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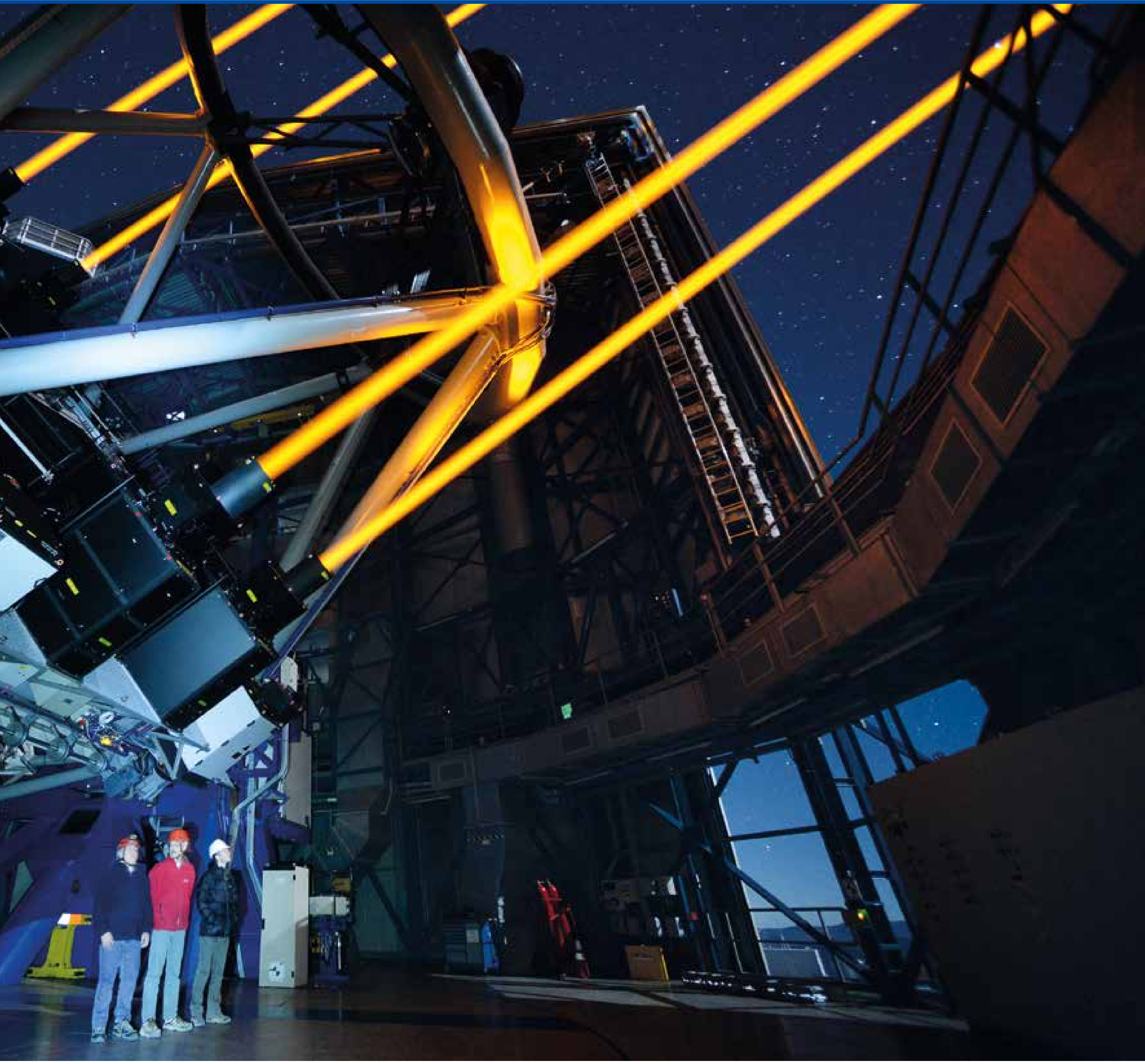

- THEME: ASTRONOMICAL SCIENCE INSTRUMENTATION
- INTERMEDIATE ROTARY STAGE FOR 200-MM WAFER SIZE COMPATIBILITY
- DSPE CONFERENCE ON PRECISION MECHATRONICS 2021 REPORT
- PRECISION FAIR 2021 PREVIEW

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The main cover photo (the Very Large Telescope (VLT) with the laser guide stars in operation) is courtesy of ESO / Fred Kamphues. Read the article on page 5 ff.

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FEATURES

DUTCH INDUSTRY IN BIG SCIENCE

(Photo: Kimon Kodossis)

Dutch society is slowly emerging from the Covid-19 pandemic, which has had a major impact on our personal lives and the way we operate in business. Dutch industry has certainly had its problems, but fortunately many companies are as busy as ever, for example in the Big Science arena... and have been over the last couple of years.

VDL has won the contract to build the support structures for the European Extremely Large Telescope (ELT), the largest optical telescope on Earth when finished. This is a return on investment for the early involvement and joint development with TNO and NOVA. The situation at CERN has resulted in the Netherlands gaining a well-balanced status for supplies due to Boessenkool and Demaco winning large contracts and many other companies winning smaller contracts. Dutch companies are also well placed to secure the Dutch share of the Square Kilometre Array construction contracts. The first contract was signed recently, and the remaining contracts will follow in the next 12 months.

Many of the companies involved in Big Science see the benefit of supplying to Big Science in the way it triggers product innovation, convinces other parties of their capabilities or keeps their best employees interested and on board.

The Einstein Telescope (ET) Pathfinder facility in Maastricht (NL) will provide opportunities for industry in the coming decade. This facility is being built to push many technologies beyond the state-of-the-art. These innovations require the involvement of the high-tech industry. The Interreg-ET2SMEs project aims to find and partially fund companies that can collaborate in these efforts. The ultimate goal is to build the Einstein Telescope and explore the universe beyond our current horizon both in time and space.

The Low Frequency Array (LOFAR) radio telescope community, with its core in the north of the Netherlands, is still growing and work is being done to upgrade the LOFAR sensor network for even better performance. At the High Field Magnet Laboratory (HFML) in Nijmegen, the facilities are being continuously expanded and improved leading to new projects and tenders. In southern France, the construction of the International Thermonuclear Experimental Reactor (ITER) has continued in spite of Covid-19, although some delays have occurred.

To support Dutch industry in its efforts to be successful in the Big Science domain, the Dutch ILO-net focuses on finding matches between the key enabling technologies in which our companies are strong and the technology roadmaps of the Big Science organisations. To do this well, our network needs to keep expanding to include more companies with unique capabilities. The collaboration and support of Mikrocentrum, the independent knowledge and network organisation for the technical manufacturing industry, plays a pivotal role in these efforts.

One of Mikrocentrum's major events, the Precision Fair, is the main event on the ILO-net calendar offering an excellent opportunity to meet many companies, catch up with familiar ones and become acquainted with new ones. In addition, together with Mikrocentrum, we organise a programme of presentations from various Big Science organisations to inform visitors about new projects and technical achievements that serve as examples.

Apart from their tenders, some Big Science organisations have increased their efforts in the domain of knowledge transfer in order to trigger industry to benefit from developed technologies and know-how. To back those efforts, we aim to showcase the technologies of those organisations and we are planning to organise events focused on knowledge transfer.

The Big Science organisations can provide a fertile breeding ground for the sales of core technologies and potential innovations for those that are willing to find out whether there is a cultural and technical match between a Big Science organisation and their company. But only then does the work begin to keep up a sustained effort in maintaining a good relationship and finding the sweet spot that will provide the desired benefits.

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FOUNDATIONS AND HIGHLIGHTS

The Netherlands plays a prominent and long-standing role in astronomy. This is due in part to the Dutch expertise in systems engineering, precision optomechanics, mechatronics and control engineering. Dutch high-tech engineering companies and research institutes are active in the ongoing developments involved for each step in bringing an electromagnetic signal (photon, radio wave, etc.) from outer space to a detector. This article presents an overview and concludes with a number of highlights.

WOUTER JONKER AND RAMON NAVARRO

"Preserving knowledge is easy. Transferring knowledge is also easy. But making new knowledge is neither easy nor profitable in the short term. Fundamental research proves profitable in the long run, and, as importantly, it is a force that enriches the culture of any society with reason and basic truth."
Ahmed Zewali, winner of the Nobel Prize in Chemistry (1999)

Introduction

The development of instruments for astronomy is an inspiring subject where science and society meet engineering and business. The science of astronomy addresses important societal topics, seeking to address big questions about our understanding of the Universe and our place in it, such as the hunt for exoplanets where life might be possible. It fosters international collaboration and advances human knowledge in the broad sense.

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Professor Jan Hendrik Oort, the Dutch pioneer in the field of radio astronomy, and H.M. Queen Juliana at the opening of the radio telescope in Dwingeloo (NL) in 1956. (Image credit: Oort archives)

At the same time, it offers goals for the high-tech industry: astronomy requires the development of optical and optomechanical instruments for ultimate precision, which boosts the expertise of the involved companies, creating visibility on the world stage and offering potential for series production. The development of such instruments brings deep technical knowledge and conceptual solutions that also find their application in neighbouring domains such as aerospace, optical satellite communication, medical instruments, defence and ICT.

For such a relatively small country, the Netherlands plays a prominent and long-standing role in astronomy (Figure 1). Dutch inventors and astronomers are credited with such achievements as: the invention of the microscope and the telescope; the discovery of Saturn's rings and its largest moon, Titan, and the Oort Cloud and Kuiper Belt structures in the solar system; finding the first hints of the existence of dark matter; and major new insights in cosmology. Frits Zernike was awarded the Nobel prize in the field of Optics and, as recently as 2018, Dutch astronomer Ewine van Dishoeck won the prestigious Norwegian Kavli Prize for astrophysics for her work on the origin of stars and planets (Figure 2).

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Professor Ewine van Dishoeck receiving the Kavli Prize for astrophysics from H.M. King Harald V of Norway. (Image credit: Fredrik Hagen / NTB scanpix)

The Dutch precision engineering industry is solidly world class in areas of expertise such as systems engineering, precision optomechanics, mechatronics and control engineering. As it stands, the Netherlands is ideally positioned to both benefit from, and contribute to, the science of astronomy (Figure 3).

From starlight to signals

In its path from outer space to a photon detector in a telescope, light is reflected off several optical surfaces to collect it and bring it into focus. The blurring effect of the atmosphere is corrected before the light is fed into the main science instruments that measure the desired properties. Dutch high-tech engineering companies and research institutes are active with the ongoing developments for each of these steps. Below is a quick overview of the steps in going from starlight to signals, followed by a few illustrative highlights.

Mirrors and support structures

The first component that starlight encounters in a big astronomical telescope is the primary mirror. Polished and finished down to an accuracy of single-digit nanometers, the mirrors are kept in that near-perfect shape using statically determined mirror support structures. Active mechanisms in these can compensate for the known, relatively slow effects of the temperature gradients that occur throughout the night, and for the changing gravity vector as the telescope pointing angle varies between horizon and zenith. The largest modern telescopes (Figure 4) have segmented primary mirrors, while the secondary, tertiary and further mirrors in the optical train can also be actively positioned, pointed and often 'warped'.

Turbulence

The only remaining significant disturbances to the image then come from outside the observatory dome, in the form of atmospheric turbulence. Turbulence varies depending on the time of day, the location on Earth and the altitude in the sky. The turbulent mixing of air layers with different temperatures distorts the optical wavefront. The typical distance over which the wavefront can still be considered 'flat' is called the Fried parameter R0 ('R-naught'), which can range from 5 cm on a typical day in the Netherlands to 20 cm on a clear night on Mauna Kea (Hawai'i, USA), one of the world's most favourable observational locations.

A small telescope with a diameter comparable to R0 will always see a more-or-less flat wavefront and so its image will be relatively unaffected. However, a large mirror can fit many times this R0 distance across its diameter. Despite the increased resolution that theoretically comes from having a larger mirror ('diffraction limit'), the practical resolution of a telescope is therefore still limited to that of a ~20-centimeter telescope due to turbulence ('seeing limit').

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The Milky Way rises over the BlackGEM telescope array in La Silla, Chile. A joint project by NOVA (Netherlands Research School for Astronomy), Radboud University (NL) and KU Leuven (Belgium), it is designed to observe the optical counterpart to neutron-star and black-hole mergers. (Image credit: Zdeněk Bardon / ESO).

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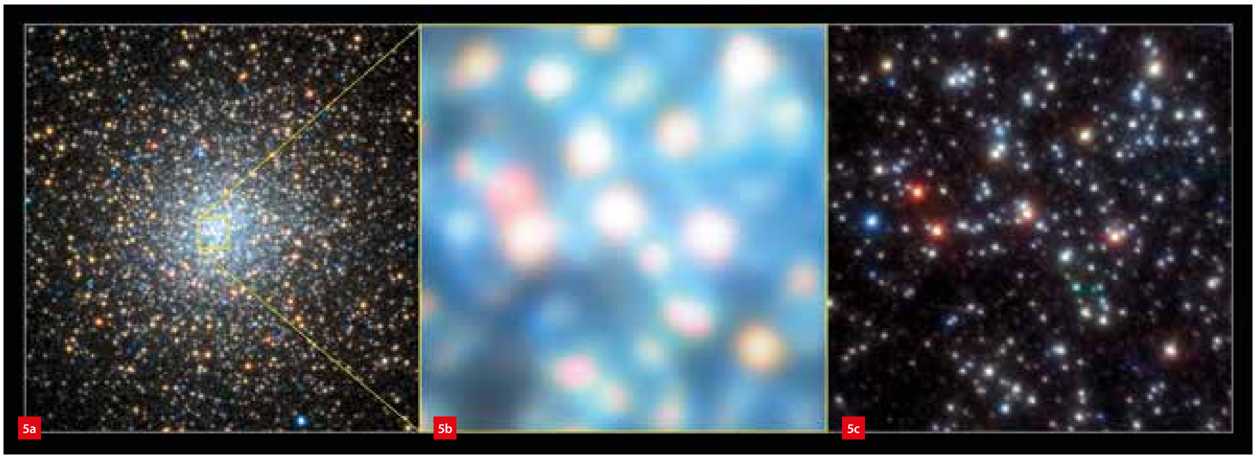
Artist's rendering of the completed Extremely Large Telescope at Cerro Armazones, Chile; red truck for scale. (Image credit: ESO)



The beneficial effect of adaptive optics (AO). (Image credit: ESO)
(a) Image of the globular star cluster NGC6388, taken with the MUSE (Multi Unit Spectroscopic Explore) instrument of the VLT (Very Large Telescope) at Cerro Paranal, Chile.
(a) A zoomed-in section without AO.
(a) The same section with AO engaged.

Wavefront sensing and natural guide stars
The optical effects of turbulence can be measured with a wavefront sensor. To determine the amount of disturbance, the nature of the undisturbed wavefront must be known. In practice this is done by observing a bright star ('guide star') that acts as a beacon/reference. Under ideal conditions, due to their incredible distance, stars are point sources of light. After the image has been distorted by the atmosphere, this is no longer the case, and this distortion of the wavefront can be measured.

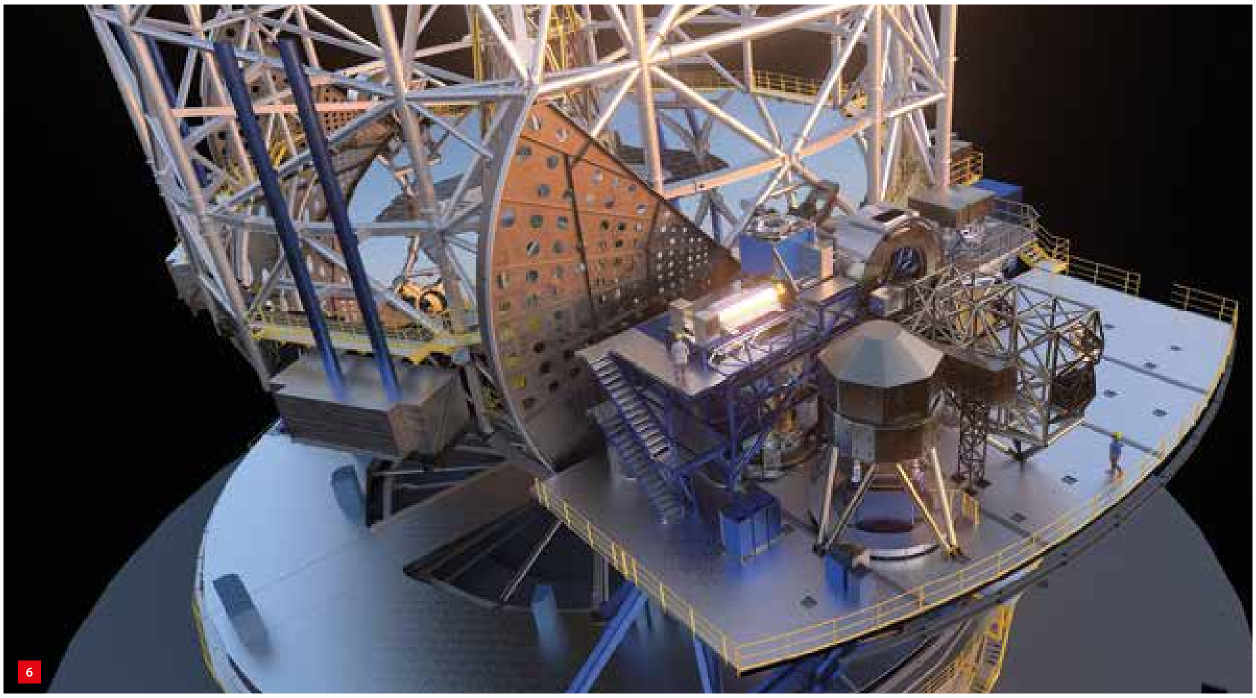
One way to do this is to divide the image of a star into many sections using a lenslet array in the pupil plane that focuses the light in many points on a detector array, and then observe how the image from each lenslet shifts in position on the detector. This in turn provides an estimate of how the wavefront can be approximated locally with a tilted plane. The integration of all these locally tilted planes gives a good approximation of the total global wavefront error, and hence of the correction needed to 'flatten' the wavefront and once again show the star as a point source.

Laser guide stars
Most of the world's large telescopes look towards such small portions of the sky that a bright-enough natural guide star is often unavailable in the field of view. In addition, the nature of the atmospheric disturbance varies over the field of view, while measurement of one natural guide star will only provide information on the image distortion in one point.
To solve these problems, astronomers have developed the concept of artificial 'laser guide stars'. Using a laser at a precisely tuned wavelength, it is possible to excite the sodium atoms in the upper layer of the atmosphere at 90 km altitude. The laser kicks the electrons in the outer electron shell to a higher energy state, and as they fall back to their ground state, they emit a photon. By focusing the laser on a small enough spot, it is possible to create a near-point source of light that can act as a beacon/reference. By projecting several such laser guide stars around the object of interest, the state of the atmosphere in the entire region of interest can be reconstructed.

Deformable mirrors
Once the wavefront disturbance has been characterised, it can be largely corrected with adaptive optics (AO), using an adaptive deformable mirror (DM). Such a DM consists of a thin mirror shell suspended on a grid of actuators. The actuators manipulate the shape of the mirror shell in real time ($\geq$ 100 Hz) to 'flatten' the wavefront of the incoming light. In this way it is possible to achieve better-than-Hubble-Space-Telescope image quality with a telescope on the ground (Figure 5).

Science instruments
When all the light has been gathered and its wavefront properly corrected, it is then fed into the detector – the actual science instrument. There are several types of instruments (Figure 6).

- Imager
  An imager is the most basic scientific instrument on a telescope. It simply creates an image of a patch of the sky. Unlike a photo camera, which uses three colour filters (red, green and blue), an astronomical camera can have many more filters, such as broadband filters as well as narrowband filters to look for specific chemical elements. The wavelengths for ground-based telescopes cover the extremes from ultraviolet, visible and infrared light to sub-millimeter radiation. For more extreme wavelengths, the atmosphere is opaque and telescopes need to be launched into space.



Artist's rendering of the ELT science platform showing the first-light instruments: an integral-field spectrograph, a diffraction-limited near-infrared imager and a thermal infrared imager-spectrograph; human for scale. (Image credit: ESO)

Even these simple imagers have several technical challenges: the images need to be crisp (sharp and rich in contrast) to the very edge of the field. The atmospheric dispersion (prismatic effect closer to the horizon) needs to be corrected with special optics. Infrared instruments need to be cooled to cryogenic temperatures. Astrometry requires the recording of the position of stars with such accuracy that you can see them move over a number of years. Imagers can be made sufficiently stable and sensitive so as to be able to detect the dimming of a star when an exoplanet temporarily crosses in front of it, thereby measuring the diameter of the planet.

- Spectrometer
  After making an image of a patch of the sky, a star can be selected for further investigation. This is done with spectroscopy: disentangling the light into many wavelength components. The resulting spectrum can provide information on chemical elements and processes in a star, or between the star and Earth. Using the Doppler effect, the velocities of celestial objects can be measured. The most accurate spectrometers can even detect the decimeter/second motion of a star, when an Earth-like planet is orbiting that star. This is used to determine the mass of a planet.

  A multi-object spectrometer can measure spectra of up to thousands of stars at the same time, with robots positioning optical fibres at the locations of stars of interest. Integral field spectrometers create a data cube of a piece of sky, for instance a galaxy. This means that a spectrum is taken for each pixel of the image, measuring 3D velocities in spiralling galaxies.

- Polarimeter
  When driving a car, you can wear sunglasses with polarised lenses to suppress glare on the road. Similarly, polarisation is used in scientific instruments to increase the contrast between a star and the exoplanet around it. An Earth-like planet at the Earth-Sun distance only reflects one photon for every 10 billion photons emitted by the star. Coronagraphy and polarisation are used to suppress the starlight by a factor of a billion in order to be able to detect and characterise the exoplanet. Polarisation is also used to measure magnetic fields in space.

- Interferometer
  An interferometer combines the light of multiple telescopes in order to achieve a higher spatial resolution than is possible with just one telescope. In radio astrometry this is relatively simple, since you can sample the electrical field, timestamp the signals and later compare these with recorded signals from other telescopes. As there are much higher frequencies in the optical domain, only intensities can be measured. This means that we have to physically combine the optical paths from different telescopes in order to create an interferogram. This is achieved in underground tunnels, with optical trains correcting the path distance between the telescopes real time to sub-micrometer accuracy. The achieved resolution for the VLT-interferometer is complementary to a telescope of nearly 200 m in diameter.

Highlight 1: ELT M1 mirror support structure

The primary mirror (M1) of the Extremely Large Telescope (ELT) is one of the most impressive and challenging aspects of the entire ELT project. Too large to be made from a single piece of glass, the 39-meter-diameter mirror will consist of 798 segments, each about 5 cm thick, measuring close to 1.5 m across and weighing 250 kg, including its support. Since the segments have to work together as a single mirror, they require specific infrastructure and control schemes. This is extremely challenging, as the full structure will be moving constantly during an observation and will be affected by wind and thermal changes. To achieve the required scientific performance, the mirror needs to be maintained in position and in shape to an accuracy of tens of nanometers across its entire 39-meter diameter.

Segment manufacturing

M1 segments (Figure 7) begin their life at German glass manufacturer Schott as blanks made of Zerodur, a glass-ceramic material that has very low thermal expansion. After the casting and machining of the blanks to their approximate shape, the segments are delivered to Safran Reosc, in France, who are responsible for shaping the segments and mounting them on their support systems, as well as for polishing and testing. VDL ETG in the Netherlands is responsible for the production and testing of the segment supports, which act as the backbone of the mirror.

Segment support

Each segment support includes axial and lateral supports and a clocking restraint, all attached to a moving frame. The axial support is a 27-point isostatic support, made of three 9-point whiffletrees (Figure 8). Each M1 segment assembly comprises a warping harness, made of nine shape actuators, which allows correction of three segment deformation modes: curvature, astigmatism and trefoil. The actuators modify the axial support forces by applying a torque at the location of the axial support tripod pivots. The load on the whiffletree can be adjusted in this way to slightly change the shape of the mirror to compensate for optical aberrations induced by gravity and thermal effects. The warping harness has a micron-range stroke and it is a 'slow' actuator (1.5 s full stroke). The segment support also includes adjustable counterweights to compensate for the shape variation of the 133 segment types.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Prototype of M1 segment support (Image credits: TNO / Henri Werij)


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Close-up of one of three 9-point whiffletrees. (Image credits: VDL ETG)

The segment support materials and components have been selected to minimise outgassing under vacuum; the entire segment assembly is loaded in vacuum vessels for ion beam figuring (fabrication) and optical surface coating (operational maintenance). On the telescope, the segment assembly will be mounted with a fixed frame that provides local stiffness to the M1 subunit and accurate reference position to the mirror assembly. A total of seven prototypes were developed jointly by VDL ETG and TNO, and successfully delivered to ESO in 2018, after which VDL ETG was awarded the contract for volume manufacturing.

Volume production

In the transition from the prototype project to the volume manufacturing project, which started in 2018, VDL and ESO joined to further refine all technical documentation. A lean production area was set up with a main assembly line, which is fed with parts and sub-assemblies from sub-lines. Each work place has dedicated tooling available, clear work instructions, and personnel receives dedicated training to work at that particular place. Every completed support structure goes through a rigorous and largely automated test sequence to ensure every single one meets the specifications (Figure 9).

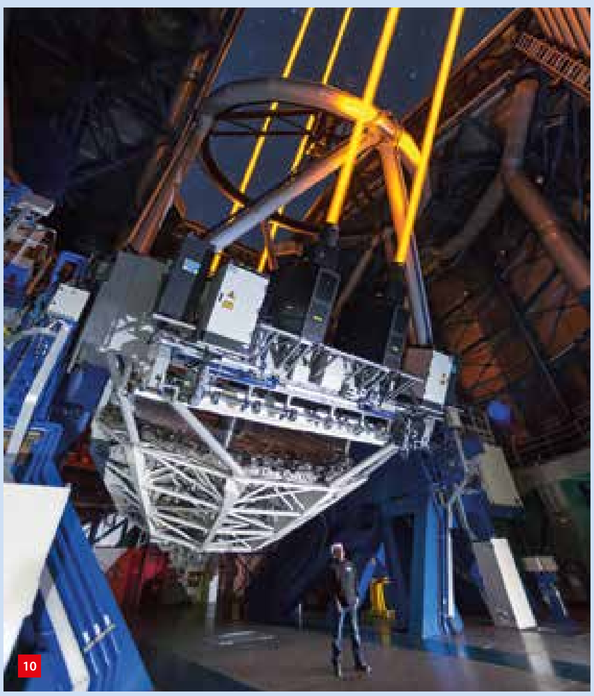
Performance testing of each unit during volume production. (Image credit: VDL ETG)

In setting up the supply chain, VDL worked closely with suppliers to define standards; suppliers were audited, and quality control plans were put in place. The most critical parts are dual-sourced to assure availability at all times. Delivery quantities of parts are optimised with suppliers for cost and operational efficiency. Since the full project lasts for four to five years, long-term agreements have been made to ensure the supply chain's continuity.
The volume production of this complex product for ESO (European Southern Observatory), and the advanced supply chain that was put in place for it, have attracted other interested parties, including the US-based Thirty Meter Telescope, the Mauna Kea Spectroscopic Explorer, and NASA's Jet Propulsion Laboratory.

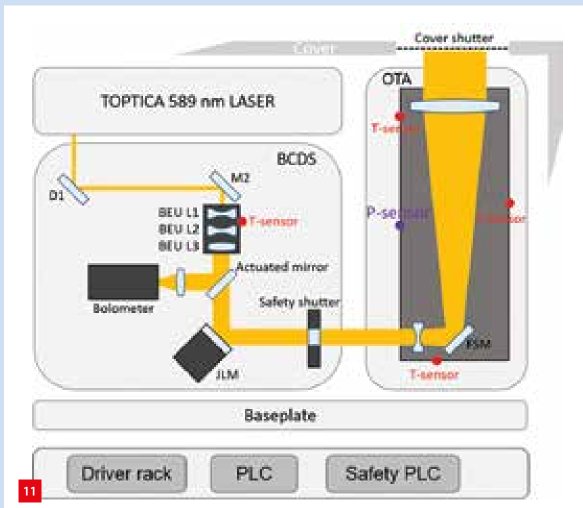
(adapted from elt.eso.org/mirror/M1)

Highlight 2: Laser guide stars

ESO's Very Large Telescope (VLT) facility at Cerro Paranal, Chile, consists of four 8.2-meter Unit Telescopes (UTs). Since 2016, one of these (UT4) has been equipped with laser launch telescopes provided by TNO. Combined with other instruments in VLT's adaptive optics facility, these allow astronomers to correct for the blurring effect of the Earth's atmosphere in real time and create images of unprecedented sharpness.



VLT UT4 with the laser guide stars in operation. The VLT LPS units are the black boxes from which the laser beam is emitted. (Image credit: ESO / Fred Kamphues)



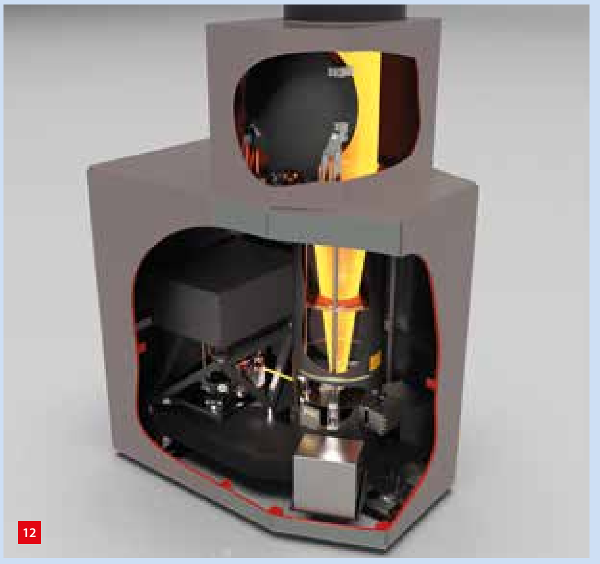
Schematic optomechanical layout of the laser projection sub-unit. (Image credit: Demcon / Ralph Pohl)

For the development of the next-generation system for the upcoming Extremely Large Telescope (ELT), ESO has once more turned to the Netherlands. Since January 2021, Demcon Focal and TNO have been working on the preliminary and detailed design of the ELT Laser Projection System (LPS).

Subsystems

The ELT LPS is an evolution of ESO's VLT reference design and consists of several major subsystems. The Beam Conditioning and Diagnostics System (BCDS) receives a Ø4.2-mm Gaussian laser input beam from the external 589-nm, 22-W continuous-wave laser. The BCDS contains a custom variable beam expander that expands the beam to Ø15 mm and controls focus, and a fast tip/tilt mirror to correct for jitter. The BCDS also performs beam diagnostics, and its propagation shutter can send the laser beam to a calibrated bolometer for absolute power measurements.

The BCDS feeds the laser beam into the Optical Tube Assembly (OTA), a 20x a-focal beam expander that expands the input beam to a Ø300-mm collimated Gaussian output beam. A Field Selector Mirror (FSM) is placed in the expanding beam between OTA's L1 and L2 lenses, and can be actuated in tip and tilt to point the output beam over a ±7-arcmin field of view within 10 arcsec absolute pointing error.
The Cover Assembly shields the LPS from dust and contamination and provides an extra layer of laser safety. The Cover Assembly has a number of access hatches to allow for easy maintenance. All motor drivers, controllers and sensor read-out electronics are housed in a separate electronics cabinet and commanded through an industrial PLC that connects to the overall ELT PLC.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Artist impression of the completed ELT Laser Projection System. (Image credit: TNO / Bert Dekker)

Requirements

The LPS (Figure 12) will have a total transmission wavefront error of < 65 nm rms, excluding tip/tilt and focus, over the full field of view and under all operational conditions. The requirements on pointing accuracy and stability are equally challenging. During operation, the LPS experiences a temperature gradient of up to 0.55 °C/hr. The thermal time constants of all OTA components will be precisely tuned to athermalise the design for these gradients. Repeatable focus errors of the LPS can be modelled, characterised and compensated using the variable beam expander. Due to the optical design, any pointing angle variations at the LPS input are demagnified by a factor of 72; lateral offsets, however, are magnified by the same factor. This requires a system-level approach for handling thermal and gravity loads.

Planning

The manufacturing, integration and testing of the first LPS is planned for 2022. Eventually, ELT will be equipped with at least four, potentially six, laser guide stars. ESO now expects ELT to achieve technical 'first light' in 2027, with scientific verification to begin shortly after.

Highlight 3: EST adaptive mirror

While the Adaptive Secondary Mirror development for the University of Hawai'i 2.2-meter telescope (UH2.2) has entered the manufacturing and integration phase (see the article on page 28 ff.), the involved partners are taking the next step. An international team of scientific institutes, coordinated by the Instituto Astrofísica de Canarias (IAC), is working on the development of the European Solar Telescope (EST, Figure 13), planned to be the largest solar telescope in the world when it becomes operational in 2027 on La Palma.


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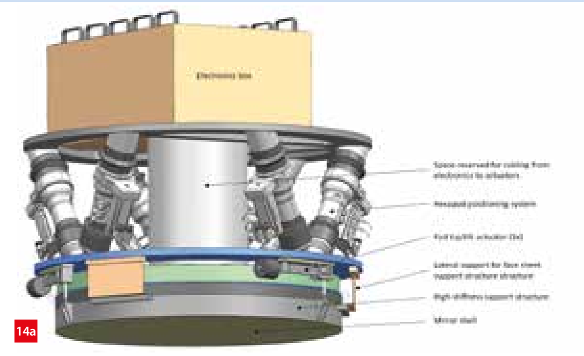
Artist's impression of the European Solar Telescope (EST) in operation. (Image credit: IAC / Gabriel Pérez)

The EST project, partially funded by the EU, will enable Europe to remain at the forefront of knowledge about our Sun and its influence on Earth. The field of view of EST will be 1.5 arcminutes, and with the Sun's apparent diameter of 30 arcminutes this means it will see only 1/400th of the Sun's surface at a time. EST will, however, be able to see this part in enormous detail, which is why some have nicknamed it the 'solar microscope'.

While the initial concept study of the EST considered a classical approach of having a passive secondary mirror and all deformable mirrors further downstream, the EST team found in their concept studies that having an Adaptive Secondary Mirror (ASM) could reduce the total number of mirrors in their system from 14 to only 6. This in turn would lower the overall cost and complexity of the telescope and



14a

14b

The EST adaptive mirror.
(a) Conceptual layout. (Image credit: TNO / Arjo Bos)
(b) Artist impression of the complete design. (Image credit: TNO / Bert Dekker)

would increase the optical throughput by nearly 50%. Building on the design and success of the UH2.2 technology demonstrator, TNO was recently awarded the contract for the preliminary design of this adaptive mirror, to be completed by late 2022.

System layout

The EST ASM (Figure 14) will have an 800-mm-diameter concave aspheric mirror shell that defines the telescope pupil. The mirror shell is supported on potentially as many as 2,000 hybrid variable-reluctance (HVR) actuators for providing corrections. The actuators require a high-stiffness mounting frame, and the investigation of design concepts and materials choices is just one of many trade-offs to be performed as part of the preliminary design study.

Next to the HVR actuators, a separate mechanism will provide fast tip/tilt and piston corrections to compensate for vibrations produced by the wind. This is especially important since EST, contrary to most telescopes, will not be protected by a dome during observations and thus will be fully exposed to the wind. While this approach produces vibrations throughout the structure and optics that need to be compensated, it also provides natural cooling and reduces turbulence in the atmospheric ground layer.

Finally, the entire assembly is mounted on a hexapod for slow, coarse positioning and alignment. If the global corrections provided by the deformable mirror (DM) actuators are nearing the end of their stroke, part of that stroke can be off-loaded to the fast tip/tilt subsystem, which can in turn be off-loaded to the hexapod.

Cooling

The solar constant, the solar energy received by the Earth, is approximately 1,360 W/m^2 and about 56% of this energy actually reaches the surface. Considering the 4.2-meter primary mirror of EST, this means the ASM will receive roughly 10 kW of light. A large portion of that optical power is taken out by a heat stop located at the intermediate focus between the primary and the secondary mirror, which only transmit the light over a small field of view. As a result, the maximum irradiance at the ASM is around 250 W.

In case of a high-power laser that emits monochromatic light, a coating can be designed to achieve 99.99% reflectance at that one particular wavelength, and hence to have minimum absorption. Over the broad spectrum emitted by the Sun such optimisation is not possible, and the broadband coating of the ASM will reflect only about 90%, resulting in a heat absorption of 25 W. To avoid generating local turbulence, an integrated cooling system is needed to keep the mirror temperature within 0.5 °C with respect to the environment. Investigation and breadboarding of cooling concepts are therefore another important activity in the preliminary design phase.

Actuator adaptations

TNO and VDL ETG together have developed, manufactured and tested several HVR generations. The lessons learned from the UH2.2 actuator development are implemented in the new High Density Actuator (Figure 15), which is also the baseline for use on EST. This latest version is rotationally symmetric to make more efficient use of the available space for the generation of actuator force, has vastly increased

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Artist impression of the latest-generation High Density Actuator. (Image credit: TNO / Bert Dekker) stiffness for higher AO-correction bandwidth, and removes the need for wire-erosion machining, which lowers manufacturing cost. Due to the 'lasagna'-style layered structure, the actuators are also easier to assemble.

The design is scalable down to an actuator pitch of around 5 mm and is also suitable for use at instrument level, where DMs need much tighter actuator spacings. Modelling predicts a force range of ±1 N in an actuator volume of Ø5 mm x 10 mm, which yields a stroke of more than 30 μm peak-to-valley at an actuator resonance of around 3 kHz.

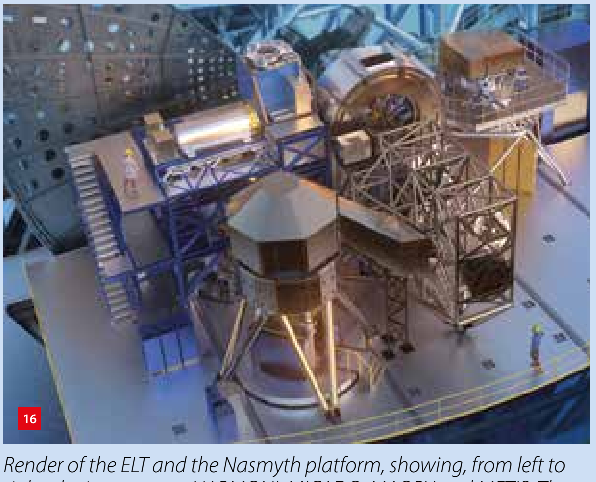
Several prototypes were recently manufactured, and at the time of writing, functionality and performance testing is ongoing.

The preliminary design study for the EST ASM will be concluded near the end of 2022, after which the EST consortium will prepare for the detailed design and realisation phase, which will take several years. This could provide an exciting opportunity for the current and new partners involved in precision engineering and electronics development.

Highlight 4: ELT instruments

The mirrors of the ELT collect, correct and stabilise the light from astronomical objects. The scientific instruments attached to the telescope analyse the light in detail. The ELT instrument suite includes cameras to capture images, and spectrographs to disperse light into its component colours. They can be combined with other functions, such as coronagraphs that block the light from a star in order to reveal its planets. Each of these instruments will allow astronomers to observe and study the cosmos in a unique way.

For a gigantic telescope, its science instruments will inevitably also be large. The instruments are located on the Nasmyth platform (Figure 16), about 25 meter above ground level. The optical beam from the telescope is 6 meter above the platform, which measures 15 m by 30 m. Three instruments will start to operate shortly after ELT achieves first light, while others will be added at a later stage. Throughout the telescope's lifetime, additional instruments will be developed to study the Universe in ever more detail.



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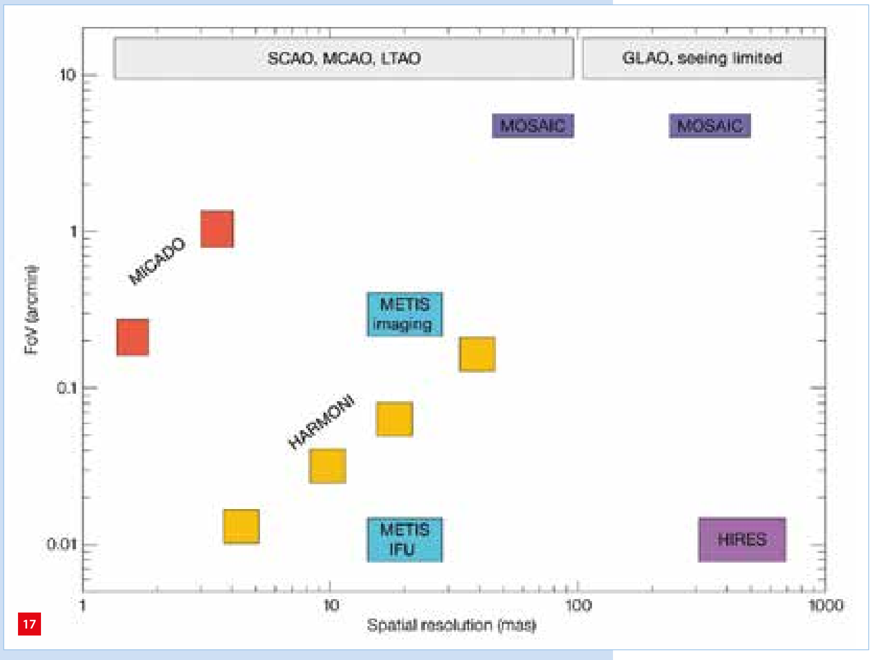
Render of the ELT and the Nasmyth platform, showing, from left to right, the instruments HARMONI, MICADO, MAORY and METIS. The platform is the same size as a basketball court. (Image credit: ESO)



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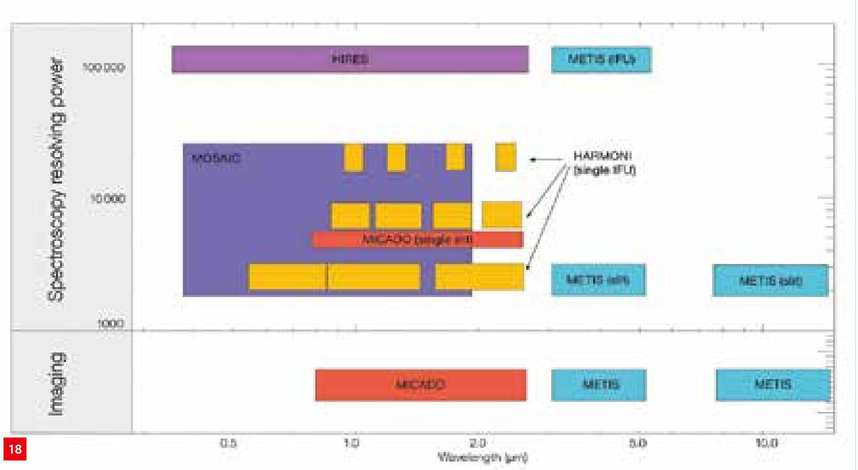
Field of view (FoV) versus resolution for various instruments, spanning several orders of magnitude. The maximum resolution of the ELT is 1.5 milliarcsec (7 nrad), which compares to being able to separate two objects that are the thickness of a human hair apart, viewed from 10 km distance. Their location (the centre of those objects) must be known with an accuracy that is even 100 times better. The maximum FoV is limited by the 2-meter diameter size of the ELT focus. There are various adaptive optics (AO) modes to combat the turbulence of the atmosphere: single-conjugate AO works great in the vicinity of a single bright star, whereas multi-conjugate AO works well in a small area between multiple bright stars. Laser tomography AO uses lasers to create artificial stars anywhere in the sky. Ground layer AO only corrects for turbulence close to the telescope. (Image credit: ESO)

Capabilities

To erect the telescope, ESO contracts industrial partners to build the various components. The scientific instruments are developed in a completely different way. International consortia of research institutes collaborate to develop the necessary technology and realise the equipment, including their calibration strategies and data-processing pipelines. These instruments have imaginative names, based on abbreviations, describing their purpose and technology. Their capabilities can be visualised in plots (Figures 17 and 18), showing the following properties:

- Spatial resolution: the crispness of the image, or how far you can zoom in.
- Field of view: the size of the image; sometimes it is just a single spec on the sky.
- Spectral resolution: how many colours can be distinguished; this is how chemical elements are found, or how the Doppler shift is used to determine velocity differences.
- Wavelength range: which colour ranges can be detected; the ultraviolet shows hot stars and violent mergers, while with infrared wavelengths you can peer in dust clouds, observing planets being formed.
- Coronagraphy: the technology to suppress the light of the star, while observing the much fainter planet right next to it; for an Earth-like planet at the Earth-Sun distance, only 1 out of every 10 billion photons is from the planet.



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Spectral resolving power versus wavelength range for various instruments. The spectral resolving power R is defined as $\lambda/\Delta\lambda$. A higher number means that the light is split into more individually distinguishable colours: R = 100,000 at λ = 1 µm means that 10-pm wavelength variations are detected. A resolution of R = 2,000 is sufficient to study the rotation speed of galaxies. At R = 5,000 it is possible to study the chemical composition of individual stars. More chemical components can be found at R = 20,000. R = 100,000 is needed to measure speeds very accurately, e.g. to see stars wobble because a planet is rotating around it. In imaging mode, dozens of filters are used, corresponding to, e.g., spectral lines of specific chemical substances. METIS is the only instrument observing wavelengths longer than 2.5 µm. (Image credit: ESO)

Overview

HARMONI (High Angular Resolution Monolithic Optical and Near-infrared Integral field spectrograph)
This workhorse 3D spectrograph will transform the visible and near-infrared astronomy landscape. 3D spectroscopy means that from small portions of the sky a spectrum is generated for each pixel. This enables, e.g., measurement of the rotation of galaxies, as derived from Doppler shifts.

MICADO (Multi-AO Imaging Camera for Deep Observations)
This high-resolution camera will offer astronomers the ability to take images of the Universe at an unprecedented depth. MICADO will create the sharpest images ever taken of faint targets. The Netherlands contributes with the unit that provides all the (colour) filters and corrects for atmospheric diffraction, as well as the data processing software.

MAORY (Multi-conjugate Adaptive Optics RelaY)
This unique instrument will not make observations itself, but will enable, by correcting for the blurring effect of the Earth's atmosphere, other instruments to take exceptional images. MAORY will use two additional deformable mirrors with thousands of actuators, in order to correct for turbulence at different altitudes in the atmosphere.

METIS (Mid-infrared ELT Imager and Spectrograph)
With a powerful spectrograph and high-contrast imager operating in the thermal infrared, this two-in-one instrument will allow to unravel some of the most pressing mysteries about the Universe. The range of METIS science is broad, from Solar System objects to active galactic nuclei. METIS is ideally suited to study the lifecycle of stars, from baby stars and their planet-forming discs to older stars nearing the end of their lives.

HIRES (HIgh REsolution Spectrograph)
This high-resolution spectrograph will allow astronomers to study astronomical objects that require highly sensitive observations. Large gratings unravel the light into a million colours, using the Doppler shift to detect minute variations in the velocities of stars and planets.

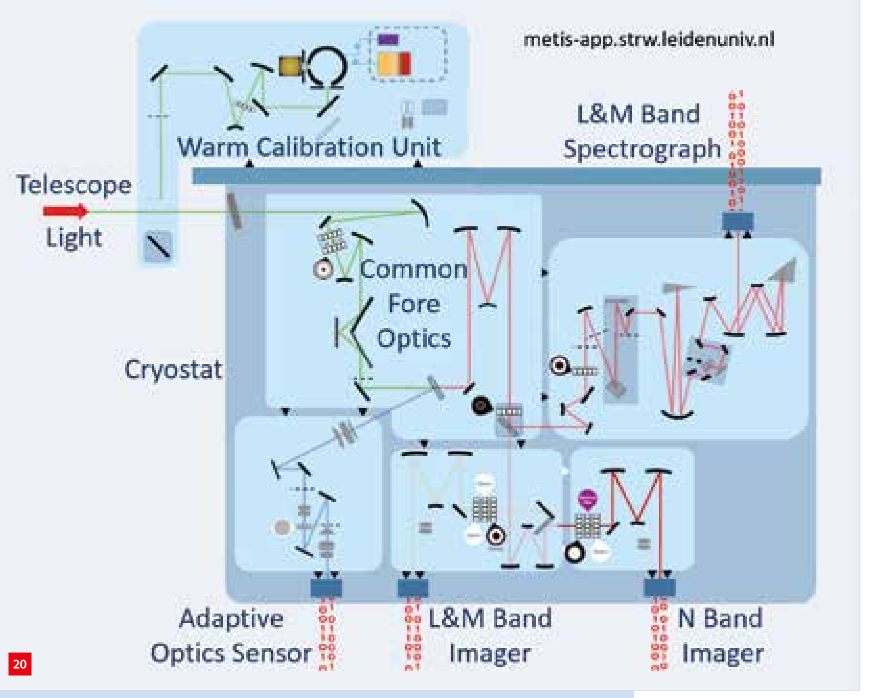
MOSAIC (Multi-Object Spectrograph for Astrophysics, Intergalactic medium studies and Cosmology)
This multitasking instrument will allow astronomers to measure the light from many objects at the same time, enabling them to quickly survey a multitude of stars and galaxies in the Universe. The Netherlands will contribute the visible spectrograph, capable of measuring the spectra of 200 objects simultaneously.

One of the highest scientific priorities for the ELT is to characterise exoplanets and, specifically, to take images of Earth-like planets. Such a giant leap from the capabilities we have today, requires significant research into new technologies over several years. Therefore, an ambitious and powerful planetary camera and spectrograph is included in the instrumentation plan. The research and development for specific components required to build it is ongoing. This project will start when the technology is ready. If the full potential of the ELT is achieved, global weather on exoplanets could be observed.

Development of METIS

The METIS instrument (Figure 19) is developed by a global consortium under the leadership of the Dutch Research School for Astronomy (NOVA). This Dutch team has to ensure that all the contributions from different partners around the world will integrate and work together seamlessly, forming an operational system with optimal capabilities to harvest science from observations. In the design phase, this involves breaking down the top-level requirements into subsystem requirements. In the realisation phase, this involves combining all hardware subsystems with electronics and software deliverables into a fully-tested functional system. This entire process takes about 20 years: ten years for technology and concept development and ten years to design, build and test the instrument.

METIS will pick up the optical beam from the telescope and process it in several major subsystems, to create the spectra and images that scientists can use for their research. The common fore-optics subsystem formats the beam for injection into the scientific cameras, and includes important functionalities such as atmospheric dispersion compensation, derotation, pupil stabilisation, chopping, and coronagraphy.
The single-conjugate adaptive optics (SCAO) subsystem, which implements an infrared pyramid wavefront sensor, is used to control the shape of the ELT-M4 deformable mirror. Because of the SCAO subsystem, all science modes observe at the diffraction limit of the ELT, yielding angular resolutions of a few tens of milliarcseconds.



Layout of the METIS instrument and its most important subsystems. Due to the thermal infrared wavelengths, most of its components are located in a cryogenic vacuum environment. Many of its dozens of optical components are adjustable, some even with extreme accuracies during observations. The Adaptive Optics Sensor produces data that is used to control deformable mirrors real time. (Image credit: NOVA; still image from live simulation at: metis-app.strw.leidenuniv.nl)

Render of the METIS instrument, together with other science instruments, on the ELT Nasmyth Platform. (Image credit: ESO)

A pair of diffraction-limited imaging cameras operate at two distinct wavelength bands in the 3-13-µm range with an 11-arcsec field of view, and include coronagraphy and medium-resolution long-slit spectroscopy. The integral-field high-resolution spectrograph operates from 2.9 to 5.2 µm and includes coronagraphic capabilities. A warm calibration unit sits on top of the cryostat, providing carefully calibrated light sources to finetune the instrument stability and sensitivity.

METIS detects thermal infrared wavelengths; this is heat radiation emitted by any material at ambient temperatures. This is perfect to detect the radiation of exoplanets. The downside it that everything on Earth also emits in the infrared, including the Earth's atmosphere, the telescope itself and any optical component in the beam. The signal is drowned in these bright background emissions, which significantly reduces the sensitivity. In order to eliminate emissions from the instrument itself, most of METIS is placed in a cryogenic vacuum environment and cooled to extreme temperatures. Liquid nitrogen is used to cool a thermal shield to 80 K, while helium pulse-tube coolers bring detectors and part of the optics down to temperatures of around 35 K.

At infrared wavelengths, very accurate subtraction of the spatially and temporally varying background is also essential. This is usually done by 'beam chopping': quickly alternating pointing between the science target and a nearby reference location. This differential measurement allows both the sky background and detector noise to be eliminated from the observation. This functionality is provided by means of a tip/tilt mirror, able to move very fast and then hold the image perfectly stable. For the development of the Metis Cold Chopper, NOVA collaborated closely with JPE, which handled the design, and with SRON and Delft University of Technology, which worked on the required advanced control strategies. A prototype of this mechanism has been described in *Mikroniek* [1].

Two other challenging subsystems and components deserve to be mentioned. The Image Derotator in the common fore-optics; a set of three flat mirrors that rotate very slowly with variable direction and speed to counteract the rotation of the Earth, thus keeping images still on the detector. This module is a challenging puzzle of tight tolerances in more than 20 degrees of freedom, with very limited alignment options, because of the operation in a cryogenic vacuum environment.

The Spectrograph contains an immersed grating. By creating the grating inside germanium with its high index of refraction of 4.2, the Spectrograph can effectively shrink in all directions by this same factor, which is a huge saving in volume, mass and cost. The downside is that the wavefront errors (position errors of the grating lines) must be tighter by the same factor, reaching single-nanometer manufacturing accuracies. This magnificent piece of engineering has been manufactured and the required tolerances have been achieved.

The METIS design is being finalised and will be reviewed and frozen in 2022. Then the period of manufacturing, assembly, integration and performance verification will start. The schedule of METIS, like that of ELT, was impacted by Covid-19. The plan is to be on sky in 2027.

REFERENCE

[1] M. Dekker, "Cold chopping of baby star light", *Mikroniek* 54 (5), pp. 19-23, 2014.

LIAISING WITH THE STARS

Dutch universities and research institutes such as ASTRON, DIFFER, Nikhef and SRON are involved in large research infrastructures to perform experimental physics research. This inherently includes the construction of various high-tech equipment for CERN, ITER, ESO, ESA, etc., the so-called Big Science organisations, whose research requires large-scale facilities. The various domains of research each have their own approach to working with industry. However, with the size of these facilities increasing over the last decades, the involvement of industry has become indispensable and fundamental, especially in the engineering domain and for the production of parts in large numbers.

JAN VISSER

In the Dutch ILO-net, industrial liaison officers (ILOs) work towards establishing links between Dutch industry and the Big Science organisations to find opportunities for companies from three angles. The first is working together in developing new equipment. The second is finding the right company that can bid competitively with tenders. And last, but not least, showcasing the technologies available for commercialisation from these organisations. To these ends, the individual ILOs work together to increase their common network, organise events, and visit companies and research facilities.

AUTHOR'S NOTE

Jan Visser, coordinator industrial contacts at Nikhef, is industrial liaison officer for CERN and ET, and coordinator of ILO-net. He acknowledges the input by institutes and companies.

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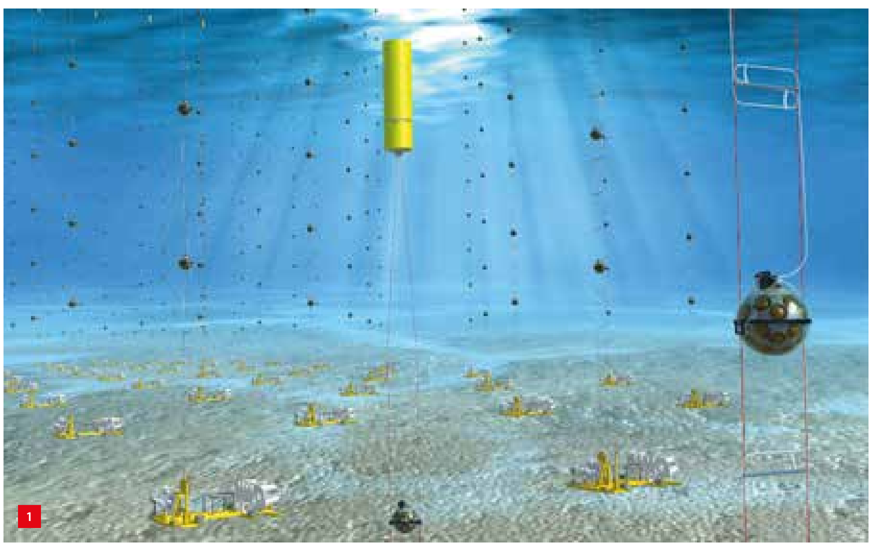
To give an impression of what has been accomplished, what is being done and which opportunities will be arising in the future, three projects in the astronomy domain are highlighted to demonstrate how the collaboration between industry and Big Science can be established. This involves:

- Km3NeT: the development, engineering and construction of the oil-filled cables for the neutrino telescope in the Mediterranean Sea, in collaboration with MCAP;
- ProtoDUNE: the construction of valve boxes for the neutrino experiment at CERN, by Demaco;
- ETpathfinder: the challenges that need to be tackled with industry in the coming years in this research facility, which is being built in Maastricht (NL) to develop the technologies required for the underground Einstein Telescope to study gravitational waves.



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Artist's impression of the KM3NeT telescope at the bottom of the seafloor, comprising several thousands of spheres, equipped with photomultiplier tubes.

KM3NeT

Despite the fact that neutrinos represent one of the most abundant forms of cosmic radiation, their detection is extremely difficult. This is due to the nature of these elementary particles: a neutrino has no charge and cannot interact with its surroundings through the electromagnetic force. Indeed, it is the mysterious aspect of these particles that makes them a desirable object of study and hence many physics experiments have been carried out to elucidate their properties. Moreover, as our Universe is filled with neutrinos, the study of cosmic neutrinos will contribute to our understanding of the Universe. A new experiment, KM3NeT, will allow us to observe high-energetic cosmic neutrinos from various astrophysical objects.

KM3NeT is a neutrino telescope presently under construction at the bottom of the Mediterranean Sea at a depth of 2.5 km (Figure 1). Using a large number of photomultiplier tubes, Cherenkov light will be observed emanating from the interactions triggered by cosmic neutrinos passing through the seawater. As the expected interaction rate is low, a neutrino telescope should be large to guarantee observation of a sufficiently large neutrino flux. This is the very reason why the experiment is being built in the depths and darkness of the Mediterranean Sea; here a large volume of seawater can act as a detection medium. The KM3NeT collaboration consists of a large number of (mostly European) universities and research institutes. The realisation of KM3NeT is now on a steady course. In dedicated sea campaigns the building blocks of the

KM3NeT experiment are being deployed in the deep sea. This is an extremely large and challenging endeavour. The deployment of the detection units is a complex process, but has proven to be a successful method to create a 3D grid of photosensitive sensors.

Building detection units (domes) that operate at a depth of 2.5 km and can communicate with a coastal station presents huge challenges. The two main challenges are the connections from the domes to the outside world and to have fibres operational under an enormous pressure of around 250 bar. The design of the connector to feed in electrical power and to extract the signals via an optical fibre required a lot of work and tests to get it right.

Nikhef engineers worked closely together with MCAP, a Dutch company specialised in cable and glass fibre assemblies. In this collaboration, an oil-filled cable was developed, providing KM3NeT with a solution that enables the fibre to correctly transmit the light back to shore. MCAP obtained new knowledge that it has put to good use in other products to expand its customer base.

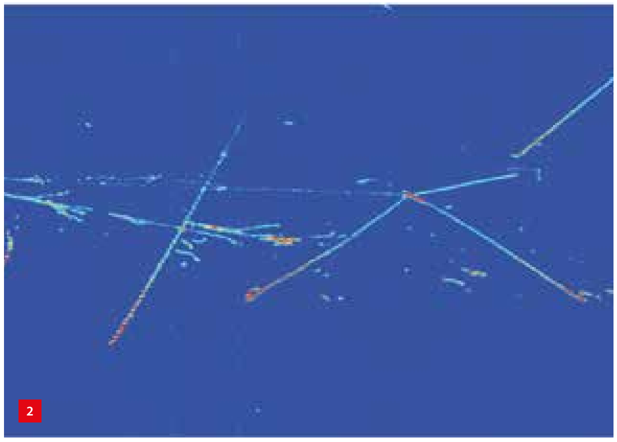
After the successful deployment of a limited number of strings with detection units, and hence a limited neutrino flux, sufficient neutrinos have now been detected to extract the first results on the quantum-mechanical properties of neutrinos, known as neutrino oscillations.

ProtoDUNE

ProtoDUNE is a precursor for the planned Deep Underground Neutrino Experiment (DUNE) and has already detected neutrinos in 2018. This international experiment is aimed at studying neutrinos to answer a number of fundamental physics questions about the nature of matter. One of the scientific goals is to study the explosions of supernovae and subsequent formation of neutron stars and black holes in real time by detecting the neutrinos fleeing from these explosions. A possible additional goal is to find an answer in the quest for the reason why the Universe is made of matter.

To this end, neutrinos are generated at Fermilab National Accelerator Laboratory in Batavia, Illinois, USA, and detected 1,300 km away at the Sanford Underground Research Laboratory in Lead, South Dakota, USA. Here, the difference in behaviour of neutrinos and antineutrinos is the key. Another topic to study is the possible proton decay that would shed light on the relation between the stability of matter and the envisioned Grand Unification Theory for the fundamental forces.

The ProtoDUNE experiment at CERN is a liquid argon Time Projection Chamber (Lar TPC) that has excellent neutrino detection capabilities providing 3D tracks of the interactions (Figure 2). Neutrinos are never detected directly, but via their interaction with argon. The system at CERN contains 770 tonnes of liquid argon in an active detection volume of 7.2 m x 6.1 m x 7.0 m.



Particle tracks in the LAr TPC.

Two ProtoDUNE set-ups at CERN form a test facility for developing liquid argon detector technologies. The core of the logistics of the liquid argon was designed, produced and installed by Demaco and consists of 38 valve boxes (Figure 3) and 90 transfer lines. Demaco designed and built the valve boxes, which are an integral part of the Neutrino Platform Proximity Cryogenics project in which four cryogenics systems are linked to four cryostats.

The valve boxes are fundamental in turning over the liquid argon every five days through a set of filters to reduce the water and oxygen impurity concentration to at least no more than 100 ppt oxygen equivalent (ppt = parts per trillion (10^{12})). This is a requirement to reach the desired electron lifetime for the operation of the TPC; generally, less than 40 ppt is achieved.

Demaco's valve boxes.

The main challenge of the project was to minimise the effect of the temperature of the surroundings and deal with the various coefficients of expansion of the different materials, each at their own temperature, in the chain during the cooling-down process. Each of the 38 valve boxes has a specific functionality requiring the careful selection of equipment such as control valves, heaters, pressure and temperature sensors, flow transmitters, purification equipment (mole-sieve and active copper), safety valves and others.

In the process, Demaco gained experience concerning argon purification and series production; both very useful for future projects. As the DUNE collaboration consists of many international partners, getting to know them will lead to new projects.

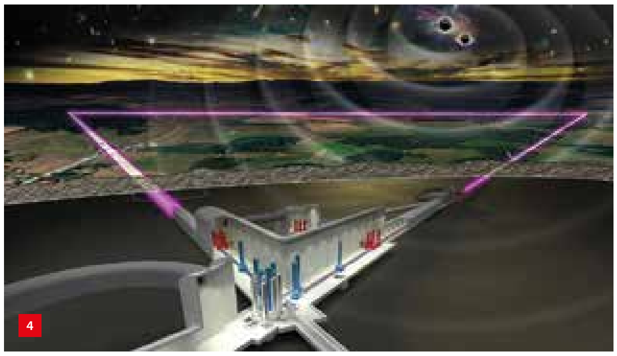
ETpatfinder

The Einstein Telescope is the proposed European next-generation gravitational-wave detector (Figure 4). In 2015, the existing gravitational-wave detectors reported the first detection. This demonstrated the power of laser interferometry in translating the miniscule vibrations in space-time into a measurable signal and then reducing the noise. This had been a decades-long endeavour of designing, creating, testing, improving and finetuning the hardware and data-analysis software. This first result in 2015 was awarded the Nobel Prize in Physics in 2017.

The current systems detect about one event per week. The aim is now to extend the physics knowledge that can be obtained from gravitational-wave detections by increasing the sensitivity for events by decreasing the noise and increasing the frequency range of the detector. From the existing infrastructures it has been learned how and where to improve.

The plan on how to improve requires ground-breaking innovations in mirror technology: composition, manufacturing and highly uniform coatings over large areas. The cooling system needs to be vibration-free, while laser requirements are narrow linewidth, high stability and high power at a wavelength of 2,090 nm. For the 120-km-long vacuum system, alternatives are being investigated for the standard stainless-steel pipes. Options are different kinds of steel with coatings. Most important for the facility is the low tolerance for residual water and hydrogen in the vacuum system.

Several of these intended developments can be tested in the ETpathfinder facility in Maastricht, in the Dutch province of Limburg. There, a vacuum system is being built in a cleanroom environment for testing prototypes, materials and procedures for their applicability in the full Einstein Telescope infrastructure. It is clear that all these innovations require close involvement from industrial partners. As this is easier said than done, the ETpathfinder organisation is reaching out to companies by regularly organising events, searching for those that have particular skills that can be useful in these developments, and inviting interested parties to get in touch.



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Artist's impression of the Einstein Telescope in the landscape of Limburg (NL).

INFORMATION
WWW.KM3NET.ORG
WWW.NIKHEF.NL
WWW.MCAP.NL
WWW.DUNESCIENCE.ORG
WWW.DEMACO-CRYOGENICS.COM
WWW.ETPATHFINDER.EU

DETECTING RIPPLES IN SPACETIME

LISA is a gravitational-wave (GW) detector in space, planned by the European Space Agency, ESA, to be launched in the mid-2030s. It will detect GWs from colliding supermassive black holes, binary systems consisting of compact objects, compact objects orbiting the supermassive black holes in the centres of galaxies, and signals from the early universe. Its technology needs accuracy in the order of picometers, as well as disturbance reduction and correction, and has been successfully demonstrated by the LISA Pathfinder mission. Dutch universities, NWO institutes, TNO and industry are participating in LISA hardware development and scientific exploration.

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Introduction

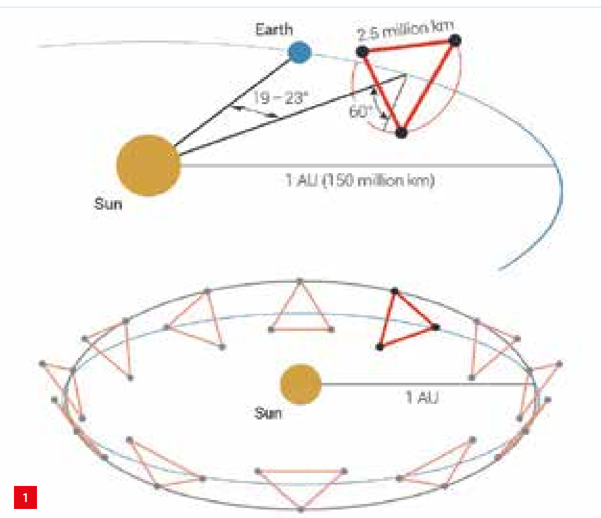
The Laser Interferometer Space Antenna (LISA) is a gravitational-wave (GW) detector in space [1]. It is designed to measure the GW-induced picometer variations in the distance between free-floating test masses separated by $2.5 \cdot 10^6$ km 'arms'. These variations are caused by GWs passing through the detector with frequencies in the mHz regime. GWs are 'ripples' in spacetime, a consequence of the theory of General Relativity, which predicts that if spacetime is distorted waves in the spacetime itself are launched. These distortions are caused, for instance, by binary systems of compact objects, and, more generally, by a varying quadrupole moment of mass/energy concentrations.

GWs travel essentially undisturbed through the Universe, causing variations in the distance between free-falling objects. In 2015, the LIGO/Virgo collaboration [2] for the first time detected (with the LIGO detector) such variations, caused by short-wavelength (high-frequency) GWs [3]. This achievement was acknowledged in 2017, when the Nobel Prize in Physics was awarded to three representatives of the LIGO/Virgo collaboration.

However, ground-based detectors such as LIGO and Virgo are only sensitive to short-wavelength GWs produced by small objects such as neutron stars and stellar-mass black holes. Larger objects in the Universe produce longer-wavelength GWs, which need larger detectors. LISA is a European Space Agency (ESA) mission selected for this purpose and will consist of three spacecraft in an equilateral triangle [4]; see Figure 1. Its launch is planned in the mid-2030s, and the international LISA consortium, in which the authors and their institutes participate, is preparing for science, data analysis and development of part of the mission hardware, while the rest of the work will be done outside the LISA consortium, by ESA with contributions from NASA and, potentially, the Japanese Space Agency JAXA.

LISA technology and challenges

LISA's basic idea for detecting a GW is similar to that of the LIGO/Virgo detectors: measuring the phase shift between the laser light travelling in different arms of an interferometer, as caused by a passing GW. The GW amplitude, hence the change in length of the arms, that the detectors aim to measure is exceedingly small: $dL/L \sim 1 \cdot 10^{-21}$. For the ground-based detectors, with an effective arm length of 10^3 km (realised by a 3 to 4 km actual distance, which is multiplied in Fabry-Perot cavities), accuracies of ~1 fm (~10^{-10} of the wavelength) are reached [5]. For LISA, with $2.5 \cdot 10^6$ km arms, an accuracy of 'only'



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Schematic of the LISA configuration, consisting of three identical spacecraft, in an equilateral triangle with sides of 2.5 million km; below, its orbit is shown [4].

AUTHORS' NOTE

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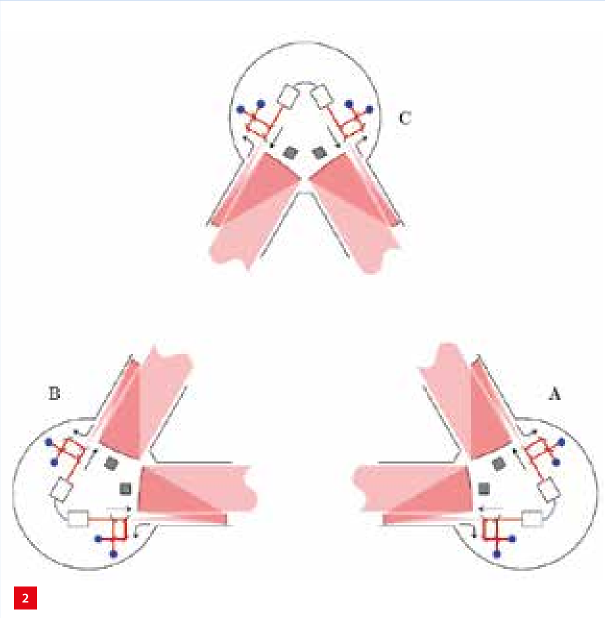


Schematic of LISA. It consists of three identical spacecraft in a triangular formation. Each spacecraft has two identical optical benches with each a test mass (grey cubes), laser beams (red lines), a telescope to receive and transmit laser beams, and several photoreceivers (blue dots) [4].

~2.5 pm (~10^{-6} of the wavelength), is needed.
This accuracy is still very challenging, and there are additional difficulties:

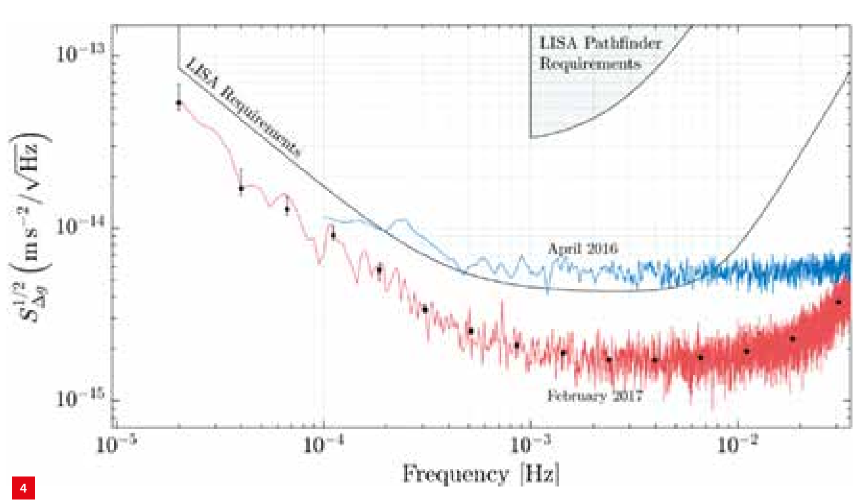
a) The laser beam diverges over the enormous distances between the test masses (reaching a beam width of ~6 km at $2.5 \cdot 10^6$ km), which means that the fraction of light that could be collected with a 30-centimeter telescope – $(30 \text{ cm}/6 \text{ km})^2 \sim 10^{-9}$ – is not sufficient for interference (the fraction of reflected light that returns would be 10^{-18}).
b) The arms are unequal in length and the arm length is changing.
c) The test masses need to be in free fall. To measure a change in the spacetime, it is critical that no other effects disturb this measurement. The distance is measured between two free-falling test masses (see Figure 2) and the spacecraft need to follow the test masses 'perfectly' (e.g., by compensating for variations in solar pressure).

The solution to points a and b is the use of heterodyne interferometry (i.e., to record the phase shift of the incoming light with respect to a local reference laser), but the problem is that the laser frequency noise (typically ~100 $\text{Hz}/\text{Hz}^{1/2}$) translates into a displacement error of ~1 $\text{mm}\cdot\text{Hz}^{-1/2}$, many orders of magnitude larger than the GW displacement. Luckily, this problem has also been solved, with 'time delay interferometry': the idea to combine signals at different places in the interferometer at different times into a virtual interferometer in such a way that the laser noise cancels [6]. The solution to point c is to create a gravitationally exceptionally quiet environment and use drag-free control to steer the spacecraft to follow the test mass.
These requirements are very challenging and impossible to test on ground, so ESA developed and launched in 2015 the LISA Pathfinder mission in order to demonstrate the feasibility in space.

LISA Pathfinder (LPF)

LPF [7] consists of one single LISA arm reduced in length to 35 cm and contained within a single spacecraft. The objectives were to demonstrate isolation of the test mass from inertial disturbances at the level of $3 \cdot 10^{-14}\ \text{ms}^{-2}\cdot\text{Hz}^{-1/2}$, rising with frequency squared above 3 mHz, over the measurement bandwidth of 1 to 30 mHz; and to perform laser interferometry in the low-frequency regime with a performance close to $10^{-12}\ \text{m}\cdot\text{Hz}^{-1/2}$.

The LTP (LISA Technology Package) core assembly in LPF. (Image credits: Airbus Defence and Space, [11])
(a) Schematic showing two gold-platinum cubes that are enclosed in vacuum containers; here without the launch-lock mechanism. The optical bench interferometer is shown between the two masses [10].
(b) Physical realisation of the optical bench. This instrument is made from a 20 cm x 20 cm block of Zerodur ceramic glass, and has a set of 22 mirrors and beam splitters bonded to its surface for directing laser beams.



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Measured residual acceleration noise in LPF [12].

Two test masses (2-kg, 46-mm gold-platinum cubes) are housed in enclosings to shield them from external influences, to allow sensing the ~3 mm gaps between test mass and housing, with a mechanism to protect them during launch [8] (see Figure 3). Drag-free control is used to follow one of the test masses, while continuous actuation is used to keep the other one in its position. Interferometry is used to measure residual (acceleration) noise on the test masses by determining their relative motions to very high accuracy. For this, an optical bench interferometer between the two masses is used, allowing scientists to precisely measure the cubes' relative motion, position and orientation without touching them.

The goal of LPF was to prove that the acceleration noise could be kept below the required picometer level. Extreme care had to be taken to balance the gravitational field of the spacecraft in order not to influence the test mass [9].

The results of LPF spectacularly prove the ability to obtain the required residual acceleration noise, reaching levels of 10^{-15} ms^{-2}·Hz$^{-1/2}$, about an order of magnitude better than the requirement and, in fact, already at the requirement for the LISA mission (see Figure 4), and displacement noise of about 10^{-13} m·Hz$^{-1/2}$ [12].

LISA status and Dutch contributions

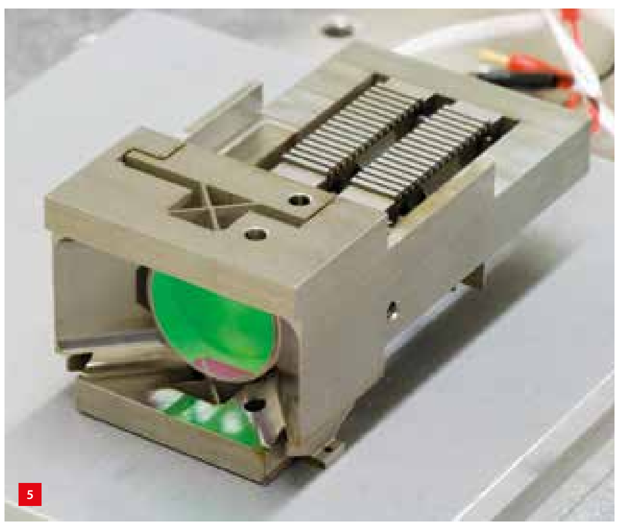
In order to fly the LISA mission, the technology demonstrated by LPF has to be further improved and expanded with better lasers, telescopes and technology to create and maintain the triangular mission configuration at a significant distance from Earth. Currently, the mission is in phase A (design), and mission adoption is planned for 2024, with a launch in the mid-2030s. In the Netherlands, several important contributions to the LISA mission are being prepared.

A Dutch consortium of SRON, Nikhef and industrial partners Bright Photonics and Smart Photonics is developing novel large quadrant InGaAs photodiodes (QPDs) with high sensitivity, for discerning the sub-nanoWatt 1064-nm laser light after interference with the local microWatt laser signal. For the larger sensitive area, low noise and high bandwidth are needed. To effectively correct slight misalignments between the interfering laser beams, the photodiode consists of four quadrants that are independently read out to sense wavefronts.

The interfering laser beams have slightly different wavelengths and the interferometric signal varies with time with a frequency between a few and 25 MHz and a peak-to-peak amplitude of about 10^{-6} (fractional rms) on an optical power of 1 mW. The heterodyne science interferometer signal will be distributed over four photoreceivers (eight other photoreceivers will be used in two local interferometers).

To be sensitive enough, the noise requirement of each QPD and its read-out electronics is challenging: below 2 pA·Hz$^{-1/2}$. Taking into account the well-predicted noise from the electronics and harness, this implies that each of the four QPD quadrants will need to have a capacitance lower than about 3 pF, while keeping a large sensitive area. These two requirements counteract each other. Hence, this puts a strong constraint on the epitaxial stack design, demanding extremely low doping levels (preferably < 10^{14} cm^{-3}), and innovative processing of the wafers into QPDs. The QPD diameter should preferably be 2.0 mm. This requires a capacitance per unit area of down to about 3 pF·mm^{-2}, allowing for some parasitic capacitance in the electronics.

At TNO, several optomechanical mechanisms for the LISA optical bench have been studied in the last twenty years [13]. The Point Ahead Angle Mechanism (PAAM) is a



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Realisation of the PAAM. The mirror is glued to a monolithical structure featuring a Haberland hinge. The mirror can be actuated by one of two redundant piezo stacks. (Photo courtesy of Leo Ploeg/TNO)

mechanism to correct the direction of the transmitted light, which is required due to the time delay in the interferometer arms that is caused by the orbital motion (Figure 1).
The PAAM concept (Figure 5) is based on a piezo-stack-actuated rotatable mirror that has an extreme dimensional stability, achieved by manufacturing (through high-precision wire erosion) a monolithic Haberland hinge mechanism out of Ti6Al4V. The critical requirements were the contribution to the optical path length (less than 1.4 $pm \cdot Hz^{-1/2}$) and the angular jitter (less than 8 $nrad \cdot Hz^{-1/2}$), which have been demonstrated by TNO and the Albert Einstein Institute. Extreme thermal stability was realised by placing the thermal centre on the surface of the mirror.

SRON, together with TNO and international partners, is studying the Mechanism Control Unit (MCU). The MCU is an electronics unit that is meant to control the different mechanisms mounted on the optical bench (in addition to the PAAM, these are the Fiber Switch Unit Actuator and the Beam Alignment Mechanism). It will provide power and command & control functions and consist of front-end electronics for the different mechanisms and digital control.

LISA science

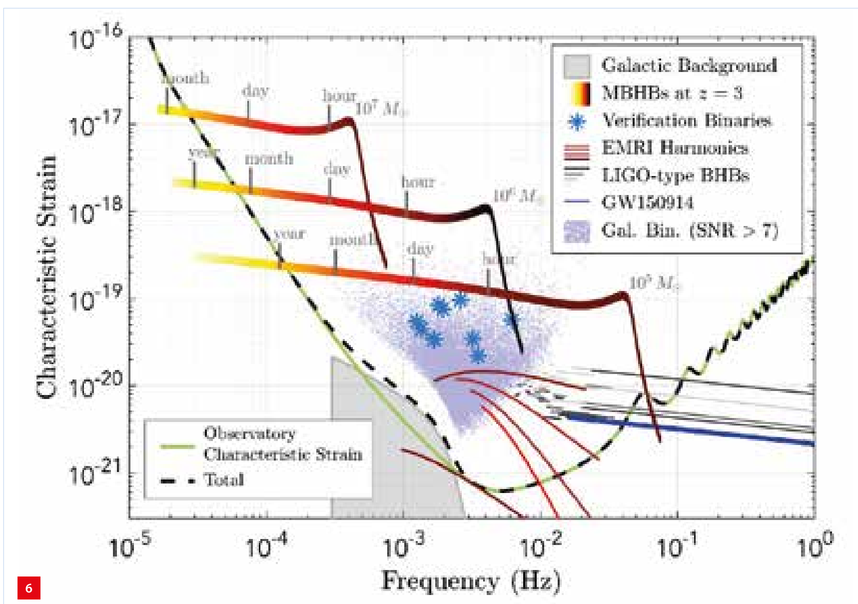
LISA is sensitive to various GW sources [14]. The most important ones are described here and depicted in Figure 6:

- *Astrophysical black holes*
  LISA will probe massive black holes over a wide, almost unexplored, range of cosmological redshift (and thus age) and mass, covering essentially all important epochs of their evolutionary history. This touches on the important question of how supermassive black holes (SMBHs) come to be; are they growing from low-mass seeds in the early Universe or were the seeds already very massive?
- *Extreme mass-ratio inspirals and the physics of dense stellar environments*
  SMBHs forming galactic nuclei are surrounded by numerous objects of much smaller mass, as is nicely demonstrated by infrared measurements in the Milky Way. This may lead to extreme-mass-ratio inspirals and offers, if those smaller objects are compact objects (stellar black holes, neutron stars and white dwarfs), the opportunity to probe the mass and spins of SMBHs between 100 thousand and 10 million solar masses. The detection will bring to light such black holes, even when they are not detectable in electromagnetic (EM) radiation, and provide a census of SMBH masses.
- *Testing General Relativity*
  LISA will be able to detect inspirals of stellar-sized black holes and neutron stars one year before their merger and test General Relativity at the limit of high velocities, in other words very strong spacetime deformations at very high signal-to-noise ratio, complementing the measurements with ground-based detectors of the actual merge event.
- *The dawn of the Universe*
  LISA probes GW wavelengths that are commensurate with the size of the Universe between 10^{-17} and 10^{-10} s. GWs emitted at that time thus provide a probe of the early Universe, when first-order phase transitions (i.e., decoupling of electroweak and weak nuclear forces), supersymmetry and extra dimensions played a strong role. In comparison, EM radiation can only probe the Universe after its 300,000th birthday and neutrinos after 1 s.
- *Ultracompact binaries*
  These are binaries consisting of a compact object orbiting another star at a distance of at most 10^6 km with a period of at most 1.5 hr. This period overlaps the LISA frequency band and the detector will be able to substantially increase the known population by many orders of magnitude to several tens of thousands, creating a rich source for understanding the evolution of binaries and a direct link to type Ia supernovae. Particularly interesting are the ones that can also be detected in EM radiation and those that host heavy black holes, such as the LIGO/Virgo prototype source GW150914; such events may first be detected by LISA and several years later by the Einstein Telescope [15]. Presumably there are millions of ultracompact binaries that will produce a stochastic GW foreground in LISA.

The Gravitational Wave Universe Toolbox [16] is an accessible tool to simulate detection of different GW sources by different detectors.

To conclude

The Dutch astronomical and physics community has embraced the GW revolution, as it has strong connections



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Predicted LISA sensitivity (green and dashed black line) with signals of several sources overplotted [4].

to Dutch astronomical focal areas, such as gamma-ray bursts, ultracompact binaries, supermassive black holes and the early Universe cosmology, and General Relativity.

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TOWARDS LARGER DEFORMABLE MIRRROS

A new type of large adaptive mirror is being developed by a consortium of TNO, VDL ETG Precision, Hyperion Technologies and Fraunhofer IPT. The adaptive mirror will be integrated in the University of Hawai'i's 2.2-meter telescope to demonstrate new key technologies. The system is currently in the development and manufacturing phase and is expected to be delivered in 2022.

STEFAN KUIPER, WOUTER JONKER AND MARK CHUN

Introduction

In ground-based astronomy, adaptive optics (AO) is a key technology for modern observatories, where it is used to enhance the image quality of a telescope by actively correcting for the blurring effect of atmospheric turbulence. The correcting element in these AO systems is a deformable mirror (DM), consisting of a thin mirror shell suspended on a grid of actuators that manipulate the shape of the mirror shell in real time.

Most AO systems used in astronomy nowadays utilise relatively small deformable mirrors that are located downstream from the main optical layout of the telescope in an instrument bay, receiving the light via several optical relays. However, there is a trend in astronomy to integrate the adaptive mirrors as part of the main optical layout of the telescope by integrating the corrective elements in the secondary mirror of the telescope, resulting in an Adaptive Secondary Mirror (ASM).

One of the main drivers is the fact that this secondary mirror is optically conjugated to the lowest layers of the atmosphere, referred to as the Ground Layer, which is typically responsible of most of the atmospheric blurring effects. Such ASM is therefore capable of effectively correcting for the blurring stemming from the Ground Layer over a large field of view. Furthermore, integrating the corrective elements in the main telescope structure significantly reduces the number of optical surfaces within the AO system, which leads to a higher optical throughput and less thermal background noise when observing in the infrared spectrum. The latter can reduce the required exposure times, enabling more science targets to be observed with the telescope through each night.

Currently, there are a number of telescopes in the world that have adopted such ASMs. The current state of the art is based on a floating thin-shell mirror, that is magnetically levitated above hundreds of voice-coil actuators, and position-controlled via an array of capacitive sensors. While showing impressive optical performance, these ASMs have not yet been widely adopted, mostly due to the high overall cost and complexity.

An industrial consortium comprising TNO, VDL ETG Precision, Hyperion Technologies and Fraunhofer IPT is developing a new type of ASM, based on an alternative actuator technology (further described below). These actuators have a high efficiency, enabling a relatively compact design of the ASM without active cooling that can be retrofitted within the same mass and volume of existing passive secondary mirrors (M2s). Due to the overall low complexity of this technology, it is inherently reliable, which is vital to ensure the required uptime of the telescope.

The consortium is currently working in close collaboration with the University of Hawai'i to develop such an ASM with the goal of demonstrating the technology on their 2.2-meter telescope (UH2.2); a CAD-rendering of this ASM is shown in Figure 1. The telescope is considered an ideal test site for this, given its moderate size, its location close to other observatories, and the fact that it already has substantial AO infrastructure, into which the ASM can be integrated.


1

UH2.2 Adaptive Secondary Mirror artist's impression. (Images: TNO)

AUTHORS' NOTE

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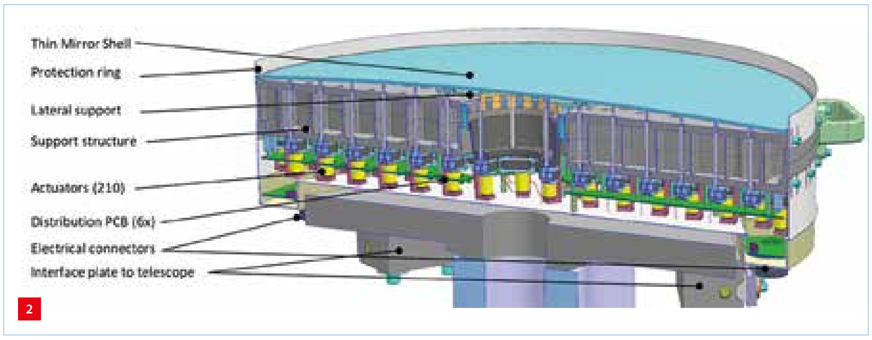
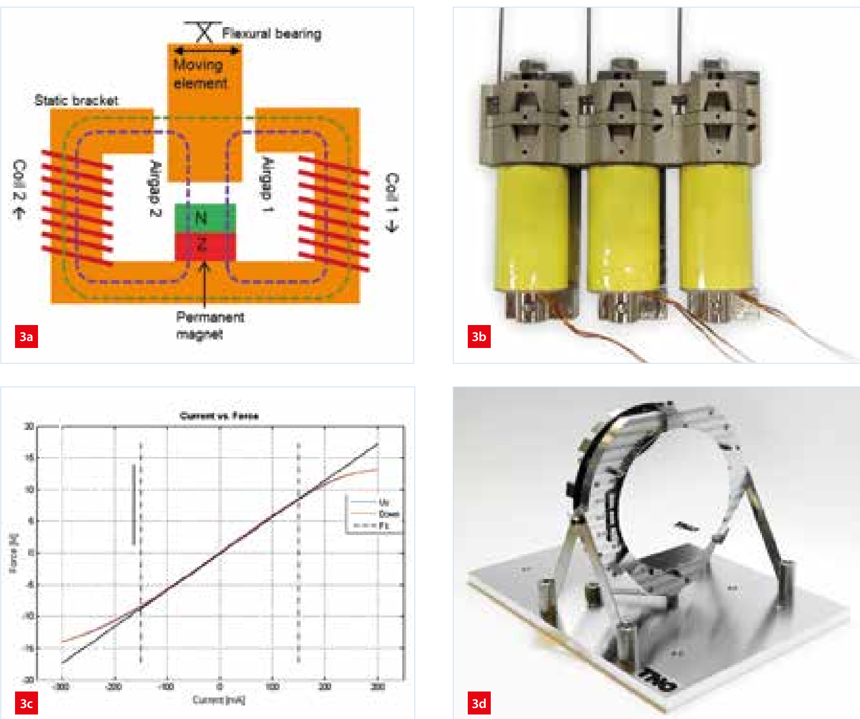


UH2.2 ASM cross-sectional view.

Furthermore, UH2.2 has a rotatable spider structure with two secondary mirrors, which allows the ASM to be installed on one of the positions (replacing the obsolete Coudé-focus secondary mirror), while maintaining the availability of the other passive M2.

Overall ASM design

A cross-sectional view of the ASM can be found in Figure 2. The mirror shell is a 620-mm-diameter, 3.5-mm-thick convex asphere, which is driven by 210 electromagnetic actuators in a circular grid. The actuators in turn are mounted on a light-weighted support structure. Flexural struts run from the mirror shell through the support structure to the actuators on the other side. Lateral movement of the thin-shell mirror is constrained by a lateral support located in the centre. The pulse-width modulation (PWM) current amplifiers are located in a separate electronics box away from the ASM. For diagnostics purposes, capacitive sensors can be placed at selected locations on the structure. However, for normal operation these are not required. Covers and seals protect the ASM from mechanical impact and dust.



Design of the electromagnetic actuator.
(a) Sketch showing the principle of the TNO variable-reluctance actuator. A permanent magnet generates a magnetic flux through a bracket and yoke of soft-magnetic material (dashed purple). When the moving element is in the central position, the magnetic fluxes to the left and right are in balance and the net force is zero. A current through the coils generates an additional magnetic flux in the yoke (dashed green), which creates a net force.
(b) Three TNO 18-mm-pitch variable-reluctance actuators.
(c) The measured force response of the 18-mm-pitch version of the actuators, showing the linear force range of ±8 N up to the point of magnetic saturation.
(d) A DM with 57 of the 18-mm-version actuators and a Ø160-mm, 1-mm-thick mirror shell.

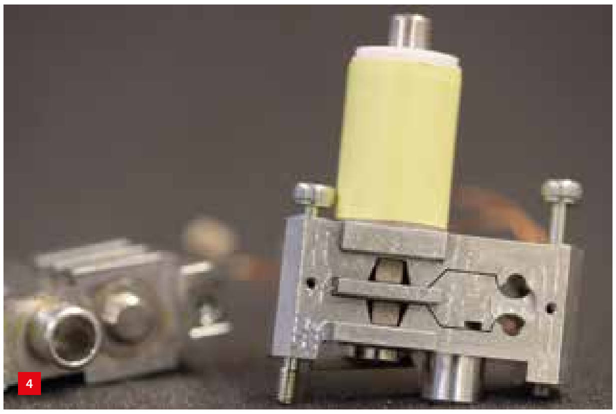
Actuator design

One of the unique characteristics of TNO's deformable mirror technology lies in the design of the electromagnetic actuator (Figure 3). This actuator is based on the hybrid variable-reluctance principle. It consists of a bracket and a moving element (yoke) made from a soft-magnetic alloy (orange). Two air gaps separate the bracket and the moving element. A permanent magnet provides a bias magnetic flux that travels through two separate paths – one through the left air gap and one through the right air gap (purple dashed lines in Figure 3a). When the moving element is centred between the gaps, the bias magnetic flux in both air gaps is equal and the magnetic forces on both sides are in balance (i.e., the net force is zero).

When applying a current through the coils, an additional flux path is created that goes around, crossing both air gaps (green dashed lines), thereby strengthening the flux in one air gap, while lowering the flux in the other air gap. This creates a force imbalance between the bracket and the moving element that is linearly proportional to the current applied to the coil. The motion of the moving element is stabilised via a flexural bearing of which the (linear) stiffness can be tuned to achieve the desired displacement range given the force output of the actuator.

The main advantages of these actuators are their demonstrated larger and more linear force output per unit volume and per unit power, as compared to alternative voice-coil actuators. The graph in Figure 3c shows the measured force response as a function of current for an actuator version with a spacing of 18 m x 18 mm. The 99.5% linear region between ±150 mA corresponds to a force output of ±8 N. The measured actuator efficiency is 38 $NW^{-1/2}$, which is around 40 times higher than that of a similarly sized voice-coil motor. These high linear force output and efficiency are particularly favourable for larger deformable mirrors, resulting in a system with large position strokes and low power dissipation; they facilitate relatively thick and thus robust mirror shells.

TNO has currently built three DMs based on the 18-mm-spacing actuators, as shown in Figure 3d. These DMs each contain 57 actuators in a rectangular grid and



Actuator for the UH2.2 ASM from an earlier test batch.

a 160-mm-diameter, 1-mm-thick mirror shell of fused silica. These DMs have been used in the framework of an ESA Technology Research Program, with the aim of studying the feasibility of AO in space telescopes, and to validate the use of AO in a free-space optical communication system. These DMs validate the performance of TNO's actuators/DMs in an environment with turbulence conditions significantly worse than at most astronomy sites.

The actuators used for the UH2.2 ASM are a further evolution of the 18-mm-spacing actuators, utilising the same magnetic circuit but with a modified mechanical interface. Actuators out of a test batch (Figure 4), as co-developed and produced by VDL ETG Precision, are used to verify the performance and manufacturability of these actuators.

The actuators are attached to the thin-shell mirror via thin struts that are compliant in the lateral directions, but stiffly transmit the actuator forces. This design for the strut interface thereby allows the mirror shell to thermally 'breathe' with respect to the rest of the system, which helps to minimise the thermally induced wavefront error (WFE). This strut is interfaced to the actuator via an internal flexural lever arm, which amplifies the linear force output of ±8 N generated by the magnetic circuit with a factor 2.6. The measured displacement range on the struts is 35 μm peak-to-valley.

Thin-shell mirror

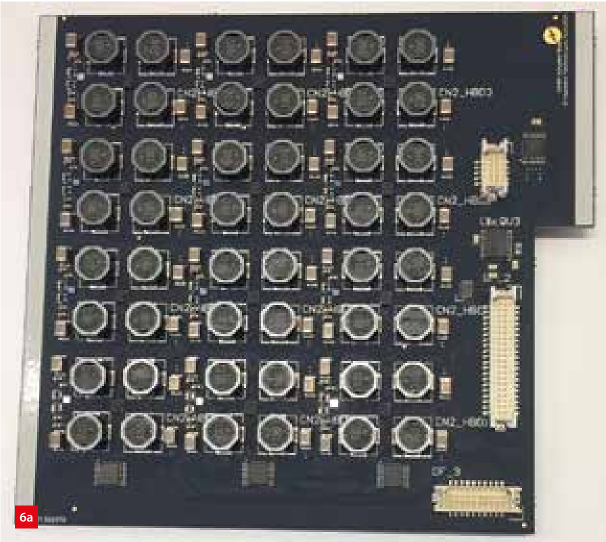
The mirror shell of the UH2.2 ASM is 3.5 mm thick; it is brought into its aspherical convex shape by using a hot-forming technique called 'slumping', in which a flat glass blank is heated in a mould until sinking into its final shape under its own weight. The slumping process for the UH2.2 ASM mirror is being developed by Fraunhofer IPT. The slumping mould is shown in Figure 5a. With a proper mould design, cleanliness and a precisely tuned time-vs-temperature curve, the glass blank follows the low-spatial-frequency shape of the mould while retaining the high-spatial smoothness of the input material. With a glass blank of high surface quality, any residual low-frequency shape error after slumping can simply be corrected with the actuators.

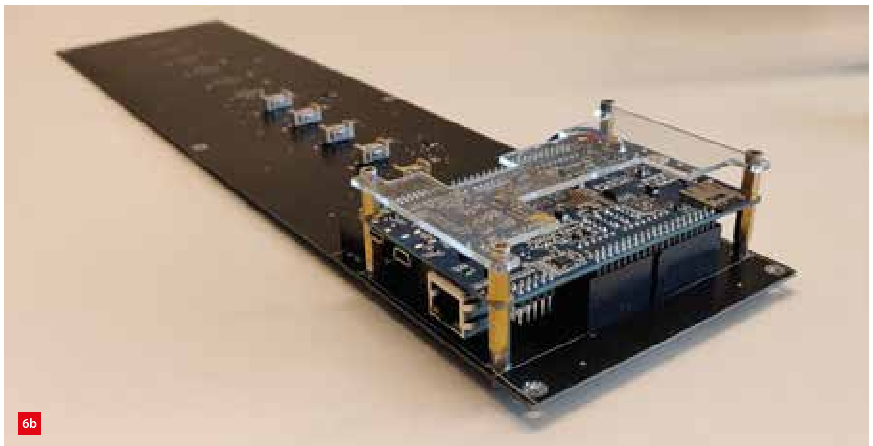
Several iterations are foreseen to tune the process parameters in order to get the mirror shape within the correctable range of the actuators. One of these slumped mirror shells is shown in Figure 5b. To guide this process development and verify the mirror shape, TNO makes use of the optical probe metrology tool named NMF600 S (Figure 5c) by Dutch United Instruments (DUI), which has successfully industrialised and commercialised the initial Nanomefos prototype developed by TNO.

This slumping process requires a considerably lower machining effort than conventional methods of mirror manufacturing, which are based on grinding and polishing starting off with a thick piece of glass. Slumping works particularly well with glass blanks of a higher thickness, which is an excellent match with the variable-reluctance DM actuators, as they are strong enough to deform such a thick shell.

After slumping, the mirror shell will go through a fine-polishing step to compensate for mid- and high-spatial-frequency shape errors of the mirror that cannot be

Thin-shell mirror production.
(a) Slumping mould as produced at Fraunhofer IPT.
(b) Fit check of the slumped mirror shell into the coating tooling.
(c) Mirror shell being measured with the DUI NMF600 S optical probe system.





Amplifiers for the DM actuators.
(a) PCB with the PWM amplifiers that each drive 24 actuators (dimensions 129 mm x 118 mm).
(b) Backplane PCB with the FPGA that will send actuator commands to 12 driver board PCBs, totalling up to 288 output channels.

compensated by the actuators. This fine-polishing step will be guided by the NMF600 S measurements. The goal is to reach a mirror surface error smaller than 20 nm rms, after compensating the lower spatial deformations with the actuators. As a final step, the mirror shell will be coated with a protective aluminium coating, using TNO's in-house coating facilities. The tooling to support the mirror shell in the coating chamber is shown in Figure 5b.

Electronics

While the previous generations of these DM actuators were driven by linear amplifiers, the UH2.2 ASM will be driven by PWM amplifiers, which have higher efficiency and thus an even lower power dissipation. Consortium partner Hyperion Technologies developed the new amplifiers for laser-communication applications and adapted them specifically for this project.

The output currents are 300 mA maximum, at less than 1 Volt. These PWM drivers are integrated on PCBs with 24 channels each, measuring 129 mm x 118 mm (Figure 6a). Twelve of these driver PCBs are interfaced via a backplane board (Figure 6b), totalling up to 288 output channels. The backplane contains an FPGA (field-programmable gate array) that receives the actuator commands from the real-time AO controller via a Gigabit Ethernet port.

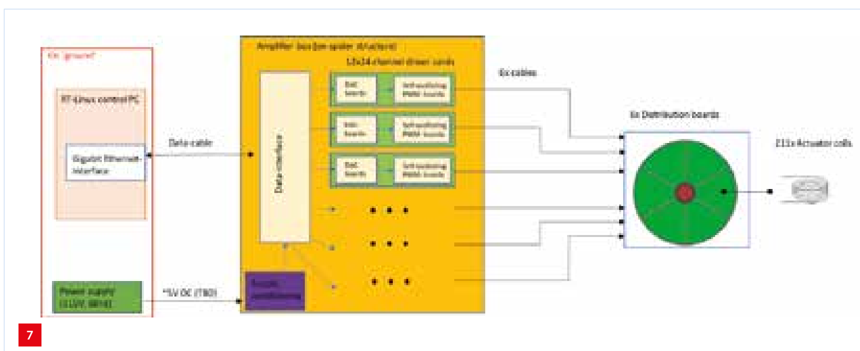
The high-level electronics architecture is shown in Figure 7. The total power dissipation when powering 210 actuators is around 20 Watt. As a result of their compactness and low-power dissipation, the PWM drivers can be stowed in the backside of the ASM without requiring active cooling. This limits the cables that go over the telescope structure towards the top-end to only a power and a data cable. The output currents of the drivers will be routed to the individual actuators via six cables and six distribution PCBs that are mounted on the backside of the ASM.

Performance analysis

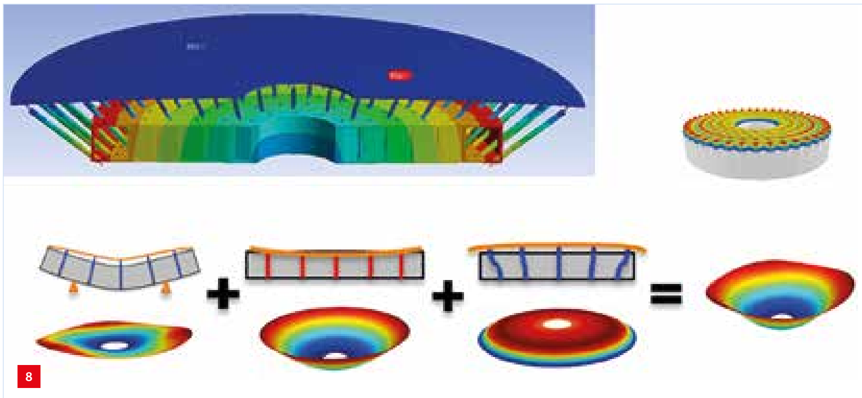
One of the main challenges in the design of the ASM was to maintain a high optical quality while being exposed to the elements at the top-end of the telescope. This includes a wide operational temperature regime from +20 °C down to –10 °C, and a changing gravity orientation when the telescope is moving in elevation. These thermal and gravitational effects are driving the design of the ASM, and have been extensively studied during the design process.

Figure 8 shows the thermal deformation of the structure as modelled with finite-element modelling (FEM), showing how the strut interface between the actuators and the mirror enables the thermal 'breathing' between the mirror shell and the support structure. After compensation of the lower spatial deformations with the actuators, the residual mirror deformations are quantified to be less than 3 nm rms over the maximum temperature excursion of 30 °C.

In full AO mode, the system is running in feedback over the wavefront sensors, and thus the low-spatial deformations of the mirror can be compensated in closed loop via the



High-level diagram of the electronics architecture for sending actuator commands to the ASM.



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FEM modelling of the thermal deformation of the ASM structure and the effect on the mirror surface after compensating the lower spatial deformations with the 210 actuators (top right).

actuators. In this AO mode, the 'best-flat' performance requirement is set to $\lambda/15$ WFE (@630 nm), which corresponds to ~21 nm rms Surface Form Error (SFE). Furthermore, the ASM should also enable static mode operation, in which a reasonable optical shape is maintained without continuous feedback from the wavefront sensor. For such static mode operation, a target WFE requirement is set at $\lambda/4$ (corresponding to 80 nm rms SFE) over its entire operating range. In this static mode operation, the thermal and gravitational effects will be compensated in open-loop based on pre-calibrated look-up tables.

Based on the FEM modelling results, an SFE budget was obtained as shown in Table 1. In this table, the mirror deformations are decomposed in (i) a focus term that can be compensated by a separate refocusing stage in the telescope, (ii) the low-spatial deformations that can be corrected by the 210 actuators, and (iii) the high-spatial deformations that cannot be corrected by the actuators. For the static mode operation, the conservative assumption is made that the pre-calibrated compensation of the low-spatial deformations is effective up to 90%. This results in a worst-case optical shape quality of 72 nm rms SFE (second-to-last row in Table 1). In full AO mode, the lower-spatial deformations are fully compensated in closed loop, resulting in a worst-case mirror deformation of 21 nm rms SFE (last row in Table 1). The latter is mainly driven by the targeted polishing quality of the mirror shell.

Breadboarding

As a kind of precursor of the UH2.2 ASM and other larger systems, TNO built a testbed DM system (Figure 9), consisting of a Ø150-mm mirror with 3.5 mm thickness and 19 of the UH2.2-style actuators. This DM has been extensively tested at the University of California Santa Cruz in the Lab for Adaptive Optics (UCSC-LAO). These tests showed good agreement with the modelling in terms of actuator stroke, linearity and power consumption. In parallel, also lifetime tests and corrosion tests have been performed to verify the long-term survival of these actuators in a telescope's operational environment. These results provided good understanding and confidence, which will be conveyed to the development and testing of larger ASMs such as the UH2.2 ASM and beyond.

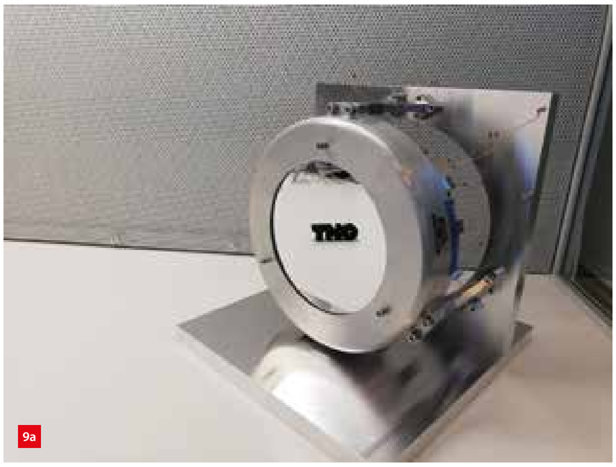
Bonding and integration

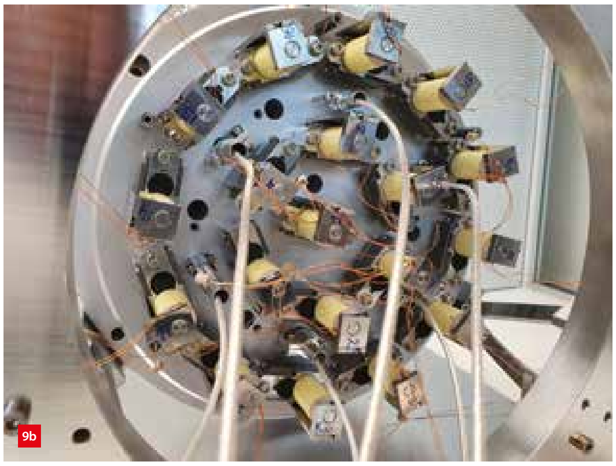
One significant challenge in the realisation of the UH2.2 ASM is the bonding process in which the mirror shell is interfaced to the actuators. This process needs to deliver more than 200 reliable bond connections that are strong enough to transmit the actuator forces over several years of operation. This bonding process is currently under development at TNO. Besides the bond strength, also aspects such as print-through towards the optical surface have been analysed and verified by measurements on the 19-actuator test bed.

Table 1
Surface Form Error (SFE) budget for the UH2.2 ASM.

	Focus	Low-spatial frequencies SFE (correctable)			High-spatial SFE	Totals
		Initial (uncorrected)		Calibrated correction (90%)	(uncorrectable)	
	pv (nm)	pv (nm)	rms (nm)	rms (nm)	rms (nm)	rss (nm)
Initial shape error	3,000	6,000	630	63	20	
Thermal effect at dT = 30 °C	3,450	490	78	8	3	
Gravity effect	631	1,230	280	28	3	
Unpowered - target 633 nm SFE (2λ WFE)			689		21	690
Static mode - target 80 nm SFE (λ/4 WFE)				69	21	72
AO mode - target 21 nm SFE (λ/15 WFE)					21	21

rss = residual sum of squares
pv = peak-to-valley
rms = root mean square





19-actuator testbed DM system.
(a) Front view.
(b) Backside view with the actuators.

During the bonding process, the mirror shell needs to be supported in such in a way that, after bonding, the mirror shape is well within the correctable range of the actuators. Given the position range of the actuators of 35 µm peak-to-valley, the design target is to keep the initial mirror shape errors within 10 µm. Given the aspherical convex shape of the mirror shell, this is not a trivial task.

To this end, special integration tooling was developed by TNO and realised by West End Machinefabriek, as shown in Figure 10. This tool contains 18 adjustable supports for the thin shell mirror which can be accurately positioned based on the feedback of a coordinate measurement machine. During the bonding process, the support frame is lowered down to several millimeters above the mirror shell via a linear guidance, allowing accurate bonding of the struts to the mirror shell and actuators. After bonding, the entire assembly is lifted from the integration tooling via the same linear guidance.

Assembly tooling for the UH2.2 ASM as built by West End Machinefabriek.

Outlook

At the time of writing of this article, the components of the UH2.2 ASM are being produced, including the actuators and structural components at VDL ETG Precision, the electronics at Hyperion, and the mirror slumping at Fraunhofer IPT. The goal is to have all components ready for integration in 2022.

After assembly, the UH2.2 ASM will undergo several performance and functionality tests at TNO in Delft (NL), before being shipped to Hawai'i for integration on the telescope. This will mark the start of the on-sky test campaign, where the ASM performance will be thoroughly verified and demonstrated in a real-world observatory setting. The ASM will become a permanent part of the observatory and will remain in use for many years to contribute to the scientific goals of UH2.2.

INFORMATION
WWW.DUTCHUNITEDINSTRUMENTS.COM
WWW.HYPERIONTECHNOLOGIES.NL
WWW.IFA.HAWAII.EDU
WWW.IPT.FRAUNHOFER.DE
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WWW.WESTENDBV.NL

SILICON PORE OPTICS FOR THE LARGEST X-RAY MIRROR

Dutch industry is developing Silicon Pore Optics (SPO); a new modular X-ray optic for the European Space Agency (ESA). Employing processes and mass production equipment from the semiconductor industry, small plates diced from silicon wafers are combined into the largest focusing X-ray mirror. It is a mission-enabling component of ESA's space-based X-ray observatory Athena, which is scheduled for launch in the (early) 2030s. This article presents the production process and discusses the challenges in meeting both the optical quality and mass-production requirements.

LAURENS KEEK (ON BEHALF OF THE SPO COLLABORATION)

Introduction

With a cost of over €2 billion, ESA aims for the large-class mission Athena [1] to be the largest X-ray observatory ever flown in space (Figure 1). As the successor to XMM-Newton (launched in 1999), Athena is expected to perform break-through astrophysical research. This research can only be performed in space, because the Earth's atmosphere efficiently absorbs X-rays. In X-rays one observes high-temperature environments of over a million degrees.

To perform the X-ray observations, Athena will host two detectors. The Wide-Field Imager (WFI) will take a census of the super-massive black holes at the centres of far-away galaxies, in order to trace how galaxies are distributed. The X-ray Integral Field Unit (X-IFU) will study the hot gas in between clusters of galaxies. This gas is thought to comprise the majority of the baryons in the universe; X-IFU will study its motion and chemical composition in unprecedented detail. X-IFU is being developed with participation from SRON Netherlands Institute for Space Research (see next article).

AUTHOR'S NOTE

Laurens Keek is a senior scientist in the High-Energy Optics business unit of cosine in Warmond (NL); cosine combines physics and engineering to create more and better measurement solutions that find their way into society faster.

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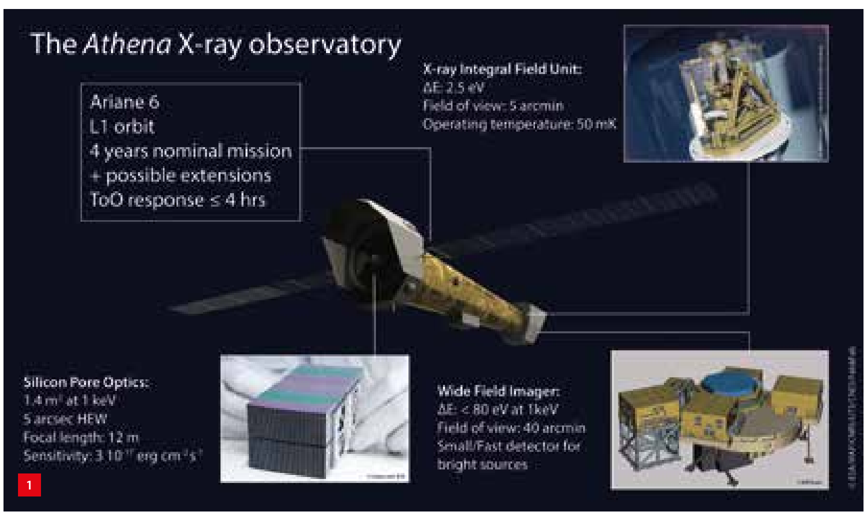


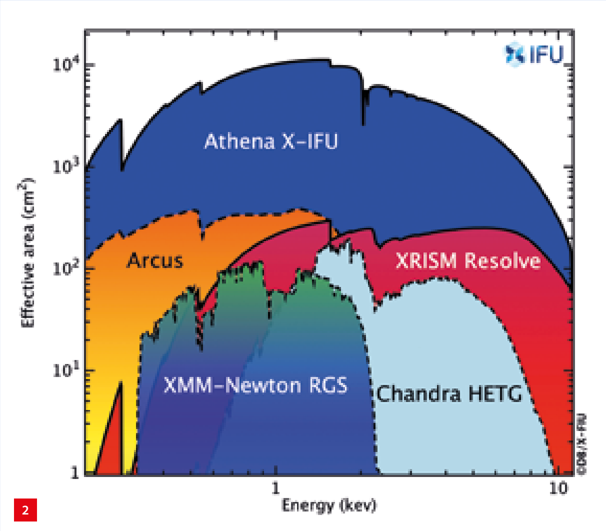
Overview of the Athena mission. (Image credits: IRAP/CNRS/UT3/CNES/Fab&Fab/ESA (satellite); IRAP/CNRS/UT3/CNES/Fab&Fab (X-IFU); WFI Team (WFI); and cosine & ESA (SPO))

The large field-of-view and high spectral resolution of the two instruments can only be used if a large number of X-rays are collected, using a 2.5-m diameter optic with a 12-m focal length. The focusing of X-rays presents a particular challenge, because under normal incidence X-rays simply pass through a mirror. Only through grazing incidence are X-rays reflected. This is achieved in the so-called Wolter telescope designs [2], which are shaped like a shell where each X-ray is reflected twice to form an imaging optic. Concentric shells can be nested to increase the collecting area of the telescope, as long as a small space is left between the shells for the X-rays to travel within a few degrees of the mirror surface. NASA's Einstein mission (1978) was the first to employ such a focusing X-ray telescope.

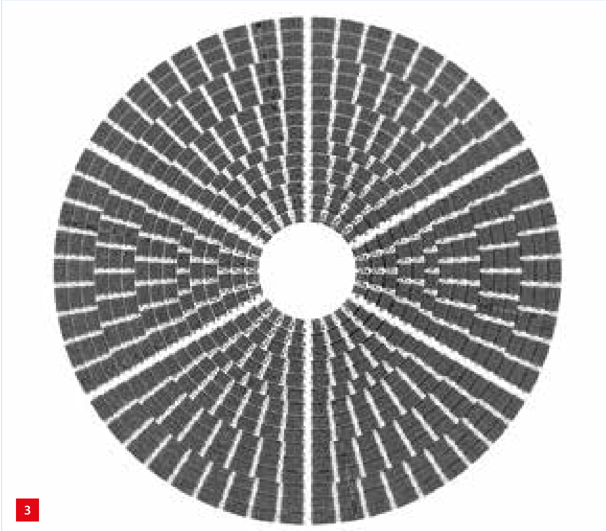
ESA's current flagship X-ray observatory, XMM-Newton, has three telescopes each consisting of 58 shells. The shells are made of nickel with a thickness of 0.47 mm to 1.07 mm. This technology cannot be scaled to the size required for Athena, as the relatively high mass of the nickel shells limits the total achievable mirror size that can be launched into space. Alternatively, mirrors have been produced out of foil (e.g., 170 μm thickness for the Japanese Hitomi mission), but with substantially reduced optical quality.

Mirror design

SPO is being developed for Athena as a new technology to create a focusing optic with an order of magnitude larger collecting area (Figure 2; see also [3]), whilst being much lighter than any existing X-ray mirror technology. The development is led by ESA/ESTEC in Noordwijk (NL) and performed by cosine in Warmond (NL) and Micronit Microfluidics in Enschede (NL), with contributions from SRON in Leiden (NL) as well as from other academic and industry partners across Europe.



Effective mirror area of the Athena SPO optics in combination with the X-IFU detector as a function of the energy of the X-rays. Athena provides over an order of magnitude improvement over current flagship missions XMM-Newton (ESA) and Chandra (NASA) as well as future missions Arcus (NASA) and XRISM (JAXA). Both Athena and Arcus will employ SPO as the mirror technology. (Image credits: X-IFU consortium)



642 SPO mirror modules are mounted in 15 concentric rings to form the mirror assembly of Athena. Alignment of the modules will be performed in a facility in Italy that is being constructed specifically for the Athena mission. (Image credits: cosine)

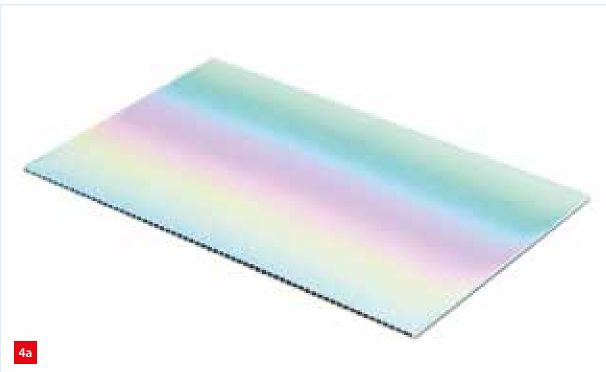
SPO is a novel class of X-ray mirror, as it segments the large optic into many smaller lenses (modularisation) and introduces a mass-production approach that is unprecedented for space missions [4]. At 110 μm, the SPO mirrors are thinner than Hitomi's foil optics. The application of stiffening ribs enables SPO to improve on the optical quality of XMM's nickel shells. Furthermore, due to a modular design, the production process is changed from making full shells to making segments.

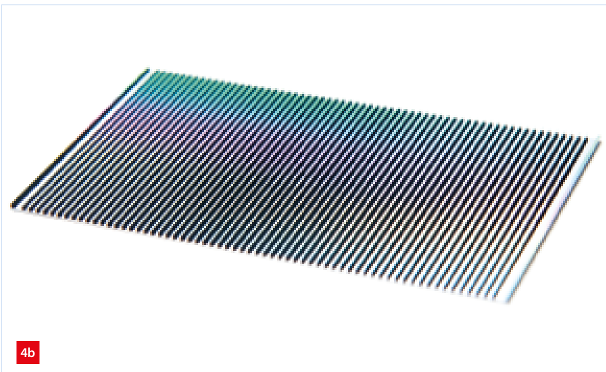
The Athena optical design needs ~300 m^2 of mirror surface, which is divided into about 90,000 small mirror plates. The plates are stacked and combined into 642 mirror modules, i.e. 642 X-ray lenslets. For Athena, the mirror modules are mounted in 15 concentric rows and co-aligned to a common focus at a distance of 12 m (Figure 3). This is the equivalent of 540 XMM shells, and provides an effective collecting area of 1.4 m^2 for a photon energy of 1 keV.

Production

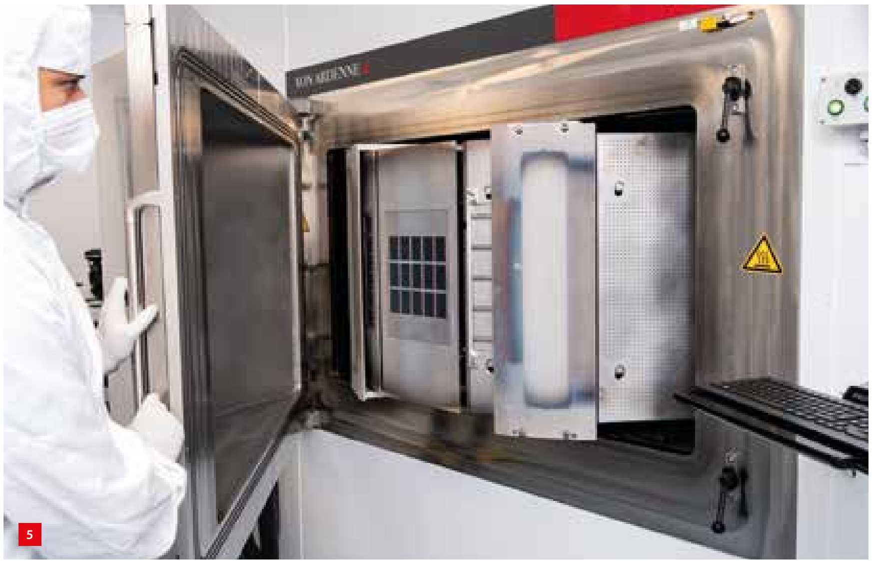
Production of SPO mirror plates starts with commercially available silicon wafers with a diameter of 300 mm and a thickness variation of less than 100 nm [5]. The wafers are diced into rectangular plates (Figure 4). At the back of the plates, the thickness is reduced by a mechanical process from 0.775 mm to a 110 μm membrane, with the exception of 'ribs' at 2.3 mm intervals. When the plates are stacked on top of each other, the ribs provide the support structure, and the open space between the ribs is referred to as the pores. Using wet-chemical etching, a wedge shape is introduced into the plates with a small angle of 3 arcsec. The achieved angle must be accurate within 1% to ensure that the stacked plates all focus X-rays at precisely the same point. The plate production is performed by Micronit Microfluidics and by Teledyne e2V in the UK.

When the plates are delivered to cosine in Warmond, visual inspection of each plate is performed. Plates are

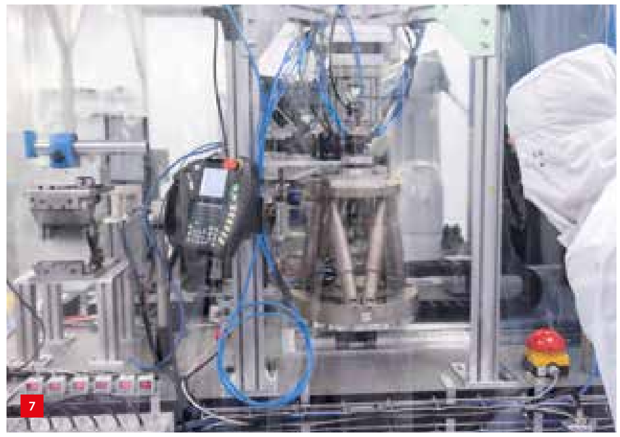




An SPO mirror plate. (Image credits: cosine)
(a) The side where the thin membrane reflects X-rays. The colour pattern appears due to the wedge shape of the plate.
(b) The bottom of the plate, where ribs have been carved into the silicon. When plates are stacked, the space between the ribs forms the pores.



Loading of SPO plates in the magnetron sputtering system for coating with iridium. Due to its high atomic number, the iridium layer increases the fraction of X-ray photons that are reflected by the mirror. This is especially important at photon energies in excess of 2 keV. The coating, therefore, extends the energy range of the telescope. (Photo: cosine)



Custom robots for the assembly of SPO mirror stacks in the cleanrooms at cosine. Inside the down-flow tent, the mandrel is mounted on a hexapod, on which the stack is assembled by the robot. Four stacking robots are operational for development in preparation for mass production. (Photo: cosine)

subsequently coated with a thin layer of iridium, which enhances the X-ray reflectivity (Figure 5). Next, a fully automated wetbench cleans the plates in preparation for stacking, using a chemical bath to remove particle contamination (Figure 6).

Stacking of the mirror plates is performed using custom developed robots inside a cleanroom (Figure 7). The first plate is pressed against a high-precision mandrel with the design shape. Subsequent plates are placed on top. The ribs of a plate adhere to the lower plate through direct silicon bonding, facilitated by the activation step in the cleaning process. A total of 35 plates are combined in one stack

The highly automated wetbench at cosine, where SPO plates are cleaned and activated prior to being assembled in mirror stacks. This prevents contamination that would reduce the bond strength of the plates, while particles trapped between bonded plates would significantly degrade the optical quality. (Photo: cosine)

(Figure 8). To prevent particle contamination, no technicians are present in the cleanroom during production. Instead, the robots are operated from a control room. Shape metrology is performed after the addition of each plate to a stack, which provides detailed quality control.

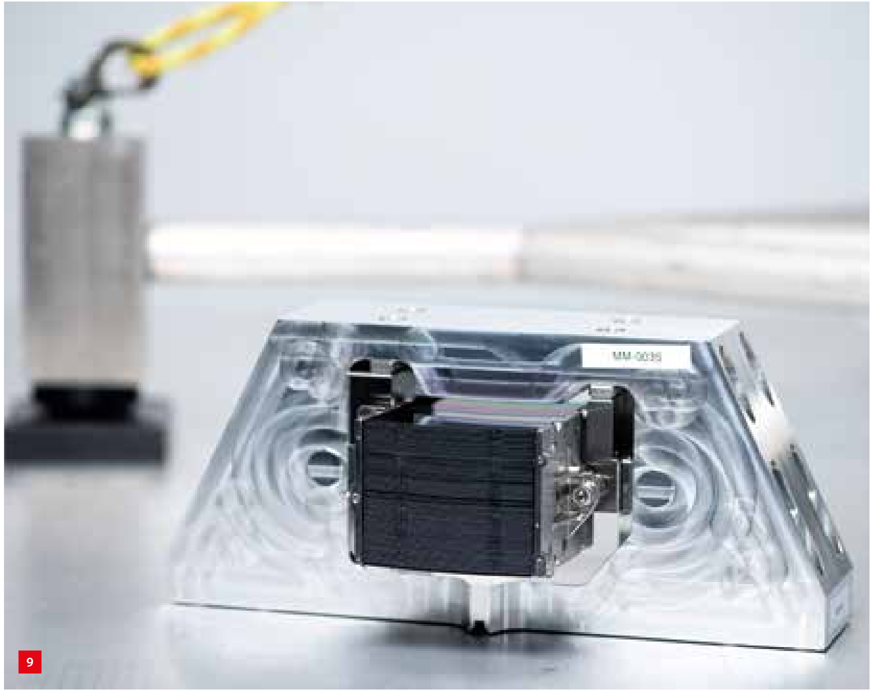
Four stacks are glued into brackets to form a mirror module [6]. The optical quality of the modules is assessed in X-ray beamlines used by cosine for ESA at synchrotrons in Berlin and Barcelona. Finally, mirror modules are subjected to shock and vibration tests to ensure that they are sufficiently strong to survive the rocket launch (Figure 9) [7].

Mission status

The Athena mission is currently in phase B1, where technology is developed to the level required for the Mission Adoption Review (MAR) to take Athena into phase C (building). Efforts are now concentrated on establishing both the optical quality of the SPO mirror modules, as well as a mass-production chain to reliably produce them on time and within specifications [8]. In parallel, the detector designs and technologies are being readied.

Five stacks of SPO mirror plates produced for a test pilot production run. Each stack consists of 35 mirror plates. The colour sheen on top of the stacks is caused by the wedge shape of the plates, which aligns all plates to reflect X-rays to a common focal point. (Photo: cosine)

Next year, ESA will perform the MAR of all components of Athena, and propose the mission for adoption to the Science Programme Committee (SPC). After adoption, the detectors, optics and spacecraft will be produced. Launch is planned to take place in the early 2030s. Athena will be the engine of discovery for a generation of X-ray astrophysicists from around the world, with the Netherlands not only providing the enabling optics but also contributing to a revolutionising detector. Moreover, SPO is already being requested for NASA candidate X-ray missions, and is also further developed by cosine for medical and other applications.



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Shock tests at cosine with a set-up built to ESA specifications. When the weighted hammer (seen in the background) impacts, a shock propagates through the table. A mounting block bolted to the table transfers the shock to the mirror module consisting of four SPO stacks. High-speed cameras monitor the mirror module and record the tests. (Photo: cosine)

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CATCHING X-RAY PHOTONS

On board the European X-ray observatory Athena, to be launched in the (early) 2030s, are two complementary instruments. The Wide Field Imager (WFI) makes high spatial and temporal resolution images with limited spectral resolution, while the X-ray Integral Field Unit (X-IFU) provides high-resolution spectra at limited spatial resolution. During operation, the Athena mirror module will be tilted so that either the WFI or the X-IFU instrument receives the focused X-ray beam. In this article, the WFI instrument is briefly discussed, while the focus is on the development of the X-IFU instrument, to which SRON makes a large contribution.

RUUD HOOGEVEEN (ON BEHALF OF THE X-IFU TEAM AT SRON)

The ESA Athena mission [1], the second L-class mission of the Cosmic Vision programme, is dedicated to study the hot and energetic Universe. Hot and energetic, as it detects X-ray photons in the range of 0.2 to 15 keV, emitted by the million-degree-hot gas of the intergalactic medium and the gas close to the event horizon of black holes. The specially developed mirror, consisting of Silicon Pore Optics (see the previous article), focuses the X-rays onto one of the two complementary science instruments on board: the Wide Field Imager (WFI) or the X-ray Integral Field Unit (X-IFU).

AUTHOR'S NOTE

Ruud Hoogeveen is a senior instrument scientist at SRON Netherlands Institute for Space Research, located in Leiden and Groningen (NL). SRON's mission is to bring about breakthroughs in international space research. The institute therefore develops pioneering technology and advanced space instruments, and uses them to pursue fundamental astrophysical research, earth science and exoplanetary research.

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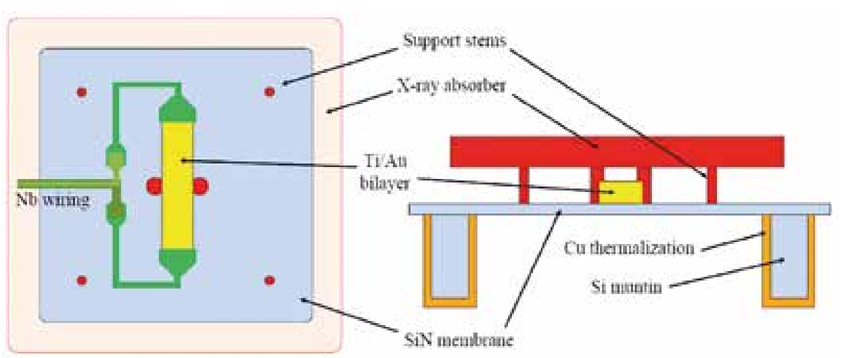
The WFI consists of a 1-Mpixel camera featuring a large field of view and high spatial resolution oversampling the mirror's point spread function, a high count rate (200 frames per second standard, up to 12,500 frames per second for the Fast Detector), and a moderate spectral resolution. The camera consists of one million p-channel MOSFET pixels integrated onto a fully depleted silicon bulk. Spectral resolution is obtained by the fact that the number of generated electron-hole pairs is proportional to the X-ray photon energy. The WFI is being developed under the leadership of the German Max Planck Institute for Extra-terrestrial Physics.



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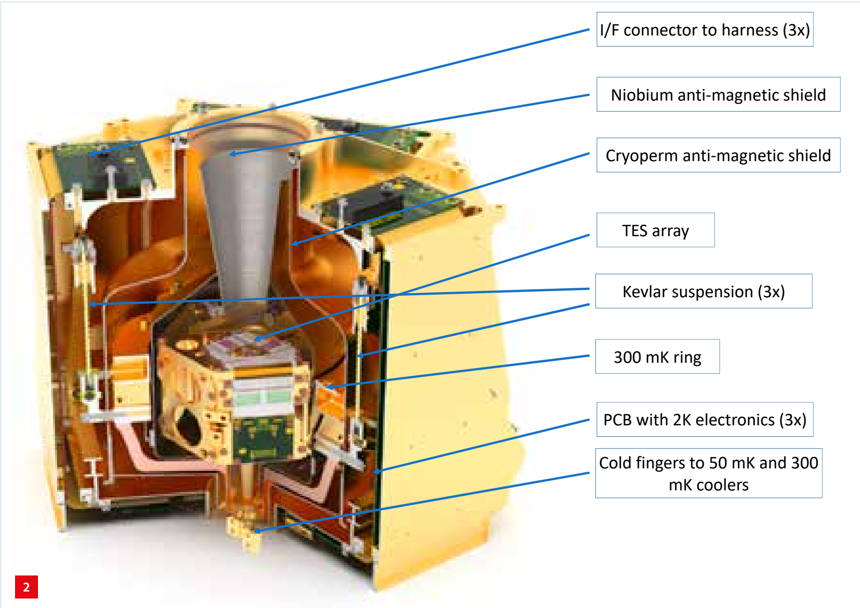
Schematic overview of a TES pixel with (on top) the X-ray absorber (gold and bismuth), relaying the heat via two gold stems to the TES sensor that is placed on a SiN membrane. Four extra stems to the membrane support the absorber. Niobium leads connect the TES to the read-out circuit. Typical sizes are 275 µm pitch for the pixels, and 5 µm thickness for the absorbers. The membrane is typically 0.5 µm thick, while the Si wafer is 300 µm thick.

The X-IFU instrument, with main contributions from France, the Netherlands, USA and Italy, focuses on the high spectral resolution of the incoming X-ray photons. A nice animation of X-IFU can be found online [2]. X-IFU employs 3,200 pixels based on micro-calorimeters. Its operational principle (Figure 1) revolves around the Transition Edge Sensor (TES). The TES is a bilayer of superconducting molybdenum or titanium, in combination with gold, deposited on a thin membrane. By adjusting the thickness of both layers, the sharp transition temperature between the superconducting state and the normal state can be tuned to about 100 mK. The bath temperature of X-IFU will be about 50 mK.

Detection principle

The TES is biased in the lower part of its superconducting transition region using a voltage. When an X-ray is stopped in the bismuth absorber, the photon energy is converted into heat and conducted via the gold layer under the bismuth to the TES. The TES warms up and increases its resistance. This is detected as a reduction of the bias current. Signal amplification is achieved with a first-stage SQUID (Super Conducting Quantum Interference Device) current amplifier at 50 mK, a second-stage SQUID amplifier at 2 K (developed by VTT, Finland), and finally a conventional amplifier in the warm 300-K electronics.

A major advantage of the voltage bias is that the ohmic heating of the TES is reduced during an X-ray detection, bringing the TES back to its nominal operating temperature much faster. In this way, the detection of an X-ray pulse takes about 1 ms. By integrating the pulse signal, the energy of a 7 keV X-ray photon can be determined with about 2.5 eV resolution, resulting in a relative resolution of about 2,500. Obviously, this can only be obtained by a very low-noise signal chain. The TES array for the X-IFU mission



Drawing of the SRON-developed Focal Plane Assembly Demonstration Model for the X-IFU instrument. The outer part is at 2 K and contains part of the cold electronics, including the second-stage amplifier SQUIDs. The inner part is at 50 mK and contains the TES detector array and the multiplexing electronics. Two shields are visible that reduce the magnetic fields from both the Earth, and from other parts of the Athena spacecraft. Between the shields a 300-mK ring is visible. The Kevlar suspension between 2 K and 300 mK is just visible left and right. A similar suspension between the 300-mK stage and the 50-mK stage is not visible. At the lower side, there are two cold fingers to the sub-K coolers. On top, there are three interfaces to the electrical harness, and the open field of view towards the optics. The FPA fits in a cube with ribs of 280 mm.

is being developed by NASA Goddard Space Flight Centre, while the SRON cryogenic and lithographic departments serve as an alternative source for the TES array.

It is clear that the 3,200 pixels of the focal plane need multiplexed read-out. With time-domain multiplexing (TDM), an array of 34 first-stage SQUIDs is employed. All pixels are biased, and at 6 MHz the pixels are selected for amplification and read-out. A total of 96 of these arrays are foreseen. The US NIST (National Institute of Standards and Technology) is developing the multiplexing SQUID arrays.

Parts of the FPA Demonstration Model. Upper left is the niobium shield, middle left the 50-mK assembly, and lower left the cold finger; the second row from the left shows the three parts of the 300-mK stage; on the right half, the 2-K parts, with the triangular Kevlar suspension (one of three).

Complicated cooling chain

Having a detector working at 50 mK in space is a real engineering challenge. Obviously, this requires both a complicated cooling chain, as well as a complex cryostat. Cooling is provided by multiple two-stage pulse-tube coolers going to 4 K, Joule-Thompson coolers, a helium sorption cooler and an adiabatic demagnetisation refrigerator. The cryostat is like a Russian doll, with a vacuum vessel at room temperature (typical size of 1.2 m), and thermal shields at 100 K, 30 K and 4 K.

In the centre of the cryostat is the so-called 2K core, consisting of the two sub-Kelvin coolers taking the temperature down from 2 K to 300 mK and 50 mK, and the Focal Plane Assembly (FPA). The FPA is being developed by SRON; see Figure 2 for a schematic overview and Figure 3 for a photograph of actual parts. One of the main challenges is to thermally isolate the 50-mK stage with the detector, the multiplexing SQUIDs and other cold electronics from the 2-K structure and interface plane, while securing a stable suspension that survives the launch loads. For this, an elegant two-stage suspension by Kevlar wires has been developed [3].

Mission status

At the moment, a Demonstration Model of the FPA is being tested in one of the SRON test cryostats. In parallel, the Engineering Model is being designed and will be realised and tested in the coming three years. It will as much as possible be representative for the Flight Model, although not all pixels will be read out. Finally, all lessons learned will be included in the design of the Flight Model. Three such models will be realised: the Qualification Model, the Flight Model and the Flight Spare Model.

Performing space research requires stamina. In the case of Athena, this certainly holds for both the mirror developments as well as the TES sensor development. Both already have about 25 years of history. But with the launch ten or more years from now, all teams around the world can increasingly focus on the final design and realisation of the mission. We are definitely moving from the research phase into the engineering phase. Exciting times are ahead of us.

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Indoles Precision – the Art of Precision Positioning

Indoles Precision is a platform for users and suppliers of products for applications in which accurate motion and positioning is crucial. Indoles creates an environment that enables a targeted and effective exchange about requirements and solutions. In this process, humans are the main factor, and therefore Indoles' motto is "how can we help each other?" Indoles is Latin for 'inborn quality', which reflects the drive to bridge the gap between technology-driven supply and application-driven demand.

XYZ linear piezo stage with 2-nm encoder, by Precibeo.

The company was founded in 2016 with the purpose of filling a gap in the communication between the manufacturers of accurate positioning products and users in the research field and the OEM equipment industry. This gap exists because manufacturers concentrate typically on making top-level products, driven by what the technology allows for (i.e. technology-driven). The users, however, would primarily like to have their positioning problem solved. No matter how technology minded and interested the customers are, their focus is usually on guaranteeing the performance and reliability of the end-product (i.e. application-driven). Indoles in Latin means 'inborn quality', which reflects Indoles' services in helping to bridge this gap and guaranteeing first-class solutions.

Portfolio

Within the range of precision-positioning, piezo technology is one of Indoles Precision's focus areas, with solutions covered by the following product groups:

- Piezo-stack actuators and stages:
  Piezo-stack-based stages for 1D, 2D or 3D motion. Their technical advantages are large sensitivity in combination with stiff and compact mechanics, allowing for high motion bandwidths and nanometer accuracies.
- Piezo stick-slip stages:
  Compact stages with piezo stick-slip propulsion. Their main advantages are self-locking, medium stroke (up to 15 mm) and step positioning in the sub-micrometer range. Applications in ultra-high vacuum or the 4-K regime are possible as well.
- Piezo LEGS stages:
  Linearly driven piezo-motor stages. Their main advantages are the relatively high driving force in combination with a centimeter-range stroke and an integrated position encoder. The joy-stick operation is ideal for research applications, but OEM solutions are also possible.
- Piezo rotary drives:
  Piezo-based rotation drives using the travelling-wave principle. The motors are compact, yet have a large torque and therefore are highly suitable for direct-drive solutions in limited spaces. This technology also allows easily for non-magnetic and ultra-high vacuum applications.

Services

Indoles Precision supplies the stages and drives mentioned above, while also offering application development and engineering support. Indoles Precision offers advice concerning the right solution to best fit its customers, which could be either piezo technology or one of various alternative technologies.

Piezo-driven miniature 1D stage, with 3.5 mm travel range and dimensions of 15 mm x 15 mm x 7 mm, by Mechonics.

INFORMATION
WWW.INDOLES-PRECISION.NL

Please check for any rescheduling, online reformatting or cancellation of events due to the coronavirus crisis.

10-11 November 2021, Den Bosch (NL)

Precision Fair 2021

The Benelux premier trade fair and conference on precision engineering, organised by Mikrocentrum. The theme of this 20th anniversary edition will be: Precision technology, the next 20 years. This year, Belgium will be the partner country. See the fair preview on page 42 ff.

WWW.PRECISIEBEURS.NL

15 November 2021, Düsseldorf (DE)

Gas Bearing Workshop 2021

Fourth edition of the initiative of VDE/VDI GMM and DSPE, focused on gas-bearing components and technology for advanced precision instruments and machines.

WWW.GAS-BEARING-WORKSHOP.COM

Virtual event

17-18 November 2021

SIG Meeting Micro/Nano Manufacturing

Special Interest Group Meeting hosted by euspen, focusing on, a.o., micro- & nanomanufacturing technologies and applications, machining technologies for moulds and microparts, metrology & quality control for microparts, microreplication and additive techniques, and assembly & handling.

WWW.EUSPEN.EU

23 November 2021, Eindhoven (NL)

DSPE Knowledge Day Engineering for Contamination Control

Presentations by FastMicro & Lans Engineering, Omneo Systems, Settels Savenije, TNO and VDL ETG. See the preview on page 78.

WWW.DSPE.NL/EVENTS

24 November 2021, Utrecht (NL)

Dutch Industrial Suppliers & Customer Awards 2021

Event organised by Link Magazine, with awards for best knowledge supplier and best parts & process supplier, and the Best Customer Award.

WWW.LINKMAGAZINE.NL

30 November 2021, Veldhoven (NL)

De High Tech Projectmanager

Theme day (in Dutch) dedicated to boosting project management skills. With cases from Frencken Europe, Hittech Multin and Philips Research.

WWW.MIKROCENTRUM.NL

1-2 December 2021, Den Bosch (NL)

Food Technology 2021

Knowledge and network event about high-tech innovations in the food industry.

WWW.FOOD-TECHNOLOGY.NL

8-9 december 2021, Eindhoven (NL)

RapidPro 2021

The annual event that showcases solutions for prototyping, product development, customisation and rapid, low-volume & on-demand production.

WWW.RAPIDPRO.NL

31 January - 4 February 2022, Zwolle and Leiden (NL)

LiS Academy Manufacturability course

5-Day course targeted at young professional engineers with a limited knowledge of and experiences with manufacturing technologies and associated manufacturability aspects.

WWW.LIS.NL/LISACADEMY

8 February 2022, Veldhoven (NL)

CLEAN 2022

This theme day, organised by Mikrocentrum, provides an expert's view on cleanliness, focusing on design, production, assembly and packaging.

WWW.MIKROCENTRUM.NL

22-23 March 2022, Zürich (CH)

SIG Meeting Thermal Issues

Special Interest Group Meeting, hosted by euspen and dedicated to thermal effects as a major contributor to errors on precision equipment, instruments and systems within precision engineering. The local host is the ETH Zürich university, which has materials & manufacturing as one of its four strategic areas.

WWW.EUSPEN.EU

15-18 March 2022, Utrecht (NL)

ESEF 2022

The largest and most important exhibition in the Benelux area in the field of supply, subcontracting, product development and engineering, showcasing the latest innovations.

WWW.ESEF.NL

30 May - 3 June 2022, Geneva (CH)

Euspen's 22th International Conference & Exhibition

The event features 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, topics will be addressed covering robotics and automation, precision design in large-scale applications, and applications of precision engineering in biomedical science

WWW.EUSPEN.EU

CELEBRATING THE FAIR'S 20TH ANNIVERSARY

This year will see 20th edition of the Precision Fair. In fact, this anniversary should have already been celebrated in 2020, but for obvious reasons the fair had to be postponed by a year. On 10 and 11 November 2021, the fair will be held in the Brabanthallen in Den Bosch (NL) – for the first time. This marks a good time to look back and to look forwards.

Beginning

In 1998, consultancy firm Berenschot conducted a study into the importance of and possibilities for precision technology in the Netherlands. This research was supported by various organisations, including TNO, NVPT (now DSPE) and Mikrocentrum, and led to the IOP (Innovative Research Programme) Precision Technology. Partly because of the promising start of the Plastics Fair in 1999, Henny Spaan (IBS Precision Engineering) suggested that Mikrocentrum should also organise a Precision Fair. After consulting with the many parties involved, the first edition of the Precision Fair was held in October 2001.

Knowledge transfer

While lecture programmes are now common, when the Precision Fair began they were still special. This process of knowledge transfer has always been an important part of the trade fair's programme. In the early years, Rien Koster (Figure 1), emeritus professor of Mechatronics, was the driving force behind the lecture programmes and the associated thematic sections. These were later coordinated with various cooperation partners. The programme has always consisted of a mix of lectures by exhibitors and independent speakers. Further innovations came in 2012, when Big Science became a permanent part of the lecture programme. Also, in 2017, a special lecture track by ASML covered the history of the company and its technology. The lecture programme now comprises more than 60 lectures.

Growth

After 2007, the Precision Fair was unable to grow any further due to a lack of space and so a progressively longer waiting list of exhibitors arose. After the financial crisis of 2008, companies looked increasingly for sales opportunities abroad. During the crisis years, there were also various initiatives with competing activities, which learnt Mikrocentrum that something had to be done. Two things were therefore most important in 2012: increasing internationalisation and enabling the further growth of the exhibition. This was realised in close collaboration with fair venue Koningshof in Veldhoven (NL) by building additional halls as well as adding temporary halls.

Big Science

The further internationalisation of the Precision Fair focused first on Germany and Switzerland. For example, the fair was profiled in German trade magazines, which also ran features on a number of exhibitors. Not so well-known to the fair target group at the time was the Swiss-based CERN research institute, which, funded by member states including the Netherlands, invests heavily in all kinds of high-precision technologies. Two visits by Mikrocentrum to CERN in 2012 resulted in large delegations from this organisation to the Precision Fair.

From 2013, the collaboration was further expanded with the attendance of representatives and liaison officers from the other international Big Science projects. In 2017, Sijbrand de Jong, the then president of the Council of CERN, gave a keynote lecture. The many contacts with the international Big Science projects that have originated at the Precision Fair have led to a large number of assignments for the Dutch business community. In the most recent edition, visitors have already registered 42 different nationalities.

1

Rien Koster during the first edition of the Precision Fair in 2001. (Photo: Bert Jansen)

EDITORIAL NOTE

This article was contributed by Mikrocentrum, the long-time organiser of the Precision Fair and an independent knowledge and network organisation that has been supporting the technical manufacturing industry for over 50 years with training, events and business.

www.mikrocentrum.nl

Network function

Throughout the years there have been good relations with the relevant industry associations, especially DSPE. This is not surprising given the more or less joint history of the two organisations. This is also reflected in the prestigious awards that DSPE presents annually at the Precision Fair, including the Rien Koster Award, which is given to a mechatronics engineer/designer who has made a significant contribution to the field of mechatronics and precision engineering.

The various universities of technology and applied sciences, schools, and research and knowledge institutions in the Netherlands are also regular guests. Each year, they surround the technology square where special presentations are held, such as those from the Big Science projects, ASML and the universities, but also, for instance, the presentation of a jet fighter engine, which was guarded day and night by two military personnel.

The Precision Fair has a real networking function and is the platform where many new and emerging technologies are introduced and explored. Over the years, the evening buffet for exhibitors has also grown into a network dinner with 500 to 600 guests, a happening in itself.

INFORMATION
Precision Fair
10-11 November 2021
Brabanthallen,
Den Bosch (NL)

Information and visitor registration at website.

WWW.PRECISIEBEURS.NL

2 Technology exhibited at the most recent physical edition of the Precision Fair, in 2019. (Photo: Mikrocentrum)

Partner country

From 2019, there is an annually changing partner country. Switzerland was the first and in 2020 it would have been the UK. This was partly due to the good contacts with euspen, the European Society for Precision Engineering and Nanotechnology, which is headquartered in the UK and has a permanent stand at the Precision Fair. For 2021, Belgium has been chosen as partner country. Companies, embassy trade officers and industry association representatives share knowledge of the local precision industry landscape and explore business opportunities.

20th edition

Due to the Covid-19 pandemic and the resulting need for more space, it was decided in 2020, after intensive consultation with exhibitors and other stakeholders, to move the Precision Fair to the Brabanthallen in Den Bosch (NL). Unfortunately, the 2020 edition could not take place despite this relocation. Now, in 2021, the 20th edition of the Precision Fair will finally take place, in the Brabanthallen on 10 and 11 November. Everyone is invited to visit this special anniversary edition and experience 20 years of Precision Fair.

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Precision Fair 2021

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Exhibitors

For the current list, including late registrations, please check
www.precisiebeurs.nl/plattegrond/plattegrond-interactief

Stand number	
312	µTOS GmbH Oberflächentechnik
332	2-S Service & Specialties B.V.
384	A. Brans Metaalbewerking BV
163	Aalberts Surface Technologies Eindhoven
375	Acclon Technologies
246	ACE Stoßdämpfer GmbH
387	Adruu BV
408	Aeronautical & Precision Engineering, Inholland Delft
523	AJB Instrument B.V.
174	alimex Benelux B.V.
514	Alumeco NL BV
144	Aluro cnc n.v.
247	Analis
105	Andes Meettechniek B.V.
439	Anteryon BV
549	Anvil Industries
122	ART-CCG Caulil Cylindrical Grinding BV
558	Astro Controls
326	ATM Oirschot
376	attocube systems AG
231	AVT Wiring & Connecting
131	Axxicon
349	B&S Technology
572	Bestronics BV
202	BIBUS Romicon
103	Biersack Technologie GmbH & Co. KG
416	Big Science ILO-net
138	Binder connector
548	BKB Precision
549	BKL
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367	Bouman High Tech Machining
158	Brabant Engineering - Neitraco Groep
403	Brainport Industies
229	Brecon Cleanroom Systems B.V.
581	Bronkhorst Nederland b.v.
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504	Bumax AB
497	Busch B.V.
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256	Capable BV
339	CCC Projects & Engineering
158	Cematec Engineering bv
563	Ceratec Technical Ceramics BV
479	Connect 2 Cleanrooms Ltd
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511	CZL Tilburg
162	D&M Vacuumsystemen B.V.
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525	Danobat
525	Danobat-Overbeck
133	DCD
225	De Ploeg Techniek BV
363	DE Ridder
512	De Rooy Slijpcentrum B.V.
121	Dekracoat BV
567	Demaco Holland bv
583	Dematech B.V.
575	Demcon
252	DIXI Polytool
365	DKAT
503	DMS
447	Doeko B.V.
297	Draadvonk.nl
383	Draline B.V.
211	Dratec Vonkerosie
404	DSPE
513	Dutch Precision Technology
350	Ecoclean
533	Edmund Optics
375	Edwards Vacuum
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175	Eltrex Motion
455	EMS Benelux BV
445	Encoma BV
415	Enterprise Europe Network Netherlands
213	Epilog Laser B.V.
359	ERIKS B.V.
206	Ernst & Engbring GmbH
333	Erowa
259	Ertec
466	Etchform
118	Euro-Techniek
402	EUSPEN
304	Ewellix Benelux B.V.
373	Exakt Fijnmechanika
232	Faes
301	FARO Benelux B.V.
474	Faulhaber Benelux B.V.
465	Festo
535	FMI
409	Fontys Centre of Expertise HTSM
139	Formatec
492	Frencken Group Ltd
238	Frerotech B.V.
377	FRT Metrology
344	GBneuhaus GmbH
155	Gereedschapmakerij GMI
106	Germefa
259	GF Machining Solutions BV
561	Gibac Chemie BV
168	Gibas
260	Gimex technische keramiek
127	GOM
484	Goorsenberg Fijnmechanische Industrie
536	GROB Benelux BV
208	Groneman B.V.
577	GTB Finish
104	Harry Hersbach Tools BV
550	Hawo B.V.
203	Hegin Metalfinishing BV
146	Heidenhain Nederland
490	Hemabo Precisie Kunststoftechniek
525	Hembrug Machine Tools
120	Hexagon
116	Hfi B.V.
159	Hittech Group B.V.
235	Hiwin Linear Technologie GmbH
480	Holland Innovative
200	Hositrad Vacuum Technology
566	HQ Precision Cleaning
204	IAC Geometrische Ingenieurs B.V.
459	IBS Precision Engineering
461	IKO Nippon Thompson Europe B.V.
392	ILT Fineworks
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323	Indoles Precision BV
316	Infinite simulation systems
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113	Interflow B.V.
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116	Jatec
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450	Jeveka
549	Job Precision
472	Johann Fischer Aschaffenburg
478	JPE
308	KC Precision Technology (Dongguan) Co.,Ltd
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451	KeyTec Netherlands
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135	KMWE Group
171	KSM
559	KUK Wijdeven
112	Kusters Goumans B.V.
116	Kusters Precision Parts B.V.
366	Kuzuflex Metal Hoses and bellows High Purity Product
342	LAB Motion Systems
218	Landes High End Machining BV
545	Larsen & Buhl
468	Lasertec BV
242	LaserTechnology Janssen B.V.
477	Laumans Techniek
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519	Levitech Technology
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344	LLT Applikation GmbH
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230	Marposs GmbH
565	Masévon Group
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216	maxon
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209	MCA linear motion robotics
341	Measuretec BV
255	Mecal High-tech Systems
482	Melotte
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354	Optics11
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346	PCB Piezotronics
167	Pfeiffer VAcuum Benelux B.V.

201	Phantom / Van Ommen
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325	Phynicx Metallurgical Solutions
593	PI Benelux
515	Pi metal Parts
476	Piezosystem Jena
123	PM
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370	Poelman Precision
111	PolyWorks Benelux B.V.
114	Precision Micro
364	Precitec Optronik GmbH
576	Pressure Control Solutions
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542	Pronexos B.V.
488	Reliance Precision Ltd
165	Renishaw
579	Rodriguez GmbH
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541	SpectraPartners
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410	TU/e High Tech Systems Center
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350	UCM
554	Ultra Clean Technology (UCT)
336	Vacom Vakuum Komponenten & Messtechnik GmbH
172	Vacutech b.v.
315	Van den Akker Fluid Service B.V.
386	Van der Hoorn Buigtechniek
226	Van Hoof Groep
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153	Weiss Nederland bv
356	Weiss Technik Nederland B.V.
499	Werth Messtechnik
116	Wilting
161	Wilting 3D Competence Center
573	Witec Motion & Precision
224	Witzenmann GmbH
126	ZEISS
311	Zentrum für Innovation und Technik
510	Zest-Innovate
537	Zilvertron B.V.
518	ZME Fijnmechanisch Atelier

INNOVATIONS ON DISPLAY

Heidenhain (stand number 146)

ACANTO absolute length gauges

These absolute length gauges for measuring stations and multi-gauging fixtures offer a high system accuracy of ±2 µm or even ±1 µm. Their compact design features a frontal profile of less than 15 mm. Multiple length gauges can be arrayed in a small space for simultaneous measurement of multiple inspection points.

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Hembrug (stand number 525)

MikroTurnGrind Vertical

The hard-turning process offers many advantages, especially for workpieces with complex shapes requiring often a combination of external and internal machining. However, sometimes surface structure and quality cannot be achieved through hard turning only. For this reason, Hembrug designed the MikroTurnGrind Vertical. This machine combines the advantages of high-precision hard turning and fine grinding in one machine. It allows the application of the most suitable process for each surface to be machined, all in one set-up without the need for multiple machines. In addition, with grinding a turn-free surface finish can be achieved.

The MikroTurnGrind Vertical complements the existing MikroTurnGrind 100 and 1000. It is a true hybrid turn/grind machine, designed for large workpieces up to a diameter of 1,000 mm. A 46-position tool changer is utilised for storing the turning tools and grinding wheels. An automated system is used for change-out of the turning ram, grinding spindle and/or milling spindle. The receiver for the turning ram or grinding spindle in the Z-axis consists of a Hirth coupling with proven, long-term accuracy, reliability and robustness. The grinding spindle speeds up to a maximum of 12,000 rpm and can be adjusted to an angle of +/– 115°.

To ensure high accuracy, the MikroTurnGrind Vertical comes with an 800-rpm hydrostatic work-spindle with run-out of < 0.2 µm (TIR, total indicator run-out/reading), and hydrostatic X- and Z-axis slides having repetitive accuracies of < 0.2 µm. Thermal stability is achieved by cooling critical machine components by maintaining oil temperature at 20 °C ± 0.1 °C. The in-house developed and proven hydrostatic bearings, used in both spindle and slides, assure that performance will not degrade over time and with usage.

WWW.HEMBRUG.COM

PI (stand number 593)

V-855 und V-857 high-load linear stage series

PI has expanded its portfolio for industrial precision automation with new high-load linear stage series. With these, PI now offers cost-efficient positioning systems for processing and inspection tasks that require high speed and repeatability over long travel ranges. These series are suitable, among others, for applications in electronics manufacturing and micro assembly, for testing sensors, or for use in inkjet printing processes. The 3-phase linear motors with recirculating ball bearing guides enable a constant load up to 1,000 N, accelerations up to 5m/s², and velocities up to 5,000 mm/s. High-resolution linear encoders also ensure a high tracking accuracy, minimum tracking errors, and short settling times. The calibrated bidirectional repeatability of the linear stages is ±0.5 µm.

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Rodriguez (stand number 579)
Kaydon thin-section bearings

Compact thin-section bearings are the right choice for all applications where compact design, low weight and miniaturisation are important, for example in robotics technology. With more than 250 different types of thin-section bearings up to hybrid versions with ceramic balls, a solution for each constructive problem is available. Kaydon thin-section bearings have a large bore diameter with a smaller bearing cross-section, achieving space savings and weight reductions of over 80%. Solid shafts can be replaced with hollow shafts and the free interior can be used for air ducts, hydraulic piping, electrical wiring or slip rings. Despite miniaturisation, the performance of a thin-section bearing is comparable to that of normal bearings in terms of precision and stiffness.

WWW.RODRIGUEZ.DE

Werth Messtechnik (stand number 499)
TomoScope® XS FOV

With the FOV model, Werth presents the third coordinate measuring machine with X-ray tomography from the powerful and compact TomoScope® XS family. The new model is less expensive and particularly easy to operate. It is a flexible device, ideally suited for fast production-related measurements of plastic workpieces that are produced in high volume. Depending on the selectable mounting direction of the detector, the new devices offer a measuring range of 120 mm diameter or height. The measurements take place in the field of view, with the 6-megapixel detector enabling a very high resolution. The measurement in OnTheFly mode and the real-time reconstruction of the digital workpiece volume ensure fast results.

WWW.WERTH.DE

BOOSTING CRYOGENIC MOTOR DESIGN

The discovery of axions could solve some mysteries of high-energy particle physics. The MADMAX experiment is based on the concept of a dielectric haloscope consisting of parallel dielectric discs whose separations can be adjusted. In the haloscope, according to theoreticians, axions can produce electromagnetic radiation at dielectric layers when a strong magnetic field is applied. This radiation can be amplified by stacking many dielectric discs in front of a mirror. JPE designed this 'booster' for cryogenic vacuum conditions. The main design challenge was the actuation principle for moving the dielectric discs. Good old drive technology, featuring rails, carriages, bearings and piezos, did the job.

BART VAN BREE

Introduction

Axions represent a class of particles, so-called weakly interacting slim particles (WISPs) [1], which emerge in theoretical models explaining several mysteries of high-energy particle physics and cosmology. Various searches for axions and axion-like particles have constrained the parameter space during the past decades, but no hints of axions have been found so far. The mass range of 1-1,000·10^{-6} eV is considered to be the region for searching dark-matter axions. A new experiment, called MADMAX, as described in a whitepaper [2], is based on the concept of a dielectric 'haloscope' for the search of dark-matter axions in the mass range of 40-400·10^{-6} eV.

MADMAX stands for Magnetized Disc and Mirror Axion eXperiment and involves a European collaboration [3] between universities (Aachen, Hamburg, Tübingen and Zaragoza), particle physics institutes (CPPM, DESY and Néel) and Max Planck Institutes (Physics and Radio Astronomy). One of the industrial partners is JPE, a Dutch innovation-driven centre of expertise in precision engineering with an extensive track record in cryogenic actuation [4]. The MADMAX experiment is planned to be mounted at DESY in Hamburg (Germany) and start operation in 2028 (Figure 1).

1

MADMAX will be mounted at DESY, including a huge magnet (under construction, on the left).

The MADMAX haloscope will consist of several parallel dielectric layers that are placed in front of a mirror in a strong magnetic field and whose separations can be adjusted. The experiment relies on the principle that axions can produce electromagnetic radiation at the transition between two non-conducting materials with different refractive indices. The axion-induced electromagnetic waves in the 10-100 GHz domain, with the frequency given by the axion mass, will be very weak even if an extremely strong magnetic field is used. Therefore, multiple dielectric discs are used simultaneously to obtain a stronger signal, and to amplify the signal.

Scanning a sizeable axion mass range with the experiment will require different relative positions of the dielectric discs. This will be achieved by moving the set of discs like an accordion, decreasing their mutual gaps from 15 to 1 mm over a period of up to 20 years. Given the extreme cryogenic vacuum conditions under which the experiment has to run (4 K), and the associated thermal contraction of any construction, the design of the haloscope is a major undertaking (as is the construction of a huge 9-Tesla dipole magnet).

Booster design

JPE was assigned the preliminary design of the so-called booster, i.e. the heart of the haloscope that has to amplify the signal. Reliability and lifetime were major concerns, given the extreme conditions and large thermal effects. Therefore, materials selection (beware of superconductivity effects) and actuation principle were the prime design challenges.

AUTHOR'S NOTE

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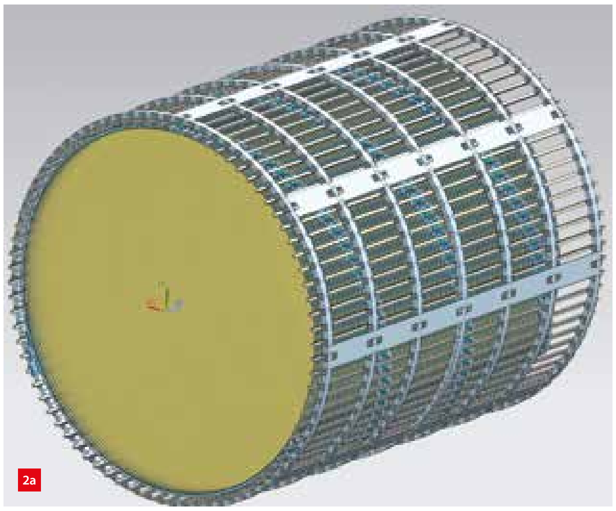
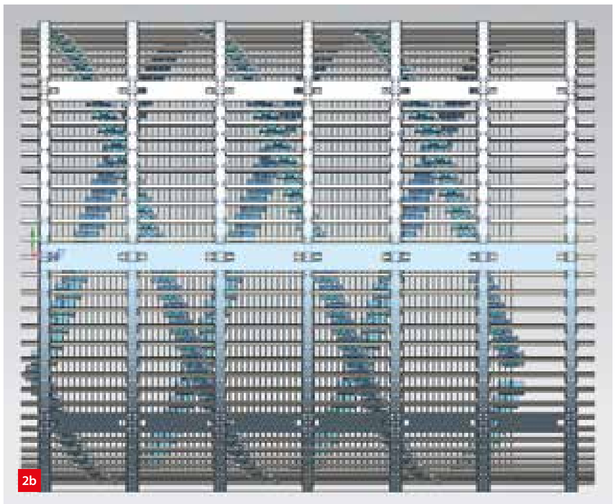




Conceptual design of the booster, with the copper mirror on the left and 80 discs contained in a backbone assembly. Each disc is fitted in a narrow ring to which three carriages (in blue/green) are attached at positions each 120° apart, and at locations on the backbone that gradually shift for each subsequent disc. This leads to a helix configuration of 3 times 80 carriages, as can be seen in the side view on the right.

'Old-fashioned' drive technology such as rails, carriages and bearings, using the piezo effect, was the only proven option.

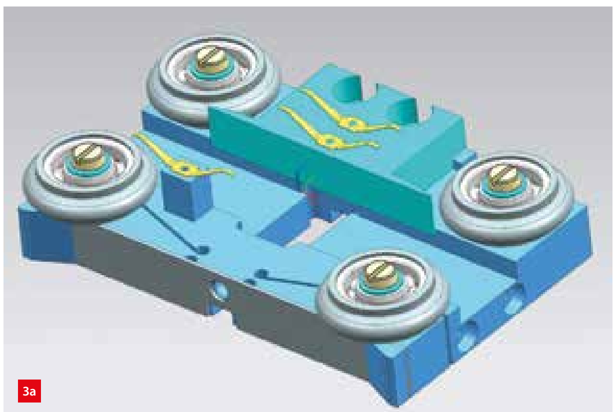
The booster will contain a total of up to 80 discs and a copper mirror. It comprises a backbone structure, roughly measuring Ø1.25 m x 1.35 m, equipped with ceramic rails along which the discs can be moved. Each disc (~1 mm thick, about 6 kg mass) is fitted in a narrow metal ring (2.5 mm wide) onto which three carriages are attached at positions each 120° apart. Figure 2 shows the conceptual design. Driven by a piezo motor and guided by four wheels, each carriage moves along a ceramic rail (Figure 3).

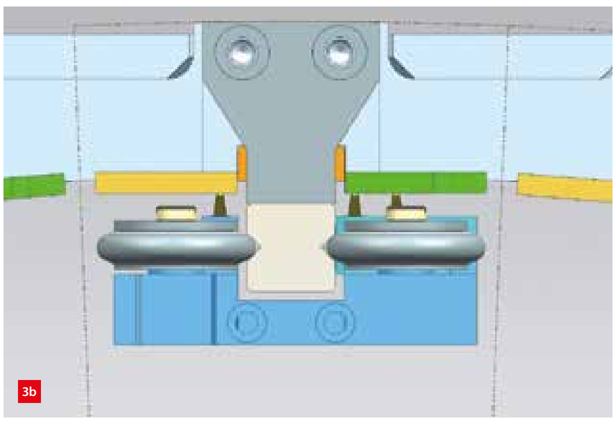
Motor design

Piezo technology was the only option for driving a carriage, as it still operates at 4 K and is not affected by a strong magnetic field, in contrast to electromagnetic actuation options. The piezo motor makes contact with the guiding rail through elastic friction wings and operates through the well-known stick-slip phenomenon [5]; see Figure 4 for an extensive explanation. The motor and rail surfaces alternate between sticking to each other and sliding over each other, subject to either static or kinetic/dynamic friction. This can produce – in a sustained cycle of slow (static) piezo expansions and sudden (dynamic) piezo contractions, or vice versa – net movement over very large ranges, more than 1 m in this case.

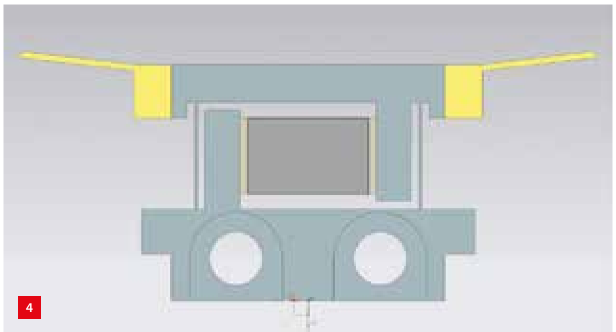
Outlook

JPE demonstrated the piezo actuation concept with a set-up comprising a rail with one carriage and one motor (Figure 5). Under 4 K environmental conditions, successful lifetime tests were performed, which convinced the MADMAX collaboration of the viability and sustainability of this concept. In the complete configuration, the motors have to ensure that the discs are parallel within a few micrometers accuracy.



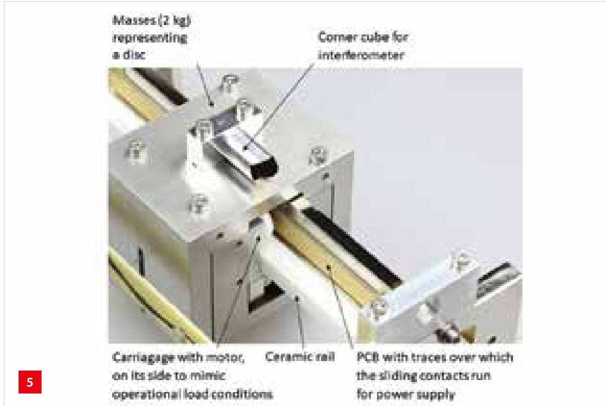


Schematic design of the carriage, of which three are attached to one disc.
(a) The disc fitted in its ring (not shown) is mounted in the narrow groove at the bottom. Driven by the piezo motor (in green) and guided by four wheels, the carriage moves along a ceramic rail (not shown), which fits in the wide groove at the top. The two yellow sliding contacts on the motor are for power supply (no cables can be used at 4 K). The other yellow sliding contact is for cooling, by dissipating heat (the minimal amount that is injected by the motor) to a copper rail (not shown).
(b) In cross-section, the carriage (blue) and the rail (ochre, attached to the backbone assembly), along which it can move. Through the sliding contacts the carriage is connected to a cooling rail (orange) and a power supply rail (green)



4

Schematic design of the piezo motor, with the piezo element (grey) and the upper beam, fitted with two elastic friction wings (yellow), which make contact with the stationary rail (part of the backbone assembly). Below are two bolting holes for connecting the motor to the carriage. When the voltage applied is gradually increased and consequently the piezo element gradually expands, the upper beam moves to the right. Through its static friction contact with the rail, the beam will stay in place with respect to the rail and hence the rest of the carriage (taking the disc with it) will move to the left. When the voltage is suddenly lowered, the piezo abruptly contracts and friction will enter the dynamic range; the beam will slip backwards with respect to the rail. As a result, a (micro) step has been made.



5

The prototype set-up by JPE. The carriage with motor is on its side, because in the booster the carriage will experience the mirror weight as a lateral load.

For this, metrology based on absolute interferometry is being developed. JPE integrated this in its position control for the discs and will supply the motors and the control electronics for a prototype with up to 20 discs. In addition, JPE is a candidate for the design of the final booster.

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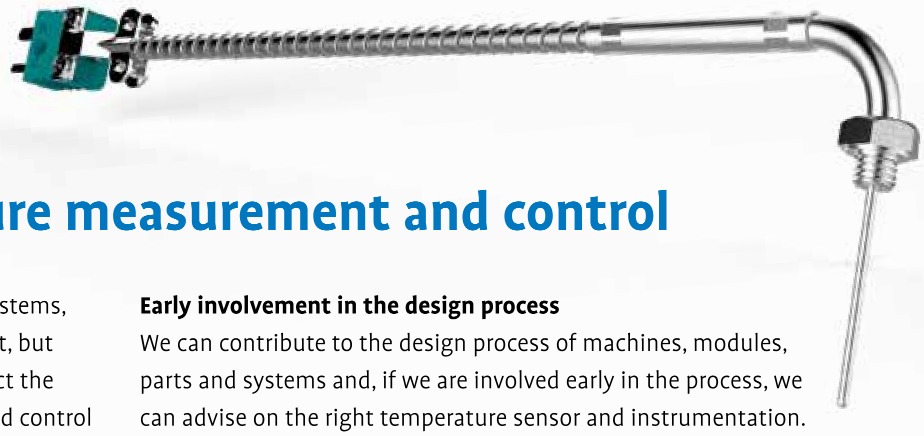

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EXTENDING ADAT2 EQUIPMENT LIFETIME

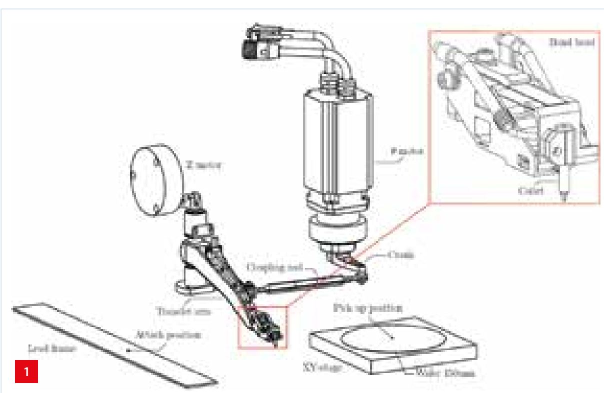
ITEC's ADAT2 (Automatic Die ATtach) systems, developed in the 1990s, are still operational in various production sites. An upgrade enabling them to handle 200-mm wafers would extend their economic lifetime even further. To this end, the design of an intermediate rotary stage was investigated.

HARM SCHEPENS

Introduction

ITEC (Industrial Technology & Equipment Center) is a leading supplier of back-end semiconductor equipment, located in Nijmegen (NL). ITEC is well known for its reliable ADAT (Automatic Die ATtach) platforms, comprising the ADAT2, developed in the 1990s, the newer ADAT3, conceived in the early 2000s, and the ADAT3 XF, introduced in 2015. The ADAT3 and ADAT3 XF systems can handle larger wafers and offer higher productivity. However, the ADAT2 platform is still operational in various production sites, where the machines produce 24,000 products per hour (24k), 24 hours a day, 365 days per year.

These sites would benefit greatly if, instead of replacing the machines with state-of-the-art systems, the economic lifetime of the ADAT2 machines could be extended with a cost-effective upgrade kit. This upgrade should enable the machines to handle the larger 200-mm wafers at a lower 18k productivity (maintaining 24k would be a bonus). The ADAT2 high-speed pick & place machine (Figure 1) uses a lightweight carbon-fibre transfer arm in combination with a collet fitted onto a bond head in order to transfer dies from a diced wafer (pick-up position) to a lead frame (attach position). A low vacuum is applied through the collet, so the die remains fixed during motion. During placement, the collet undergoes peak accelerations of up to 150 g.



1 Schematic overview of the ADAT2 high-speed pick & place mechanism.

AUTHOR'S NOTE

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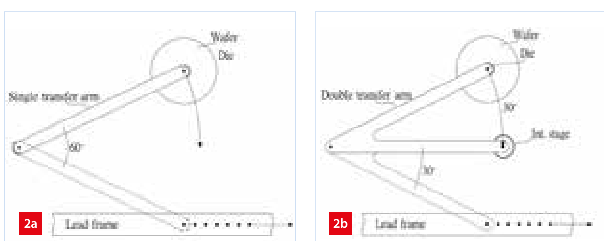
Increasing throughput

During its lifetime, the ADAT2 system has been upgraded multiple times, generally to enhance throughput. To this end, the drive train stiffness was increased and dynamic behaviour improved. The latest upgrade kit replaced aluminium and steel parts with carbon-fibre retrofits, which resulted in excellent properties regarding weight, stiffness and dynamic behaviour. These properties were optimised to such an extent that there was arguably not much room for further improvement in this area. Also, the ADAT2 platform was not suitable for wafer sizes above 150 mm, which was what prompted ITEC to investigate the possibility of an upgrade for wafer size.

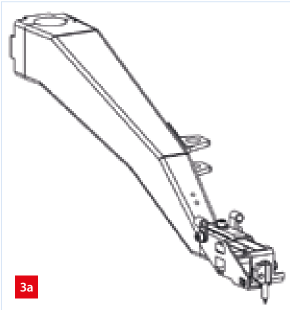
The throughput time in ADAT2 operation consists of several phases that can be optimised:

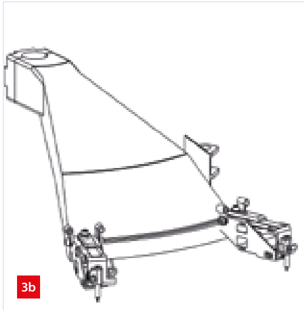
- picking time;
- motion time;
- settling time;
- placement time.

In the approach followed here, the focus is to shorten the motion time by reducing the transfer distance of the dies. Currently, the dies are moved over a distance of approximately 240 mm by a transfer arm travelling a stroke of 60°. This distance can be reduced with a concept that uses a new transfer arm in combination with an intermediate stage. The new transfer arm can be fitted with two bond heads, so that two dies can be transferred simultaneously. The 'double-transfer arm' transfers the dies over a distance of



2 Schematic overview of the existing and the new solution.
(a) Single-transfer arm.
(a) Double-transfer arm.



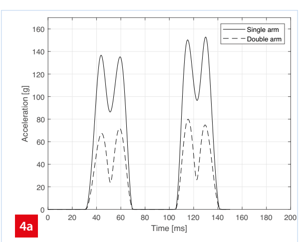


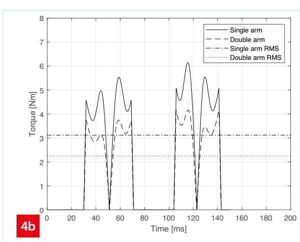
SolidWorks motion simulation models of the two solutions.
(a) Single-transfer arm.
(b) Double-transfer arm.

approximately 120 mm with a stroke of 30°. For clarification, in Figure 2 the new procedure is schematically represented and compared with the existing 'single-transfer' solution.

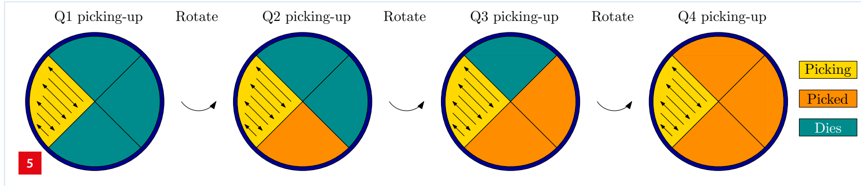
During the first cycle, the double-transfer arm places a die on an intermediate stage, then during the second cycle two dies are simultaneously moved from the wafer to the intermediate stage, and from the intermediate stage to the lead frame. With the double-transfer arm, the transfer of a single die from the wafer to the lead frame takes more time. However, the system throughput is not defined by the transfer time of a single die; it is determined by the motion time of a single stroke (30° vs. 60°). At first glance, the double-transfer arm seems counter-intuitive because it is larger/heavier and will not be able to operate with the same accelerations as the single-transfer arm. However, the double-transfer arm travels only half the stroke of the single-transfer arm and therefore requires lower velocities and accelerations.

A first-order-of-magnitude study was performed to estimate the impact of the double-transfer arm. Two simulation models, representing the single- and double-transfer arms, respectively, were created to compare driving torques and accelerations at the bond head. The two simulation models and the resulting motion profiles in acceleration and torque are shown in Figures 3 and 4.
The graphs show the decrease of the required torque at equivalent throughput. The models have not been optimised yet, but clearly the graphs show that there is an upward potential in terms of throughput for this concept. The down-side of using a double-transfer arm is that it requires an intermediate stage to place a die and pick up the same die.





Results of the simulation models of Figure 3 (for the 24k setpoint).
(a) Acceleration profiles.
(b) Torque profiles.



Altered picking-up process in which the wafer is rotated in Rz.

This means that the transfer of a single die from the wafer to the lead frame needs more interactions and involves an increased risk of die chipping. The picking up of the dies and their landing on the lead frame is a controlled process. However, the interactions with the intermediate stage are tricky: dies may chip when the impact forces are too large. To prevent the dies from chipping, a new concept for an intermediate (rotary) stage was required, which is addressed below.

Increasing wafer size compatibility

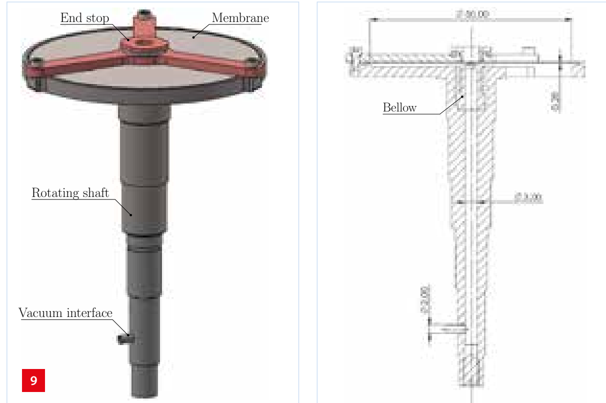
The current ADAT2 platform is capable of handling a 150-mm wafer. In order to handle wafers of 200 mm, the stroke of the XY-table needs to be increased. This is not possible, however, due to volume conflicts. Therefore, a different solution is provided: the XY-table can be upgraded to an XY-Rz-table in combination with an altered picking-up process, which is represented schematically in Figure 5.
In the new process, dies from a quarter of the wafer are picked up first and then the wafer is rotated 90°, after which dies from a second quarter can be picked up. This process is repeated until the wafer is empty. The altered process makes it possible to cover the entire wafer, but when the wafer has been rotated (and thus the dies), the dies have to be de-rotated before being placed on the lead frame. This correction has to been done between picking up the die from the wafer and placing it on the lead frame. The intermediate (rotary) stage is an ideal location for performing this task.

Rotating collet

A rotating collet as an alternative solution for die de-rotation was also investigated. Figure 6 shows the concept design, 3D-printed in aluminium. A bellow coupling is used to couple the collet and the motor shaft's rotation, while releasing the other degrees of freedom. The motor mass does therefore not contribute to impact forces on the die. It does, however, pose a risk for dynamic performance, because mass is added at the tip of the transfer arm. A rotating collet enables 200-mm wafer capabilities for the ADAT2, but increasing throughput may be a challenge.

Rotating collet (a coin was included in the image for size reference).

7 The intermediate stage with an exploded view on the right.



9 Die interface with a section view on the right.

Intermediate (rotary) stage

The intermediate stage consists of three sub-assemblies: the stage actuation, the bearing housing and the die interface. The stage actuation consists of an actuator with a motor coupling that drives the die interface, which is subsequently mounted backlash-free in the bearing housing. The 3D model with an exploded view highlighting all the sub-assemblies is shown in Figure 7.

Stage actuation

The stage is actuated with a commercial off-the-shelf maxon motor. This will not be discussed further.

Bearing housing

The bearing housing holds two angular contact ball bearings to constrain the rotating shaft radially and axially. The concertina holder can be used to mount the bearings without any backlash and elimination of all play. This design is directly inspired by Wim van der Hoek's design principles as depicted in his "*Des Duivels Prentenboek*". The 3D model and a section view of the bearing housing are shown in Figure 8.

Die interface

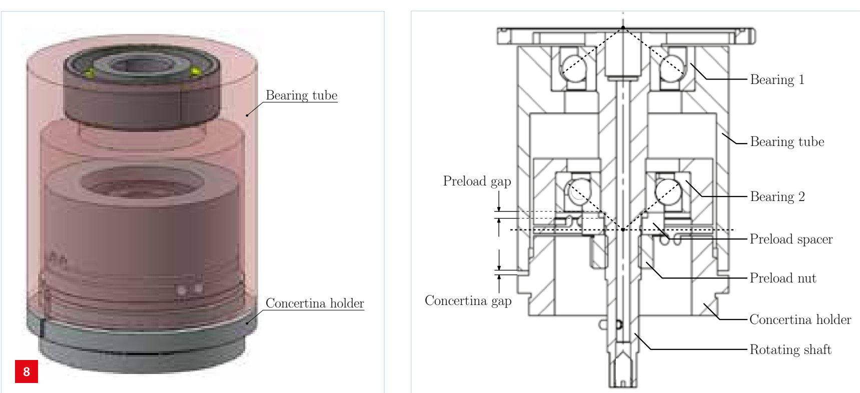
When using the rotating stage as an intermediate step in the process, each individual die makes more impacts; this increases the chance of die chipping. The die interface is designed to reduce the impact forces on the dies when they are placed, and hold the dies in position during the orientation correction (de-rotation). The sub-assembly of the die interface and a section view are depicted in Figure 9.

The interface consists of a membrane that is connected to a rotating shaft via a bellow, an end-stop and a vacuum interface. The vacuum interface is used to apply a small vacuum to the dies through the rotating shaft and a small hole in the membrane (visible in Figure 10). The vacuum ensures that the die remains in contact with the membrane during the orientation correction.

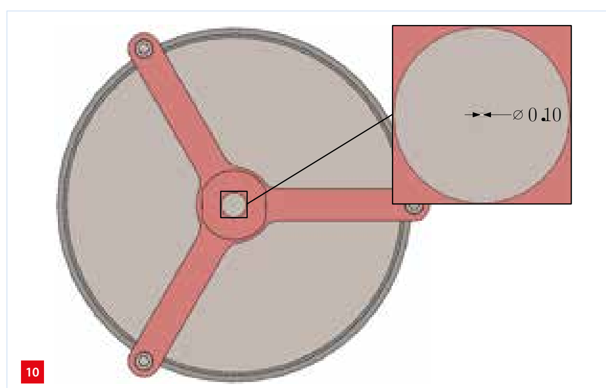
The first problem that was tackled in this design was the reduction of impact forces in order to prevent dies from chipping. The impact force can be calculated according to the following equation:

$$F_{\text{impact}} = v_0\sqrt{mc}$$

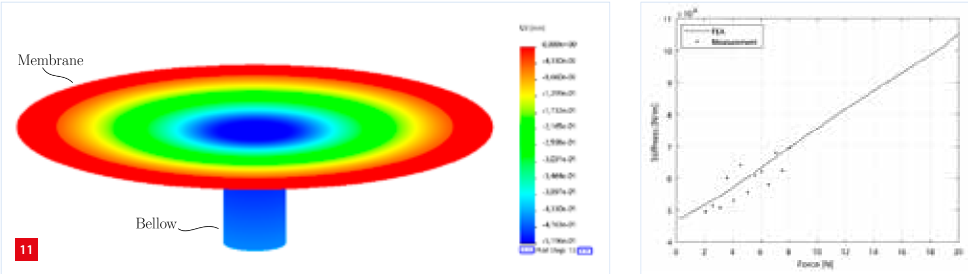
The equation shows that the impact force can be reduced by lowering the impact velocity of the dies, or the mass and the stiffness of the landing surface. It is not desirable to lower the impact velocity in the process, for reasons of throughput, so only two parameters can be altered. The simplest design that can satisfy the requirement for both parameters is a membrane, since it has relatively low stiffness and mass.



8 Bearing housing with a section view on the right.

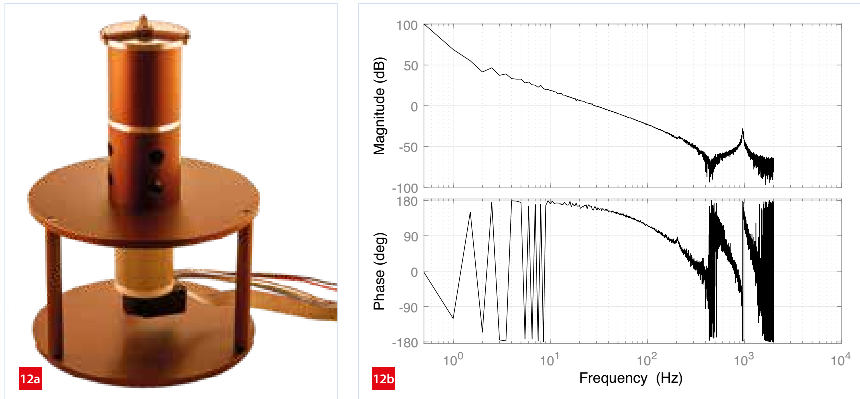


10 Vacuum hole in membrane.



FEA model with the corresponding stiffness plot on the right.

Since the stiffness is of paramount importance for this membrane, it has been optimised using finite-element analysis (FEA). The FEA model and its resulting stiffness graph are shown in Figure 11; note that the stiffness increases with deflection, which is typical for a membrane. From the FEA plot it can be concluded that the initial stiffness of the stage is approximately 48 N/mm and increases to approximately 105 N/mm when 20 N is applied. The actual measurements on a functional model (fumo, see below) over a range of 2 to 8 N yielded matching values for the stiffness and its increase over the force range. This indicates that the FEA yields an accurate representation of the design model and that reduction of impact forces on the dies can be achieved.



Functional model (fumo).
(a) Design.
(b) Measured Bode plot.

Functional model

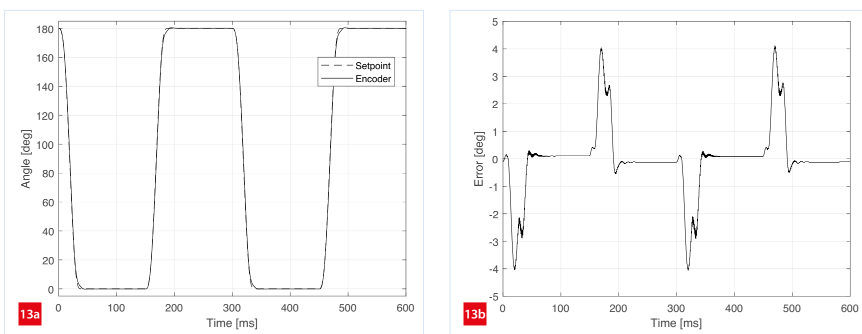
The 3D model was converted into a fumo in order to verify whether the stage can correct the rotation within the available time frame, impact forces can be reduced, and dies can be gripped. The resulting fumo and its corresponding Bode plot are given in Figure 12.

Measurements have been performed on the fumo to verify the design assumptions. A controller was designed and a minimal servo bandwidth was calculated to guarantee that the rotation can be executed within the motion time of the transfer arm. The setpoint with encoder signal and the resulting tracking error are given in Figure 13. Note that the stage is within the specified orientation correction (the maximum required value of 180° was set here) after 39 ms, while the specified time budget for this action was 45-62 ms.


Rendering of the upgraded ADAT2 system with the intermediate rotary stage.

Conclusion and outlook

This study has shown that the ADAT2 lifetime can be extended in terms of 200-mm wafer size compatibility. The next step would be to implement the (prototype-quality) fumo in an existing ADAT2 platform (which would require a few adaptations for mounting) and verify if die chipping can be prevented when dies are placed on the intermediate stage. Figure 14 shows how the rotary stage would fit in the existing machine with a double-transfer arm.



Setpoint.
(a) Encoder signal.
(b) Resulting tracking error.

THE MULTIDISCIPLINARY NATURE OF PRECISION ENGINEERING

In mid-September, the fifth DSPE Conference on Precision Mechatronics was organised as a special edition, in view of the uncertain pandemic situation. It combined two elements: one, inspirational presentations by various invited international speakers, partly online and partly in person; and two, the opportunity for the community to meet/network and exchange ideas in a pleasant atmosphere. Once again, this conference made clear that precision engineering has grown to become truly multidisciplinary, contributing to societal challenges such as the energy transition, our ageing society and disaster management.

JOS GUNSING

The real-life part of the conference took part in a hangar of Royal Netherlands Air Force Historical Flight at the military airport of Gilze Rijen (NL). The programme and special setting attracted a decent crowd of over 50 (Figure 1).

The conference programme (see the text box) centred around three societal challenges – the energy transition, our ageing society and disaster management – to which precision engineering can contribute, and the required enabling technologies. Maarten van Andel addressed the first of these challenges in his lecture, strongly emphasising the reduction of energy consumption; in the short term this brings more than the production of renewable energy will do. This is in line with the Trias Energetica philosophy, introduced forty years ago, presented here in descending order of preference:

- using less energy by e.g. driving more slowly, taking shorter showers, lowering the heating setting, etc.;
- using renewables when possible;
- using as little fossil fuel as possible when 1 and 2 have already been applied.

Concerning the challenges of our ageing society and disaster management, the application of robotics can help. Auke Ijspeert and Sangbae Kim shared their insights on, respectively, the understanding of the nervous system working for locomotion, and the proprioceptive working of animal/human actuation. Hajime Asama showed how the Fukushima nuclear power plant disaster boosted developments in robots specifically designed for disaster management (from inspection up to removal), including specific sensory approaches.

The DSPE Conference audience in front of a Tiger Moth. (Photo: Royal Netherlands Air Force Historical Flight)

AUTHOR'S NOTE

Jos Gunsing is founder/owner of MaromeTech, a technology & innovation support provider, based in Nijmegen (NL). He was formerly professor of Robotics & Mechatronics at Avans University of Applied Sciences in Breda (NL). Currently, he also is a DSPE board member and the chairman of both the Wim van der Hoek Award jury and the organising committee for the Gas Bearing Workshop 2021.

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Lecture programme

- Maarten van Andel, director Applied Natural Sciences at Fontys University of Applied Sciences, Eindhoven (NL), www.fontys.nl
  Facts and fiction about sustainable energy: How can each of us make a real contribution?
- Jon Kelly, senior mechanical project engineer at Diamond Light Source, Didcot (UK), www.diamond.ac.uk
  The Diamond Light Source Synchrotron: How Precision Engineering Empowers Scientists
- Sangbae Kim, professor of Mechanical Engineering and director of Biomimetic Robotics lab, MIT, Cambridge (MA, USA), biomimetics.mit.edu
  Robots with Physical Intelligence
- Patrick Naulleau, senior scientist and director of the Center for X-Ray Optics at Lawrence Berkeley National Laboratory, Berkeley (CA, USA), www.cxro.lbl.gov
  EUV Lithography and the path to atomic scale patterning
- Theresa Spaan-Burke, innovation director of IBS Precision Engineering, Eindhoven (NL), www.ibspe.com
  Thermal Effects and Precision Systems
- Auke Ijspeert, professor at EPFL and head of Biorobotics Laboratory, Lausanne (CH), www.epfl.ch/labs/biorob
  Investigating animal locomotion using biorobots and assisting humans with bio-inspired robotics technology
- Hajime Asama, professor of Robotics, University of Tokyo, Tokyo (JP), www.robot.t.u-tokyo.ac.jp/asamalab/en
  Robot Technology for Disaster Response and its Societal Dissemination
- Tjin Swee Chuan, professor at Nanyang Technological University, Singapore, and co-director of The Photonics Institute, Singapore, www.ntu.edu.sg/tpi
  Singapore's Precision Engineering Industry and the role of photonics

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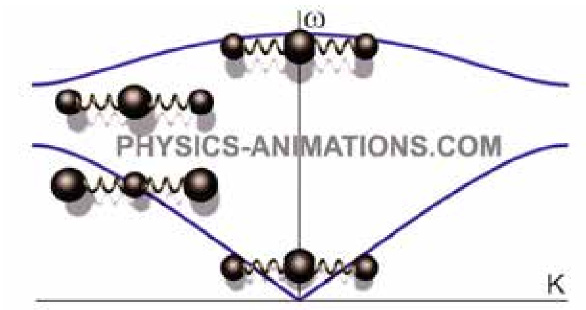
Of course, this requires enablers like developments in the semicon and photonics industry, as indicated by Patrick Naulleau and Tjin Swee Chuan, showing how Moore's law is not losing its validity yet, and how Singaporean photonics research contributes to and benefits from precision engineering, respectively.

Research on thermal aspects, from physics to application, contributes to our understanding of equipment behaviour, as explained by Theresa Burke, while Jon Kelly showed how materials research benefits from a huge synchrotron facility and how precision engineering contributes to that.



2 Phonon dispersion

Phonon, a quantum packet of waves with a defined vibration energy.

Physical boundaries – research, applications and interactions with precision engineering

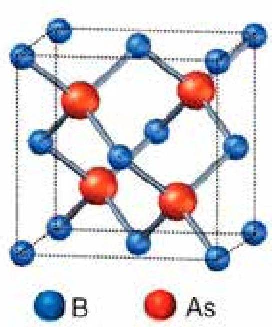
Thermal behaviour research

Theresa Burke started with an extensive explanation of the physics background of heat and temperature, ranging from classic thermodynamics including entropy to the quantum character of heat transport by way of phonons; packets of waves with a defined vibration energy (Figure 2).

This theory can be applied to the prediction of heat conducting capabilities of materials and even the design of new materials, such as boron-arsenide (Figure 3), with heat conduction coefficients up to 1,300 W/(mK) (cf. natural diamond and synthetic diamond up to > 2,000 W/(mK)). With this approach, a completely new class of materials, e.g. for high-power electronics, could be developed.

Naturally, measuring temperature is a challenge, especially when it comes to accuracy/resolution and when approaching e.g. the 0-K area. Some methods are:

- standard platinum resistance thermometers (SPRTs) (as specified in the ITS-90); uncertainties can be less than ±0.001 °C;
- acoustic thermometry; the speed of sound in a gas is directly linked to the average velocity of molecular motion (which represents the temperature);
- Johnson noise thermometry, measuring voltage fluctuations across a resistor;



3

Boron-arsenide crystal lattice.

4

Diamond Light Source synchrotron.

6

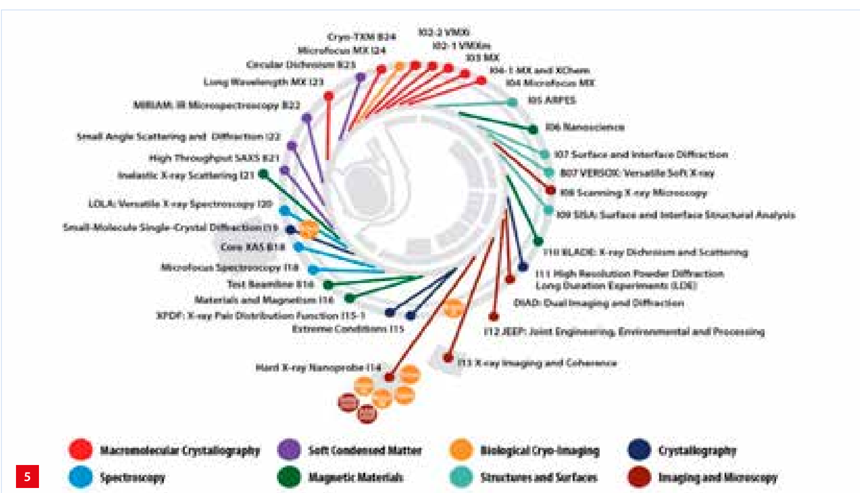
Accelerating and beam aligning magnets for synchrotron storage ring.

- absolute radiometers;
- flexible graphene thermistors, suitable for freeform surfaces, with a 16 times higher resolution than e.g. that of platinum thermistors.

Regarding thermal behaviour of equipment for high-accuracy machining and measurement, some 75% of errors are due to thermal issues, especially thermal drift. Up until around 2010, equipment manufacturers shifted responsibilities in many cases to the equipment users, making them responsible for the environmental conditions as well; later, they increasingly took it upon themselves to create the optimal conditions in and around the machine. Drift of the tool cutting point is an issue that is a subject for modelling. Very complex models were drawn up, causing the necessity for model reduction. Meanwhile, experiments have shown that a combination of modelling, temperature measurement with many (>> 100) miniature sensors, and smart algorithms lead to significant improvement of the tool cutting point drift, with reductions of 40% or more.

Materials research

In the Diamond Light Source synchrotron (Figure 4), electrons are accelerated in a ring with 562 m circumference



5

32 dedicated beamlines connected to the synchrotron ring, one each for specific experiments.

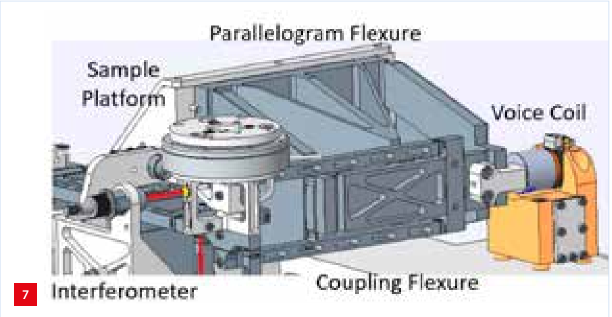
to almost light speed in order to have them gain an extremely high energy (3 GeV). The synchrotron light emitted by the relativistic electrons is projected into the 32 beamlines (Figure 5) in which experiments can be carried out to elucidate materials structures, study virus particle shapes leading to effective vaccines, etc.

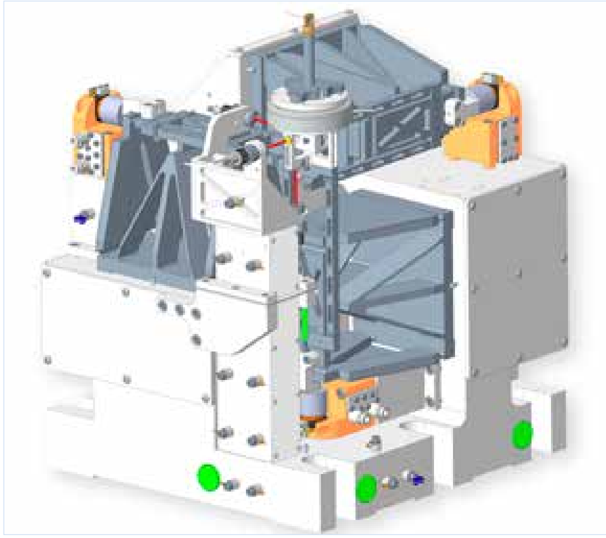
Jon Kelly explained that the X-ray beam energy and flux is so high that complete structures such as a motorbike engine and jet engine turbine blades under load can be investigated in some of the beamlines.
Other subjects of research include:
- solar panels: alternative materials, increasing power output;
- superconductors: understanding of material behaviour under cryogenic conditions;
- batteries: ageing, dendrite formation;
- information for climate models on the melting of ice caps;
- viruses and vaccines, e.g. for Covid-19.

Precision engineering benefits from the research listed here, but is also greatly needed to fulfil the demand for continuous innovation, because:
- X-ray spot sizes are reducing (motion errors must reduce);
- X-ray flux is increasing (e.g. biological samples being damaged more quickly demands dynamic scans);
- detectors are getting faster (efficient dynamic scans possible);
- scientists have new ideas (e.g., high throughput via automation);
- synchrotrons are competing to deliver world-class performance.

Thus, the best-quality tools empower scientists to perform the best-quality science.

Examples of the roles precision engineering can play include:
- Main electron storage ring (Figure 6):
  The 5-m steel magnet support girders were machined flat to 20 μm.





7 *Sample stage with mm travel and nm resolution for beamline I14 , in close-up (left) and overview.*

- Beamline I14:
  This Hard X-ray nanoprobe beamline is a specialised facility for nanoscale microscopy. The nanoprobe provides a flexible end station with a beam size of 50 nm, optimised for scanning X-ray fluorescence, X-ray spectroscopy and diffraction. The sample scanner (Figure 7) has:
  - millimeter travel range with nanometer resolution;
  - voice-coil-actuated flexure stage;
  - interferometer feedback;
  - internal thermally stabilised air cooling;
  - closed-loop temperature control;
  - 100 nm thermal drift in 12 h.

All in all, Kelly made it very clear that precision engineering is a strong enabler for the synchrotron research, while also benefitting from the research itself.

Photonics research

Tjin Swee Chuan gave an overview of applied research topics/institutes for lasers & optics as one of seven key areas in a Singaporean research industry programme with strong links to precision engineering/manufacturing (Figure 8). He presented the priorities for research over the next ten years for lasers & optics:

- integrated photonics and flat optics;
- imaging systems metrology and sensors;
- laser and fibre optics;
- displays and lighting;
- disruptive applications, including ultrafast THz communication and quantum applications.

8 *Key growth areas for Singaporean precision engineering/manufacturing.*

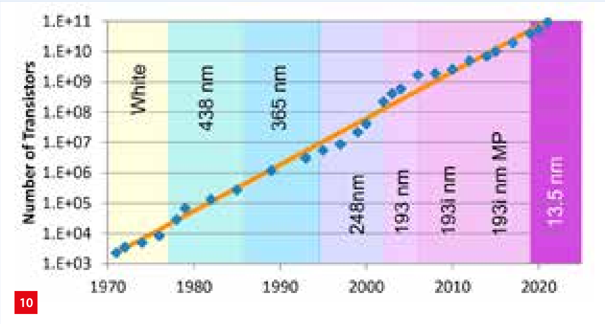
In The Photonics Institute (TPI), under Chuan's co-directorate, seven research centres are active with more than 250 researchers and students (Figure 9). It is therefore clear that in Singapore, precision engineering, also in the field of laser & optics, plays an important role, and is helping to boost the development of electronics, communication equipment and, for example, robotics.

Semicon developments and research

Patrick Naulleau started with the statement that Moore's law is still valid after 50 years (Figure 10). The first predictions that Moore's law would definitely end soon date back to 1997. He gave the example that a 200-Gb memory, nowadays an SD card of $25, would in 1970 have cost a tremendous $400 billion.

In the semiconductor industry, a dominant factor for high-end lithography has been the reduction of wavelength in order to realise ever smaller features in ICs. Nowadays, top of the bill is the 13.5 nm wavelength from an EUV light source. EUV (extreme UV) requires ultimate precision engineering not only with respect to mechanical (stage) design, but also in mirror manufacturing; extreme shape tolerances are required, with multilayer MoSi coatings (up to 33 bilayer coatings) to obtain an overall reflectivity of approx. 70%. Having,

9 *The Photonics Institute (Singapore) with core research areas linked to the several schools.*



10

Moore's law with respect to lithography wavelength.

for example, 11 mirrors in the EUV illumination light path ultimately means that a mere 2% of the original light energy is left over to illuminate the photoresist layer on the wafer.

Several options to decrease the minimal feature pitch can be considered, in order to continue following Moore's law into the near future:

- shorter wavelength: challenges on source, multilayer and photoresist;
- higher numerical aperture: geometric and multilayer limits;
- double patterning: positioning accuracy and throughput challenges, with focus on precision engineering.

The conclusion from this is that 13.5 nm may be the final wavelength, which gives way to double patterning as a feasible road to follow in which precision engineering rather than wavelength reduction will be the driver. Past experience with applying double patterning in DUV (deep UV) processes may help a little, but naturally with the extra complexity due to the much smaller sizes, additional physical phenomena have to be taken into account.

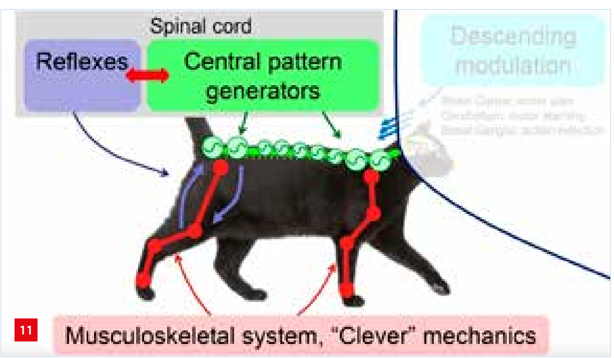
Robotics research and application

With respect to robotics, two very interesting lectures on the backgrounds of animal/human locomotion revealed some interesting insights.
Making the connection between neuroscience, bio-mechanics and robotics forces us to think about aspects of motion learning and execution, and vision/perception concepts. Our brains are not capable of coordinating the motion of our limbs in detail; according to Auke Ijspeert, this is carried out by so-called central pattern generators in the spinal cord (Figure 11), the same part that plays a role in reflexes.

Based on this concept, he carried out simulations (Figure 12) and built several salamander-like robots that showed the coverage of the model in practice. It proved to be robust/fault-tolerant and was also applied in the European Symbitron exoskeleton project, aimed at symbiotic human-machine interactions in wearable exoskeletons to enhance mobility for paraplegics.
Sangbae Kim's lecture on robots with physical intelligence was highly complementary to Ijspeert's contribution, as it dealt with so-called proprioceptive actuation. Proprioception – a biological kind of 'sixth sense' – is the force and position measurement/awareness in muscles, tendons and joints. For a quick and direct response to unwanted motion, Kim proposed colocated sensing and actuation for robotics. Colocation is a known concept in high-tech equipment for obtaining high accuracy, and can of course also be applied for undisturbed sensing and actuation. Kim also discussed the combination of conscious and subconscious actions for execution of quick movements, thus indirectly referring to the work of Ijspeert.

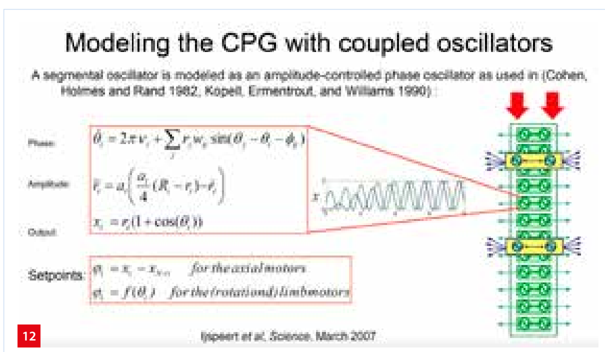
Hajime Asama explained how the Fukushima disaster (Figure 13) plays a big role in boosting the development of all sorts of robots for carrying out operations in several phases of disaster response. Early experiences just after the Fukushima disaster showed that many aspects needed technology boosts, amongst others:

- dealing with unknown and unstructured environments;
- communication failures;
- misoperation;
- issues due to (heavy) radiation levels;
- robots being not mature enough for this type of operation;
- apart from hardware development, further development of vision, perception, deep learning, machine learning, teleoperation and autonomous action is necessary in order to be able deal with the radiation levels.



11

Concept of central pattern generators responsible for (loco)motion linked to the brain and musculoskeletal system.



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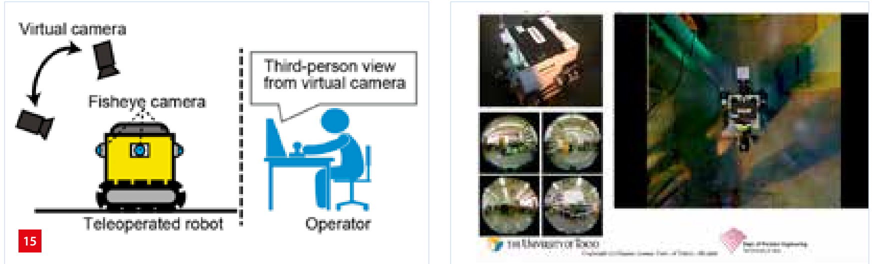
Modelling central pattern generators.

Fukushima's nuclear power plant just after the tsunami and subsequent accident.



Bird's-eye-view camera system, consisting of four fisheye lens cameras.

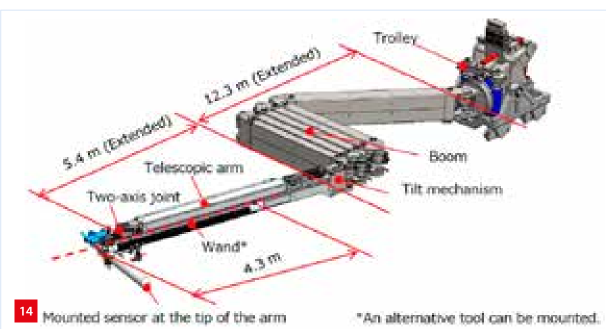
Over the coming decades, the damaged nuclear power plant will require many tasks to be performed, including:

- investigation, measurement and mapping (images, radiation, etc.);
- sampling (dust, contaminated water, concrete core, fuel debris, etc.);
- removal and transportation of rubble and fuel, including fuel debris, etc. (cutting, suctioning, handling);
- handling, transportation, removal, set-up of devices, instruments, equipment, etc.;
- decontamination and shielding;
- fixing of contaminated water leakages;
- waste and contaminated water management;
- dismantling of facilities as the final stage.

A very broad research programme has been set up, while in the meantime several new robots have been put into service, such as an extendable arm access device for maintenance (Figure 14). One of the developments required for better vision/perception led to the bird's-eye-view camera system (comparable to a 360°-view camera for cars), consisting of four fisheye lens cameras in combination with stitching software (Figure 15). This led to much better vision/perception, thus contributing to fewer misinterpretations with respect to the environment.

Conclusion

It can be concluded that precision engineering both benefits from and contributes to many types of research enabling many new applications and the extension of existing ones.



Extendable arm access device for maintenance of the control rods used in a nuclear reactor; the payload on the end is 10 kg.

Adrian Rankers and Annemarie Schrauwen deserve a big thank-you for organising this once-again successful meeting. Of course, the conference would not have been a success without the contributions of all the authors, the advisory board, the audience and certainly the volunteers from Royal Netherlands Air Force Historical Flight, plus the caterers.

Conference venue

In 1969, a group of former fighter pilots from Royal Netherlands Air Force initiated Royal Netherlands Air Force Historical Flight (*Koninklijke Luchtmacht Historische Vlucht*). Over the years, historic airplanes like the Tiger Moth, Spitfire, Beaver, Harvard, Fokker S.11 and B25 Mitchell joined the collection and were carefully restored to airworthy condition. The conference started with a tour led by pilots and aviation engineers. Figure 16 gives a brief impression of the premises, the aircraft and the technical treats.

Impression from the Royal Netherlands Air Force Historical Flight tour. (Photos: Jos Gunsing)

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MEASURING MICRORADS OVER METERS OF STROKE

For closed-loop xy-stage control applications, attocube presents an interferometric displacement sensor solution in which both displacements and angles can be detected with bandwidths up to 25 MHz. Using multiple IDS3010 sensor heads, position control of a wafer stage in multiple degrees of freedom can be achieved, including compensation for yaw rotation.

THOMAS HIRSCHMANN, GREGOR SCHINDLER, ISABEL GREISBERGER, MARK BRAUN AND DOMAGOJ RADONIC

Introduction

Today's strive for EUV (extreme ultraviolet) and electron-beam technologies in the semiconductor industry requires nanometer-accurate and reliable positioning of, for example, wafers, reticles, beam-alignment stages, optics, mirrors, etc. Especially fast and long-range movements can only achieve nanometer precision if corresponding high-end sensors are utilised for closed-loop motion control. Additional challenges stem from the required ultrahigh vacuum (UHV) and cleanroom compatibility, exposure to high temperatures and, with the tendency towards bigger wafers, the necessity for the highest accuracy over large travel ranges.

The interferometer displacement sensor model IDS3010, developed by attocube according to the Fabry-Pérot interferometer principle [1], allows movement control and displacement detection with picometer resolution, nanometer accuracy, and up to 25 MHz real-time data outputs. The fibre-based device provides three channels for measuring multi-axis stage displacements as well as determining the angular changes. UHV-compatible and miniature sensor heads provide high flexibility for different use cases and tool integration. A typical application in the semiconductor industry is multiple-DoF (degree of freedom) position control of the wafer stage.

Figure 1a visualises the main stage control applications for a 'traditional' xy-stage case, where the moving stage is equipped with two mirrors and the optical components of the interferometer are fixed to the machine frame. Figure 1b shows the xy-stage control where the sensor heads are fixed to the moving stage and the mirrors are fixed to the frame. This configuration is possible due to the fact that attocube's sensor heads are fibre-based, small and light-weight (outer diameter of only 14 mm and weight of only 7 grams).

Figure 1 highlights just two xy-stage control applications for the IDS3010, but the interferometer's ability to operate in various environments and working distances (up to 5 m) provides nearly unlimited possibilities for other motion control applications. This article demonstrates the IDS3010 capabilities by showing results from a laboratory test set-up that replicates a typical semiconductor industry 3-DoF set-up.

AUTHORS' NOTE

Thomas Hirschmann (head of business sector Motion & Sensing), Gregor Schindler (application engineer), Isabel Greisberger (application engineer), Mark Braun (application engineer) and Domagoj Radonic (application engineer) are all associated with attocube systems, located in Munich, Germany.

This article is based on attocube's Application Note Motion&Sensing 37.

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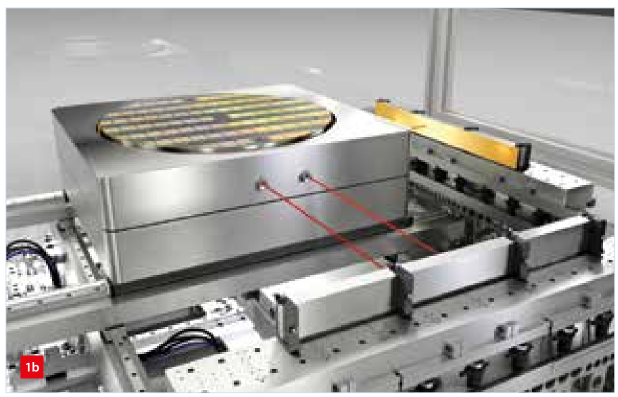


Two xy-stage control application examples using the IDS3010 sensor.
(a) Two sensor heads (SH1 and SH2) measure the displacement on the yz-mirror surface. The SinCos signal of SH1 is used for closed-loop control of the x-axis. SH1 and SH2 are horizontally separated by 40 mm, therefore the yaw rotation can be calculated and utilised as the real-time compensation for a 4-DoF set-up. The third sensor head (SH3) controls the y-axis.
(b) Miniature sensor heads mounted on the moving wafer stage, while the mirrors are fixed to the frame.

Technology demonstrator

The measurement set-up, a technology demonstrator similar to the example shown in Figure 1a, consists of an electromagnetic xy-stage that has a 1-m travel range along the x-axis. Two high-quality planar mirrors were placed on the moving stage, which function as the measuring surfaces. To control the stage position, an IDS3010 with three stationary collimated sensor heads (model M12/C1.6/wf) was used.

The IDS3010 allows instantaneous position feedback through available real-time data outputs (SinCos, AquadB, HSSL, Linear Analog Output, and BissC). These interfaces provide the real-time inputs for closed-loop positioning control systems. For laboratory tests, the SinCos data output with 5 MHz bandwidth and nm resolution was used.

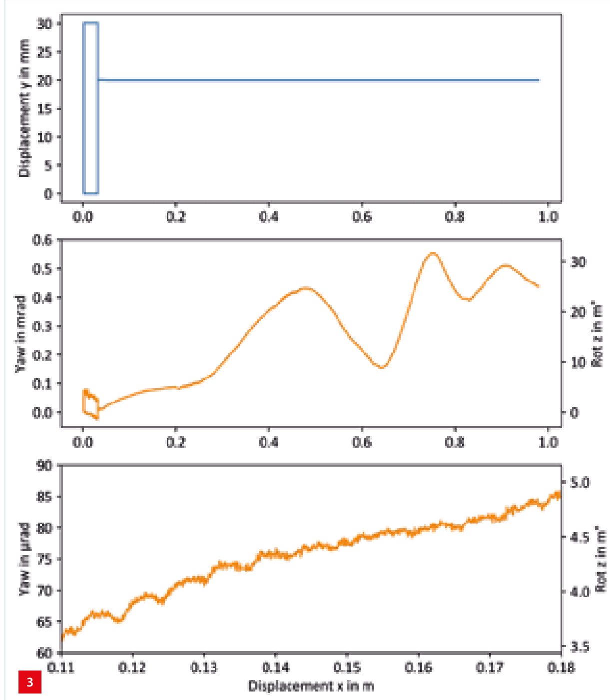
As the displayed tests were executed at ambient conditions, attocube's environmental compensation unit (ECU) was used to ensure accurate measurements [2]. Environmental compensation is not needed under vacuum conditions, which is the standard for sophisticated semiconductor applications, leading to even higher levels of precision.

Two sensor heads (SH1 and SH2) measure the displacement on the yz-mirror surface. The SinCos signal of SH1 is used for closed-loop control of the x-axis. SH1 and SH2 are horizontally separated by 40 mm, therefore the yaw rotation can be calculated and utilised as the real-time compensation for a 4-DoF set-up. In the present 3-DoF set-up, the yaw rotation along the x-axis could not be compensated for. The third sensor head (SH3) controls the y-axis. The sensor heads are connected to the three sensor axes of the IDS3010 via flexible optical fibres. No additional optics are required.

When measuring on a plane mirror, the M12/C1.6/wf sensor head angular tolerance, which describes how much the measurement target can tip/tilt before signal loss occurs, is specified to be ±20 millidegrees at a distance of 1 m. In the trade-off between accuracy (low angular tolerance) and usability/stability (higher angular tolerance), this tolerance level is still user-friendly (i.e., not too tight), when aligning the set-up of a precise xy-stage, but it also guarantees low cosine errors. This is an additional benefit in comparison to other interferometer manufacturers. On top of that, this measurement principle allows attocube to have a large sensor head portfolio, including an option for measurement over a range of 5 m on a plane glass surface instead of on a mirror.

Measurement results

Figure 2a presents the xy-displacement values of an exemplary drive. First a square of 30 mm x 30 mm was realised. After that, the x-axis was moved over a total stroke



Test results for closed-loop control of xy-stage movement.
(a) Displacement data: the x-axis was moved with a stroke of 1.0 m, while the y-axis was moved only 30 mm and included an offset distance.
(b) Yaw (rotation of the z-axis), in the range of 30 millidegrees.
(c) Zoom-in of the yaw rotation highlighting detailed angular movements in the range of tens of microdegrees.

of 1.0 m. At this point, it is important to comment that SH3 needs to have a certain offset distance of around 300 mm so that the SH1 and SH2 can measure up to 1 m.

The corresponding yaw (rotation around the z-axis) of the xy-stage movement is shown in Figure 2b. The graph shows that the yaw rotation increases up to around 30 millidegrees by moving the x-axis up to 1 m. Figure 2c shows repeating angular deviations in the range of microdegrees, which are primarily caused by the distances between the magnetic poles distributed along the motion axis. The yaw rotation could be compensated if the electromagnetic stage would have additional precise rotation equipment.

Conclusion

The IDS3010 proves itself as a suitable tool for closed-loop xy-stage applications. Both displacements and angles can be detected with bandwidths up to 25 MHz. The miniaturised sensor heads allow flexible integration and ensure the right combination of usability and accuracy for demanding positioning tasks. Moreover, the lightness of the sensor heads (7 grams) offers new set-up possibilities, which could reduce the moving mass significantly.

REFERENCES

[1] "Interferometric displacement sensor for integration into machine tools and semiconductor lithography systems", patent US10260863B2.
[2] National Metrology Institute of Germany (PTB) calibration certificate; Calibration mark: 54012 PTB 15; 2016.

STRESS-FREE PRODUCTION

PECM (precision electrochemical machining) is a way of removing metal using an electrochemical process. PECM is generally used for manufacturing complex or difficult-to-machine parts in large series. Common applications include injector valve plates used in common-rail injection systems and the production of shaving heads. The PECM process is a further development of the PECM technology by French company PEMTec SNC. In the Netherlands, Ter Hoek as a PEMTec Application Center is looking to further exploit the benefits of this technology.

HENK NIJLAND

Introduction

As a production technology, PECM is used widely to produce large numbers of parts under constant, stable conditions. In the PECM process, the tool (cathode) is advanced into the workpiece (anode). An electrically conductive electrolyte (salt water) flows into the gap between cathode and anode, where the metal is dissolved accurately on the anode, while on the tool side (cathode) the water in the electrolyte is split into hydrogen and hydroxyl ions as a corresponding reaction. The dissolved metal ions can react with the hydroxyl ions to form metal hydroxides as shown in Figure 1.

In this way, the electrode's shape is projected inversely onto the metal. The precise current pulse synchronised with the oscillating tool and the very small working gap are the basis for the precision of this technology. The PECM process follows the three steps as described in Figure 2.

The advantages of PECM are:

- Precisely shaping nearly all metals.
- Processing independent of material hardness.
- Processing of superalloys (Inconel, Hastelloy etc.) and PM (powder metallurgy) steels.
- Short processing times.
- Dimensional accuracy in serial production.
- Stress-free processing.
- No thermally induced zone.
- No microcracks.

Table 1 compares PECM with other popular technologies: turning, milling and die-sinking EDM (electrical discharge machining).

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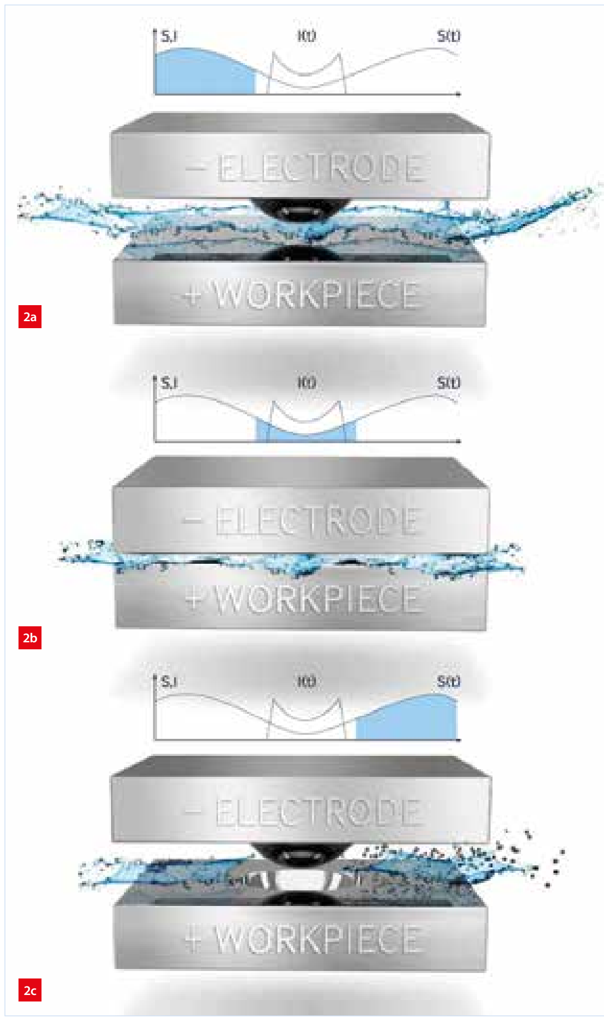
1

Reaction of metal ions with hydroxyl ions to from metal hydroxides.

Ter Hoek uses the PEM800 machines from PEMTec. They consist of four parts: PEMCenter, PEMAqua, PEMControl and PEMPower. PEMAqua is the electrolyte processing

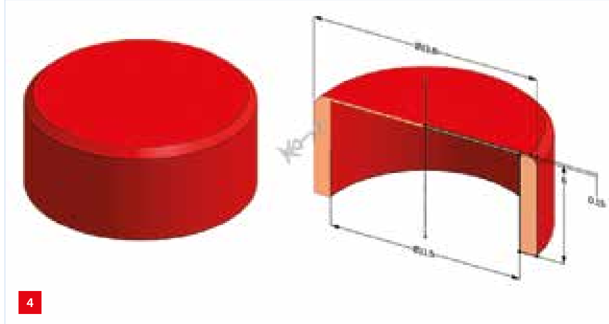


PECM processing steps. (Source: PEMTec)
(a) The machining gap is opened and fresh electrolyte is injected into the gap.
(b) The machining gap is closed. The tool and workpiece approach each other up to a few micrometers, a controlled current pulse is triggered and the material is removed by anodising the surface.
(c) The machining gap is opened and the electrolyte with the dissolved material is flushed out of the gap.

Table 1
Comparison of various manufacturing technologies.

	Turning	Milling	Die-sinking EDM	PECM
Residual stress	++	++	+	--
Microcracks	--	--	++	--
Heat-affected zone	--	--	+	--
Contamination	+	+	+	--
R_a (µm)	0.2	0.15	0.6	0.15
Costs (single piece)	↓	↓	↓	↑
Costs (large series)	↑	↑	↑	↓

R_a = approx. surface roughness



	Dimension (mm)
Height	6
Outer diameter	13.6
Inner diameter	11.5
Diaphragm thicknesss	0.15

Diaphragm part.

plant, PEMControl houses the automation, PEMPower holds the generators that produce the electrical pulse and in PEMCenter (Figure 3) the actual process takes place.

Over the past years, more and more customer requests have found their way to the Ter Hoek Application Center, mostly concerning hard-to-machine parts machined from hardened stainless tool steels (up to 60 HRC), but also molybdenum- and nickel-based superalloys such as alloys 625 or 718.

Application test

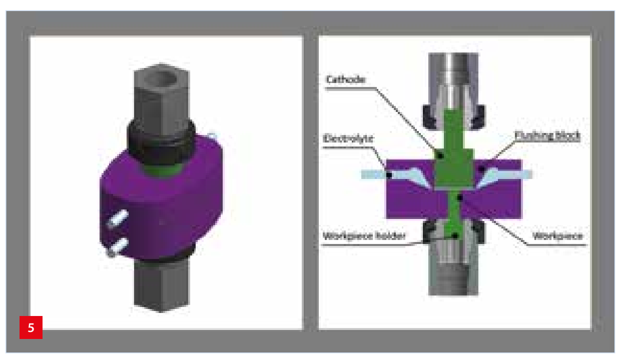
One recent test application was to make a thin diaphragm in alloys 625 and 718, which are known as hard, difficult-to-machine materials due to their low thermal conductivity, high hardness, chemical reactivity and low elastic modulus. In the PECM process, these material properties have little to no effect on the machinability; in fact, alloys 625 and 718 are relatively easy to machine using PECM. In this application, with material thicknesses in the range of 0.1 to 0.3 mm, with standard production methods like milling and turning the residual stress causes the thin material to bulge. The goal of this test: stress-free machining of alloy 625/718.

PEMTec PEM800 machine.

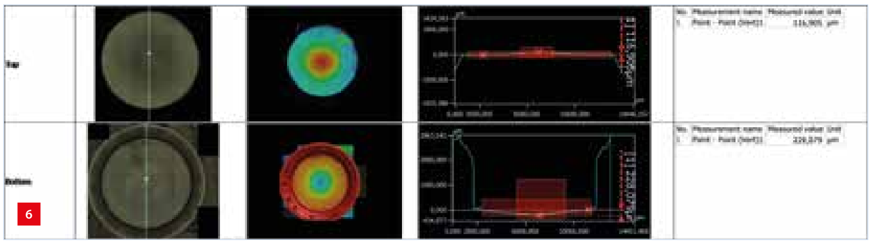
The geometry of the pre-machined part in Figure 4 makes it difficult to machine the inside of the product; for that reason, the choice was made to design and manufacture a tool for machining the top side of the product.

A tool (Figure 5) has been designed based on two flushing blocks and two collet chucks. An adapter and workpiece-holder were manufactured to ensure good electrical contact, robust positioning and good electrolyte flow across the part. As the top side of the part must be absolutely flat, central electrolyte flow is not possible, hence a cross-flow construction was chosen. The flushing blocks create the possibility of controlling the electrolyte pressure in the machining gap during the current pulse. In this way, the expansion and therefore the size of the hydrogen gas bubbles in the electrolyte can be controlled. Since the gas is an isolator, bigger bubbles create higher electrical resistance and lower current density in the gap, resulting in poor machining, less precision and/or lower surface quality.

The machine actions are determined by a table with command lines. In this table, voltage, pulse time, frequency, electrolyte pressure, machining speed and the exact timing of the pulse can be programmed. The program used to run this application lowers the cathode to 0.08 mm before



PECM tool.


Laser microscope analysis of the inside and outside of the part.

contact with the workpiece, while the z-position of the workpiece is acquired with another command. In this way, the required machining depth can be accurately determined. Machining begins with a machining gap of 30 μm. The z-axis speed is adjusted to the actual removal rate of the material, with the gap voltage (u_{min}) set to 9 V and a pulse time of 2.5 ms at 50 Hz oscillation.

After machining, the part was measured with a confocal laser microscope; the results are shown in Figure 6. The top material has an average thickness of 0.123 mm

The results show that the top side has bulged. The top side height difference is 116.9 μm, while on the inside there is a height difference of 228.08 μm. Consecutive test runs have been carried out to see if the process repeats itself. All the test runs showed comparable results, where the parts with higher material thickness bulged out less. The cause of the problem is either residual stress in the pre-machined part or uneven material removal due to movement of the diaphragm during the PECM process. To determine the cause of the problem a second test had to be carried out.

Second test

The second test was carried out on a non-machined piece of material. To ensure that there was no stress in the material after machining, the workpiece had to be machined using PECM at both sides. The tool (Figure 7) consisted of a small flushing block, a surface-ground cathode, a machining table and a collet chuck.

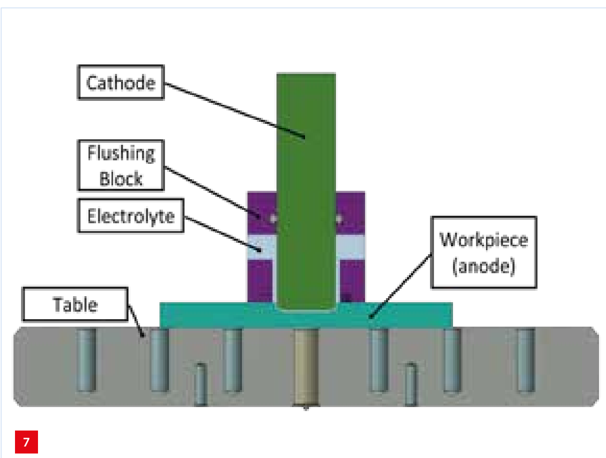
The same program as applied on the pre-machined part was used: 9 V, 2.5 ms @50 Hz, aiming at a material thickness of approximately 0.1 mm. The machining speed was set to 0.225 mm/min. For measurement, a 3D image was again made with a confocal laser microscope (Figure 8). The thickness of the material was measured with a micrometer gauge.

The thickness of the material ended up at 0.09 mm. An 18.7-μm bulge is visible in the analysis results, which is a factor of 6 smaller than in the previous test. The remaining bulge is probably the effect of movement of the diaphragm due to oscillation of the tool and the lack of any support during the last PECM operation

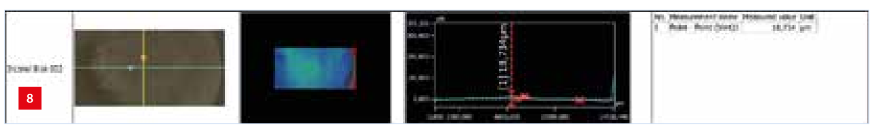
Conclusion

The PECM-machined part shows virtually no bulging. Based on the test results it can be concluded that the residual stress of turning on the inside of the part has caused the topside to bulge. It is possible to machine alloy 625 and 718 diaphragms even below 0.1 mm using PECM technology. To prevent bulging in this kind of application, there are multiple solutions:

- annealing the part before PECM;
- a second PECM process to machine the inside to remove the stress-induced material;
- a die-sinking operation on the inside to remove the stress-induced material.



PECM tooling for second test.


Laser microscope analysis result of the second test.

Prodrive Technologies – high-end mechatronics and off-the-shelf products

Prodrive Technologies is a strongly customer-oriented company that develops and delivers a wide range of highly competitive products, systems and solutions, which enable new advancements for customers in their markets. Examples of these solutions include customised cameras that exceed existing resolution and speed specifications, optical metrology systems with improved reliability, and high-precision motion stages. As a result of its innovative approach, Prodrive Technologies is among the fastest-growing technology companies in Europe.


Prodrive Technologies' solutions include high-precision motion stage and off-the-shelf product lines such as motion controllers and servo drives.

Prodrive Technologies excels at the smart design and cost-efficient production of high-end mechatronic systems. Its solutions often consist of several submodules, integrated into one complex system with challenging requirements concerning position accuracy, repeatability and cost. In fulfilling these requirements, integral system design is important. Also, Prodrive Technologies supports an extended lifetime over the product lifecycle to guarantee quality and availability. Its innovations result from research into and adoption of new process technologies, such as advanced packaging.

Customised and off-the-shelf products

Prodrive Technologies is also developing off-the-shelf product lines, such as drives, controllers, linear motors, actuators, position systems and cameras. These products leverage the company's many years of know-how and skill acquired while designing and manufacturing customised high-tech products, yielding high quality at competitive prices. Its off-the-shelf products, designed in close cooperation with several lead customers, help to shorten the design cycle for future optomechatronic systems and custom products.

Design of complex, multidisciplinary systems

Prodrive Technologies has a highly skilled research, design and engineering force of over 800 engineers in various fields, such as optics, physics, motion control, software, magnetics, precision mechanics, digital and analogue electronics. The force includes a team of system architects with different backgrounds, who can bring all these competences together to design complex, multidisciplinary systems.

Integral approach

The integral approach taken towards all these competences, combined with in-house manufacturing, enables optimised performance and quality for the best price, culminating in a unique market position. Prodrive Technologies' customers are key players in markets such as front- and back-end semiconductor equipment, life science and medical equipment, display equipment, building infrastructure, and industrial equipment. They apply its solutions to the heart of their systems to make a difference within their respective markets.

Pico Scaler

Developed by Prodrive Technologies, the Pico Scaler offers a high-accuracy position measurement solution for precise motion systems. It is ideal for (vacuum) stages where high reliability and long availability matter, and features sub-nanosecond latency synchronisation and absolute position measurement. This is combined with uncompromising digital integration options for seamless synchronisation between the measurement and motion control system. Prodrive Technologies' optical expertise provides innovative interferometer solutions focusing on reducing total cost of ownership for OEM equipment partners.

INFORMATION
WWW.PRODRIVE-TECHNOLOGIES.COM

SEVEN NOMINATIONS FOR 2021 WIM VAN DER HOEK AWARD

Mechanical design based on the design principles defined by Wim van der Hoek is very much alive. The Philips engineer and part-time professor at Eindhoven University of Technology passed away in 2019, but his name lives on in the prize named after him and his ideas are still taught. The nominations for the Wim van der Hoek Award 2021 testify to this. The jury received a total of seven nominations from two universities of technology and one university of applied sciences for students who applied existing or new design principles in their graduation work. The award will be presented on Thursday 11 November, under the auspices of DSPE, at the Precision Fair (see page 42 ff.).

Candidates

Tom Berkers
(Eindhoven University of Technology)

Voice coil actuated stage for cryogenic environments – Technology development, design and realization of actuator and demonstrative stage

"Tom is a pleasant person from Brabant with a great interest in precision mechanical engineering. Building equipment that works according to the well-known Van der Hoek's design principles fascinates him immensely. That is why the graduation assignment at JPE in Limburg suited him perfectly. His challenge was to design a voice-coil actuator that can actuate in high vacuum and under cryogenic conditions over a stroke of 5 mm with sub-micrometer accuracy. He also had to design a stage to validate and demonstrate the working principle of this actuator. For this, he extensively studied (electro-) magnetism), mechatronics, material properties and manufacturability. During the design of the demo stage, all of Van der Hoek's design principles were addressed: elastic hinges, avoidance of play and friction, stiffness compensation, weight compensation, etc., all for the purpose of minimising dissipation and increasing accuracy. Despite Covid-19, Tom was able to build, assemble and validate the operation of both the actuator and the stage, and the product has now been included in the JPE catalogue."

Jette Bloemberg
(Delft University of Technology)

MRI-Ready Actuation System for a Self-Propelling Needle – A Design and Experimental Approach

"Jette did some very interesting research into a new type of self-propelled steerable needle for prostate procedures under MRI. She developed a perfectly working prototype, bio-inspired by the anatomy of parasitic wasps, building on previous work from the Bio-Inspired Technology research group in Delft. She raised this research to an entirely new level. For MRI compatibility, she designed an entirely novel, manually driven fine-mechanical propulsion mechanism and printed this from plastic. For the experiments in human prostate tissue, she set up a very close collaboration with a well-known urology group at the Amsterdam Medical Center and used the centre's MRI-laboratory scanner for her experiments. As the space within this MRI-scanner was limited, she also developed a special experimental facility in which the tissue could be stored and moved with near zero friction. Jette is one of the best master students ever in the research group. She is a very hard worker, strongly driven, and incredibly organised. Having a bachelor's degree in Industrial Design, she is an excellent designer; her design is one of the few examples of an intricate mechanism made entirely with 3D printing."

Marjolein Daanen
(Fontys Engineering University of Applied Sciences)

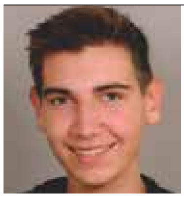
Thermal drift compensation – Implementation and realization on a three degrees of freedom sample manipulation stage

"Marjolein has worked with great enthusiasm within Thermo Fisher on the implementation and creation of drift compensation for a 3-DoF stage for an electron microscope. This stage is completely designed from elastic elements, is driven by piezo motors and can position itself on a nanometer scale. However, thermal drift limits the performance of the stage, which is very difficult to solve mechanically. She therefore laid the foundation for predicting and subsequently compensating for this thermal drift. To this end, she drew up and validated a thermomechanical model of the stage. Subsequently, drift compensation was successfully applied to a set-up specifically developed for this purpose. To do this, she had to master theory and experimental skills beyond her training curriculum. What is characteristic is her structured working method, in which she leaves nothing to chance. Marjolein also radiated her personality and passion for technology in her extracurricular activities. She examined, for example, the question of how we can encourage young people to use their creativity more and how they can be stimulated at the same time to develop themselves."

Nick Habraken
(Eindhoven University of Technology)

Robotic Microsurgical Anastomosis: A Slave Manipulator Redesign

"As an extremely inventive and very practical person, Nick designed a new manipulator for microsurgery. Microsurgery requires the utmost concentration and dexterity from surgeons. In order to relieve them and improve the quality of the operations, Microsure designed a surgical robot with which the surgery can be performed via a master-slave system using conventional instruments. His new slave manipulator with seven degrees of freedom offers, in addition to an improvement in accuracy, a much greater freedom of movement and a better view of the operating site. It is a typical example of VanderHoekean design: exact control of degrees of freedom; light, stiff and compact drives; backlash-free and low-friction drives. Nick made very clever use of the limited space in the operating area. In addition to the function, he also extensively researched manufacturability and the options for assembly and sterilisation. His extensive experience in dismantling and analysing all kinds of precision-mechanical and mechatronic equipment came in handy; practical knowledge and experience that he is happy to share with colleagues."



Rens Mollemans
(Fontys Engineering University of Applied Sciences)

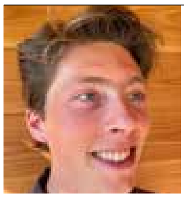
Weigh- and dosing system for test and training purposes

"Rens completed with great enthusiasm, on budget and in a professional manner his project for a weighing and dosing system at Actemium. Well-thought-out design and broad analysis of the mechanical design are his strengths. This enabled him to create the system within the stipulated period. Moreover, his skills in electrical engineering and programming are above average; this contributed to the fact that he developed the entire installation independently and got it working. Rens is enthusiastic, social, motivated and loves a challenge. With his mechatronic background, he can hold his own in mechanical engineering, electrical engineering, and IT. He likes to be involved in a project from start to finish, so that he can really see the result of his work. With his perseverance and creative thinking, he possesses valuable qualities to bring complicated projects to a successful conclusion. He is always looking for ways to expand his knowledge, for example by participating in technical challenges, such as the First Robotics Challenge in the USA."

Joost Rijnen
(Eindhoven University of Technology)

Design of a Towing Carriage for Vessel Maneuvering Simulations

"Building on his childhood experiences in heavy engineering, Joost worked on the Towing Carriage at Bosch Rexroth. This concerned a draft design for an installation that can control a ship model (8 meters long, 100 tonnes) in a wave basin in six degrees of freedom (DoFs) and actuate it in four DoFs. The desired positioning accuracies were sub-millimeter (accuracy/stroke in the order of 1:100,000) and the desired natural frequency was also extremely challenging. After extensive analysis, it appeared that he could only meet this challenge with a typically VanderHoekean out-of-the-box approach. The result is a textbook example of constraining DoFs for advanced students. He extensively calculated the draft design and assessed its feasibility. Having spent his childhood on a farm, Joost already had experience and affinity with 'heavy' technology. In addition, he was already working at various technical companies as a mechanic, draftsman and designer, and of course he built floats (carnival wagons). Now he has turned his hobby into his job and people at Bosch Rexroth are extremely happy with this social, creative and practical colleague."



Jorn Veenendaal
(Fontys Engineering University of Applied Sciences)

Machine Learning for Mechatronic Development – A ball bearing friction estimation case

"Jorn approached his graduation assignment at MI-Partners enthusiastically, analytically, conscientiously and with great drive. It involved the development of a Machine Learning model for predicting frictional properties of linear – ball – bearings, for very small displacements (several tens of micrometers). Currently, it is difficult to predict friction in practical situations with a specific friction model, because of parameters that can change under the influence of temperature, accumulation of grease and other hard-to-predict properties. That is why he developed a Machine Learning model to initially implement the specific friction model and then to grasp the more difficult, deterministic properties. Jorn is clearly a technician with a passion for technology and, above all, he is versatile and eager to learn. He is also a mentor to a FIRST Robotics team and a member of a student debating society."

OPTOMECHANICAL SYSTEMS DESIGN COURSE

End of September, a new real-life edition of the Optomechanical Systems Design course was given in Eindhoven (NL). The DSPE initiative targets mechanical, mechatronic and optical engineers, offering a broad overview of this omnipresent multidiscipline. It contains numerous design examples that illustrate the tricks of the trade in optomechanical systems design, which increasingly impacts the overall performance of high-tech systems. One of the objectives of the course is to help engineers from the various disciplines develop a common optomechanical language.

The course was attended by over 20 participants, who were generally very positive in their feedback, appreciating the overview of the field, the in-depth treatment of various topics, the teacher-class interaction and the exercises, while noting some critical points: "make it longer"; "more exercises"; "more basics"; and on the other hand: "more in-depth and less general information." Anyhow, more courses to follow.

Participants of the Optomechanical Systems Design course that was held end of September in Eindhoven.

WWW.DSPE.NL/EDUCATION

POSTAGE-FREE: "WIM VAN DER HOEK (1924-2019) – A CONSTRUCTIVE LIFE"

The DSPE publication "Wim van der Hoek (1924-2019) – A constructive life" will be for sale in the DSPE stand (number 404) at the Precision Fair on 10 and 11 November 2021 (see page 42 ff.). On the spot, visitors can purchase the book for €49.50 (€39.50 for DSPE members) without having to pay the additional postage of €6.50.

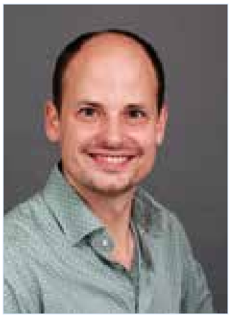
After the passing away of Wim van der Hoek, in early 2019, DSPE took the initiative to publish a book about the Dutch doyen of design principles. It covers Van der Hoek's formative years, including World War II 'adventures', his career at Philips and Eindhoven University of Technology, where he developed his breakthrough ideas on achieving positioning accuracy and controlling dynamic behaviour in mechanisms and machines, and their reception and diffusion. It concludes with his busy retirement years in which he continued to tackle – technical as well as social – design challenges, believing that technology should support people.

His specialism, dynamic behaviour and positioning accuracy, was the main subject of his part-time professorship at Eindhoven University of Technology, from 1961 to 1984. There, he undertook the endeavour to enthuse freshmen for the mechanical engineering profession and to teach fourth-year students (some 600, over the years) design as a confrontation between criticism and creation. In his lecture notes, he built on his research at Philips. He collected examples of designs that were lightweight, sufficiently stiff and play-free with regard to dynamics in his famous "The Devil's Picture Book" (*Des Duivels Prentenboek*, DDP), which he presented as a source of inspiration for upcoming and experienced designers. Now, the book about Wim van der Hoek conveys the same enthousiasm.

INFO@DSPE.NL

WWW.DSPE.NL

Lambert van Beukering & Hans van Eerden (eds.), "Wim van der Hoek, 1924-2019, A constructive life – Design principles and practical learnings between criticism and creation", ISBN 978-90-829-6583-4, 272 pages, published by DSPE.



Ralph van Oorschot is the owner and only employee of 12Solve. With a background in applied physics and mechanical engineering, he has more than ten years of experience in multidisciplinary system development and system architecting. Three years ago, he started as a freelancer to help companies in complex system development projects in the Eindhoven (NL) area.

He can assume the role of a lead system architect for automation and (high-accuracy) assembly/production machine and test equipment development.
In addition, he can help companies to professionalise their product creation process, taking the role of a critical technical reviewer or just helping with projects that are technically stuck and need a fresh outsider view.

INFORMATION
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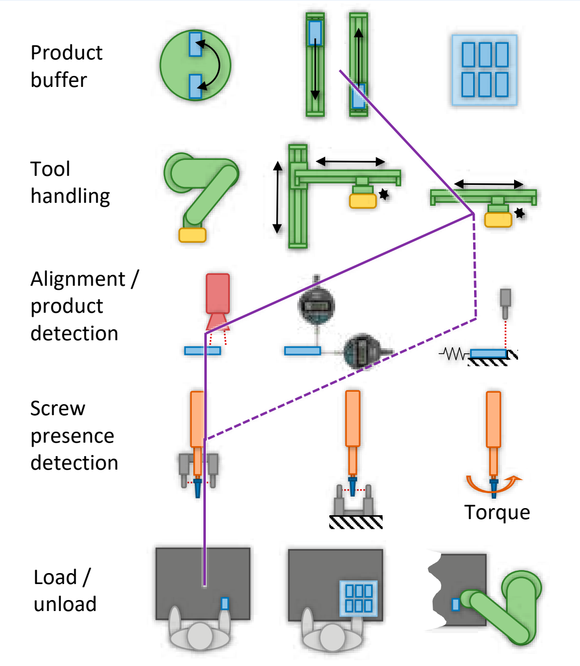
WWW.12SOLVE.NL

12Solve – the added value of a (freelance) system architect

In complex development projects, the system architect is in charge of translating customer requirements into a design and, in most cases, also realising the system. The journey towards the best system design is partly a creative process and the system architect can optimise and derisk this process as much as possible. If internal resources are scarce, 12Solve can bring in an experienced freelance system architect.

One of the first tasks of a system architect is to translate (either internal or external) customer requirements and demands into measurable and verifiable system requirements. These mostly multidisciplinary high-level requirements are then decomposed into 'smaller' monodisciplinary functional requirements for individual modules or individual disciplines. In this way, each module can be developed relatively independently by a single person or small team, while compliance with the overall system requirements is guaranteed. In parallel, a conceptual system design is created, for which a lot of trade-offs have to be made that exceed the boundaries of disciplines and modules. Here, tolerance chains, budget divisions, brainstorm sessions and morphologic overviews can help. In the system architect's very versatile role, a helicopter view over the complete project is required, while having sufficient in-depth disciplinary knowledge for tackling specific issues.



Simplified example of a morphologic overview for development of a machine.

Multidisciplinary perspective

Traditionally, machine development starts with an experienced mechanical engineer in the lead of the conceptual design, resulting in a mechanical concept relatively early in the process. However, high-tech system development projects tend to become more complex along with strict planning; there is no room for iteration loops and thus a right-first-time approach is mandatory. As disciplines such as software and control become more dominant, the conceptual design must be approached from a multidisciplinary perspective. A common pitfall with the traditional monodisciplinary approach is that the design still contains a lot of uncertainties and risks, concerning requirements such as throughput, uptime, measurement accuracies and safety. The system architect has the tools and knowledge to sufficiently create certainties and derisk an intrinsically uncertain development process.

System architecting resource availability

A current challenge is the lack of personnel to staff projects. A flexible pool of resources, quite common for disciplines such as mechanical and software design, could be very beneficial for system architecting too. Specific knowledge may be lacking in some fields, but this knowledge gap can usually be closed quickly, especially if a freelancer starts with background tasks and gradually takes over more system architecting responsibilities. Building up a long-term relationship with a limited number of freelance system architects will also help in making a flying start for future projects. A freelance system architect will contribute new expertise as well as broad experience of various ways of working in development projects. There is thus every reason to contact 12Solve for a freelance system architect when growth is limited by system architecting resource availability.

ECP² COURSE CALENDAR

COURSE (content partner)	ECP² points	Provider	Starting date
FOUNDATION			
Mechatronics System Design - part 1 (MA)	5	HTI	to be planned (Q2 2022)
Mechatronics System Design - part 2 (MA)	5	HTI	8 November 2021
Fundamentals of Metrology	4	NPL	to be planned
Design Principles	3	MC	9 March 2022
System Architecting (S&SA)	5	HTI	15 November 2021
Design Principles for Precision Engineering (MA)	5	HTI	15 November 2021
Motion Control Tuning (MA)	5	HTI	20 June 2022
ADVANCED			
Metrology and Calibration of Mechatronic Systems (MA)	3	HTI	2 November 2021
Surface Metrology; Instrumentation and Characterisation	3	HUD	to be planned
Actuation and Power Electronics (MA)	3	HTI	to be planned
Thermal Effects in Mechatronic Systems (MA)	3	HTI	14 December 2021
Dynamics and Modelling (MA)	3	HTI	30 November 2021
Manufacturability	5	LiS	31 January 2022
Green Belt Design for Six Sigma	4	HI	to be planned
RF1 Life Data Analysis and Reliability Testing	3	HI	to be planned
Ultra-Precision Manufacturing and Metrology	5	CRANF	to be planned
SPECIFIC			
Applied Optics (T2Prof)	6.5	HTI	1 November 2021
Advanced Optics	6.5	MC	24 February 2022
Machine Vision for Mechatronic Systems (MA)	2	HTI	upon request
Electronics for Non-Electronic Engineers – Analog (T2Prof)	6	HTI	to be planned
Electronics for Non-Electronic Engineers – Digital (T2Prof)	4	HTI	to be planned
Modern Optics for Optical Designers (T2Prof) - part 1	7.5	HTI	21 January 2022
Modern Optics for Optical Designers (T2Prof) - part 2	7.5	HTI	28 January 2022
Tribology	4	MC	8 March 2022
Basics & Design Principles for Ultra-Clean Vacuum (MA)	4	HTI	to be planned
Experimental Techniques in Mechatronics (MA)	3	HTI	to be planned (Q3 2022)
Advanced Motion Control (MA)	5	HTI	21 March 2022
Advanced Feedforward & Learning Control (MA)	3	HTI	18 May 2022
Advanced Mechatronic System Design (MA)	6	HTI	to be planned
Passive Damping for High Tech Systems (MA)	3	HTI	23 November 2021
Finite Element Method	2	MC	4 November 2021
Design for Manufacturing (Schout DfM)	3	HTI	10 March 2022

Please check for any rescheduling or 'virtualisation' of courses due to the coronavirus crisis.

ECP² program powered by euspen

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

WWW.ECP2.EU

Course providers

- High Tech Institute (HTI)
  WWW.HIGHTECHINSTITUTE.NL
- Mikrocentrum (MC)
  WWW.MIKROCENTRUM.NL
- LiS Academy (LiS)
  WWW.LIS.NL/LISACADEMY
- Holland Innovative (HI)
  WWW.HOLLANDINNOVATIVE.NL
- Cranfield University (CRANF)
  WWW.CRANFIELD.AC.UK
- Univ. of Huddersfield (HUD)
  WWW.HUD.AC.UK
- National Physical Lab. (NPL)
  WWW.NPL.CO.UK

Content partners

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

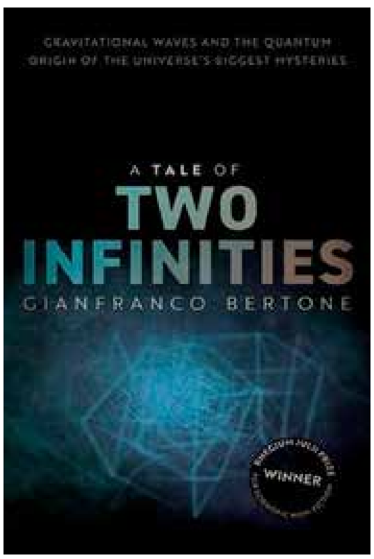
Multi-messenger astronomy

Amsterdam-based professor Gianfranco Bertone has written an accessible book about fascinating topics in astronomy, such as black holes, dark matter and dark energy. Recently, a Dutch and an English edition were published, "*Tussen twee oneindigheden – De aanstaande revolutie in ons begrip van de kosmos*" and "A Tale of Two Infinities – Gravitational Waves and the Quantum Origin of the Universe's Biggest Mysteries", respectively.

In his latest book, Bertone investigates the extraordinary potential of 'multi-messenger astronomy' to revolutionise our understanding of the Universe. This new discipline combines the traditional approach based on the observation of light from celestial objects, with new methods based on other 'messengers'. These include gravitational waves, neutrinos and cosmic rays, all carrying information that is otherwise inaccessible. The author combines his discussion of multi-messenger astronomy with an exploration of the physics connecting the vast Universe and the infinitely small.

The book is accessible to a general audience with no former knowledge on the subject, while being supplemented by endnotes and a detailed bibliography for the more experienced reader.

Gianfranco Bertone is professor of theoretical astroparticle physics at the University of Amsterdam (NL) and director of the European Consortium for Astroparticle Theory. In 2013, his first popular science book, "Behind the Scenes of the Universe – From the Higgs to Dark Matter", appeared.



The Dutch edition (EAN 9789085717386) was published in September by NewScientist, the English edition (EAN 9780192898159) in October by Oxford University Press.

WWW.NEWSCIENTIST.NL

GLOBAL.OUP.COM

DSPE Knowledge Day Engineering for Contamination Control

Contamination control is crucial for modern-day precision engineering. Two years ago, DSPE organised a first knowledge day about this topic, dedicated to Engineering for Particle Contamination Control. This successful event prompted DSPE to organise a second knowledge day in spring 2020, which however had to be postponed because of the Covid-19 pandemic... until 23 November 2021. Now, this afternoon event will be devoted to design aspects aimed at dealing with contamination or minimising the implications of contamination. In addition, information will be shared regarding tools that support the design (and test) phase of a project.

The event is highly relevant for precision engineers involved in designing advanced mechatronics systems. Presentations will be given by Paul Blom (senior system engineer at VDL ETG), Sven Pekelder (CTO at Settels Savenije), Freek Molkenboer (senior systems engineer at TNO), Cees van Duijn (contamination control expert at Omneo Systems), and jointly by Rob Lansbergen (senior system engineer at Lans Engineering) and Erik Vermeulen (CEO at Fast-Micro).

The DSPE Knowledge Day on Engineering for Contamination Control is organised by DSPE in collaboration with VCCN (Association of Contamination Control Netherlands), and will be hosted by Mikrocentrum in Eindhoven (NL). More information and registration at the DSPE website.

WWW.DSPE.NL/EVENTS

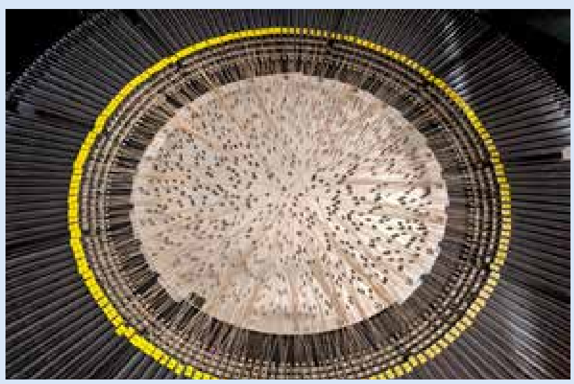
Ingenious 'woven' spectrometer

WEAVE, an ingenious spectrometer with a large number of movable glass fibres, is almost ready for use by astronomers. This has been announced by a team of astronomers and technicians under the leadership of Scott Trager (University of Groningen). Trager is professor in stellar evolution and the chair of the WEAVE Survey Consortium that is set to deliver overview studies of the Universe. The spectrometer, including the two robots that arrange the glass fibres in changing configurations, has been successfully installed in the Dutch-British-Spanish William Herschel Telescope (WHT) at La Palma (Spain).

WEAVE stands for WHT Enhanced Area Velocity Explorer and is partly made in the Netherlands. The instrument can focus on over 900 stars or galaxies at the same time. With high precision, it unravels starlight into thousands of separate colours. The core of WEAVE comprises movable glass fibres that can be arranged individually in a way that they do not disrupt one another. From a short distance, it appears like a piece of lace or a loom, hence the name WEAVE. With WEAVE, astronomers can study the formation of stars and research how galaxies and the Universe change.

Over the coming five years, WEAVE will generate millions of spectra of stars and galaxies. The data from WEAVE could, for example, be linked to the data collections of the LOFAR telescope and of the Gaia space satellite. Through this, astronomers will gain further insight into how our Milky Way was formed, how the stars in this galaxy have evolved and how other galaxies are comprised.

The spectrometer comprises of various components. The so-called prime-focus corrector ensures that each glass fibre absorbs more than 80% of the starlight. The fibre positioner consists of two robots that arrange the over 900 glass fibres in the desired configurations within an hour. Two cameras, each with 12,000 x 6,000 pixels, gather the resulting spectra. Two cryostats containing fluid nitrogen cool the digital cameras down, so that no image distortion occurs.



Close-up of the heart of WEAVE; 700 of the 950 glass fibres were meticulously positioned by two robots that are outside the frame. The yellow ring is around 60 cm in diameter. (Photo: Gavin Dalton/Oxford University/STFC)

WWW.RUG.NL/RESEARCH/KAPTEYN

Tom Oomen receives Japanese award

Tom Oomen, professor in the Control Systems Technology group at Eindhoven University of Technology in Eindhoven (NL), is the winner of the 7th Grand Nagamori Award, a prestigious prize in the field of motor technology.
Last month, he won the award for his research on "Advanced motion control for precision mechatronics: identification, learning, and control", involving the development of control methodologies for improving the precision of semiconductor manufacturing equipment, and related control applications. Besides his academic output in this area, he has already published several articles in *Mikroniek*. The Nagamori Award is an international award given by Nagamori Foundation of Kyoto, Japan, "to vitalize the research and development of motor, power generator, actuator, and other related technologies, and support research and development engineers."

WWW.TOOMEN.EU
WWW.NAGAMORI-F.ORG/EN

Entangling next-generation photonics and quantum technologies

With the exponential growth of our information society, the end of traditional scaling in communications and computing comes in sight. To continue the trend in computational power and energy-efficient communication, emerging photonics and quantum technologies are the future. The Eindhoven Hendrik Casimir Institute (EHCI) will create a unique and optimal environment to enable these fields to grow synergistically. The new institute was officially launched last month during the opening of the academic year at Eindhoven University of Technology (TU/e) in Eindhoven (NL).

The new institute was named after the Dutch physicist Hendrik Casimir (1909-2000), who is most famous for his work on superconductivity and quantum physics, most notably the Casimir effect: the phenomenon where two plates placed very close to each other subtly attract each other due to quantum fluctuations.
This is analogous to how the two research fields underpinning the institute will be working close together.
But perhaps more importantly, because of his role as director of the Philips Research Lab in Eindhoven, Casimir understood better than anyone how fundamental knowledge and new technology are intertwined. Science ultimately finds its way into technology and at the same time science is driven by new technological advances. This so-called science-technology spiral symbolises the philosophy of the new institute.
The new institute will smartly 'entangle' two major technology fields: the light-driven communication technology of photonics and quantum technology. Both hold great promise in overcoming the limits that our current computation and communication technologies are slowly but surely reaching, for example in terms of miniaturisation and energy costs. From the computing power to the number of devices connected to the internet: it all doubles every 2-3 years. This trend can only be sustained with breakthroughs in materials, processes and devices, integrating these holistically into systems.

The work at the institute will be done at various hierarchical levels: from ground-breaking science in materials, via novel devices and innovative circuits, to disruptive systems that will shape our future world. This approach, already successfully applied at TU/e to bring integrated photonics technology from the lab to real-world applications, will also be used for quantum technology and other emerging information technologies.

The aim is that in ten years' time the institute will make significant contributions to new computing paradigms like quantum and neuromorphic computing; to novel technologies for making communication far more energy-efficient and secure, and compacting biosensors for detecting diseases; and to metrology sensors with atomic-scale resolution.

WWW.TUE.NL/EHCI

A look inside the machine in which nanowires were grown that made it possible for silicon to emit light. This TU/e finding was named 'Breakthrough of the Year' by PhysicsWorld last year. (Photo: Nando Harmsen)

Focus on surface metrology

Aerotech, manufacturer of high-performance motion control and positioning systems, has founded a new subsidiary, Peak Metrology. Concentrating all activities around high-precision metrology, Peak Metrology draws on Aerotech's extensive know-how in positioning systems, but focuses exclusively on supporting industrial customers with solutions for surface metrology up to complete integration.

Peak Metrology offers a wide range of products for surface metrology applications, including turnkey machines. Surface analysis is often integrated directly into the production chain as a quality assurance process, for example in semiconductor production during wafer inspection or the manufacture of flat panels. Here, the quality is assessed after almost every process step, for which a fully automated in-process inspection with object feeding, measurement and subsequent further processing is usually triggered. It is essential that measuring and positioning cycles are precisely synchronised.

A cooperation with metrology specialist Keyence has been started, first exhibits of which will be presented at Control 2022, from 5 to 6 May in Stuttgart (Germany).

Integration of the Keyence wide-area 3D measurement system VR5000 into an Aerotech positioning system.

WWW.AEROTECH.COM

Timesavers celebrates 25th anniversary

Timesavers International, headquartered in Goes (NL), is specialised in building machines for deburring, edge rounding, laser oxide removal, heavy slag removal, finishing and precision grinding of sheet metal parts and plates. The company started as Linden Machine Factory in 1939 and merged with Timesavers USA exactly 25 years ago.

Timesavers has developed a leading deburring process, the rotary brush machine. In 2016, they have even won the Red Dot award for the 42 RB series. Timesavers is constantly looking for improvement and works on innovations to increase productivity and ease of use for their customers. They are currently working towards operator-independent machines and helping businesses to automate their business. The wide range of machines, from small manual grinders to very high-end machines, are all developed in-house. Each machine is equipped with a PLC and HMI, and to optimise screen control Timesavers has introduced an HMI with pictograms.

At the recent BlechExpo in Stuttgart (Germany), Timesavers introduced the 22 Series WRBW 600-mm-wide rotary brush machine for deburring, edge rounding, finishing and laser oxide removal, as an addition to their portfolio of the larger 32 RB and 42 RB series deburring machines.

WWW.TIMESAVERSINT.COM

Anti-vibration technology for metrology

Environment is a very important factor in metrology. When measuring in the order of nanometers, even seemingly small amounts of motion in the measurement path can be significant. Data acquisition takes place over time, so any environmental change during the measurement shows up in the data. The presence of vibration during a laser interferometer measurement can cause fringe print-through, drop-out, and in some cases, the inability to collect data at all.

Leading optical metrology innovator Zygo Corporation has developed an array of anti-vibration solutions over the years, in response to the trend that laser interferometry is transitioning away from carefully controlled lab environments as a growing number of applications demand reliable solutions in environments where it was previously impossible to achieve quality metrology. The most recent solution is FT-QPSI, a measurement mode with vibration-robust performance. It can be used on the Verifire MST (for multi-surface test applications, which are particularly susceptible to vibration) anywhere FT-PSI (phase-shifting interferometry-based Fourier transform) can be applied.

QPSI acquisition is a model-based approach that addresses rigid-body vibrations, and increases vibration tolerance without sacrificing lateral resolution. ZYGO claims QPSI is a breakthrough in precision optical testing, eliminating noise and ripple print-through in phase data due to small vibrations, and providing reliable data that would otherwise be 'noisy' with traditional PSI acquisition. QPSI measurements require no special set-up or calibration, and cycle times are typically equivalent to standard PSI measurements. QPSI is today included as standard on ZYGO's range of interferometers, enabling reliable high-precision measurements in the presence of vibration from manufacturing equipment.

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