5	HTI	20 June 2016
Design Principles Basic (SSvA)	5	HTI	to be planned
Motion Control Tuning (MA)	6	HTI	15 June 2016
DEEPENING			
Metrology and Calibration of Mechatronic Systems (MA)	3	HTI	22 November 2016
Actuation and Power Electronics (MA)	3	HTI	11 October 2016
Thermal Effects in Mechatronic Systems (MA)	3	HTI	28 November 2016
Summer school Opto-Mechatronics (DSPE/MA)	5	HTI	4 July 2016
Dynamics and Modelling (MA)	3	HTI	12 December 2016
Summer School Manufacturability	5	LiS	7 November 2016
SPECIFIC			
Applied Optics (T2Prof)	6.5	HTI	to be planned
Applied Optics	6.5	MC	15 September 2016
Machine Vision for Mechatronic Systems (MA)	2	HTI	23 June 2016
Electronics for Non-Electronic Engineers – Basics Electricity and Analog Electronics (T2Prof)	6	HTI	to be planned
Electronics for Non-Electronic Engineers – Basics Digital Electronics (T2Prof)	4	HTI	5 September 2016
Modern Optics for Optical Designers (T2Prof)	10	HTI	9 September 2016
Tribology	4	MC	1 November 2016 (Utrecht) 4 March 2017
Design Principles for Ultra Clean Vacuum Applications (SSvA)	4	HTI	3 October 2016
Experimental Techniques in Mechatronics (MA)	3	HTI	28 June 2016
Advanced Motion Control (MA)	5	HTI	7 November 2016
Advanced Feedforward Control (MA)	2	HTI	14 November 2016
Advanced Mechatronic System Design (MA)	6	HTI	to be planned
Finite Element Method	5	ENG	in-company only
Design for Manufacturing – Design Decision Method	3	SCHOUT	in-company

DSPE Certification Program

Precision engineers with a Bachelor's or Master's degree and with 2-10 years of work experience can earn certification points by following selected courses. Once participants have earned a total of 45 points (one point per course day) within a period of five years, they will be certified. The CPE certificate (Certified Precision Engineer) is an industrial standard for professional recognition and acknowledgement of precision engineering-related knowledge and skills. The certificate holder's details will be entered into the international Register of Certified Precision Engineers.

WWW.DSPE.NL/EDUCATION/LIST-OF-CERTIFIED-COURSES

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

Content partners

- Dutch Society for Precision Engineering (DSPE)
  WWW.DSPE.NL
- Mechatronics Academy (MA)
  WWW.MECHATRONICS-ACADEMY.NL
- Settels Savenije van Amelsvoort (SSvA)
  WWW.STTLS.NL
- Sioux
  WWW.SIOUX.EU
- Technical Training for Professionals (T2Prof)
  WWW.T2PROF.NL

COMBINED YPN VISIT TO MAXON MOTOR AND BIOMASS TECHNOLOGY GROUP

On the 16th of February, DSPE's Young Precision Network paid a combined visit to maxon motor, known for its DC motors and high-precision drives and systems, and Biomass Technology Group (BTG), specialist in the conversion of biomass into useful fuels.

After a warm welcome in the new building of maxon motor in Enschede, the Netherlands, Steven van Roon from maxon gave an introduction. Maxon motor is known for its precise and reliable electrical motors, gearboxes, sensors and control systems. This combined knowledge qualifies maxon as a premier supplier of precision drivetrain systems. As it turns out, three quarters of all maxon's products are specials. This seems to be its strength; maxon is in the transition from being a general motor supplier to becoming a specialist with the know-how of designing custom motor solutions.

Steven van Roon discussed the Very Large Telescope (VLT) laser guide star optical tube assembly project, in which maxon motor assisted TNO with a custom solution. After his introduction, the YPN party was offered a tour past the assembly line, clean room, debugging line and logistics department.

BTG's CEO René Venendaal gave an inspiring presentation about BTG and its sustainable pyrolysis process, which is an (almost) self-supporting process to convert biomass into useful fuels and energy in seconds instead of millions of years. In the future it can contribute to a more sustainable energy supply for our 'energy-sick' world. The company is a pioneer and has to solve a lot of problems in the process, resulting in new ideas, solutions, patents and spin-offs.

Impression of the YPN visit to maxon motor.

After the presentation, René Venendaal gave a tour through their testing facilities, where they test and improve the pyrolysis process on a small scale. Although they are still piloting it and expect it to be fully operational in a few years, they are already researching the use of crude pyrolysis oil in diesel engines. The main problem is the oil's acidic properties. BTG showed a modified one-cylinder diesel engine with custom-made parts (such as injector nozzles with 0.2 mm precision holes) made from stainless steel and exotic materials. New experiments are planned for a four-cylinder diesel engine.

YPN would like to thank maxon motor and BTG for organising the visit and their inspiring talks.

WWW.MAXONMOTOR.NL
WWW.BTGWORLD.COM

Thank you, Twin Media

For over fifteen years Twin Media, the full-service graphical and editorial consultancy from Culemborg, the Netherlands, has taken care of the publication of Mikroniek. Throughout this period, Mikroniek has developed into a magazine with an international audience and an up-to-date high-tech appeal. Twin Media has made an important contribution to this feat.
With a view of streamlining its business, DSPE, Mikroniek's publisher, has decided to allocate the realisation of the Mikroniek publication, in addition to all the society's printing jobs, to Drukkerij Snep in Eindhoven, the 'hometown' of Dutch precision engineering. On behalf of the DSPE board and the Mikroniek team, we would like to express our gratitude to Twin Media for their professional efforts.

Hans van Eerden, editor Mikroniek
Hans Krikhaar, president DSPE

ALIVE AND KICKING: OPTO-MECHATRONICS SUMMER SCHOOL

The Opto-Mechatronics Summer School is the place to be in the first week of July this year for anyone working in the field of precision engineering who wants to develop/ enhance their professional knowledge. Experts will share their expertise of designing opto-mechatronic instruments that are actively controlled and operate in a non-perfect environment. Typically, these systems include semiconductor equipment, metrology systems, microscopes, printers, space instruments and high-tech production equipment.

■ The summer school is targeted at engineers working at an academic level with a background in physics, mechanics, electrical or control engineering, who feel they have reached the limits of their discipline and want to learn more about designing a complete opto-mechatronic system.

Summer school Opto-Mechatronics

Precision Technology

The summer school provides a system overview and core disciplines are introduced through case studies. Hands-on training is provided by leading Dutch professors and scientists in the field of precision engineering working at Delft University of Technology, Eindhoven University of Technology (TU/e), ASML, TNO, Philips, ESO (European Southern Observatory) and Mechatronics Academy.

The 5-day programme comprises:

1. Systems engineering & basic modelling
   The focus is on the systems engineering side of product development, and the optical delay line of ESO's Very Large Telescope (VLT) is the subject of a case study.
2. Optical design
   An overview of the optical aspects of the delay line is followed by an introduction to optical design approaches. Practical work includes the optical design program Zemax.
3. Control design
   A tutorial will be delivered on the principles and methods of motion control, focusing on the typical control challenges of a delay line, which can be seen as a linear motion system: servo behaviour, vibration disturbance rejection, sensor noise and closed-loop stability.
4. Opto-mechanical design
   High-quality mechanics will guarantee best performance in terms of optical quality/ stability and control performance. As such, lightweight and stiff structures are crucial in achieving this goal. The design of the existing ESO delay line will be used to explain the requirements for such a structure.
5. Actuation, sensing & dynamics
   The essential aspects of realising high-performance active positioning and control systems for optics will be presented. To conclude, performance-determining mechanical system dynamics and vibration isolation will be covered, briefly touching upon the new field of adaptive optics.

■ ESO's VLT optical delay line. (Photo courtesy of Fred Kamphues/TNO)

The evening programme includes social activities and presentations bij representatives from ESO (on experiences with the VLT) and ASML (systems engineering and wafer steppers).

Organised by DSPE and the High Tech Institute, this year's Opto-Mechatronics Summer School will take place 4-8 July 2016 at the TNO premises on the TU/e campus in Eindhoven, the Netherlands. Registration closes on 1 June 2016 or once there are 40 registrations, whichever is first.

WWW.DSPE.NL/EDUCATION/SUMMER-SCHOOL-OPTO-MECHATRONICS

ECP² PREMIERE IN TAIWAN

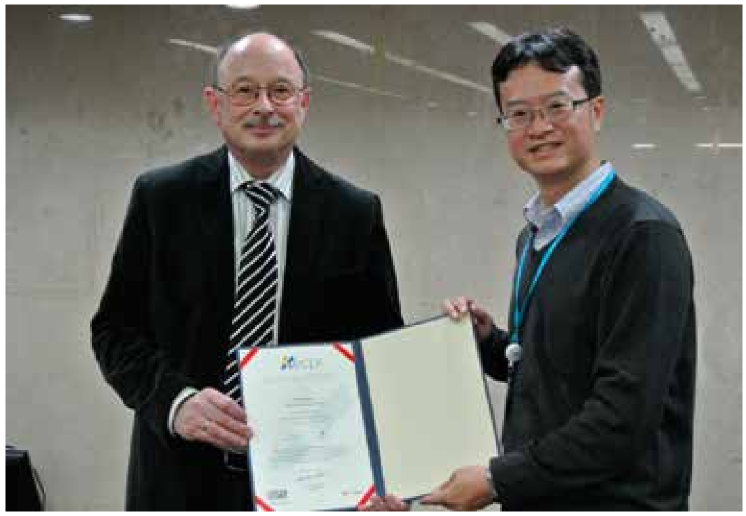
Last month, Jan van Eijk, Rob Munnig Schmidt and Adrian Rankers travelled to ITRI (Industrial Technology Research Institute) in Taiwan to deliver the Mechatronic System Design training, provided by Mechatronics Academy through The High Tech Institute (see also page 38). ITRI (more than 5,000 employees) was founded in 1973 and opened a Netherlands office in 2013, at the High Tech Campus in Eindhoven, to expand its network to Dutch high-tech companies.

The initiative to bring the well-known training from the Eindhoven region to Taiwan was taken by Prof. Shuo-Hung Chang, former executive vice president of ITRI, professor at National Taiwan University and co-founder of TSPE (Taiwan Society for Precision Engineering). After a meeting with DSPE president Hans Krikhaar and Adrian Rankers in 2013, Prof. Chang was convinced that large multi-disciplinary teams can only be successful on a system level if team members combine three elements:
- excellence in their own discipline;
- basic understanding of adjacent disciplines;
- cooperative attitude and skills.

The two-week training took place from 18-29 January 2016 at ITRI College in Hsinchu. The sixteen participants varied in age, experience and technical background, ranging from mechanical, electrical and materials engineering to computer science. Most of them were ITRI employees, one participant came from the Textile Institute and three assistant/associate professors from universities also attended.

Initially, the interaction was limited, partly due to the language barrier. Also, our typical Dutch approach to making complex matters as simple as possible, to estimate order of magnitudes and to 'bend' numbers to make the calculation easier (e.g. $0.25 \cdot 6^2 = 0.25 \cdot 40 = 10$) needed some adaptation. However, the ice was broken by the 'Humanware' module, dealing with the most complex aspect in a development project, being the 'humans', and focussing on essential soft skills like the 'art of active listening' and 'giving feedback'. The group recognised the difficulty and the importance of cooperation, but indicated that they had previously never spent any time on this topic. Overall, the focus on the essential basics of each discipline in a systems context, the combination of theory and practice, the abundance of exercises and industrial cases, and the attention paid to soft skills, was much appreciated.

At the end of 2015, euspen and DSPE launched the new combined certification program for precision engineering post-graduate education, called ECP², as the European successor to DSPE's Certified Precision Engineer program. The participants of the Mechatronic System Design course were the first to receive the new combined euspen/DSPE certificate.



Participant Hsiang-Hung Chang receiving the euspen/DSPE ECP² certificate from Prof. Rob Munnig Schmidt.

ECP2EU.WPENGINE.COM
WWW.ITRI.ORG/ENG

Martin van den Brink Award gala dinner

On 26 May 2016, during the Dutch Technology Week in the Evoluon in Eindhoven, the Netherlands, the Martin van den Brink Award gala dinner will be held. Prominent representatives from the high-tech industry will attend. Members of DSPE and Brainport Industries are participating as a partner and have reserved tables at cost-price, to entertain their business relations in the particular Evoluon ambiance. During this event, the Martin van den Brink Award, for the best system architect in precision engineering, will be handed out for the second time.

INFO@DSPE.NL (INFORMATION)
WWW.DSPE.NL/EVENTS/AWARDS

OPEN WINDOW ON THE FUTURE OF SMART OPTICS SYSTEMS

To celebrate the opening of a new and expanded smart optics laboratory, and the installment of an extra professor, the Delft Center for Systems and Control organised an international event. This included a one-day school on smart optics technologies and a symposium, with renowned researchers who gave the audience a look into groundbreaking developments, and involved them in some futuristic thinking.

TIJMEN VAN OLDENRIJK

One of the spearheads at the Delft Center for Systems and Control (DCSC) is the research on smart optics systems, work which was awarded with an ERC Advanced Grant to undertake the daring project "Integrated Real-time Feedback Control and Processing for Image Restoration (iCON)". To celebrate the official opening of the Smart Optics Lab at DCSC under the supervision of Prof. Michel Verhaegen, and the inauguration of Prof. Gleb Vdovin, which signals another expansion, an international symposium was held at Delft University of Technology (TU Delft), the Netherlands, on 3 and 4 March 2016 (Figure 1).

1 *The symposium was held in the Aula Conference Centre of TU Delft.*

The symposium, "Open Window on the Future of Smart Optics Systems", aimed to:

- identify basic principles and strategies for the development of smart optics systems in the multidisciplinary and international environment formed by universities, industries and public bodies;
- introduce industry representatives and young scientists to the main principles of building smart optics systems, based on the integration of the mechanical, optical, electronical and control subsystems;
- share the latest achievements in the technology and applications of smart and adaptive optics, with presentations delivered by scientists from the UK, the USA and the Netherlands.

AUTHOR'S NOTE

Tijmen van Oldenrijk works at the Delft Center for Systems and Control as an assistent, and is doing graduate studies in science communication.

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The Smart Optics Lab that was opened is a breeding environment for the development (by the DCSC Smart Optics team, Figure 2) of new optics and imaging instruments that make better trade-offs between performance on one hand and cost, complexity and maintenance on the other hand. The key in optimising this trade-off is to integrate systems and control methodologies from the onset of the instrument design.

Smart Optics Technologies school

The event started on a small scale with the One-day School on Smart Optics Technologies, chaired by Prof. Gleb Vdovin. He is the founder of OKO Technologies, a company that develops and produces adaptive optical components and solutions, and will be chairing research on "Integrated Design of High Resolution Imaging Systems".

2 *The DCSC Smart Optics team, headed by Prof. Michel Verhaegen.*
3 *Prof. Chris Dainty (right), the 2011 president of the Optical Society of America and one of the pioneers in the field of adaptive optics, opened the School on Smart Optics Technologies and took part in the discussions.*
4 *Prof. Michel Verhaegen of DCSC teaching methods of predictive control for adaptive optics.*

The school was fully booked with industry and academia participants from across Europe, and some internal participants, not lucky enough to have a chair inside the classroom, were standing in the corridor, just to be able to listen to the lectures. The opening word was presented by the 2011 president of the Optical Society of America, Prof. Chris Dainty, one of the pioneers in the field of adaptive optics (Figure 3). He commented that Gleb Vdovin was one of the key people who made adaptive optics technologies widely accessible, also to the Ph.D. student who does not have the multi-million dollar budget that space agencies have.

In the next lecture, Dr Oleg Soloviev, senior researcher and lecturer at DCSC and senior associate at OKO Technologies, outlined the principles of wavefront correction and sensing, and gave practical examples of devices to perform these tasks. Then Prof. Vdovin delivered a lecture on deformable mirrors and other types of wavefront correctors including defocus correctors, adaptive lenses and Alvarez lenses.

After a tasty Dutch-style lunch, Prof. Verhaegen instructed the audience about optimal methods of predictive control in adaptive optics (Figure 4). The afternoon programme was continued by a lecture on ophthalmic adaptive optics, delivered by Prof. Chris Dainty, and on the design of high-density micromachined wavefront correctors, delivered by the director of the Boston University Photonics Center, Prof. Thomas Bifano, who is also co-founder and CTO of Boston Micromachines. The school was concluded by the practical demonstration of a working adaptive optical system, operating in either optimisation or phase-conjugation modes.

Imaging-centred DCSC projects

A short video on the DCSC website gives a quick and personal impression of some of the imaging-centred projects.

Hans Verstraete: *"I studied control systems at Imperial College in London, and I am now a Ph.D. candidate working on wavefront-sensorless algorithms for aberration correction in optical coherence tomography (OCT). OCT is a 3D imaging technique often used to image the human retina and its layers. With adaptive optics and a smart optimisation algorithm that performs very well under noisy conditions we can maximise the quality of the OCT image without using a wavefront sensor."*

Dean Wilding: *"I studied physics at Cambridge University followed by photonics at Imperial College London, and now I am a Ph.D. candidate working on adaptive light-sheet fluorescence microscopy. My research is to use controllable optical elements to both correct for the effects of optical inhomogeneity scattering and absorption, but also modify the properties of light so the microscope operates better than it could before. I have been working on extending the field of view in the light-sheet microscope, with my ultimate goal for the whole project being the complete correction of the illumination and the detection in the microscope."*

Paolo Pozzi: *"I did my Ph.D. in Italy, where I worked on both the technical aspects of microscopy and some neuroscience applications. I am here to accept the challenge to make high-tech which should be simple to use. In particular I am making this set-up, which is a completely digital microscope with no moving part, and it uses a cheap and harmless LED instead of an expensive and dangerous laser. It can make images inside a thick sample in three dimensions, and it uses adaptive optics to keep the images sharp, no matter how deep inside the sample you are looking. This will be really useful for our collaboration with the neuroscience department in Rotterdam."*

Symposium

Prof. Verhaegen chaired the open symposium on 4 March, attended by around 150 participants, and delivered a short welcome address. After that, Prof. Dainty gave a speech devoted to the development of smart optics technologies from the fifth decade of the past century to our days. Adaptive optics began as a military technology, to track satellites, and to observe the defects in the protection tiles of the space shuttle during its flight. The ability to see these defects was crucial for the safety of the space exploration.

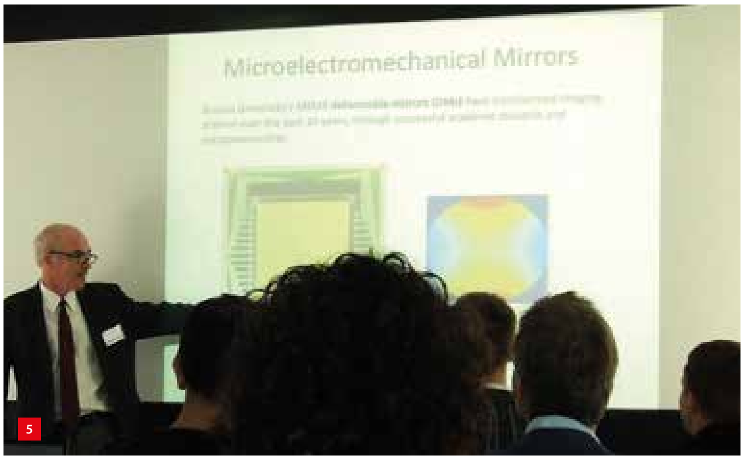
Then, Prof. Bifano delivered a lecture on wavefront compensation, that allows to achieve a wide field of view. The usual problem in adaptive optics is the limited field of compensation: the image can be made very sharp, but only over a very limited area. Using the new approach that moves the compensation place from the pupil to the object, the Boston scientists solved the problem. Professor Bifano reported on microscopic images with adaptive optics compensation, using microelectromechanical mirrors (Figure 5), covering the whole field of view.

The third speaker, Dr Ivo Vellekoop from the University of Twente, explained how adaptive control allows to obtain images through scattering biological tissues. This new technology has numerous applications in biomedical imaging, medicine and biology.

The last speaker, Dr Volker Sorger, director of the Nanophotonics Labs at George Washington University, delivered a speech about applications of nano-optics and nanomaterials for the optimisation of optical information interconnects (figure 6). The smaller the number of photons spent to transfer one bit of information, the faster is the line and the higher is the efficiency. His research would allow to reduce the number of photons per bit from millions and hundreds of thousands, to hundreds, promising an impressive progress for the future internet.

The morning session was concluded by the dean of the Faculty of Mechanical, Maritime and Materials Engineering, Prof. Theun Baller, who pushed the symbolic button, celebrating the official opening of the Smart Optics Lab within DCSC.

Lunch time was devoted to poster presentations of the diverse imaging-centred projects carried out at DCSC (see the box on the left).



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Inaugural speech

In the second part of the symposium, Prof. Gleb Vdovin delivered his inaugural speech, devoted to the integration of optics, mechanics, electronics and control into a single technology of smart optics. Such a synthetic approach allows to drastically improve the quality of optical systems, and make them smaller and cheaper at the same time. The speech included a live demonstration (Figure 7).

The reception that closed the symposium was a last and well-received opportunity to take advantage of this smart integrated event. The organisers at DCSC plan to host such events more often in the future. ■

5 *Prof. Thomas Bifano of the Boston University Photonics Center teaching on microelectromechanical mirrors.*
6 *Dr Volker Sorger of George Washington University giving an overview of current research on applications of nano-optics and nanomaterials for the optimisation of optical information interconnects.*
7 *Prof. Gleb Vdovin of DCSC doing a live demonstration in his inaugural lecture.*

7

INFORMATION
WWW.DCSC.TUDELFT.NL

MOTION SETPOINT TYRANNY AND MULTI-MATERIAL PRINTING

This year's High-Tech Systems event (HTS 2016) took place in Eindhoven, the Netherlands, and featured an appealing conference programme with sessions on smart industry, additive manufacturing, robotics and agro & food. Among the highlights were presentations on motion control for robots and on multi-material printing.

High-Tech Systems 2016 was organised as a one-day conference and exhibition with the focus on high-tech systems and key enabling technologies. This edition (the 4th) was devoted to high-end system development for markets where smart engineering and technology make a difference. HTS 2016 took place last month in a compact setting with a lively atmosphere and a lot of interaction between visitors and exhibitors. The event attracted nearly 40 exhibitors and over 700 visitors.

As in previous years, the conference programme was the stronghold of High-Tech Systems. It was kicked off by Prof. Maarten Steinbuch from the Eindhoven University of Technology (TU/e), who talked about the role of mechatronics in the systems engineering of next-generation multi-physics, high-tech systems, and Lasse Kieffer, global compliance officer of Universal Robots, who provided a keynote speech on collaborative robots and international standards.

Four sessions

The main body of the conference comprised of four sessions:

- Smart industry, with topics ranging from the Fourth Industrial Revolution in the Netherlands and the 'productisation' of supply companies to cyber security and predictive maintenance.
- Additive manufacturing: 3D printing of functional materials, metals, optics and devices such as robot grippers.
- Robotics: topics such as configuration, mobility and motion control, and applications such as bird control and surgery.
- Agro & food: innovations such as an unmanned cleantech tractor, and high-tech opportunities in livestock production, potato farming and horticulture.

Robot control

Herman Bruyninckx (professor at KU Leuven University, Belgium, and TU/e) gave a presentation titled "Robot systems of the future: moving them badly makes them better". The subtitle conveyed his message even better: "How to escape from the tyranny of the motion setpoint?"

Mobile manipulation robotics hardware is becoming more and more affordable, in 'low-tech' and 'mid-tech' implementations, but it is still being controlled as if it were high-tech equipment with many degrees of freedom and sensors. This results in high costs and, paradoxically, poor behaviour. The reason is that the interaction between the robot and the environment, crucial for its operation, is not treated as a guideline for the control but as a disturbance that has to be 'controlled away'.

Bruyninckx argued that programming and controlling mobile manipulation tasks has to change, based on a 'task-skill-action' approach employing optimisation of constraints regarding the relationships between task, robot, environment and objects. This should lead to a revolutionary step change in applications, with expensive and high-speed/high-accuracy robots being replaced by 'cheap and lousy' solutions.

3D printing revolution

Revolutionary in many aspects is also additive manufacturing (AM), or 3D printing. Richard Hague, a professor at the University of Nottingham, UK, and director of the EPSRC Centre for Innovative Manufacturing in Additive Manufacturing, talked about "3D deposition of functional materials for the additive manufacturing of smart devices". He showed how AM's central concept of design freedom can be taken beyond the geometrical domain. When multiple materials can be simultaneously deposited, this opens up the potential for creating functionalised, 'active' devices 'printed' in one build operation.

Though simple in concept, Hague stated, this discrete deposition of dissimilar materials throughout the volume of a part creates significant technical challenges, particularly in the deposition of useful materials. Current research in Nottingham focuses on multifunctional AM, predominantly utilising jetting-based technologies for the co-deposition of both structural and functional materials for electronic, pharmaceutical and biological structures and devices on varying length scales.

One example is multi-metal printing. Hague's research group works with the world's first multi-metal printer that can jet metals directly from the melt at temperatures up to 1,600 °C. This printer, comprising four printheads for – in principle – four different metals, was designed and built by Demcon, based in Eindhoven and Enschede, the Netherlands. In the next presentation, Ralph Pohl, mechatronic system engineer at Demcon Advanced Mechatronics, discussed the design of this machine, which employs an inkjet-based printing concept developed by Océ Technologies. It allows for in-depth research on AM principles, such as the printing of multi-metal 3D objects – the next step in the 3D printing revolution. ■

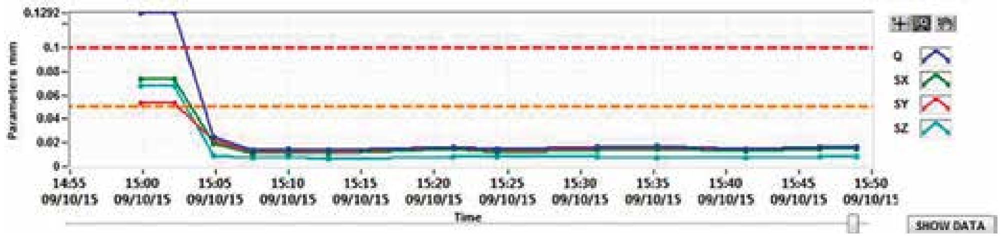
INFORMATION
WWW.HIGHTECHSYSTEMS.EU
WWW.MECH.KULEUVEN.BE/EN/PMA
WWW.EPSRC.AC.UK/RESEARCH/CENTRES

Next-generation 5-axis machine tool metrology

IBS Precision Engineering, metrology experts in Eindhoven, the Netherlands, has launched a new 'Industry 4.0' technology, the Rotary Inspector. It delivers a clear and traceable quality statement for 5-axis machine tools across the factory. As the complexity and precision of machine tools has increased, traditional methods of measuring their performance are failing. With the Rotary Inspector, IBS has pioneered technology which addresses the limitations of current techniques; including automation, dynamic measurement and reduction of the measurement time.

The Rotary Inspector.

KMWE, high-tech supplier for mechatronic systems and complex machined components with headquarters in Eindhoven, is already a customer of IBS for measuring tools. KMWE deploys over 50 state-of-the art machining centres and its strategy is to be ahead in innovation and technology, in machine equipment but also in processes. Therefore, KMWE was looking for a measuring tool which enables them to conduct quick performance tests on machining centres for both static and dynamic behaviour.



Automatic compensation of a 5-axis machine with a Heidenhain 640 controller. The Q value was reduced from 129 to 16 microns in minutes. Also shown are the underlying maximum individual axis errors (Sx, Sy and Sz).

In cooperation with IBS, KMWE started a project integrating the Rotary Inspector into the machine for measuring. At this moment a pilot is running on five different types of machining centres and the results are very promising. A measuring cycle, in only one minute, during normal production runs, results in a statement about the accuracy status of the machining centre.

The Rotary Inspector is a smart tool for the kinematic quality assessment of 5-axis machine tools following ISO-standardised measurement and generating KPIs defining the geometric and dynamic performance of the machine. Information is provided at a group, cell or factory level, in an auditable manner and real time. As part of the total 5-axis machine tool accuracy also pivot line offsets and squareness errors are calculated.

Two quality figures are derived from the machine measurement. The Q value is the maximum geometrical error. It provides a boundary for the product form accuracy that may be achieved under 5-axis machining. The *P* value is a measure of the largest measured dynamic error of the machine, resulting from issues such as backlash or worn bearings. Such errors will be seen in the surface finish of the machined product. With the geometrical and dynamic error data available, manufacturers now have the option for compensation.

WWW.KMWE.COM
WWW.IBSPE.COM

Integration of the Rotary Inspector into a maching centre.

Dutch vacuum highlight: "Vacuum Science and Technology"

Early this year, "Vacuum Science and Technology" was published by The High Tech Institute as a completely revised international edition of the Dutch reference publication "Basisboek Vacuümtechniek".
In this English edition, the authors Bert Suurmeijer, Theo Mulder and Jan Verhoeven (honorary members of the Dutch Vacuum Society, Nevac) have included all relevant knowledge for anyone working in research, instrumentation, development or production of vacuum technology. Important updates have been added on vacuum pumps, pressure measurement, ion sources, leak detection and cleaning and working discipline.

Since the Dutch version was published in 2000 by Nevac, both industry and science have made significant progress in the field of vacuum technology. Vacuum has entered into more industries and areas of research. The production of solar cells and organic displays has left its infancy, science has focused en masse on nano-related subjects and meanwhile the chip industry is on the brink of performing the most crucial step in IC production, lithography, in vacuum.

It took a few years, but now there is a very detailed reference book that deals with the basic physics and principles that form the foundation of modern vacuum technology. It is an excellent reference book and training manual with a clear layout, offering training in various disciplines and exercises in two degrees of difficulty.

WWW.HIGHTECHINSTITUTE.NL/EN/PAGE/BOOK_VACUUM_SCIENCE_AND_TECHNOLOGY

Fully automated compensation for distance measurements

■ *IDS interferometer (left) and fully automated ECU.*

When performing interferometric measurements in ambient conditions, air refractive index fluctuations can be a limiting factor: variations in surrounding pressure, temperature and humidity can cause measurement inaccuracies in the 10 ppm range. Especially for applications where highest precision is key, these deviations have to be measured and accounted for.

With the ECU (Environmental Compensation Unit), attocube offers the first interferometer compensation unit providing fully automated air refractive index correction down to the sub-ppm range: when connected to attocube's IDS interferometer, the ECU automatically detects the absolute sensor/target separation, calculates the actual air refractive index, and compensates any incremental measurement. In addition, the environmental data are recorded and stored for future reference.

WWW.ATTOCUBE.COM

20-bit absolute magnetic ring encoder

Renishaw's associate company RLS has launched the new AksIM™ true-absolute magnetic rotary encoder for embedded OEM motion control applications, offering up to 20-bit resolution and zero hysteresis in a unique through-bore configuration. It consists of a true-absolute encoder readhead and a separate corrosion-resistant magnetic ring with a unique single-track code embedded. The readhead is available in either a fully sealed IP64 housing or as a board level encoder. The encoder operates at speeds up to 10,000 rpm. AksIM is suitable for a diverse range of motion control applications, including robotics, pan-tilt/azimuth-elevation platforms, automation systems, and medical equipment.

WWW.RLS.SI/AKSIM

PI presents

Physik Instrumente (PI) has launched a range of new actuators. This includes a series of compact ultrasonic rotation stages for fast scanning applications. Ultrasonic piezomotors are often the best choice of drive, because they are small, fast, and silent. In addition, they are also self-locking when de-energised, but can still hold the load that they move. Additional brakes are not necessary and no heat is generated when they are at rest.

PI now has three further ultrasonic rotation stages in its portfolio, which can reach velocities up to 720º/s with a very dynamic stop-start behaviour. They have a very compact design and their edge lengths of 20, 30 or 50 mm with a height of only 10, 12 or 19 mm allow easy integration even where space is limited. Their drive torques are 5, 10, and 25 mNm, with a rotation range of more than 360°. Vacuum-compatible versions (to 10^{-6} hPa) are also available.

A piezoceramic ring motor acts directly on the rotating platform. Because mechanical components such as gearheads are not necessary for transmitting the force, the drives are virtually wear-free and very reliable. The integrated, direct-measuring, incremental encoder enables reliable position control and repeatability. Depending on the version, the minimum incremental motion is 0.03º, 0.006º or 0.003º.

The new product offerings also feature voice-coil linear actuators in new designs for position and force control with high resolution. Magnetic direct drives have advantages when compared to classical spindle-based solutions, especially with respect to wear and dynamics. Since they largely dispense with mechanical components, there is hardly any friction, less play and therefore more precision. At the same time, costs are lower and energy efficiency increases.

The new PIMag® voice-coil linear drives are suitable for travel ranges up to 10, 15 or 20 mm and reach velocities up to a maximum of 750 mm/s. An integrated optical linear encoder for direct position metrology ensures reliable position control and repeatability with a resolution of up to 0.01 µm. Because the feed force of the magnetic direct drives depends on electrical current, the linear actuators can not only be used for motion, but also for generating force. An optional force sensor enables application of defined forces to a maximum of 10 N, with a resolution of up to 1 mN.

New in PI's product portfolio: a compact ultrasonic fast rotation stage (left) and a highly dynamic linear stage.

PI also presents new voice-coil direct drives with integrated linear encoder for high-velocity industrial scanning applications. The highly dynamic ultracompact linear stages can reach velocities of up to 250 mm/s and scanning frequencies of some 10 Hz. The friction-free drive works with travel ranges from 5, 10 or 20 mm and is particularly suitable for applications in industry and research that require 24/7 operation.

Thanks to its crossed roller guides, the linear stage attains a travel accuracy of 1 µm. Cage creep is also reliably prevented. The linear stage is connected to the controller via a single cable, which includes both the power and the encoder signal. This ensures easy and space-saving integration into customer systems. The integrated direct-measuring, optical linear encoder allows a reliable position control and repeatability of ±500 nm. The sensor resolution is less than 10 nm, the minimum incremental motion is 20 nm.

Challenges, dilemmas and methods in software development

On 25 May 2016, the Software-Centric Systems Conference in Eindhoven, the Netherlands, is devoted to complex software development, featuring software engineering trends, automatic testing, zero-defect software, dynamic reconfigurable software architectures, etc. One of the speakers is Theo Engelen, responsible for EUV source software development at ASML. He will talk about challenges, dilemmas and methods in managing large industrial software products.

For almost a decade, the EUV source has been ASML's promise to the semiconductor industry to enable Moore's law beyond the 10 nm node. This puts pressure on development teams to show continuous improvements of the EUV products. As software can be easily introduced on customer systems there is a demand to deliver regular upgrades with new functionality and performance improvements while at the same time maintaining quality and avoid regression issues at all systems.

WWW.ASML.COM
SOFTWARECENTRICSYSTEMS.COM

New hexapod guaranteeing positioning accuracy specifications

Aerotech presents HexGen™ hexapods as a significant advance in six-degrees-of-freedom positioning performance. The HEX500-350HL high-load, precision hexapod is suited for applications in x-ray diffraction, sensor testing, and high-force device manipulation. With its high-load capacity, large travels, high speeds, and sub-micrometer precision, it is the only hexapod on the market that provides guaranteed positioning accuracy specifications, so Aerotech claims.

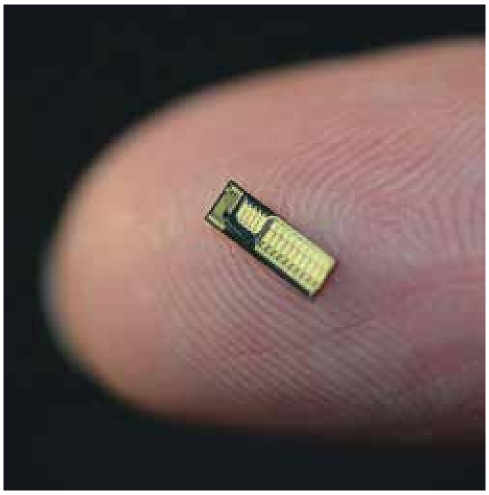
The HEX500-350HL is actuated with six high-accuracy struts that are built with precision preloaded bearings, ball-screws, and drive components. Unlike competitive hexapods driven by DC brushed servomotors, the HEX500-350HL is driven by AC brushless, slotless servomotors that maximise device lifetime and performance. The servomotors are directly coupled to the actuator ball-screw enabling increased drive stiffness, higher positioning accuracy, and better minimum incremental motion (20 nm in XYZ and 0.2 μrad for θxθyθz) when compared to competitive designs that use belts or compliant couplings. The strut pivot-joints are engineered to provide low friction and high stiffness enhancing overall hexapod performance.

The HEX500-350HL is designed with a 150 mm diameter clear aperture in both the platform and base to allow for workpiece access from the bottom. The hexapod can also be vacuum-prepared for demanding applications in synchrotron sample or optics adjustment, semiconductor manufacturing and inspection, or satellite sensor testing.

WWW.AEROTECH.COM

First optical 'System-on-Chip' product family

Photonic integration start-up, EFFECT Photonics, a spin-out of Eindhoven University of Technology, the Netherlands, has launched the first product family based on its optical 'System-on-Chip' technology platform. This platform integrates all the active and passive components of a DWDM (Dense Wavelength Division Multiplexing) system within a single chip, without traditional gold box packaging.



EFFECT Photonics' proposition addresses the soaring demand for affordable bandwidth between data centres and back from mobile cell towers by bringing DWDM technology to the edges of the network. By using the high integration 'System-on-Chip' technology, port density can be increased by over six times and operational expenses reduced by 40% when compared with existing approaches.

EFFECTPHOTONICS.NL

European Cryogenics Days

At CERN in Geneva, Switzerland, the European Cryogenics Days will be organised on 9-10 June 2016. This matchmaking and conference event aims to explore the subject of cryogenics and its developments at CERN and to show its impact on society and research. The event is intended for both researchers working in cryogenics and industry representatives who benefit from this enabling technology's many applications. Topics include accelerator and detector cryogenics, instrumentation for cryogenic systems, and future applications.

WWW.B2MATCH.EU/CRYOINEUROPE2016

MATLAB: next release, next event

Last month, MathWorks issued its R2016a release of MATLAB and Simulink. Main additions to the MATLAB programming environment are the MATLAB Live Editor and App Designer. R2016a also includes a number of new features in Simulink to help speed model development and simulation.

The MATLAB Live Editor offers a new way to create, edit, and run code. Results and graphics are displayed together with the code that produced them in a single interactive environment, speeding exploratory programming and analysis. Now, scientists and engineers can add formatted text, mathematical equations, images, and hyperlinks to create an interactive narrative that can be shared with others.

App Designer provides an enhanced design environment and UI component set for building MATLAB apps. It integrates the two primary tasks of creating an interactive application – laying out the visual components, and programming the behavior of the app. The generated code is object-oriented, which makes it easier to share data between the different elements of the app, and the compact structure makes it easier to understand and maintain.

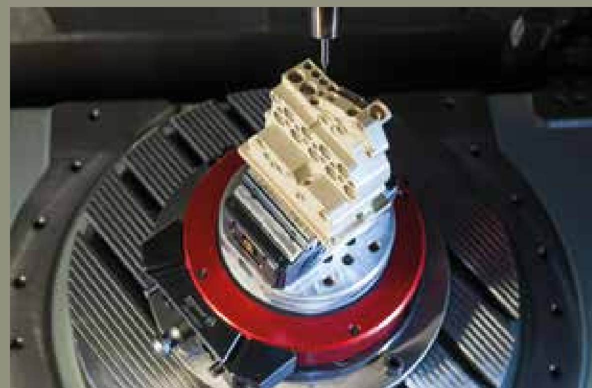
Undoubtedly, R2016a will be discussed during the MATLAB EXPO 2016 Benelux, which will be held on Tuesday 28 June in Eindhoven, the Netherlands. The programme comprises guest speakers from industry and academia, MathWorks presentations and MathWorks partners presenting their products and demos. One of the keynotes will be delivered by Katya Vladislavleva, CEO and Chief Data Scientist, DataStories (Evolved Analytics): "From Data Science to Data Stories: Bridging the Gap to Digital Transformation".

WWW.MATHWORKS.COM
WWW.MATLABEXPO.NL

Katya Vladislavleva, CEO and Chief Data Scientist at DataStories (Evolved Analytics), will deliver a keynote at the MATLAB EXPO 2016 Benelux.

BKB Precision – Precise plastics machining for the precision industry

When plastic parts become critical because of complexity or accuracy, BKB Precision is the machining supplier to involve. The company's knowledge of engineering and high-performance plastics and ability to turn and mill down to 3 µm makes it the ideal partner for challenging products. With state-of-the-art machinery and ISO 9001-2008 certified processes, BKB Precision can make the almost impossible possible with plastics.



A complicated manifold on a 5-axis machining centre.

BKB Precision is the trading name of Van den Berg Kunststofbewerking, a high-end supplier with over 33 years' experience. BKB Precision works for many quality brands in the semicon, medical, defence, aerospace, food, optical and chemical industries. Based at Science Park Ekkersrijt in Son (near Eindhoven), the Netherlands, BKB Precision produces prototypes, small series and everything in between.

5-axis machining centres with a robot cell for 24/7 operation.

The production facility is totally climatised to secure the dimensions of the machined products. The shop floor comprises milling machines (up to 6,500 x 2,500 x 300 mm), 3-, 4- and 5-axis simultaneous milling machines, turning and combined turning/milling machines (8-axis).

Sharing knowledge is at the heart of everything BKB Precision does. BKB Precision helps customers in the design-to-manufacture process to design a product by sharing knowledge about the characteristics of the plastics, how plastics behave during the machining process and their applicability for some of the part's functions under different circumstances. In short, knowledge and capabilities that are really important to deliver precise parts.

Delivering quality is also important. BKB Precision realises that the market has become even more demanding in terms of the durability, reliability and traceability of products. As a link in the manufacturing chain, BKB Precision is happy to help customers meet these requirements. If requested, BKB Precision can supply the following reports: Certificate of Conformity, First Article Inspection Report, measurement reports and materials certificates.

A detailed list of machinery and an overview of the plastics BKB Precision works with can be found online. ■

A product machined from Vespel, a high-performance plastic.

INFORMATION
WWW.BKBPRECISION.COM

Development

TNO
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TNO is an independent innovation organisation that connects people and knowledge in order to create the innovations that sustainably boosts the competitiveness of industry and wellbeing of society.

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ACE has developed into a leading engineering and consultancy firm with a strong focus on mechanics and mechatronics. Services include conceptualization, development, engineering and prototyping.

member DSPE

Development and Engineering

SEGULA Technologies Nederland BV develops advanced intelligent systems for the High Tech and Automotive industry. As a project organisation, we apply our (engineering) knowledge to non-linear systems. This knowledge is comprised of systems architecture and modelling, analysis, mechanics, mechatronics, electronics, software, system integration, calibration and validation.

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

member DSPE

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