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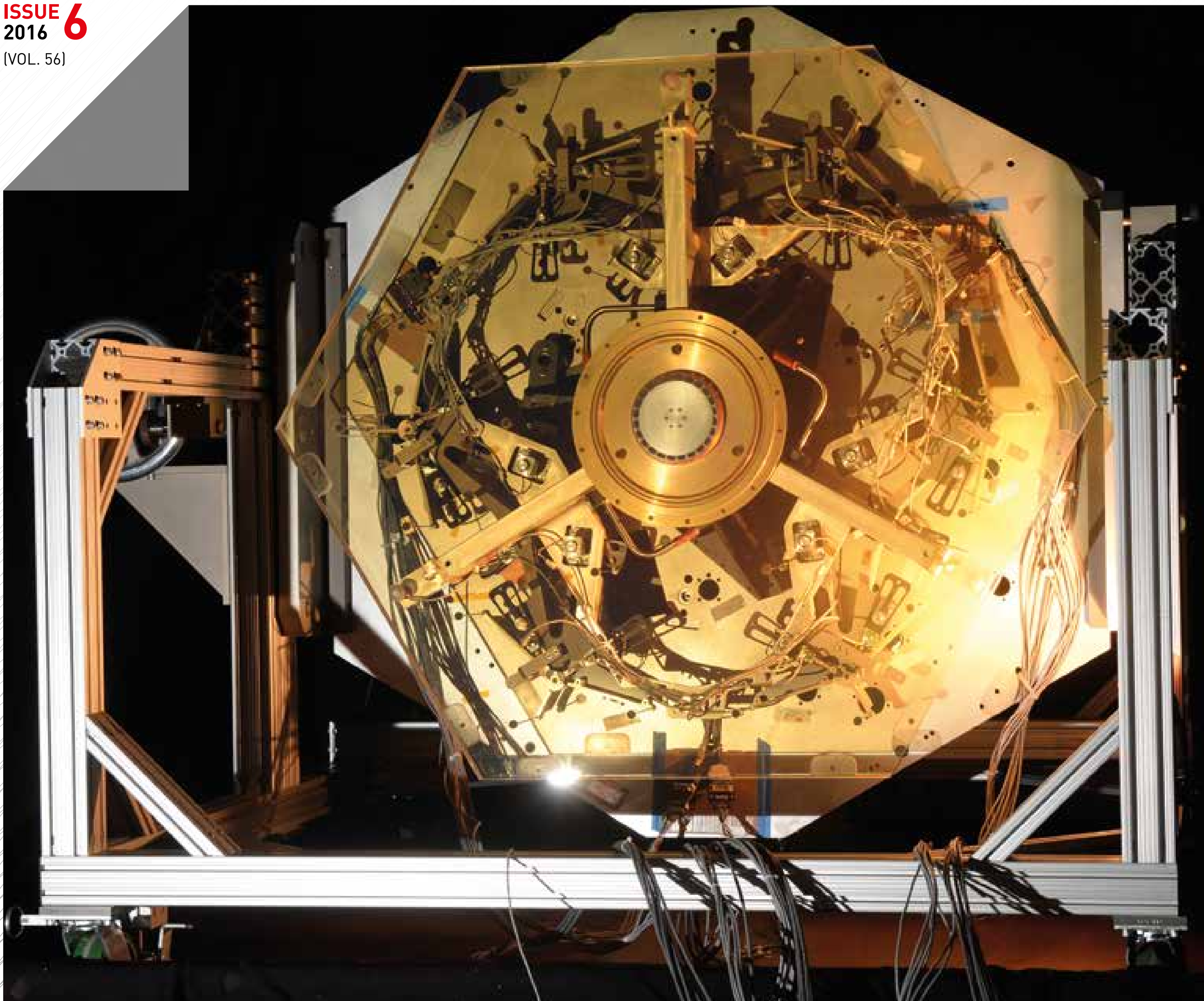

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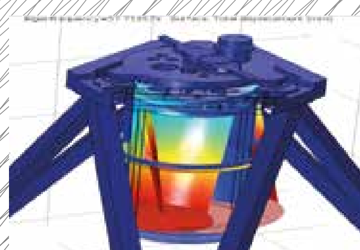
■ **2016 PRECISION FAIR** IMPRESSIONS ■ **VIBRATION-'FREE'** CRYOGENICS



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FEATURES

PUBLICATION INFORMATION

Objective
Professional journal on precision engineering and the official organ of DSPE, the Dutch Society for Precision Engineering. Mikroniek provides current information about scientific, technical and business developments in the fields of precision engineering, mechatronics and optics.
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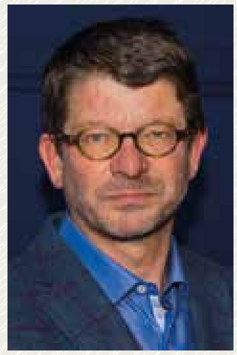
The main cover photo (featuring a segment of the Thirty Meter Telescope) is courtesy of TMT/Harris/Fred Kamphues. Read the article on page 10 ff.

ASTRONOMICAL INNOVATION



The theme of this issue of Mikroniek is 'Astronomical instruments'. Astronomy is associated with huge-scale, high-performance, precision work and ideas. Humans' interest in space and what lies beyond our planet has made our lives more comfortable in lots of ways. Without space research, we would not have satellites, which we use for GPS navigation when driving, or for satellite telephony. Space research also has also given us a better insight in how our world was formed and may have helped us to believe that we are not the only living beings in the universe.

Precision technology is making a substantial contribution to astronomical research, and the competence thus developed is finding application in other areas of technology. This is a typical characteristic of precision technology: applying competences acquired in one area to other areas. This was clearly apparent at the 2016 Precision Fair: I was able to visit different companies from the Eindhoven region and was amazed to see how many technology enterprises have been initiated using the research conducted by, and hence the competence built up by, Philips. One example of this was the winner of the ir. A. Davidson Award (announced during the Precision Fair) Wouter Aangenent, who is working at ASML Research as senior architect for mechatronic systems.

In the 1950s, Antoon Davidson and his successor Hein Post took the initiative within Philips to document and distribute technology throughout the whole company. This unique knowledge sharing has become normal practice within the precision engineering community in the Netherlands, with DSPE acting as a binding element.

Talking about Philips and awards, let's not forget Wim van der Hoek. At the age of 92 years, Wim attended the Precision Fair to witness the granting of the Wim van der Hoek Award 2016 to Niels Giessen. The influence of Wim's design principles is still recognisable in modern precision designs.

Another knowledge sharing activity, in collaboration with Brainport Industries, was the visit to the Precision Fair of Optence (one of the eight photonic clusters in Germany, located in the Wetzlar area). Ahead of the Fair, DSPE organised company visits for them to Sioux, Tegema, Demcon, BKB, NTS, ASML and FEI (Thermo Fisher). A return visit will be scheduled during the W3+ Fair 2017 in March in Wetzlar.

Sharing is also for season's greetings. DSPE wishes you and your relatives a happy New Year, and for you and your company an astronomical 2017.

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EXTREMELY LARGE, HIGHLY ACCURATE

The E-ELT is the European Extremely Large Telescope with a primary mirror of 39 meters that is being developed by ESO for the European astronomical community and ESO members. For the realisation of the E-ELT, TNO Space and Scientific Instrumentation proposes several technical contributions. These are, among others, the mirror support structure, the actuators required for these mirror segments, and optical metrology to control the alignment or phasing. This overview shows how E-ELT technologies are cutting edge while also needing to be robust and low cost for a facility of this size.

JEROEN HEIJMANS, JAN NIJENHUIS AND ARJO BOS

AUTHORS' NOTE

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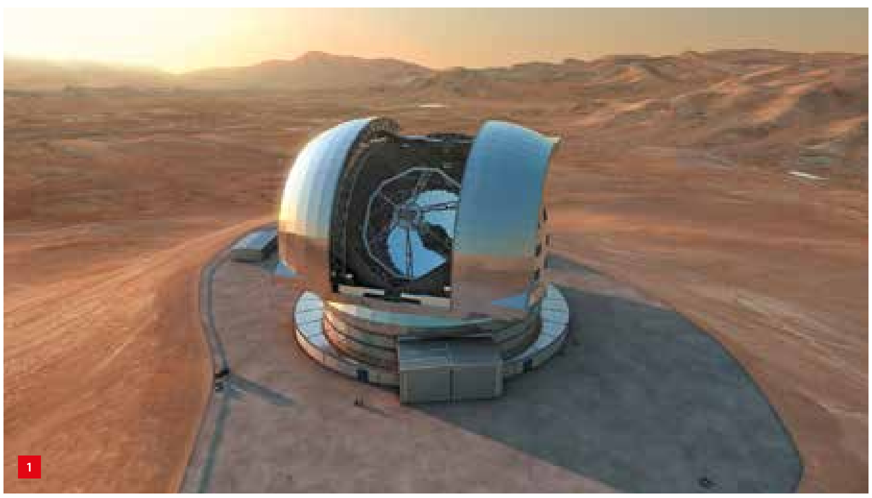
The E-ELT [1] will be based in Chile near the other ESO (European Southern Observatory) telescopes and is the largest of the three giant optical telescopes (the Giant Magellan Telescope, GMT, the Thirty Meter Telescope, TMT, and the E-ELT) that are currently being developed in the world (Figure 1). Besides some healthy competition there also exists a cooperative attitude between the developers as can be read from the following article (page 10 ff.), on the TMT. Up to now, 8-10m sized telescopes have been the largest available telescopes for many years and the limited number of telescopes that exist are in high demand worldwide. As observation times are often long and availability is limited the competition is fierce to get access to telescopes.

The segmented-mirror technology has achieved a breakthrough in creating even bigger telescopes that enable completely new science. Large telescopes mean high-resolution imaging, especially in combination with adaptive optics (AO), which has been the second technology enabler to realise these large telescopes. Resolution can be limited by atmospheric conditions and AO technology is capable to compensate for these conditions making the necessity to go into space for clear skies no longer a requisite.



1 *The proposed design of the E-ELT situated in Cerro Armazones, Chile. (Illustration courtesy of ESO)*

The giant telescopes that can be realised on Earth have a great collective area that enables observing faint objects, looking deeper into the universe, or direct imaging of distant objects or even exoplanets. The imaginable (and imageable) new science that these telescopes create is extensive and so will the number of surprises be that have not yet been predicted.

This year, a contract was assigned for the enormous 79m high dome to the Italian Ace consortium and, not insignificant, the final design of TNO for the primary mirror (M1) support structure was approved by ESO. This is the kind of progress needed to achieve the planned first light of this telescope in 2024.

The Netherlands makes a significant contribution in the European astronomy programme, both on the scientific level and in the technical developments. TNO has developed instrumentation for ESO since 1997 with the delay line for the Very Large Telescope 's interferometer (VLTi) together with Airbus (formerly Fokker Space). From then on a large number of instruments have been developed by TNO for ESO, in recent years with partners such as the Dutch consortium NOVA and currently with VDL.

For the realisation of the E-ELT, TNO proposes several technical contributions. These are the mirror support structure, the actuators required for these mirror segments and optical metrology to control the alignment or phasing. The laser guide stars that have been developed for the VLT are also designated for the E-ELT. TNO has proposed in the past to also develop the large deformable M4 mirror and more recently the M2 and M3 mirrors. The latter have been awarded to other European companies in a competitive bidding process as is common for these large European facilities.

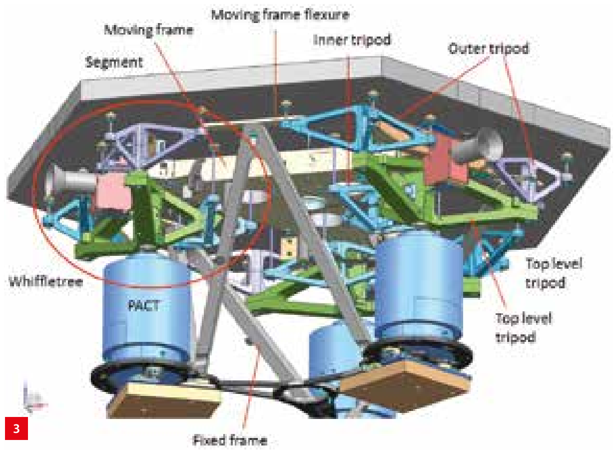
M1 support structure

In 2010, TNO delivered three prototypes for the M1 segment support structure to ESO. These prototypes have been tested extensively in a specific test set-up. This has resulted in an updated specification requiring improvements concerning performance, maintenance and cost reduction.
In February 2015, the contract was signed between ESO and the Dutch consortium VDL/TNO/NOVA to design and build an engineering model and four qualification models for the M1 segment support structures. TNO is responsible for the design and testing assisted by NOVA while VDL ETG, as the prime contractor, is responsible for the total development, manufacturability and possible future series production.

It was decided not to just upgrade the design but push for a new design based on the proven principles of the prototype but with much improved maintenance characteristics and improved performance. Furthermore, bringing down the production cost was felt as an urgent need. This has led to a new design that indeed meets these goals. Figure 2 shows the first engineering model that has been designed by TNO and realised by VDL and will be put to the test by NOVA Astron.

All 798 segments are supported by the same support structure consisting of three whiffletrees (Figure 3). In the lateral direction each segment is supported by an identical membrane. The whiffletrees and lateral support are connected to the Moving Frame (MF) which acts as an intermediate body before being connected to the telescope structure itself. With the addition of a clocking strut between the MF and the segment, a statically determined connection between segment and MF is realised. Combined this is called the Segment Assembly (SA).


2



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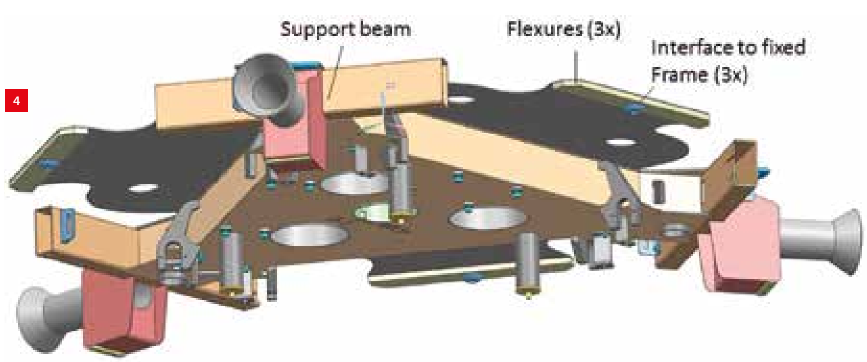
Three segment position actuators (PACTs) are placed in between the telescope structure and the Moving Frame to control the segment height and tip/tilt rotations. While changing the elevation angle of the telescope the combined mirror shape of the 798 segment should not change during deformation of the telescope structure. Finally, three flexures connected to the Fixed Frame (FF) make sure that the MF can only move in piston and tip/tilt mode, i.e. lateral motions and rotations around the optical axis are prevented.

To sum up, the main functions of the MF are:
1. Intermediate body between the telescope and the segment, minimising the impact of the PACT operation on the surface form error.
2. One of the most important elements in the stiffness chain from segment to telescope structure, determining the natural frequencies for Tx, Ty (lateral modes) and Rz (clocking).

The MF is made of 1.5mm thick stainless steel plates (Figure 4). The plates are welded together mainly using laser welding. This provides a continuous connection between the sheet metal parts while the laser guarantees that heat transfer to the box is minimised. This results in a box that does not warp due to differential thermal expansion during the welding process.



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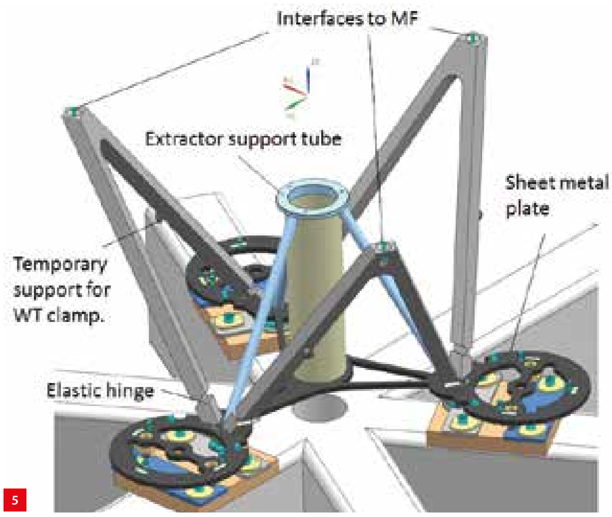
2 *The first engineering model of the M1 segment support structure.*

3 *The definition of the various sub-assemblies of the segment support structure.*

4 *The new design for the Moving Frame.*



5 *The design for the Fixed Frame.*

The Fixed Frame (Figure 5) is attached to the telescope structure at three points. It is also attached to the three horizontal sections of the MF-flexures. The FF mainly consists of six struts which minimise the obstruction of the Segment Assembly. The struts are loaded in tension/ compression which guarantees optimal use of material.

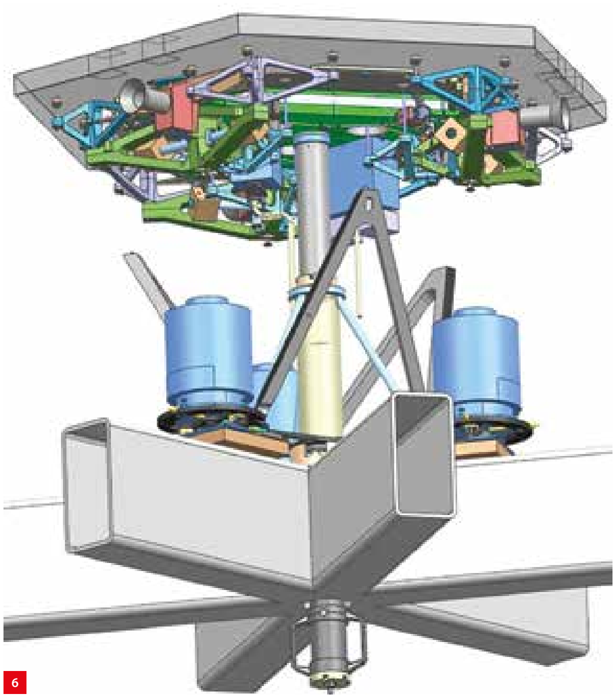
The three lower connections of the six struts are interconnected by a triangular plate (Figure 6) which also supports the central tube that accommodates the extractor (see below). The top end of that tube is connected by three struts to the lower support points of the FF. Hence a very efficient combination of functions has been realised. The triangular plate has three circular extensions that serve as temporary supports for the PACTs. Additional connections between these support platforms and the telescope structure provide the required stiffness.

The parabolic primary mirror is made up of 133 unique segments and comprises 798 segments in total: six identical copies of each unique segment.

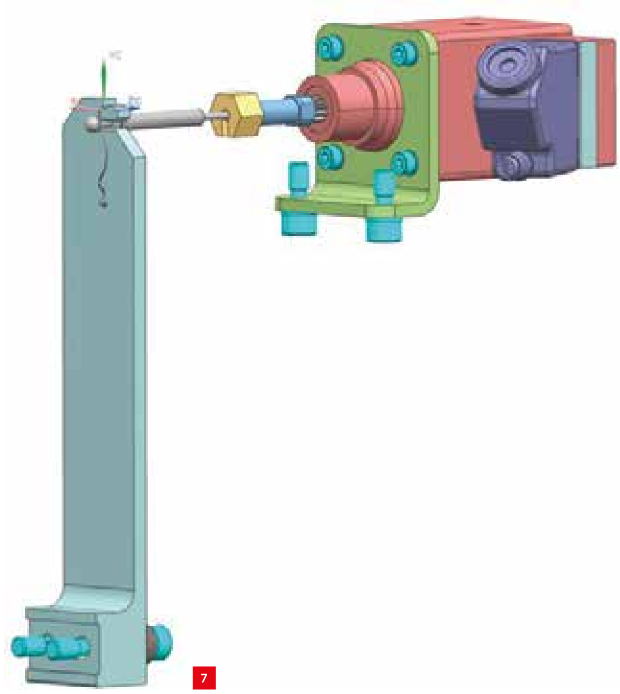
Every 1.5 years the mirrors need to be recoated. This means that they have to be removed from the telescope and brought to the coating facility. The tool for this operation, named the extractor, is inserted from underneath into the Fixed Frame structure. Then the Segment Assembly is disconnected from the FF and PACTs followed by the extension of the extractor by a total of nearly 300 mm. A specifically designed crane lifts the SA from the extractor and lowers it down to a carriage which will bring it to the coating facility. Another SA with an identical segment on it will then by re-installed into the telescope so that observations during the night can continue.
This exchange scheme is possible because for each unique segment there are seven identical copies available of which six are in use at any given time.

So far, little has been said about the performance of the system, especially the surface form error and the dynamic performance. The requirement of 25 nm rms for the surface form error has been met. The error portion induced by mechanical tolerances, temperature changes, thermal gradients, PACT piston movement, etc., amounts to approximately 13 nm rms. Especially the thermal performance is very good. For a temperature change of 20 °C only 2.3 nm rms error was predicted.

The differences in surface form error of the various segments are such that they can be compensated using passive and active means. Passive compensation is obtained by installing



6 *The extraction of the Segment Assembly.*



7 *The warping harness that introduces a corrective bending moment into the mirror.*

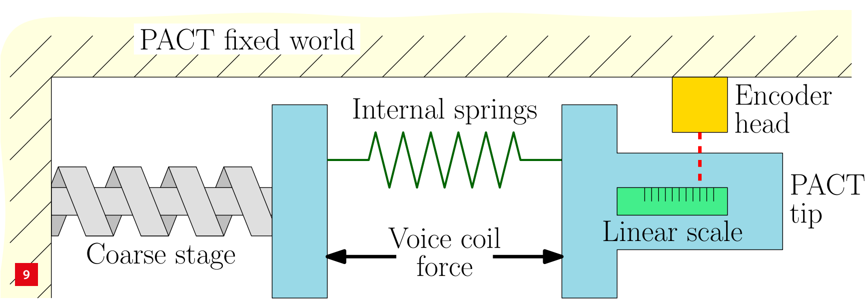
8 *The final design for the M1 segment support.*

9 *Schematic of a segment position actuator, PACT, showing the dual-stage design.*

specific counter-balance masses at strategic places. For each unique segment the balancing will be different. It is the result of an extensive set of finite-element model calculations.

With passive means only systematic errors can be compensated which is why also active means are provided. Surface form corrections are obtained by pushing against the tripods at strategic places using so-called warping harnesses (Figure 7). The harder the actuator pushes or pulls, the bigger the segment deformation will be. The maximum applied deformation of the segment is around 1 micrometer. Figure 8 shows the final design for the M1 segment support

Strict requirements exist for the dynamic performance of the segment to optimise performance of the PACT actuators and to survive earthquakes. Eigenfrequencies required for the piston and tip/tilt motions are 66 and 55 Hz, respectively, for this assembly having a mass of almost 250 kg. TNO has been successful in this by meeting the requirements with a general margin of 10% by design. Mid 2016, ESO approved the final design of the segment support



that meets all requirements and the realised first model will be verified by tests starting in December 2017.

Segment position actuator

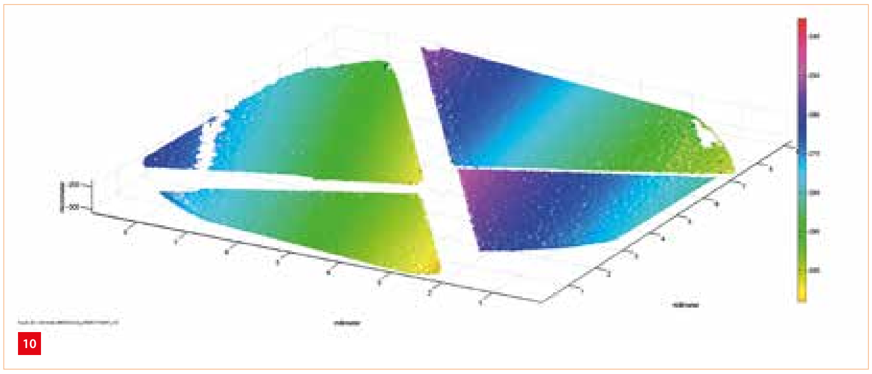
The three segment position actuators (PACTs) that actively control height and tip/tilt angles of each of the 798 mirror segments are required to have sufficient stroke (15 mm) to be able to reposition the segment to its nominal position, compensating for the deflections of the underlying telescope structure. In addition, the actuators need to provide the resolution and accuracy (1.7 nm rms) necessary for phasing the primary mirror in the presence of disturbances, dominated by wind and ground disturbances. To cover the large dynamic range, a dual-stage design has been adopted (Figure 9).

TNO has been working since 2005 on these long-stroke and nanometer-accurate actuators for the Wind Experiment Breadboard of ESO. The actuators must operate at angles between –85° and +85° with respect to the vertical (zenith), varying the axial load between 0 and –900 N while keeping the power dissipation below 1.5 W. This limited power budget is needed to prevent the air from heating up, which would distort the image quality of the telescope.
To achieve this, an off-loading mechanism is applied with a voice coil as fine stage. The coarse stage is driven by a DC-motor and a leadscrew. An elastic straight-guide is applied to minimise hysteresis and friction, also having a positive effect on lifetime. The PACTs should have a mean time between failure (MTBF) of 40 years, and be low cost.

Segment phasing and alignment (OCT) sensor

At the edge of each of the 798 segments, six sensors are placed for mirror-to-mirror alignment. These sensors have a limited measurement range and require calibration to translate the measurement signal into surface-to-surface alignment. TNO has proposed an additional direct measurement with an optical metrology system based on Optical Coherence Tomography (OCT). This optical measurement system has previously been designed for industrial height profiling, which could be adapted to fulfil the needs of a segment mirror alignment metrology system.

The current applications for the OCT system are for inline inspection of manufactured components where sub-micrometer profile accuracy is required [2]. Some early tests with the existing system show the possibility of co-phasing multiple objects, as can be seen in Figure 10. An average standard deviation σ of 52 nm is achieved. The system is capable of two measurements per second on a 6mm x 6mm field of view with a 1mm depth. Improved phase interpolation in the interlock amplifier and interferometric triggering is anticipated to result in the targeted σ of 5 nm.



10 *Measured height map of four neighbouring surfaces separated by a gap with the existing TNO Optical Coherence Tomography system. Height +/– 20 µm over 9 mm x 9 mm.*

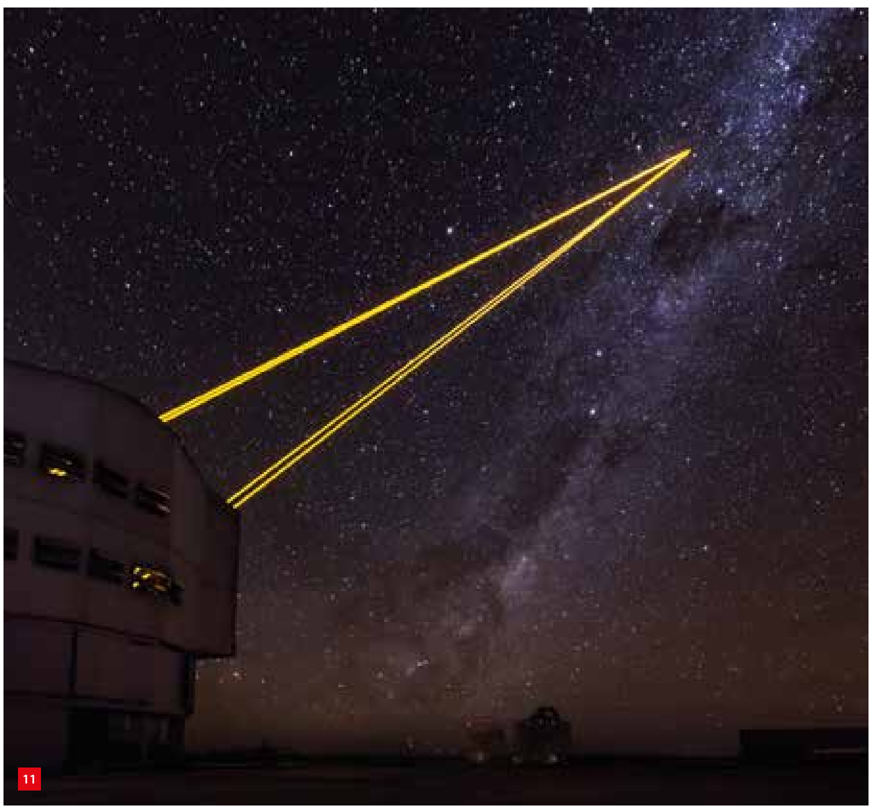
11 *Laser guide stars at the VLT, the beams are visible from outside the telescope due to Rayleigh scattering. The artificial stars are above 90km height. (Illustration courtesy TNO/H. Werij)*

12 *The Optical Tube Assembly which creates a laser guide star.*

Laser guide stars

In April of this year, ESO started operating the four-laser guide star facility as part of the adaptive optics system at the VLT [3]. The photo of this event (Figure 11) shows the orange-coloured 589nm laser beams due to Rayleigh scattering with air molecules. An artificial star is created as a spot of less than 1 arcsecond above 90km height where atmospheric sodium atoms are excited by the laser and emit a flux. With the four artificial bright stars that can be positioned in the (small) field of view of the telescope the adaptive optics system now has clear objects to optimise image quality to, rather than being dependent on the availability of a 'natural guide star'.

The optical tubes (Figure 12) that TNO developed expand the 22Watt laser from 15 to 300 mm with a wavefront quality better than 50 nm rms. This is achieved by a two-lens system of which the large secondary lens is an asphere.



A tip/tilt mirror enables beam steering with an accuracy better than 0.3" (1.5 µrad) to position the artificial star in the right location in the telescope image. These optical tubes will also be the baseline for the laser guide stars of the E-ELT.

Conclusion

Technologies required for the E-ELT are both cutting edge while also needing to be robust and low cost for a facility of this size. TNO has focussed on a number of technologies [4] that both fit with the strategies of its Optomechatronics department and are crucial to the success of the E-ELT. In 2018, the first eight mirror support structures will be delivered and TNO looks forward to a bright future of astronomy.

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30 M DIAMETER FOR 7 MILLI-ARCSEC RESOLUTION

The Thirty Meter Telescope has been designed to meet the demands of the scientific community for a next-generation observatory. TMT will have approximately three times the resolution and nine times the collecting area of the current 10m-class telescopes. Advanced adaptive optics capabilities will allow highly sensitive, diffraction-limited observations from a wavelength shortward of 1 μm to the mid-infrared over most of the sky. A 20arcmin-diameter field of view facilitates the deployment of wide-field, multi-object spectrographs. These capabilities will enable groundbreaking advances in a wide range of scientific areas, from the most distant reaches of the Universe to our own Solar System.

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History

Optical astronomical telescopes have been around for a little over 400 years. Galileo's first refractor had a tiny 1.5cm aperture. Isaac Newton achieved a big improvement in optical quality in 1668 by building the first practical reflecting telescope. This type of telescope quickly became the norm in astronomy and primary mirror apertures grew gradually from 20 cm in the late 17th century (Christiaan Huygens) to the current 10m-class telescopes (Keck, VLT, Gemini, Subaru, GTC, etc.). Apertures doubled in size approximately every fifty years.

The new class of extremely large telescopes – European Extremely Large Telescope (E-ELT), TMT, and the Giant Magellan Telescope (GMT) – break away from this four centuries old trend (Figure 1). History teaches us that breaking a trend, brings high technical and financial risks to a project. The 1.2m Herschel in 1789 and the 6m Russian BTA-6 in 1976 are examples of telescopes with limited success.

1 *Telescope progression. (Data source: Wikipedia)*

In 1977 a team of astronomers from the University of California (UC) and the California Institute of Technology (Caltech) came up with a plan for a successor of the 5m Hale Telescope in Palomar. Initially, the idea was to design a scaled-up version of the Hale Telescope. However, a primary mirror with a 10m diameter would require a heavy structural support system and a very thick piece of glass to maintain a good optical surface. Cost estimates for a 10m telescope, using a monolithic primary mirror, were in excess of one billion dollars.

Jerry Nelson, a young and innovative astronomer and physicist, proposed a different approach. Instead of using a monolithic mirror, he advocated a segmented primary. But this presented another challenge: co-phasing all segments to form a continuous reflective surface. This approach required advanced sensor technology, control algorithms and computer power. But if the technology could be mastered, there would, theoretically, be no limit to the size of a reflecting surface. Nelson said in an interview at the time, "The Hale Telescope was very innovative for its day, but in terms of advancing the state of the art – or at least pushing the available technology to its limits – it's been downhill ever since for optical telescopes. It is time for a forward step, not just making improvements in an old design."

The UC/Caltech committee invited Nelson and his team to develop his idea. In 1979 they presented their segmented mirror approach to the committee, which was subsequently chosen over several other concepts. The new telescope would become the twin telescope W.M. Keck Observatory (Figure 2).

2 *The twin Keck telescopes. (Photo: Fred Kamphues)*

3 *Primary mirror segments of the Gran Telescopio Canarias (GTC) in La Palma. (Photo: Fred Kamphues)*

The twin Keck telescopes are located on the summit of Maunakea in Hawaii. Both identical telescopes have a 10m primary mirror, composed of 36 hexagonal segments. The segments are aligned by 160 electronic sensors and 108 position actuators. Since first light in 1993, the W.M. Keck telescopes have been the most productive observatory in the world.

Although the elevation of 4,145 meter reduces a significant part of the atmosphere's turbulence, long exposures still cause image blurring. Both Keck telescopes are therefore equipped with an advanced Adaptive Optics (AO) system, including Laser Guide Stars and Deformable Mirrors. The combination of excellent seeing and Adaptive Optics, enables Keck to produce images that rival the resolution of the Hubble Space Telescope.

Due to the success of Keck, the concept of segmented primary mirrors has been adapted by many other observatories around the world, including the Gran Telescopio Canarias, currently the largest optical telescope in the world (Figure 3). It is also the baseline design for the future Thirty Meter Telescope (TMT) and the European Extremely Large Telescope (E-ELT).

TMT International Observatory

The TMT project was born out of the merging of three earlier large-telescope projects: CELT, the California Extremely Large Telescope; VLOT, the Very Large Optical Telescope; and GSMT, the Giant Segmented Mirror Telescope. In 2003, TMT convened a Science Advisory Committee to help match the technical capabilities of the TMT with the demands of the scientific community for a next-generation observatory. Their efforts were instrumental in forging the Detailed Science Case for TMT, which continues to guide the design of the project.

TMT will have a 30m primary mirror, composed of 492 hexagonal segments. TMT's dramatic increases in collecting aperture and spatial resolution, will revolutionise studies of early star formation in the Universe, the evolution of galaxies, the characterisation of extra solar planets and the understanding of the fundamental physics of dark matter and dark energy.

TMT Systems Engineering.

The TMT International Observatory has its headquarters in Pasadena, California and includes five partner countries with participation from multiple organisations and industrial partners in the design and implementation of the observatory subsystems. TMT is comprised of 32 individual subsystems which include optical systems, instruments, AO systems, controls, mechanical systems, supporting software and hardware and the infrastructure required to support their operation.

In a project with so many time zones, the work never stops. A significant challenge for TMT Systems Engineering is to enable multiple international partners and suppliers to work on these self-contained subsystems, whilst having confidence that when they are integrated as a system they will meet the system level performance requirements.

TMT Systems Engineering has developed processes to support this distributed development, while maintaining the ability to respond and trade cost and schedule with requirements, budgets and performance at the system level. The key approaches that have been adopted include the following:

- Maintain a clear flow-down from science cases to system and subsystem requirements, enabling a clear understanding of trade-offs, and an ability to make changes as needed in an efficient manner.
- Maintain a logical system decomposition that can describe each subsystem in terms of requirements that are consistent with system performance and interfaces that clearly define responsibilities, functions and designs.
- Provide an efficient change process that supports appropriate review and efficient approval cycles at the needed project level.
- Document and agree the configuration of the system and subsystems in a manner that is clear and enables efficient change when required.
- Organise the Project and Systems Engineering (SE) team such that there is direct interaction between SE and partner organisations, while maintaining the appropriate reporting relationships between the TMT and partner work package managers.
- Maintain requirements and interfaces in a common DOORS (dynamic object-oriented requirements system) database, providing all project stakeholders access to the database and its products.
- Maintain a common observatory geometry database that accepts models from subsystem teams and incorporates them into a common digital mock-up (DMU) of the observatory. Make this database available to stakeholders within the project.
- Provide a verification and acceptance test process that emphasises the importance of verification and pre-shipment acceptance of subsystems before shipment to the observatory.

TMT Design

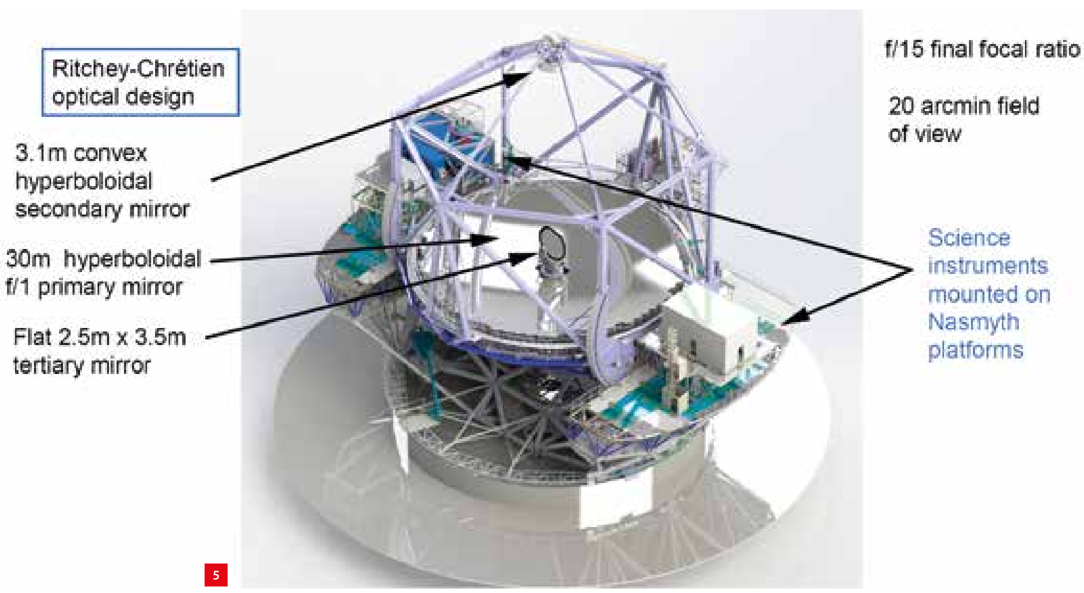
TMT's enclosure (Figure 4) features an innovative calotte design. Its circular aperture and spherical shape preserve the exceptional image quality of the telescope while minimising costs. The compact calotte design, with its smooth exterior, even while open for observing, is significantly less affected by unbalanced wind forces. This will lower the induced vibrations to the structure and optics.

The selected optical configuration for TMT is a 3-mirror Ritchey-Chretien design (Figure 5), providing a 20arcmin field of view. The science instruments are located on the two Nasmyth platforms. Figure 5 shows the TMT digital mock-up.

The telescope structure is designed as an altitude-over-azimuth (alt-az) mount. This allows the telescope to be very compact (relatively speaking) and provides direct load paths from the telescope down through the structure to the pier and foundations. TMT's primary mirror will be composed of 492 closely spaced hexagonal segments. A total of 1,476 actuators and 2,772 sensors will control the overall shape of the primary mirror to just a few nanometers.

TMT will be able to support instruments that are sensitive through the atmospheric windows from 0.31 to 28 µm. The atmosphere limits the angular resolution ('seeing-limited image quality') to about 0.5 arcsec. However, using adaptive optics (AO) a diffraction-limited angular resolution of 7 milliarcsec can be achieved at a wavelength of 1 µm. TMT's Adaptive Optics Instrument will produce images ten times sharper than those of the Hubble Space Telescope.

4 *TMT calotte enclosure. (Image: TMT/NAOJ)*



5 *TMT digital mock-up (DMU). (Image: TMT/ Eric Wilde)*

as a sphere. After removal of the forces and moments, the spherical surface will elastically deform into the desired aspherical shape.

After polishing, the round blanks are cut into a hexagonal shape (which may release some residual stresses and can deform the segment) and mounted on the Segment Support Assembly (SSA).
The SSA is a balanced whiffletree support, insensitive to gravity. 27 Thin flexures are attached to the back of the mirror to provide axial support. The lateral support (required when the telescope points towards the horizon) is provided by a central metallic diaphragm recessed into the glass. The segment with support system is shown in Figure 7. The segment size for TMT is almost identical to that for E-ELT and there is a good information exchange with ESO (European Southern Observatory) in Garching, Germany to benefit from each other's lessons learnt.

After segment assembly, Polished Mirror Assemblies (PMAs) are finished with ion beam figuring (IBF). Residual errors from IBF and mounting in the Mirror Cell (a small clocking error of a few micrometers creates strong astigmatism) are removed with an active Warping Harness. 21 Actuators apply small moments to the whiffletrees and can correct low-order segment aberrations such as focus and astigmatism.

The Secondary Mirror (M2) is a 3.1m convex hyperboloid. It reflects the light from the *f*/1 primary mirror and converts it to an *f*/15 beam for the science instruments. It will have a passive whiffletree support and a hexapod for active alignment. The M2 detailed design phase has not started yet. Procurement of the M2 will start in early 2018.

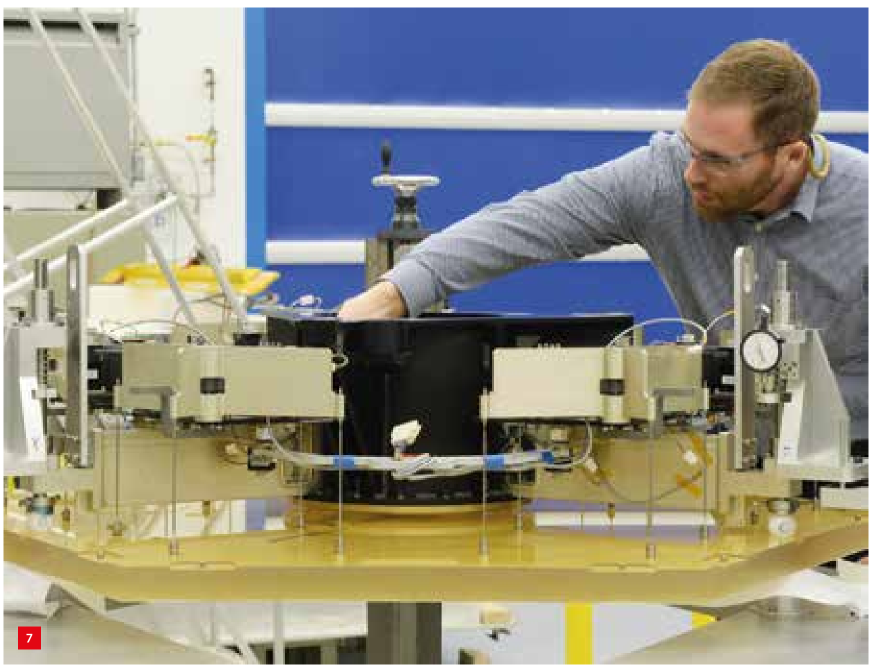
Optics

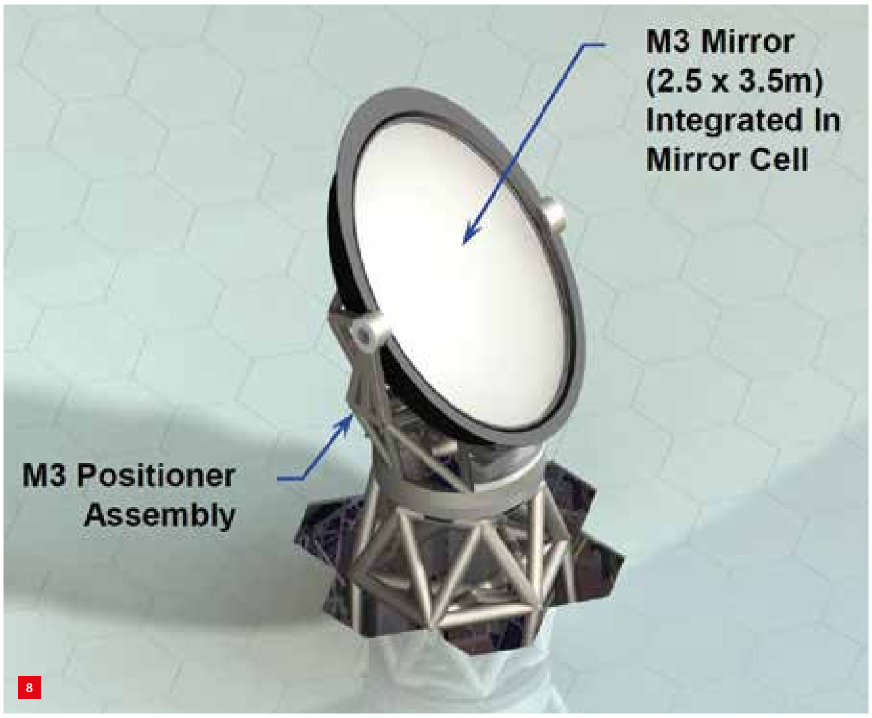
TMT is particularly drawing on Keck experience in the design of the primary mirror. The segmented TMT Primary Mirror (M1) is a 30m diameter concave hyperboloid. The focal ratio of the TMT M1 is faster than Keck (*f*/1 vs. *f*/1.75). This leads to segments that are more aspheric for a given size. It was the main reason to make the TMT segments 20% smaller than the Keck segments. The smaller segments can also be thinner. The segments are made from zero-expansion Clearceram-Z, with a thickness of 45 mm (Figure 6).

The Primary Mirror segments are already in production. Polishing of the aspheric segments is done with a technique called stress mirror polishing (derived from Keck). In this technique, forces and moments are selectively applied to the edges of a mirror blank in order to warp the blank to the desired degree of distortion. The segment is polished

6 *Primary Mirror blanks at Ohara in Japan. (Photo: TMT/NAOJ/Ohara)*

7 *M1 segment assembly at Harris, Rochester NY. (Photos: TMT/Harris/Fred Kamphues)*

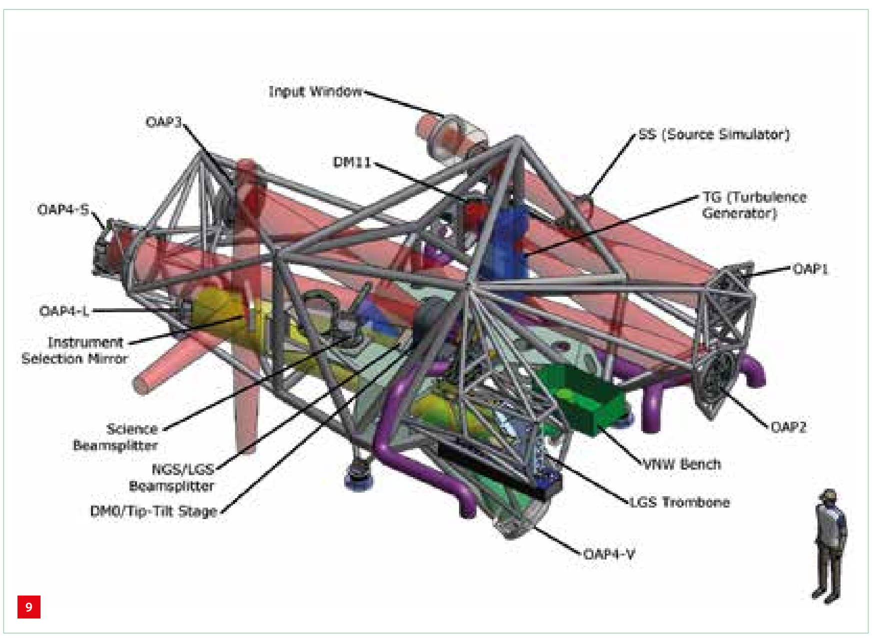




8 *TMT Tertiary Mirror (M3). (Image: TMT/Eric Wilde)*

9 *Narrow Field Infra-Red AO System (NFIRAOS). (Image: TMT)*

The Tertiary Mirror (M3) is articulated to allow it to direct starlight to any of the instruments placed on the Nasmyth platforms (Figure 8). Instruments along the elevation axis itself do not require motion of the Tertiary, but instruments off the elevation axis require modest rotations of the Tertiary as a function of zenith angle. This feature allows all instruments to be stationary on the platforms and instruments will be live and ready for observations at all times. Each instrument will point towards the Tertiary. This will allow the astronomer to switch between any instruments, and be ready to begin integration on a new target in under ten minutes.



Adaptive Optics

The TMT first-light Adaptive Optics (AO) facility consists of the Narrow Field Infra-Red AO System (NFIRAOS) (Figure 9), the associated Laser Guide Star Facility (LGSF) and the AO Executive Software (AOESW).

NFIRAOS is located on the TMT Nasmyth platform and relays light from the telescope to three science instrument ports after sensing and correcting for wavefront aberrations introduced by atmospheric turbulence and the observatory itself. NFIRAOS is a multi-conjugate AO (MCAO) system, which provides uniform, diffraction-limited performance in the J, H, and K bands. NFIRAOS includes two deformable mirrors, six LGS Wave Front Sensors (WFSs), one high-order Pyramid WFS for natural guide star AO, and up to three low-order, IR, natural guide star on-instrument wavefront sensors (OIWFSs) and four on-detector guide windows (ODGWs) within each client instrument. The first-light LGSF system includes six sodium lasers to generate the NFIRAOS laser guide stars (Figure 10).

First-light instruments

Infrared Imaging Spectrometer (IRIS)

IRIS (Figure 11) is a near-infrared (0.84 to 2.4 μm) integral field spectrograph and wide-field imager being developed for first light for TMT. It mounts to the advanced AO system NFIRAOS and has integrated On-Instrument Wave Front Sensors (OIWFSs) to achieve diffraction-limited spatial resolution at wavelengths longer than 1 μm. With moderate spectral resolution (R ~ 4,000-8,000) and large bandpass over a continuous field of view, IRIS will open new opportunities in virtually every area of astrophysical science. It will be able to resolve surface features tens of kilometers across Titan, while also mapping the most distant galaxies at the scale of an individual star-forming region.

Wide Field Optical Spectrometer (WFOS)

The Wide Field Optical Spectrometer (WFOS) will provide near-ultraviolet and optical (0.3-1.0 μm wavelength) imaging and spectroscopy over a more than 40 arcmin^2 field of view. Using precision-cut focal plane masks, WFOS will enable long-slit observations of single objects as well as short-slit observations of hundreds of objects simultaneously. WFOS will use natural (uncorrected) seeing images.

Acknowledgements

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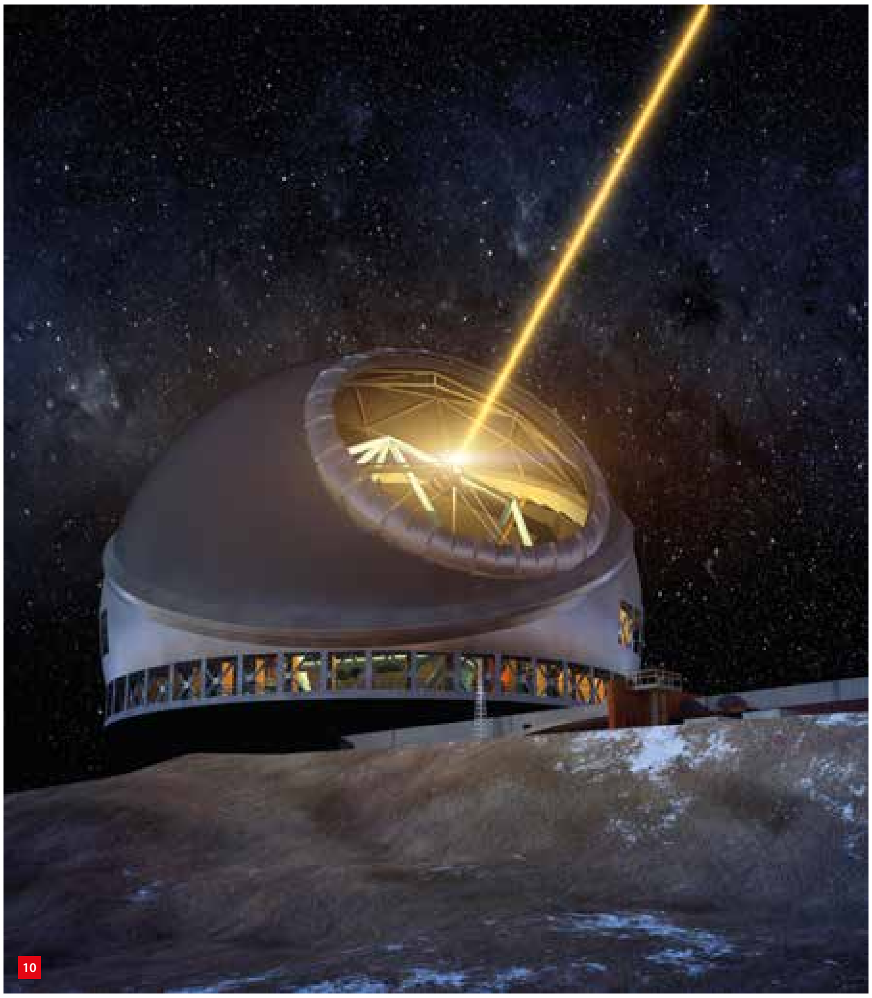
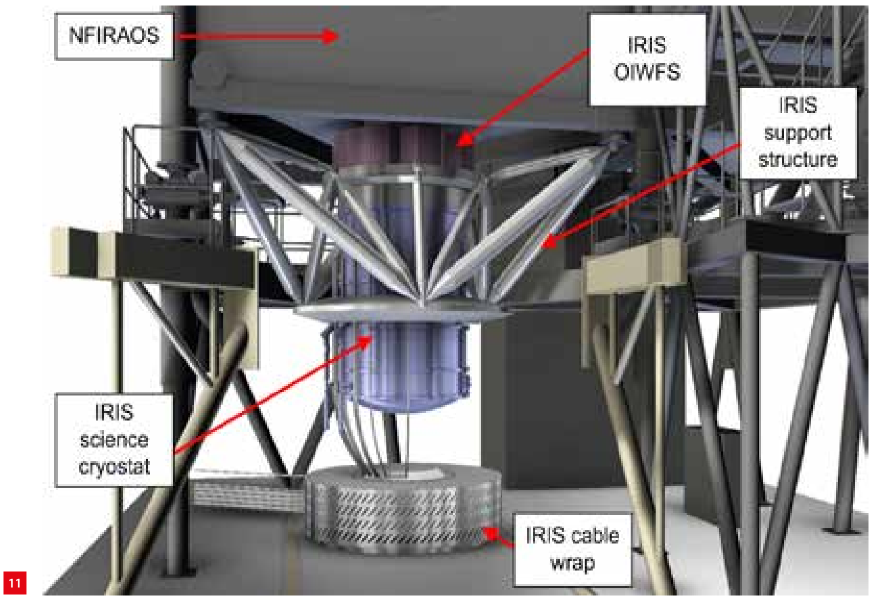
Columbia Knowledge Development Fund, the Association of Canadian Universities for Research in Astronomy (ACURA), the Association of Universities for Research in Astronomy (AURA), the U.S. National Science Foundation, the National Institutes of Natural Sciences of Japan, and the Department of Atomic Energy of India. ■

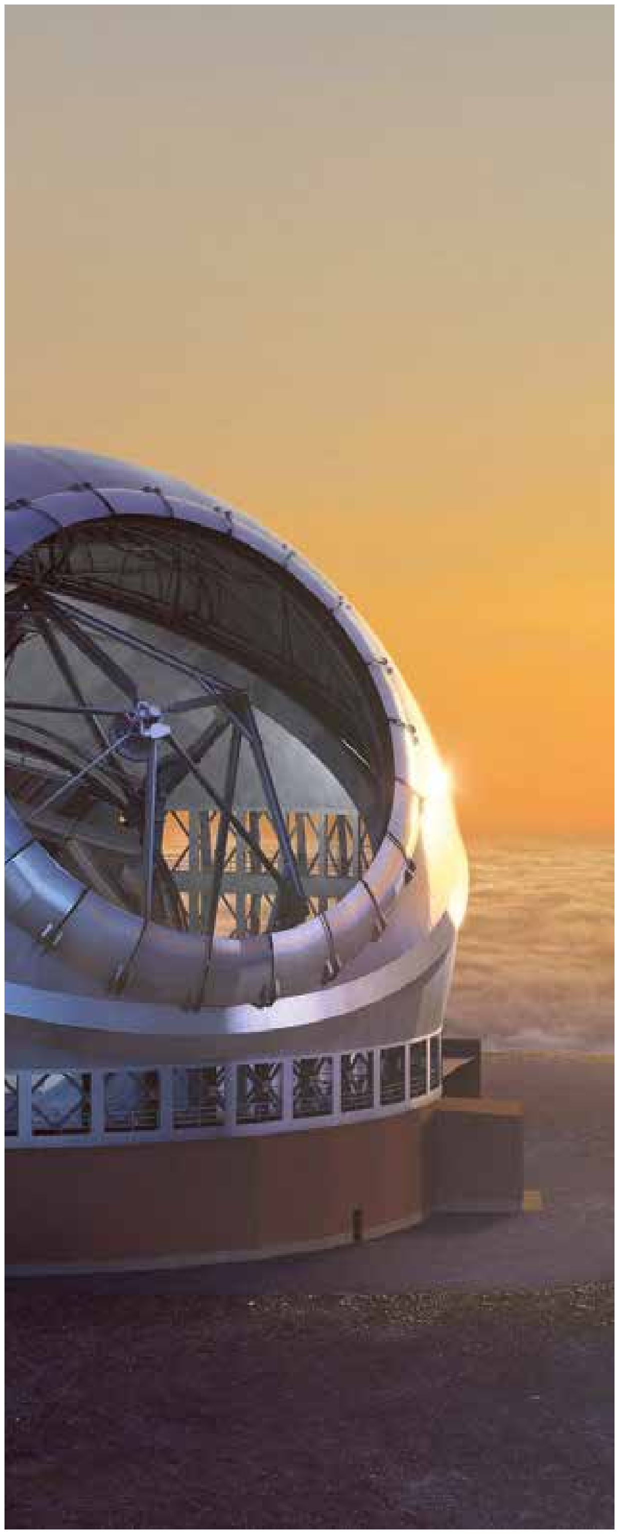


10 *TMT centre-launched Laser Guide Star Facility. (Image: TMT)*

11 *The IRIS instrument. (Image: TMT)*

of India and their supported institutes, and the National Research Council of Canada. This work was supported as well by the Gordon and Betty Moore Foundation, the Canada Foundation for Innovation, the Ontario Ministry of Research and Innovation, the Natural Sciences and Engineering Research Council of Canada, the British





UPCOMING **EVENTS**

23-24 January 2017, Coventry (UK)

Special Interest Group Meeting: Quality Control for Additive Manufacturing

Topics include the UK strategy for additive manufacturing, dimensional metrology & non-destructive testing (NDT), surface metrology, in-process metrology & NDT, and materials metrology.

WWW.EUSPEN.EU

25 January 2017, Delft (NL)

Smart sensing for industry

Workshop organised by the Netherlands' national metrology institute, VSL. One of the benefits of smart sensor networks is the ability to get real-time and non-invasive insights into product quality during the entire production process. However, there still remain some key challenges that need to be addressed before smart sensing can become a vital element in zero-defect manufacturing.

VSL

Dutch Metrology Institute

WWW.VSL.NL

7-9 March 2017, Veldhoven (NL)

RapidPro 2016

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

WWW.RAPIDPRO.NL

15-16 March 2017, Wotton-under-Edge (UK)

Lamdamap 2017

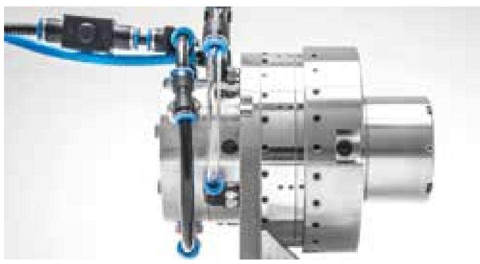
Twelfth edition of this event, focussed on laser metrology, coordinate measuring machine and machine tool performance. Venue is the Renishaw Innovation Centre.

WWW.LAMDAMAP.COM

27 March 2017, Düsseldorf (GE)

Gas Bearing Workshop

Second edition of the initiative of VDE/VDI GMM, DSPE and the Dutch Consulate-General in Düsseldorf (Germany). Gas bearings are important components or integral technology of most advanced precision instruments and machines. This workshop invites all engineers, scientists, system architects and users of gas bearings to share the state-of-the-art.



WWW.GAS-BEARING-WORKSHOP.COM

27 April 2017, Cranfield (UK)

Ultra Precision Conference 2017

Organised by the Cambridge and Cranfield MRes cohort of the EPSRC Centre for Doctoral Training in Ultra Precision Engineering, this event is devoted to "Advances in Ultra Precision – Innovating the Future ".

WWW.ULTRAPRECISION.ORG

18-19 May 2017, Aachen (GE)

29th Aachen Machine Tool Colloquium

Since 1948, the Aachen Machine Tool Colloquium has given trend-setting impulses for production technology in a 3-year cycle. The general topic of AWK 2017 is "Internet of Production for Agile Enterprises".

WWW.AWK-AACHEN.DE

29 May – 2 June 2017, Hannover (GE)

Euspen's 17th International Conference & Exhibition

This event will once again showcase the latest advances in traditional precision engineering fields such as metrology, ultra-precision machining, additive and replication processes, precision mechatronic systems & control and precision cutting processes. Furthermore, new topics will be addressed covering the revision of the SI and applications of precision in biomedical sciences.

WWW.EUSPEN.EU

31 May – 1 June 2017, Veldhoven (NL)

Materials 2017, engineering & technology

Trade fair, with exhibition and lecture programme, targeted at product developers, constructors and engineers. The focus is on properties - applications - solutions.

MATERIALS

Properties • Applications • Solutions

WWW.MATERIALS.NL

ACCEPT ERRORS, CANCEL EFFECTS

Infrared instruments on large telescopes require a total wavefront error (WFE) of < 50 nm. The static aberrations of the mirrors in these telescopes can be compensated by means of a 'set-and-forget' deformable mirror. A design was made in which the mirror surface is controlled using actuators that provide nanometer resolution at cryogenic temperatures combined with high positional stability. The stiff design provides a high resonance frequency (> 200 Hz) to suppress external disturbances. It is shown that a typical 2 µm rms WFE can be corrected with a 38 nm fitting error, providing diffraction-limited performance.

ROBIN TRINES, HUUB JANSSEN, SANDER PAALVAST, MAURICE TEUWEN, BERNHARD BRANDL AND MICHIEL RODENHUIS

AUTHORS' NOTE

Robin Trines, Huub Janssen, Sander Paalvast and Maurice Teuwen all work for Janssen Precision Engineering (JPE), based at Maastricht-Airport, the Netherlands. Bernhard Brandl and Michiel Rodenhuis work at the Leiden Observatory of Leiden University, the Netherlands. Robin Trines did his Master thesis project on the design described here at Eindhoven University of Technology, the Netherlands.
Measurements on the deformable mirror demonstrator were performed at the NOVA Optical/IR group in Dwingeloo, the Netherlands. Their support is acknowledged.
Part of this work was presented at the SPIE Astronomical Telescopes + Instrumentation 2016 conference in Edinburgh, Scotland.

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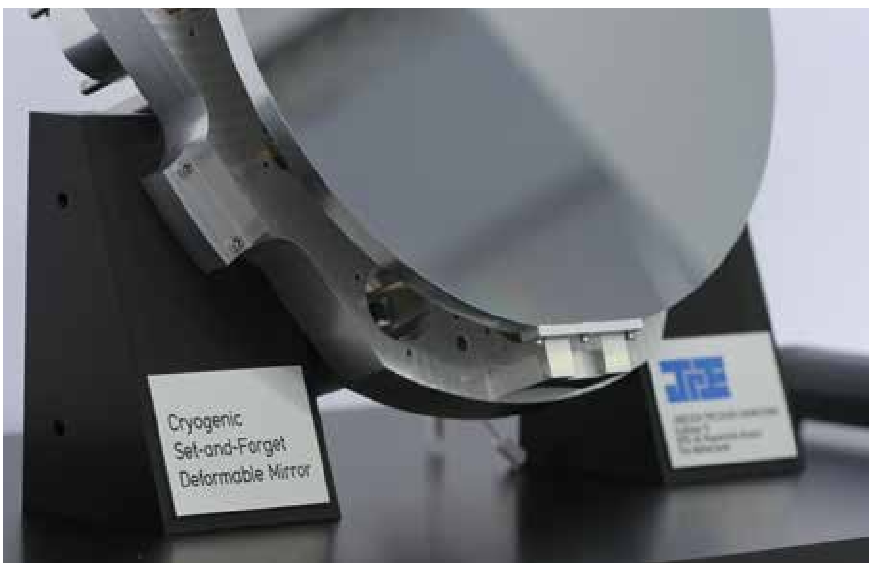


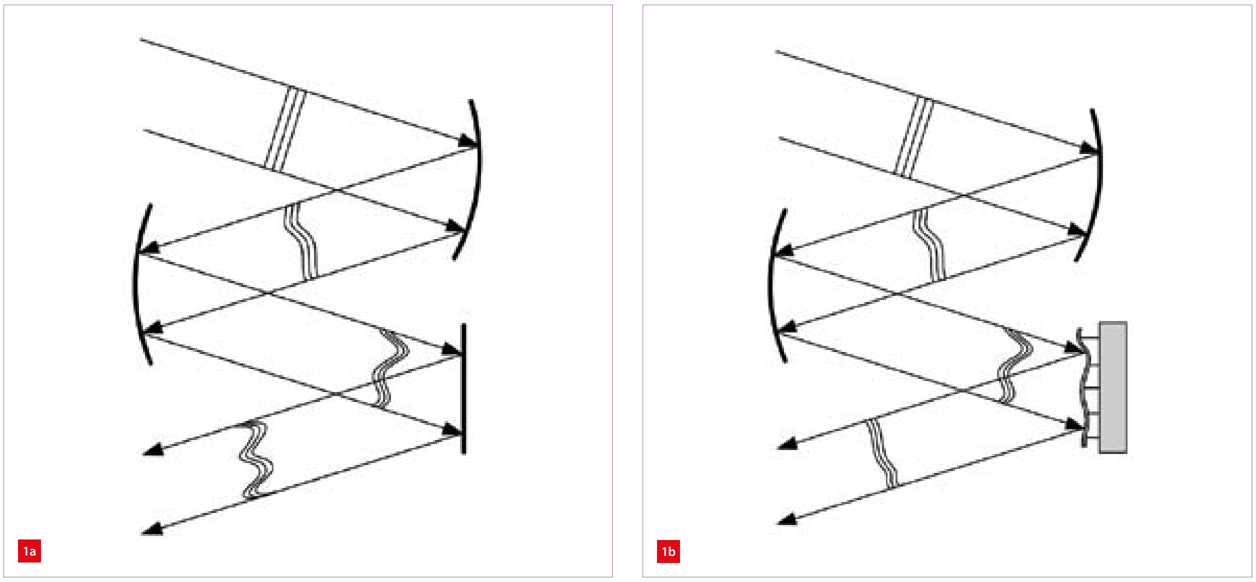
options significantly increase the total cost and cannot compensate for manufacturing errors.

Introduction

Just like any other optical system, high-end optical instruments on modern large telescopes, such as METIS (Mid-Infrared E-ELT Imager and Spectrograph) [1], are subject to static aberrations. These aberrations, which distort the incoming wavefront and introduce errors in the observed image, arise from misalignments and manufacturing tolerances in the system's components. They are often reduced by extensive optical designs containing either a large number of mirrors or complex free-form components. Both options significantly increase the total cost and cannot compensate for manufacturing errors.

Another error source in infrared (IR) optical systems arises from cooling the system to cryogenic temperatures (to prevent the system's own IR radiation disturbing the measurements). The large temperature difference between assembly and operating conditions causes thermal shrinkage. In systems consisting of more than one material, this leads to additional aberrations.

Many of the aberrations cannot be predicted in the design and integration phase with sufficient accuracy and hence can only be measured once the system has been fully assembled and cooled down. A deformable mirror can be used to compensate for these aberrations (Figure 1), without having to warm the system up to ambient temperatures. This is an example of an active optics system. It comprises a wavefront sensor to measure the wavefront error (WFE), an actuated mirror to correct the wavefront, and a control system to send the feedback from the sensor to the mirror.



1 *Wavefront error generation (WFE) and compensation in multiple-mirror set-ups.*
(a) Each mirror adds to the wavefront error.
(b) A deformable mirror can compensate for the accumulated WFE.

Note: Active optics is not to be confused with adaptive optics. This is used to correct for atmospheric distortions at relatively high frequencies (100 - 1,000 Hz), whereas an active optics system operates on a much longer timescale (<< 1 Hz) and typically corrects for the influences of temperature, gravity, and (manufacturing-related) mechanical stress. The active optics approach is especially interesting for systems with complex free-form mirrors or cryogenic systems where access to iterative realignment is very difficult.

Requirements

The goal was to design a flat, deformable mirror, which can operate in a vacuum and at cryogenic temperatures to correct for static aberrations in IR optical systems. The requirements were derived from the METIS design, and in some cases adapted to create a more general product.

Table 1 lists functional requirements. In addition, since the mirror will be operating in a cryostat, no energy should be dissipated after the desired mirror shape has been achieved. Hence a 'set-and-forget' system design. To allow a broad application, the design should guarantee performance of the deformable mirror in any orientation. Therefore, gravity-induced effects were to be minimised.

Table 1. Functional requirements for the deformable mirror.

Diameter	200 mm
Wavelength	1 - 20 μm
Temperature	40 - 300 K
Pressure	10^{-9} - 1 bar

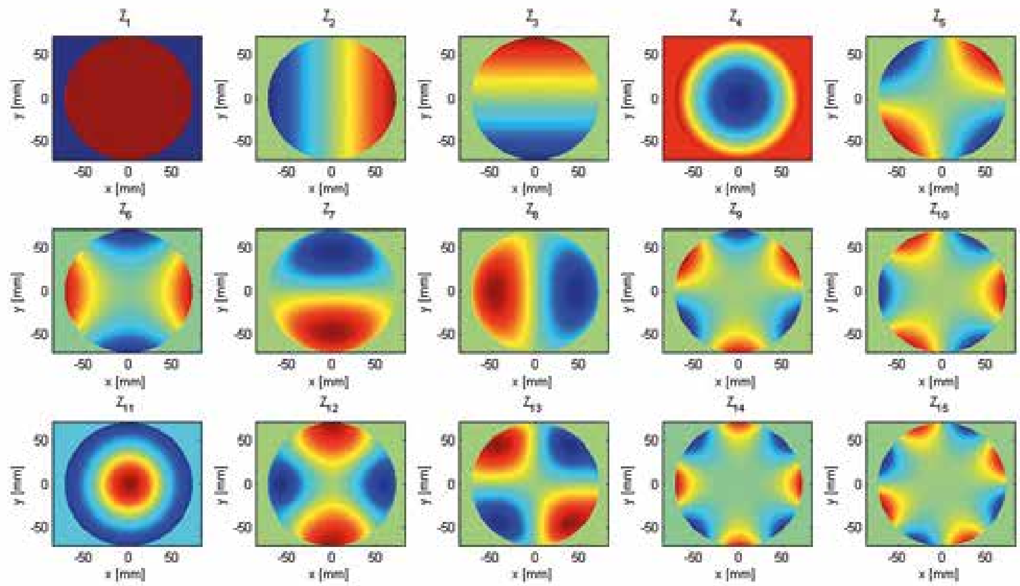
The performance requirements were based on a maximum WFE of 2 μm rms, which can be expected in METIS and comparable optical applications [2]. An analysis of the mirror has been performed (see below) to quantify what level of correction is achievable. It turns out that a bidirectional actuator stroke of ±5 μm is required, with a resolution at the mirror surface of approximately 1 nm. After tuning, the mirror should remain stable within the nm-range for several hours in order to perform measurements with the instrument.

The mirror is only used statically, so the resonance frequency is not relevant for any control objectives. However, the system should not be excited at any resonance frequency by environmental disturbances. A resonance frequency of at least 200 Hz is assumed to be sufficient to prevent this.

For a diffraction-limited system, a maximum rms WFE error of $\lambda/14$ is allowed [3]. With a minimum (IR) wavelength of 1 μm, this produces a maximum rms WFE of 70 nm.

Mirror modelling

The performance depends on how accurately the shape of the wavefront can be produced by the mirror (to create differences in optical path length that compensate for the deviations of the wavefront from flatness). This is called the fit quality and is influenced by the type of actuation (force or moment) and parameters such as mirror thickness, mirror diameter, actuator positions and number of actuators. To understand what influence these parameters have on the system performance, the mirror surface has been modelled using the finite-element method (FEM).



2

2 *The first 15 Zernike modes for describing the deformation of a surface.*

There are several ways of mathematically describing a wavefront. A common method in optical design is using Zernike polynomials, a sequence of orthogonal polynomials defined on the unit disk. These polynomials have increasing radial and azimuthal order. Any wavefront on the unit disk can be described by an infinite series of Zernike modes, just as any 1D function can be described by an infinite series of sinusoids. The deformable mirror should be able to accurately correct the incoming wavefront in the first 15 Zernike modes, i.e. up to the fourth radial order (Figure 2). The FEM calculations were used to determine, per Zernike mode, the contribution of each actuator to the shape of the mirror surface. The difference between the obtained wavefront and the Zenike profiles is the WFE. The better the fit quality is, the lower the WFE will be.

When it comes to deforming the mirror surface, one can apply either a moment or a force at a specific location. One simulation was performed with forces in *z*-direction and one with tangential moments. For the low-order Zernike modes, force actuation proved to perform significantly better in terms of fit quality.

The mirror thickness was varied from 2 to 20 mm, but this had no significant effect on the fit quality. This leaves the optimum thickness to be determined as a trade-off between the allowable sag due to gravity (thickness should not be too low) and the available actuation force (thickness not too high). FEM calculations pointed to a value of 10 mm and a maximum actuator force of 30 N.

To minimise edge effects (fewer nearby actuators to control mirror curvature result in a larger remaining error), the diameter of the mirror can be increased. Given the optical diameter of 200 mm, a diameter of 250 mm turned out to be satisfactory: it significantly reduced the fitting error, without drastically changing the overall dimensions of the system. The mirror was designed with a diameter of 270 mm to provide some surface around the perimeter for the attachment of the outer actuators.

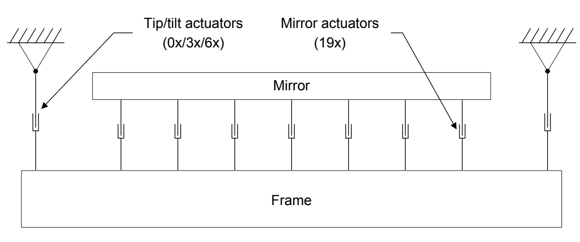
There are several possibilities for the layout of the actuator grid. Given the circular shape of the mirror, either a grid composed of concentric rings, or a hexagonal grid seem to provide the most uniform distribution of actuators. FEM analysis showed no significant difference in performance. The hexagonal grid has the advantage that the actuator spacing is constant throughout the grid. This minimises the gravitational sag and maximises the available volume per actuator.

The number of actuators behind the mirror determines the maximum spatial frequency that can be achieved when deforming the mirror surface. Simulations with a hexagonal grid consisting of 7 actuators showed insufficient correction for the higher-order Zernike modes. A simulation with 19 actuators yielded a significantly higher level of correction. Further addition of actuators (to a total of 37) would limit the available volume per actuator and drastically increase the cost of the system.

Design

The concept for the active mirror system is schematically depicted in Figure 3. The system comprises the following main components:

- mirror
- mirror actuators
- frame
- (optional) tip/tilt actuators



3

3 *Schematic of the deformable mirror concept.*

4 *Two concepts for constraining the mirror's in-plane DoFs.*
(a) Three tangential struts.
(b) Folded leaf springs.

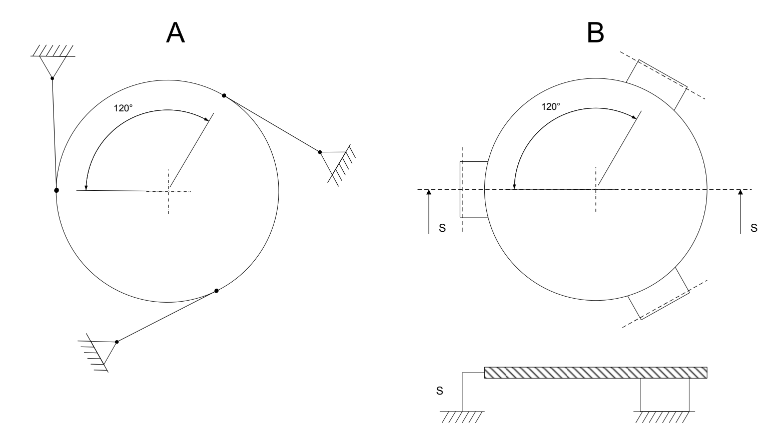
5 *Design of the folded leaf spring for constraining a mirror's in-plane DoF.*

The mirror consists of a flat disk of 6061-T6 aluminium with a diameter of 270 mm and a thickness of 10 mm. The front of the mirror is polished to obtain an optically flat surface. A global flatness of 5 μm and a local flatness of 0.1 μm /Ø60 mm were considered sufficient. Behind the mirror are 19 identical push/pull actuator modules that control its shape. These modules are mounted on a rigid aluminium frame. The actuators are organised in a hexagonal grid with an inter-actuator spacing of 62.5 mm.

Since the mirror diameter is larger than the optical diameter, only 7 of the 19 actuators are inside the optical area. This reduces the effective error from so-called actuator print-through. The remaining 12 actuators provide greater control over the curvature near the edge of the optical area, which reduces errors from edge effects and increases the system performance.

At the back of the mirror 19 pads with threaded holes are included for the laterally compliant struts that connect the actuator modules to the mirror. Three reference surfaces with radial slots at the back of the mirror are used in the assembly stage to align the mirror to the frame. To minimise parasitic forces and moments, the struts are flexible. Phosphor bronze is used since it combines the desired mechanical properties with a relatively high thermal conductivity for cooling the mirror. The struts provide a stiff connection in z-direction, and together they constrain φ and ψ rotations of the mirror (for definitions, see Figure 7). The stiff design results in resonance frequencies of above 200 Hz, as confirmed by hand calculations of the total mirror-strut system and FEM analysis of internal strut resonances.

The design leaves x, y and θ still to be constrained. Two concepts for this are shown in Figure 4. Option (a) shows three tangential struts, each constraining one in-plane degree of freedom (DoF). A disadvantage of this option is that a change in z-position or thermal expansion of the tangential struts causes a parasitic rotation of the mirror around the z-axis. This disadvantage is overcome in option (b). Here, the tangential struts are replaced by folded leaf springs, designed to have a low stiffness in z-direction to minimise undesired forces and moments that would otherwise deform the mirror. Each leaf spring constrains one DoF along its fold line. Because of this advantage, the folded leaf springs were implemented in the design; see Figure 5.



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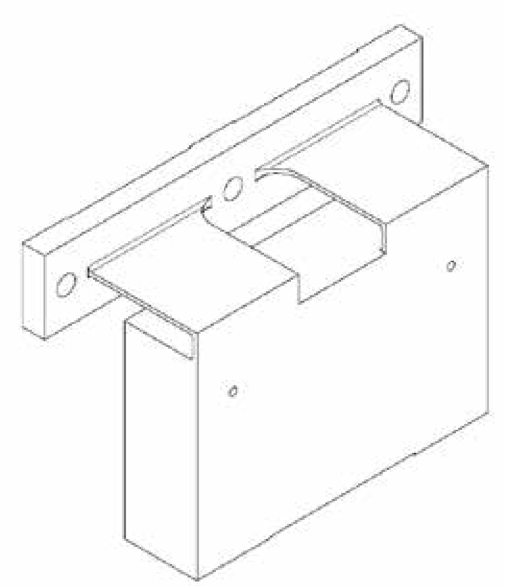


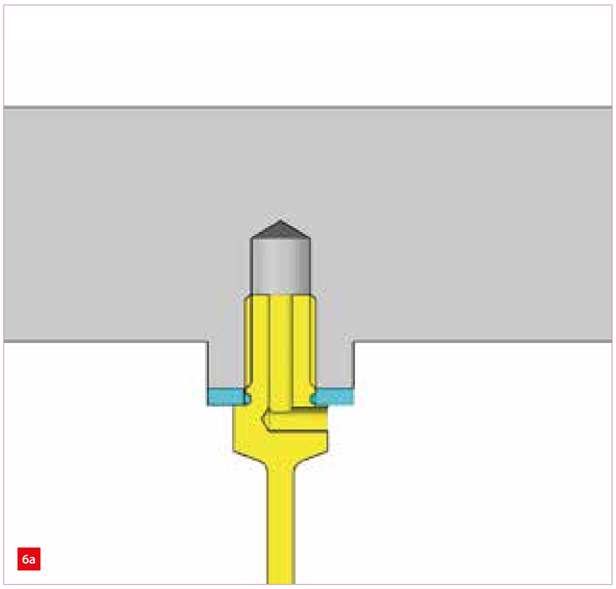
5

The connections of the struts to the mirror cause local internal stresses. These create optical artefacts in the corrected wavefront at the strut locations, the so-called print-through effect. The magnitude is difficult to predict and has been quantified by measurements (Figure 6). First results yield a 182 nm rms WFE. One method of reducing the print-through is to apply a defined pretension in the threaded holes during finishing of the mirror surface. Alternatively, the mirror surface can be polished after assembly.

Figure 7 provides an overview of the mirror design. The frame should provide a stiff and stable base for the actuator modules. Aluminium 6082-T6 was chosen because of its high thermal conductivity, which is required for cooling the actuators and the mirror. The frame consists of a 25 mm thick plate with 19 interfaces for the actuator modules. At the top surface of the frame, three slightly elevated reference surfaces were designed for the folded leaf springs that constrain the mirror.

6 *Print-through.*
(a) Cause: the connection of a strut to the mirror.
(b) Effect: interferometer measurement of the residual WFE reflecting the hexagonal actuator grid.

7 *Design overview.*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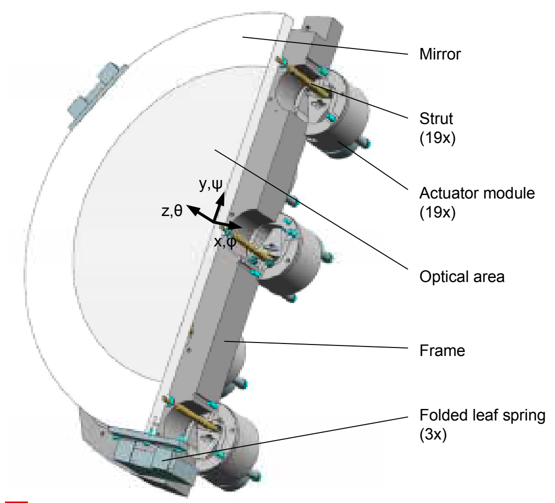

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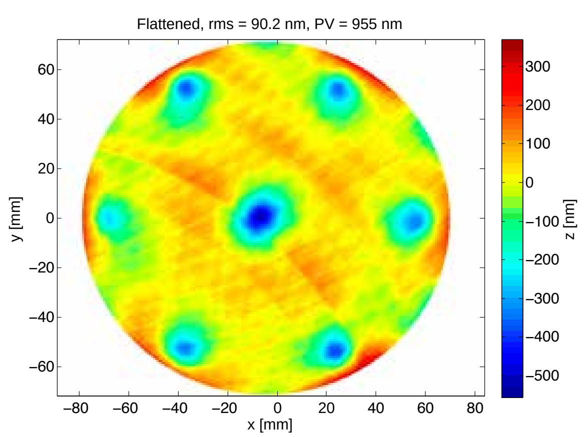


6b

Several alternatives were considered for the interface from the frame to the fixed world. Since the interface provides the thermal connection to the cold plate of the cryostat, a material with a high thermal conductivity is required. Both aluminium (e.g. 6082-T6) and phosphor bronze (e.g. CuSnP8) combine a high thermal conductivity with the desired mechanical properties.

By matching the thermal expansion coefficient and length of the interface with the rest of the system, a thermal centre is created at the centre of the mirror surface. This makes the *z*-position of the mirror independent of the temperature, increasing the thermal stability of the system. Due to the non-linearity of expansion coefficients over the long temperature trajectory, care must be taken to achieve this thermal centre within the operating range of 40 - 80 K. Within this temperature range, the thermal expansion coefficients of the used materials are significantly lower than at room temperature. This further increases the thermal positional stability of the mirror surface.

By directly bolting the frame to the fixed world, the stiffest connection is obtained. However, this allows no realignment of the frame after assembly. Alternatively, an interface with three DoFs allows manipulation of the frame's position and orientation in situ. If the tip/tilt actuators have a stroke of e.g. 0.2 mm, the assembly tolerances of the interface on the fixed world can be relaxed significantly. The resolution of the tip/tilt actuators does not necessarily have to be within the nm range, since the mirror actuators can perform fine adjustments.

A third possibility is an interface with six DoFs, for instance designed as a hexapod. This could be interesting for future applications with freeform mirror shapes. For a flat mirror, however, there is no additional advantage compared to a 3-DoF stage. Moreover, even with parallel hexapod kinematics, the elastic elements that are required for the six DoFs cause a significant loss in stiffness. Modal analysis showed that the stiffness was insufficient to provide a resonance frequency above 200 Hz.

Actuator module

Each actuator module is driven by a PiezoKnob actuator [4] [5], which is a commercially available component from JPE. This actuator is vacuum- and cryo-compatible and provides nanometer resolution. When the desired position is reached, the actuator locks on friction and no energy is dissipated – set and forget –, making it very suitable for this type of cryogenic high-stability application.

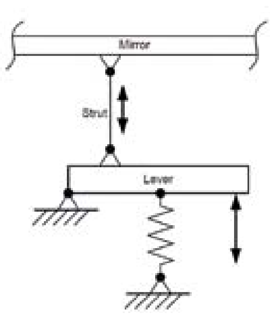
The PiezoKnob (Figure 8) consists of a spindle that rotates in a stationary nut. This drives the spindle forward, resulting in a linear translation of the tip. The inertial drive generates torque pulses that move the spindle with nm steps. Friction in the spindle thread locks the actuator in position, even when the power is turned off. The CLA2601, which has a maximum load of 50 N, is used for this application. Because of its minimum load of 10 N, a preload force is required. Since the actuator module has to be able to push and pull on the mirror, a preload force of 30 N is applied at the PiezoKnob. This produces a functional bidirectional force range of ±20 N.

8

To determine the best approach for manipulating the mirror surface, various concepts for the actuator modules were compared. A direct actuator is relatively simple, but lacks force amplification. Hence the mirror has to be relatively thin and is therefore vulnerable to disturbance forces and moments. A lever actuator does provide force amplification and it still has a relatively simple design, which is beneficial for manufacturing costs and robustness.

The lever amplifies the force output, while reducing the step size. The increased force allows for a thicker mirror, which is less sensitive to external disturbances. The range is also reduced, but this causes no problems since the actuator has a large range and the required stroke is limited. A 1:5 lever actuator was designed consisting of a rigid base, a lever, a flexible strut, a strut mounting mechanism and the PiezoKnob actuator (Figure 9). A tension spring preloads the lever onto the actuator. This allows the actuator module to generate both pushing and pulling forces. An elastic hinge is used in the lever to avoid play, friction and hysteresis.

The elastic hinge, the lower pole of the strut, and the contact point between the PiezoKnob and the lever are placed on a horizontal line to minimise parasitic displacements. The lever is designed to be as short as possible. This improves the bending stiffness and minimises the overall dimensions of the actuator module. This allows for a higher possible actuator density in future applications. The hinge is designed sufficiently wide, so that it provides a stiff support for the bottom of the strut, and no additional guide mechanism is required.



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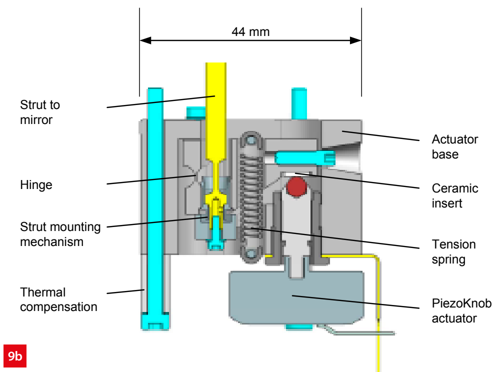


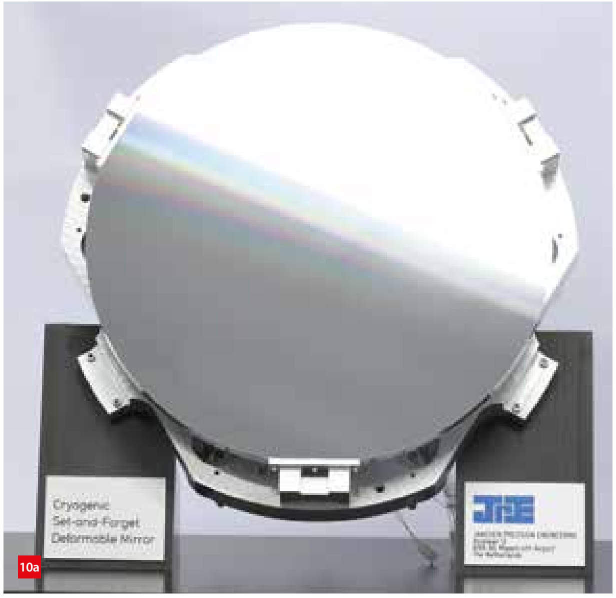
9b

Characterisation and conclusion

A demonstrator was constructed (Figure 10), using 6 actuator modules and 13 dummy modules. From measurements on this demonstrator, a maximum fitting error of 38 nm rms was derived for the full system, as compared to an expected 53 nm rms, based on the FEM model of the mirror and the 2 μm initial WFE.

8 *The CLA2601 PiezoKnob cryogenic actuator.*

9 *Design of the actuator module.*
(a) The lever concept.
(b) Cross-section showing the critical components.



10 *The demonstrator.*
(a) Front view
(b) Back view with (dummy) actuator modules.

This overestimation is explained by a simplification in the model, where the actuator force is applied to a single node, leading to a relatively sharp peak above the actuator. In reality the actuator function is smoother, and therefore more suitable for approximating Zernike modes.

To determine the stroke of each actuator, measurements were taken over the full range: from the reference position forwards to the upper force limit (push), backwards to the lower force limit (pull) and forwards to the reference position. The measured bidirectional actuator stroke was found to vary from 834 tot 4,855 nm rms, whereas the required stroke only ranges from 428 to 856 nm rms. Resolution was found to be between 0.078 and 0.24 nm rms deformation in the measurement area, allowing for accurate control.

Therefore, the design of the deformable mirror provides the stroke and the resolution to provide IR instruments on modern large telescopes with adequate compensation of a total wavefront error of 2 µm rms, yielding a residual error below 50 nm rms. These improvements will open the door for exciting new astronomical observations in the future.

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Precision Point

The knowledge JPE has gained on Zernike modes and deformable mirrors has been collected in a Precision Point sheet, as part of JPE's free precision engineering knowledge database.

www.janssenprecisionengineering.com/page/zernike-modes

MTA – system supplier for the high-tech industry

MTA, based in Helmond, the Netherlands, is an innovative and flexible high-tech company specialised in the development and manufacturing of mechatronic modules and systems. Its clients are world-class OEMs in the packaging, food, graphics and high-tech industries. MTA profiles itself as a reliable, dedicated partner for its customers on key performance conditions: quality, flexibility, innovation and cost management.

As a system supplier, MTA manages the complete lifecycle of a system, starting with development and engineering all the way through series production and finally end-of-life management. At each of these lifecycle stages, MTA continually strives to achieve an optimum balance between quality, lead-time and cost – building on its global supply chain partners, supported by MTA's own production facilities in the Netherlands and Eastern Europe.

Examples of high-tech systems realised by MTA.

Development & engineering

A multidisciplinary team of mechanical and electrical engineers manages projects of up to 15,000 man hours, covering all mechatronic aspects of the product design. MTA prefers to be involved as early as possible, starting with a business case and requirements definition and finally delivering a fully functioning prototype ready for series production.

Project management

Project and logistics management are absolutely key at MTA. Project execution is handled by a team of experienced project managers and project engineers. MTA's lean organisation and standardised work methods underlie its well-managed order creation process and reliable delivery performance.

Supply chain management

MTA's supply chain team uses a global sourcing system to select suppliers with the best price-to-quality performance ratio. The team cooperates closely with strategic domestic and international supply partners and considers quality, flexibility and price level to be critical performance indicators. MTA transfers key knowledge to its strategic supply partners through exchange and training programmes.

Production

MTA has its own CNC production facilities. Its flexible workshop covers a variety of complex CNC processes, ensuring the agility necessary for its needs. Both of the MTA divisions, in the Netherlands and Eastern Europe, have a climate-controlled measuring facility equipped with the latest measuring tools and equipment, including a CNC 3D coordinate measuring machine.

Assembly & testing

Mechatronic modules and systems are assembled and tested in a climate-controlled production area over 2,000 m^2 big. MTA manages quality and reproducibility through its self-designed Assembly Quality System (AQS). ■

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COOL DEVELOPMENTS ON SAFARI

Research of the relatively cool parts of the universe where new stars and planets are born requires a telescope with extremely sensitive detectors, based in space where Earth's atmospheres can't get in the way. SRON recently proposed such a space telescope, called SPICA, to be the fifth medium-sized mission (M5) in the Cosmic Vision programme of the European Space Agency (ESA). Cryogenic detectors, cooled down to below 1 K, form the basis for SPICA's far-infrared spectrometer SAFARI. This spectrometer allows astronomers to peer deeper into space than ever before.

LEXI CARVER, CHRIS DE JONGE AND RENSKE VAN DEN BERG

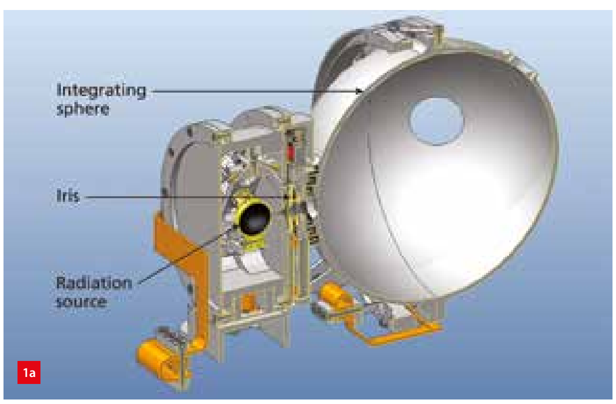
Heat management is extremely important in outer space, especially for cryogenic systems that are actively cooled to extremely low temperatures. The ultrasensitive cryogenic detectors SRON developed for SAFARI will be able to pick up weaker far-infrared radiation than any previous IR space cameras. The instrument shall be developed to fly to space aboard SPICA (Space Infrared Telescope for Cosmology and Astrophysics).

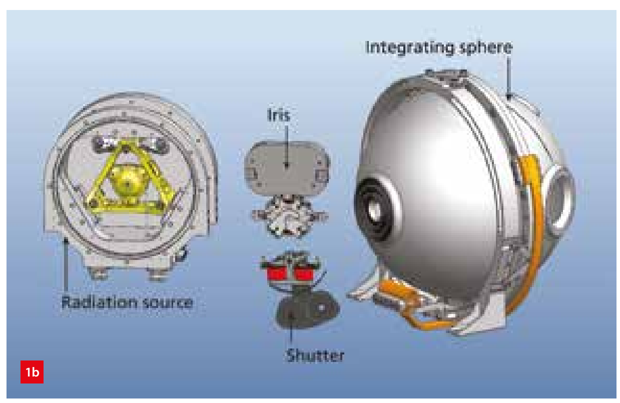
Precise on-ground and in-space calibration and characterisation is crucial to the accuracy of the detectors and the success of the mission. SRON developed a thermal calibration system using finite-element simulations, to make sure the detectors will accurately tell us exactly what they see. To design and optimise these calibration systems, the team at SRON turned to a COMSOL Multiphysics® simulation as their guide.

Calibration system

The calibration source for SAFARI contains a black-body cavity that provides radiation with a known spectrum depending on the source temperature. However, SAFARI's detectors are so sensitive that the radiation produced by the source has a power that is approximately a million times too high and would completely blind the detectors. The solution to this problem is to dilute the radiation with apertures and an integrating sphere. After passing through the integrating sphere, radiation with the correct power and spectral distribution is then reimaged onto SAFARI's detector arrays for calibration.

Besides the source, the complete calibrator (Figure 1) has multiple mechanical mechanisms, such as a shutter to close the source and an 'iris' mechanism to fine-tune and modulate the output power, adding further flexibility to the calibration procedure.





1 SAFARI calibration system.
(a) Cross-section.
(b) Individual hardware components.

AUTHORS' NOTE

Lexi Carver worked as a technical marketing engineer with COMSOL, the developer of multiphysics software. Chris de Jonge is a Ph.D. candidate at Rijksuniversiteit Groningen and worked with SRON's calibration source designing team. Renske van den Berg is in charge of communications and media relations at SRON (Netherlands Institute for Space Research), based in Utrecht and Groningen, the Netherlands.

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All of these systems are operating in a super-dark and cold environment at 4 K. If the equipment would exceed this temperature, it would start to 'shine' in the far-infrared, providing unacceptable background radiation that would again be blinding to the ultra-sensitive detectors. The black-body source itself is placed in an extremely light-tight housing, as the temperature of the source can be set between 95 and 300 K to generate the correct spectrum.

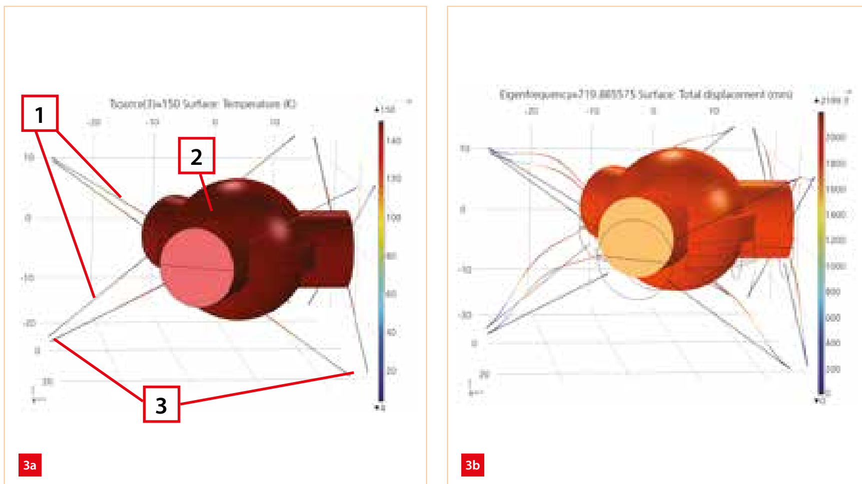
Besides the problem of light-tightness, there is the problem of the large temperature difference between the source and the 4 K environment, because the available cooling power at these temperatures is limited to just tens of milliwatts. To account for this, a thermally insulating suspension system for the source had to be designed. The SRON team needed a stiff suspension that would prevent heat transfer from the hot-source to the rest of the device while also having a high resonance frequency.

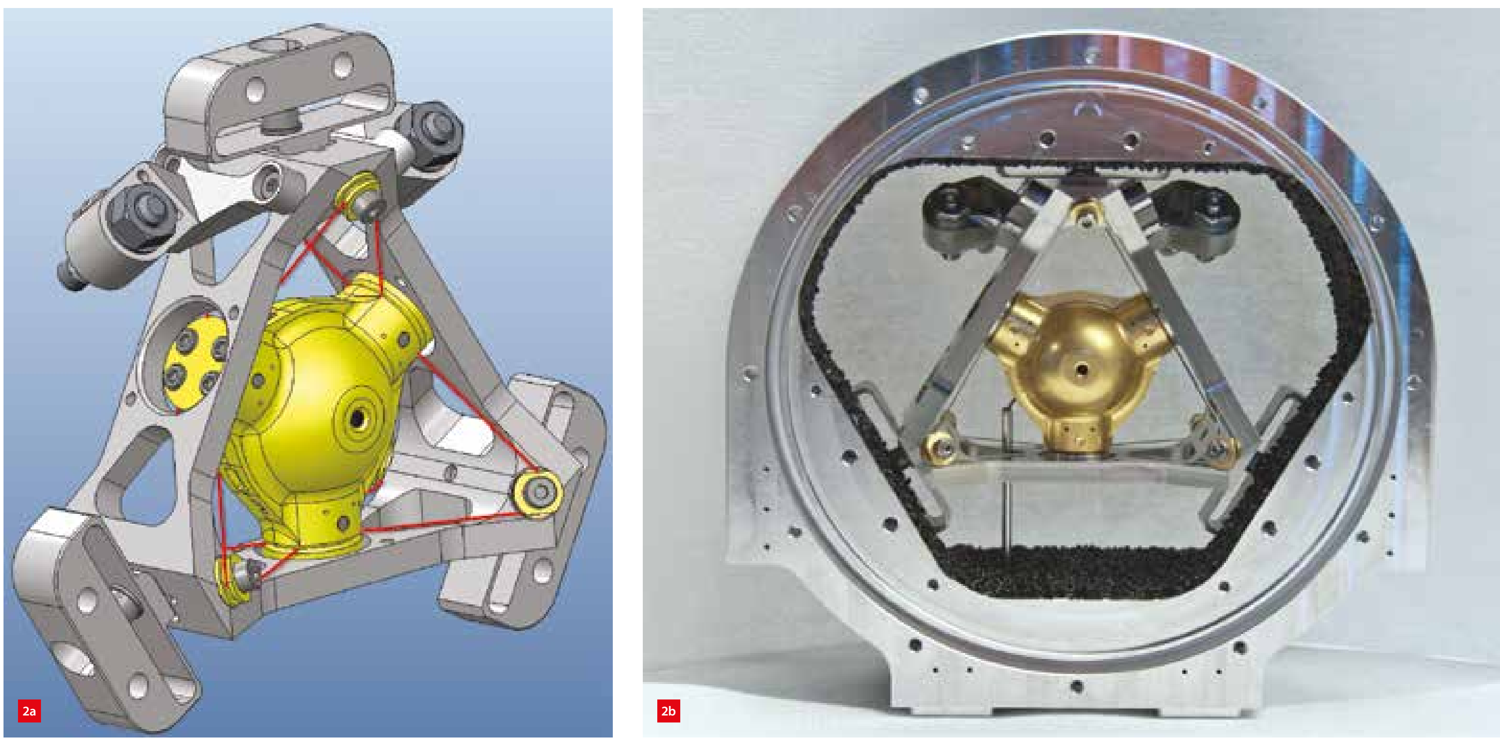
Thermally insulating suspension system

Using simulations the heat load through the suspension was evaluated and modal analyses were performed on suspension concepts with different geometries and materials, seeking a trade-off between mechanical stiffness and thermal load. COMSOL allowed to quickly study different geometries that would otherwise be difficult to analyse. Because of the large temperature gradient over the brackets and thermal properties that change very quickly as a function of temperature, temperature-dependent material properties had to be implemented.
Ultimately, the solution that had the best combination of mechanical stiffness and thermal insulation was chosen.

Based on the results, the team designed and optimised a configuration of thin (100 μm) stainless steel wires to hold the radiation source to a triangular frame (Figure 2).

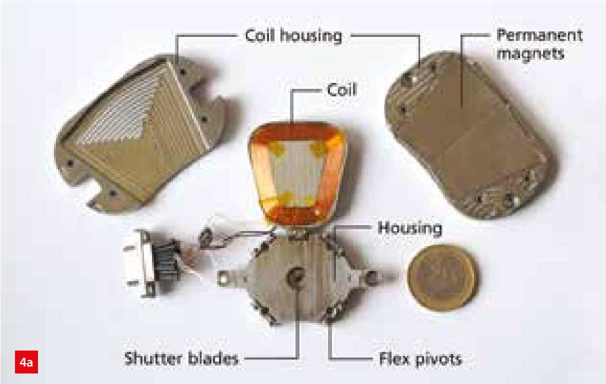
Because stainless steel has low thermal conductivity at cryogenic temperatures and the cross-section of the wires is very small, heat conduction through the wires was limited, which the simulation confirmed (see Figure 3). For a source temperature of 150 K, the design has a heat-load of 10.17 mW of conducted heat and has a resonance frequency of 720 Hz.

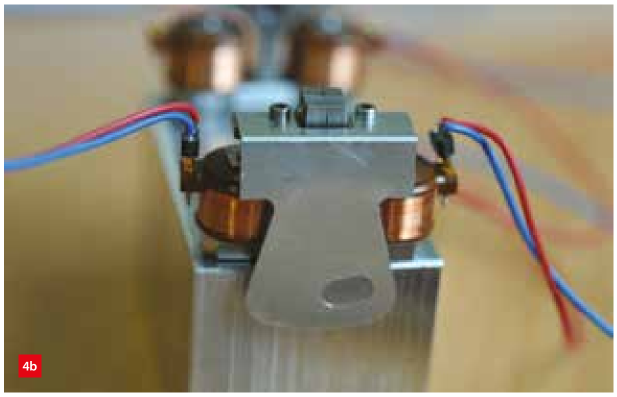




2 Radiation source with suspension system.
(a) CAD drawing, with stainless steel suspension strings highlighted in red.
(b) Actual hardware.

3 Thermal model of the radiation source system.
(a) The source with (1) stainless steel suspension strings, (2) the radiation source body, and (3) the interface between the suspension rig and the 4 K surrounding environment.
(b) Modal analysis of the source, showing a resonant frequency of 720 Hz.





Iris and shutter mechanisms

Next, the coil-driven iris and shutter mechanisms were optimised (Figure 4). The iris is driven by a voice-coil actuator and contains four stainless steel blades that rotate around frictionless torsion-spring bearings. The shutter is a magnetic latching device.

The iris coil and housing geometry were optimised (simulation results are shown in Figure 5), aiming to minimise the current and dissipated heat during actuation. By performing a parametric sweep over the main design parameters on the air gap and number of coil windings, the team developed an optimal coil design that has a low driving current of 38 mA and a dissipation of just 1.6 mW.

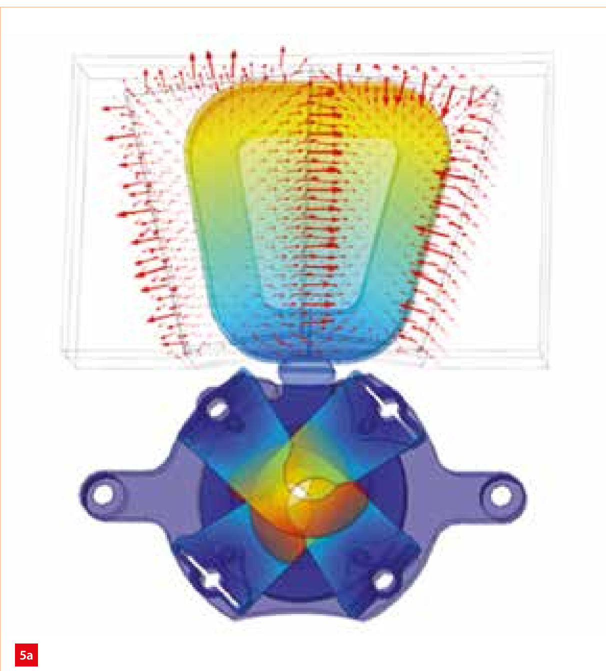
On the way

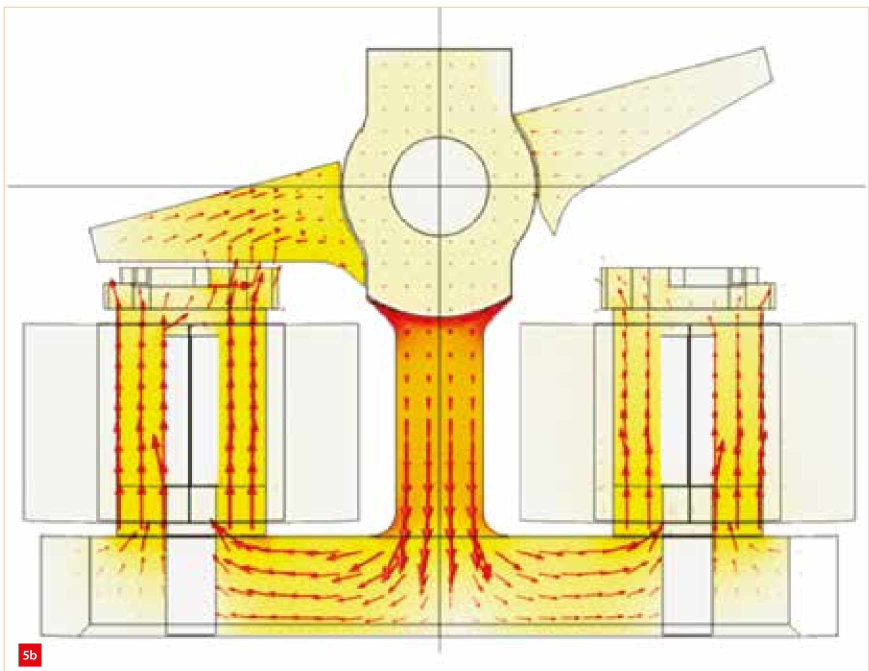
Because of SAFARI's sensitive detectors and the need for dissipative mechanisms in cryogenic systems, maintaining a controlled thermal environment is vital to the success of SPICA's mission. COMSOL allowed the team at SRON to optimise their design for the best thermal, material, and structural conditions possible at extremely low temperatures. Tests of the SAFARI calibration source confirm the accuracy of the simulations.

SRON, being the principal investigator, recently proposed SPICA/SAFARI as M5 candidate for ESA, to be launched in 2029/2030. The space agency will make a pre-selection in June 2017 and a final selection in 2019. ■

4 The optimised mechanisms.
(a) Components of the iris assembly, including the coil, wiring, and housing. The edges of the blades (internal) are visible through the center of the aperture.
(b) Shutter mechanism.

5 Simulations using the Multibody Dynamics Module and AC/DC Module of COMSOL. The geometry was imported using the COMSOL LiveLink™ for Creo™ Parametric.
(a) Model of the iris mechanism showing the total displacement (surface plot) and magnetic flux density (arrows) of the blades and coil, respectively.
(b) Model of the shutter mechanism. Magnetic force was studied as a function of coil current and anchor angle.

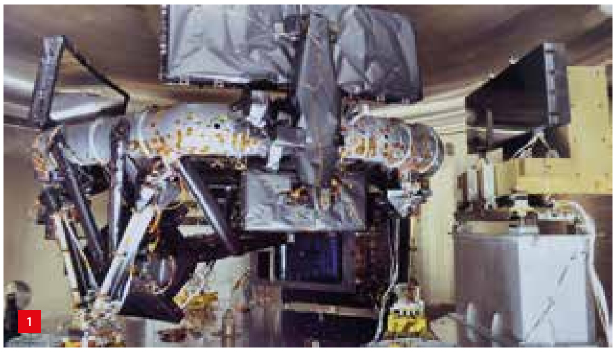




1,000 DAYS IN SPACE

On 15 September 2016, ESA released the data of the first 1,000 days of measurements from the Gaia mission. The large data package included 1.1 billion star positions, motions, brightness values and more, as well as surprises such as supernova detections. Thanks in part to the accurate space interferometer BAM developed by TNO.

JEROEN HEIJMANS



1 *Gaia still on Earth inside a big vacuum chamber. Visible are the SiC torus with its two 1.5m telescope mirrors on top looking at the AFMA (Autocollimating Flat Mirror Assembly) calibration module (right, in gold). (Photo courtesy of Airbus, prime contractor of Gaia)*

In December 2013, Gaia (Figure 1) arrived at her stable Lagrange-L2 point, 1.5 million kilometers from the 'night side' of Earth. The European Space Agency (ESA) had sent her on a mission: create an ultra-precise three-dimensional map of stars in our Galaxy [1]. Soon after unfolding her sunshield and making first observations it was discovered that some issues existed. Besides more than expected amounts of stray light, it was discovered that there was a clear instability of the two telescopes. This was a major concern for the astronomers awaiting the release of the new highly accurate star map. It was unclear if the measured instability was indeed occurring or if the Basic Angle Monitoring (BAM) metrology system developed by TNO was producing wrong measurements.

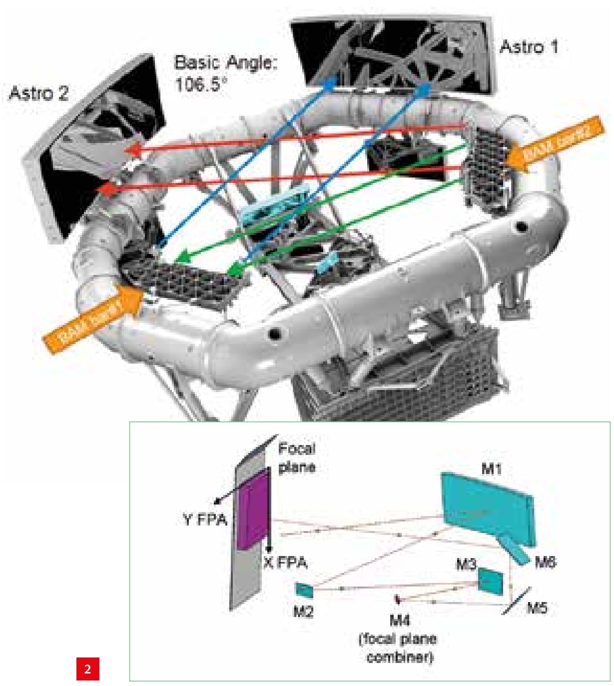
Scientific importance

The parallax of a star provides its position by changing the viewpoint. In the image, the location of a nearby star changes position with respect to a distant background. To obtain absolute parallaxes, the differential positions in stars observed in fields of view separated by a large angle (106.5°) are determined by simultaneous observations with two telescopes whose lines of sight are separated by a fixed, large basic angle. When a significantly large number of measurements are acquired, with different orientations on the sky, the individual proper motions and parallaxes can be determined for each star in an iterative manner [2]. Since the two telescopes image on the same array of detectors, this indeed means that two different parts of the sky need to be individually tracked and unravelled.

However, deriving absolute parallaxes relies on the basic angle either being stable, or at least known to 0.5 micro-arcsec (2.4 pico-rad), should the SiC satellite structure prove not to be stable enough. The developed metrology to measure this angle, BAM, comprises an interferometer, described in more detail in [3], which needs to measure with a resolution of 3.6 pm, representing a 0.66 micro-fringe change for a 850nm laser. Early technology studies at TNO showed in 1999 that these resolutions can indeed be achieved with a stable interferometer and by tracking the fringes on a CCD.

Results

In 2007, TNO started on the construction of the space hardware. Figure 2 shows a pair of laser beams aimed at the 1.45m telescope mirrors. These interfere at the focal plane array where the images are placed over a billion-pixel-CCD camera array. One CCD is dedicated to measuring the fringes of the BAM system and a series of actual measurements are shown in Figure 3. It provides a summary



2 *The two pairs of BAM laser beams reflect off the first telescopes. The inset shows the continued path length over the six telescope mirrors before the beams interfere on the focal plane array (FPA). (Courtesy of ESA)*

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He acknowledges the input from the TNO Gaia team.

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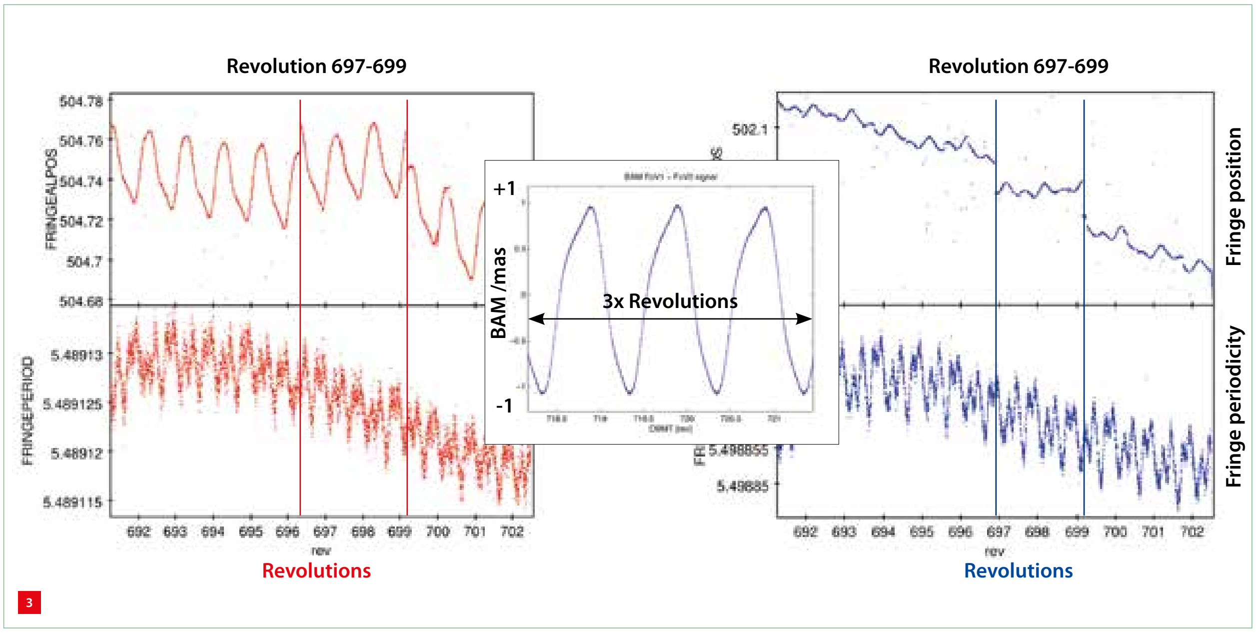

3 *BAM fringe location (top) and period (bottom) for telescope 1 (left) and 2 (right) covering a time interval of three days [4]. Trend lines and labels have been added for clarity. The centre figure shows the calculated periodic amplitude of angular instability of +/–1 mas. In the six-hour rotation period, residuals of the µ modelled Fourier components are at the tens of µas level forming the limit of model prediction.*

of what was measured and how stable a SiC space telescope actually is.

The red (left) and blue (right) lines in Figure 3 show the interference fringe measurements for the two different telescopes. These should be smooth lines but instead show oscillations when Gaia spins around once every six hours. In addition, the satellite also slowly changes its orientation to scan the complete sky. The slowly drifting signal is of no concern to the data as the BAM measurement is only required for short-term instabilities associated with the spin velocity. The two abrupt changes that appear in the figure, marked by the two vertical lines 697-699 can be traced back to disrupting on-board activities such as spin up or down.

In summary, tens of milli-arcseconds of instability are measured but these can be modelled with an accuracy of 10 micro-arcseconds. For the first data release all the star positions have been corrected on the basis of the BAM measurements, enabling Gaia to be the most accurate 'all-sky astrometric survey'. The stray light arriving at the detectors causes, at least for the moment, that the faint stars can only be measured with limited accuracy. Faint stars that become contaminated with too much noise are automatically rejected from the catalogue.

Conclusion

The BAM has been called the most accurate space interferometer by ESA scientists. An incredible measurement accuracy is achieved by the instrument, but not in the least also by characterising and scrutinising the measurement signal to produce an uncertainty of less than one millionth of a fringe! Years of effort at TNO to create an ultra-stable interferometer that can even be launched and operated at 100 K has paid off and gives great confidence in TNO's future as a supplier of highly stable optical instruments.

TNO is currently developing ultra-stable laser communication systems for space together with companies such as the Dutch Nedinsco and the Swiss RUAG. Besides the BAM system, TNO has also provided the Wave Front Sensors, contributed to the Fine Sun Sensors and developed the 'on ground' scanning calibration telescopes (AFMA).

Gaia's massive data map is already changing the way astronomers view the Milky Way and more data will be released in late 2017 with even more details and higher accuracies, but also new data from yet unreleased photometry of the two spectrometers. Discoveries based on the first data release have been proposed, but have yet to be confirmed. Some of these discoveries will be presented early next year [5]. ■

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IN SEARCH OF MULTI-FUNCTIONALITY

While functionality is naturally one of the most important features of precision technology products, multi-functionality can be a valuable property for machining aids to have in order to acquire this functionality. When examining trends in machining technology, multi-functionality is certainly a conspicuous one, and there were many signs of it at the, once again, highly interesting 2016 Precision Fair, which attracted nearly 300 exhibitors and 3.650 visitors.

FRANS ZUURVEEN

True, the Precision Fair may not the most obvious venue for finding multi-functional machining centres. Nevertheless, hard-cutting specialist Hembrug Machine Tools demonstrated how multi-functionality can work in its hydrostatic precision-cutting machines, which can be equipped with grinding or polishing units (see Figure 1). (The specifics of these machines are explained more fully in an article on Hembrug in the forthcoming issue of Mikroniek.) An interesting exercise in different approaches to multi-functionality is to contrast Hembrug's precision-maching tools with Schaublin precision lathes (also profiled in Mikroniek [1]). This renowned Swiss company has also integrated a grinding unit in their turning machines, but Schaublin lathes have conventional mechanical slides instead of hydrostatic ones.

2016 Precision Fair impression. (Photo: Mikrocentrum)

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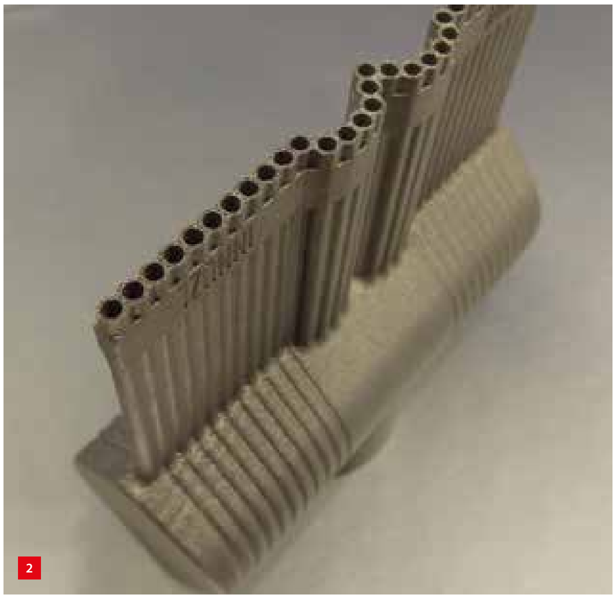
1 *The turntable of the Hembrug vertical hydrostatic turning machine Mikroturn V4 with a run-out accuracy of 0.2 μm. This machine can be equipped with a grinding or a polishing unit.*



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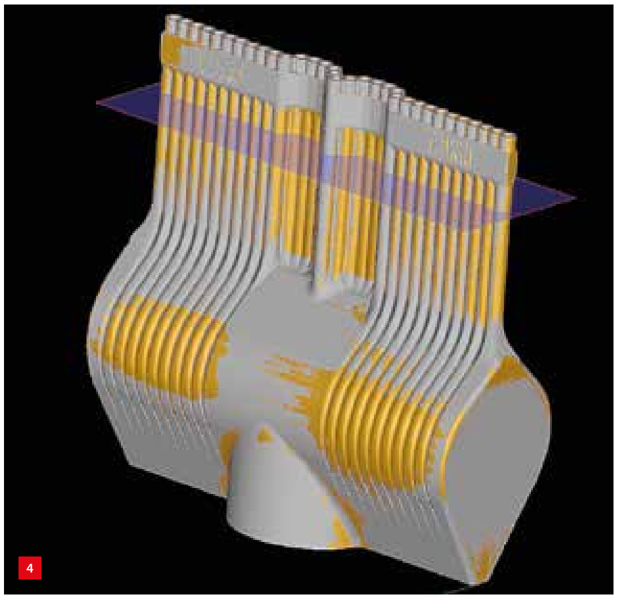

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2 A product from AAE additively manufactured using an SLM Solutions 3D printing machine.

3 CT working principle: an X-ray point source generates an image on a flat X-ray sensor. The object rotates, after which a computer calculates a 3D image from successive 2D images on the sensor.

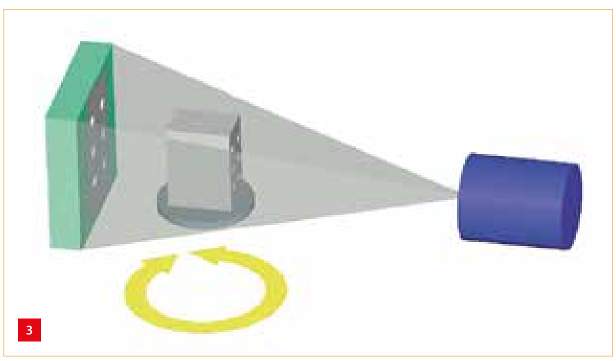
4 A Tomoscan measurement result of the AAE product shown in Figure 2. The colour yellow indicates deviations from CAD values.

Multi-functional co-operation

Another kind of multi-functionality displayed at the fair was a co-operation of precision measuring specialist Werth and mechatronics specialist AAE. AAE has installed a 3D printing machine from SLM Solutions in their High-Precision Parts department and showed in the stand, which they shared with Werth, a 3D-printed part with complicated internal channels (see Figure 2). This is a cooling unit developed by Innogrind for the prevention of grinding burn.

Figure 2 makes it clear that additive manufacturing (AM) enables the production of products that are nearly impossible to make using conventional metal-cutting operations. AAE admits, however, that there may be small problems related to 3D printing, as the channels in this product showed some minor leaks. Werth's Tomoscan measuring machine reveals the why and where, as this instrument can 'look' with its X-rays inside objects and perform accurate measurements, unlike conventional measuring instruments that only observe the exterior.

Figure 3 shows schematically the working principle of the Tomoscan: an X-ray point source generates a 2D image on a flat X-ray sensor with a square pattern of pixels. This is



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somewhat comparable to the medical application of computer tomography (CT), the difference being that in the latter the human body stays static, while in industrial CT the object rotates. A 3D image can be calculated from 2D images at various rotational positions. In this 3D image precision measurements can be taken. Figure 4 shows how the Werth Tomoscan helped to discover the position of the leaks in the AAE product: a good example of multi-functional co-operation.

Multi-functional 3D printers?

Essentially, AM is a cleverer method of producing a precision product than the subtractive way of conventional machining, which uses sharp tools or cutters to remove all parts or particles that are not needed from a large block of solid material. Nevertheless, combining AM with conventional machining in one hybrid machine would be an excellent example of multi-functionality.

The Precision Fair offered the opportunity to investigate the existence of such a combination. A specialist who was showing the precision capabilities of his conventional workshop reacted, "combining 3D printing with conventional cutting is virtually impossible because the technologies 'bite' each other. 3D printing particles may damage the precision slides of the cutting section, while the cooling and cutting fluids endanger the 3D deposition process."

But the 3D printing specialist at AAE was less sceptical. He recalled an example of an application of 3D printing added to a multi-axis machining centre: specifically, the hybrid five-axis machining centre Lasertec 65 3D sold by the American company DMG Mori. In this machine, a nozzle-based metallic particle-depositing laser head can rapidly replace a spindle with a rotating end-mill. Obviously, the milling head finishes a product surface or cylindrical wall after the 3D laser deposition of a few layers, aiming at a higher product accuracy. The starting point for this hybrid machining centre is the Deckel Maho monoblock five-axis milling machine, alas not on show on this exhibition.

Multi-functionality in measuring

Another clear example of multi-functionality is being able to measure a workpiece during a machining process, thus avoiding wasting time transporting a half-finished product to a measuring room. Well-known measuring firms like Mitutoyo provide such on-the-spot measuring tools, which were also not shown on the fair, but what was on show was a Mitutoyo Apex 574 coordinate measuring machine (CMM) with a measuring range of 500 x 700 x 400 mm³. A few meters farther along was a Zeiss Accura with a still larger range of 1,000 x 1,200 x 800 mm³.

Such CMMs are certainly examples of multi-functionality, due to their combination of precision hardware and useful software. I could not help but compare these machines to how it was done in the sixties: the cumbersome writing down of measurements on paper and the calculation of the average value and standard deviation with a mechanical calculator, a Facit or Burroughs. Today's measuring machines not only calculate such data in a split second, they also facilitate the fast programming of the machine by moving the stylus along the positions on the product to be measured, subsequently rearranged to deviations in respect to CAD data.

It was good to see that Zeiss from Oberkochen in Germany continues to provide optical and mechanical high-precision products. When the Zeiss company was founded in the 19th century in Jena, Carl Zeiss, Ernst Abbe and Otto Schott were a winning team. In 1889, Zeiss founded the Carl Zeiss Stiftung, making his optical company the co-property of his workers, while Ernst Abbe invented algorithms to calculate Zeiss' optical systems, and Otto Schott developed new sorts of glasses to manufacture the innovative lens systems from Abbe and Zeiss. This multi-functionality avant la lettre still forms the foundation of today's precision optics.

Also remarkable is the Aberlink Xtreme CNC CMM, presented by Steen Metrology Systems from Belgium. This innovative measuring machine uses a non-Cartesian coordinate system with three linear actuators with integrated measuring scales (see Figure 5). The accuracy amounts to 3 µm, somewhat less favourable than for conventional CMMs, but its robust design makes it an ideal instrument for workshop applications. It is clear that recalculating transducer displacement results into (X,Y,Z)-values requires strong computer capacity, as well as being able to display measurement results in a customer-friendly way.

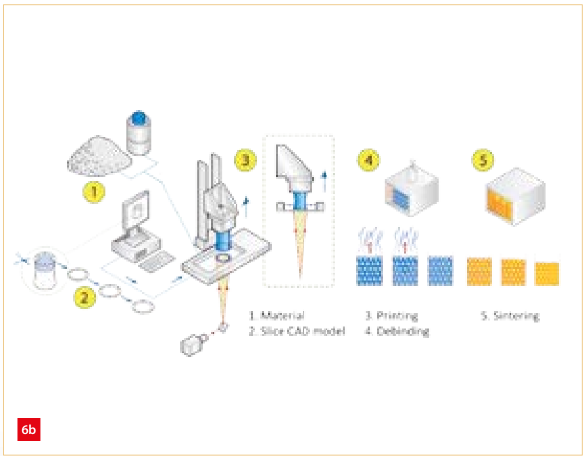
5

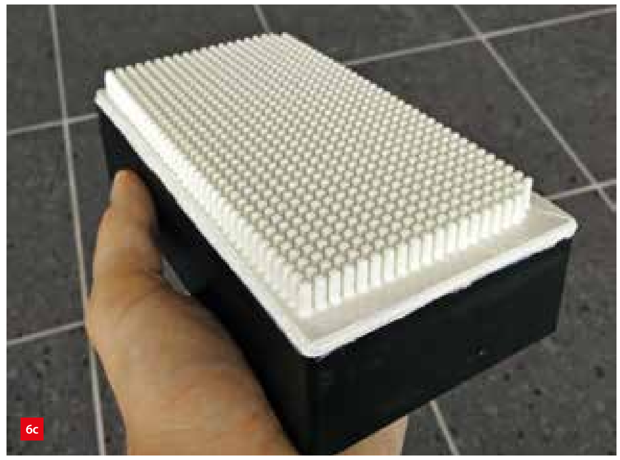
5 *The Aberlink Xtreme CNC measuring machine uses a non-Cartesian coordinate system. The display shows user-friendly Cartesian-coordinate results, thanks to recalculating transducer displacements.*

3D printing ceramic products

For more than fifteen years, Formatec has specialised in ceramic injection moulding (CIM). This process technology uses a mixture of plastic and ceramic grains, called 'feedstock'. When heated, this mixture is injected into a mould, using a common plastic injection machine. This results in a so-called green product. After sintering in a furnace with inert gas, the green product converts into a hard ceramic product, as the plastic burns out. The limiting factor for process accuracy is that shrinkage of 20 to 30% occurs, depending on the materials selected. The good news is that the shrinkage factor is predictable, resulting in an ultimate precision of ±0.3% (i.e. ±3 µm per mm).

A disadvantage of the CIM process is that it needs a mould, which requires time and money to make. Formatec has addressed this by founding a daughter company: Admatec Additive Manufacturing Technologies. Admatec produces ceramic products directly from SLC (SLiCe format) data files without needing a tool. Its Admaflex 130 machine thus applies 3D printing technology (see Figure 6a).





The Admatec AM process starts with a fluid-like slurry, which consists of ceramic grains in UV-sensitive liquid resin. The product – from zirconium oxide ZrO_2 or aluminium oxide Al_2O_3 – is built up from below by consecutively depositing 0.3 mm thick layers of slurry on a foil, which deposes them on the underside of the product (see Figure 6b). Each new layer is locally UV-illuminated in a slice-dependant pattern controlled by the machine software. This results in local hardening of the slurry. Ultimately, a 'green' product results again, which undergoes the same process as applied in Formatec's CIM-procedures, resulting in extremely hard ceramic products (see Figure 6c). An extra advantage is there is no need to design products in such a way that they can be easily taken out of moulds.

Proofs of precision

As was the case with previous fairs, precision-machining companies exhibited evidence of their capabilities to accurately grind, mill or turn products from solids. Mogema, part of Aalbers Industries, showed a huge load lock for entering a high-vacuum recipient (10^{-8} bar), see Figure 7. In appearance it may be a rather roughly designed product, but integrated guides for transporting LEDs to be evaporated at low pressure ask for narrow tolerances.

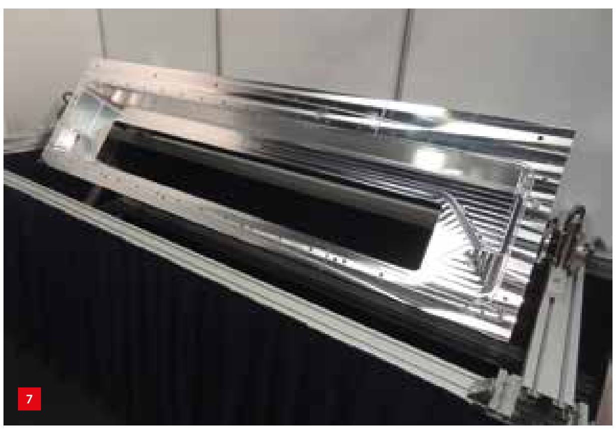
Wilting displayed a complicatedly formed magnetic-core housing for CERN (see Figure 8). CERN demands narrow tolerances for the surfaces that have to support the accelerator coils. The Wilting machining specialist explained that his company does not have in-house 3D printing machines, but rather uses 3D Systems in Belgium (formerly LayerWise) to produce 3D-printed parts for it, after which they are finished in the Wilting workshops.

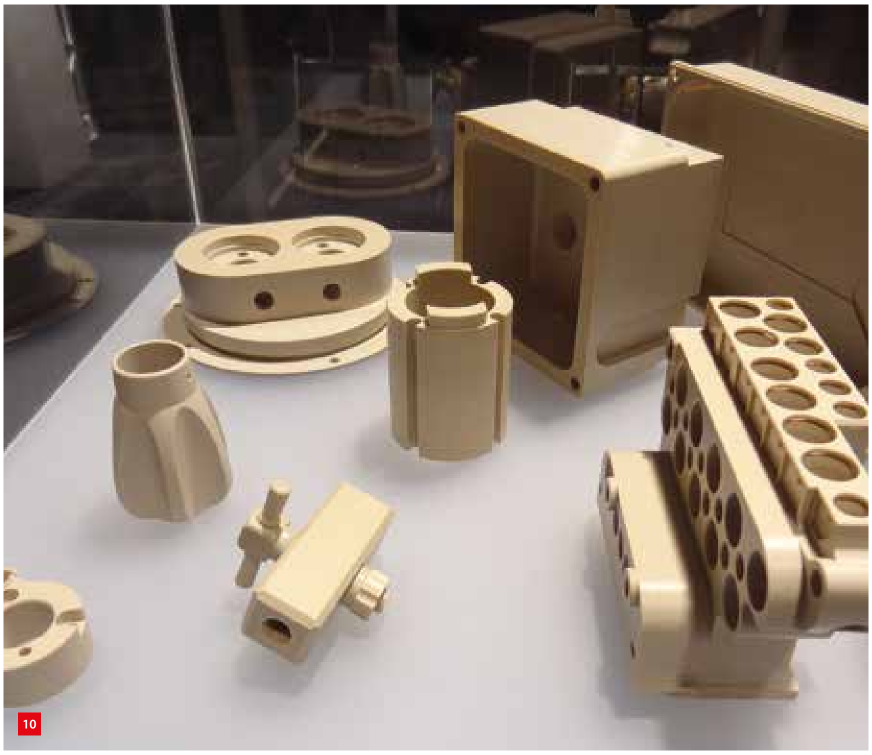
6 *3D ceramic printing technology from Admatec.*
(a) The Admaflex 130.
(b) The principle.
(c) A batch of 750 ceramic parts produced with an Admaflex 130.

7 *A high-vacuum load lock, produced by Mogema.*

8 *A complicatedly formed magnetic-core housing for CERN, produced by Wilting.*

9 *A cardboard roller for the highly accurate cutting and folding of cardboard sheets, produced by AJB.*





10 *Products from PEEK, an engineering plastic resistant to temperature and humidity changes, produced by Hemabo.*

11 *Impressions from the 2016 Precision Fair. (Photos: Mikroecentrum)*

AJB Instrument, an off-shoot of Madern International, specialises in delivering components for the packaging industry. At first sight these products may have little to do with precision engineering, but the cardboard roller shown by AJB (see Figure 9) is a real precision product. It had to be manufactured with tolerances down to 2 μm for the highly accurate cutting and folding of cardboard sheets.

Many products on exhibition are made from steel or aluminium, but Hemabo demonstrated its capability to manufacture precision products from plastic. Its products from transparent PMMA, poly methyl methacrylate, are spectacularly glittery, but it also uses a more high-end engineering plastic called PEEK, polyether ether ketone, because of its better resistance to temperature and humidity changes (see Figure 10).

Miscellaneous

Roelofs Meetinstrumenten showed hand-held measuring tools from Swiss measuring specialist Sylvac. They did not look very spectacular, but their special feature is the wireless transmission of measuring results from each Vernier caliper or screw micrometer to a computer, which converts them to data such as average value and stochastic uncertainty range. Sylvac delivers not only the hardware but also the software.

Another exhibitor worth mentioning is VSParticle, a start-up company from Delft University of Technology specialising in the development of nanoparticle generators. Similar to 'droplets on demand' in printers, its generators deliver 'nanoparticles on demand' to integrate them directly into a process or product. The generators work according to a spark ablation process, which can be interrupted at will to produce nanostructured agglomerates.

Ter Hoek Vonkerosie is generally known as a supplier of wire-, laser- or spark-eroded precision products, but it has widened its machining technology expertise to a new field of interest: precision electro-chemical machining (PECM). (See also the News pages in this issue.) The PECM process enables reaching tolerances of 2 μm and surface quality values of 30 nm R_a. The relatively high process speed with oscillating electrode makes PECM particularly suitable for the series production of precision parts and components.

To conclude

Were there examples of multi-functionality at the 2016 Precision Fair? Decisively yes. One could even say, looking at all the examples of precision technology craftsmanship, the interesting lectures and the many meet-and-match opportunities provided, that the Precision Fair itself (Figure 11) is a clear example of multi-functionality. ■

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Coresy – realising higher product profitability

The need for cost reduction is growing as more and more companies struggle with global competition and increasing operational costs. Product costs can be reduced by assessing material and manufacturing costs and systematically classifying, identifying and optimising the specific cost drivers. Coresy, based in Helmond, the Netherlands, offers a systematic approach for product cost reductions.

The services offered by Coresy include:

- Consultancy & training for product cost management.
- Software development for product cost estimation and analysis.
- Staffing & support for cost reduction projects.

Coresy's customers are companies in the optical, medical, semiconductor and other high-tech industries.

Coresy offers product cost reduction support to companies in the optical, medical, semiconductor and other high-tech industries.

Consultancy & training

The cost management process must be embedded into a company's organisation to secure the profitability of its products. Coresy helps companies create awareness about this process and integrate it successfully by:

- Identifying the key elements of product cost optimisation in the organisation.
- Offering training workshops on, for example, Design for Manufacturing, Design-to-Cost principles and Cost Engineering in the areas of mechanical, optical and electrical manufacturing processes.
- Supporting supply chain optimisation and pricing negotiations.

Cost estimation software

Achieving results in product cost reduction starts with implementing a transparent and efficient cost estimation or calculation tool. Coresy supports the set-up of efficient, customised tools by offering:

- Tool design and calculation methodology according to a company's financial norms and worldwide standards.
- Knowledge-based calculation software using machine, labour and process algorithms and databases.
- Fast set-up routines for the manufacturing flow.
- Product calculation template for efficient cost engineering.
- Transparent and easy-to-understand reports.

Staffing & support

Coresy can support cost reduction projects by:

- Taking over project leadership.
- Contracting out cost engineers with specific competencies to work at the customer's location.
- Offering outsourcing possibilities for cost-engineering projects.

INFORMATION

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MOUSE PRECISION

Optical mouse sensors are a cost-effective alternative for position measurement systems requiring micrometer accuracy. Two techniques to further increase the performance of such a sensor are proposed; i.e. an optical magnification of the tracking surface projected onto the mouse sensor, and a compensation of the undesired dynamics caused by filters implemented in the mouse sensor chip. These improvements have been integrated into a precision stage design which has been successfully built and validated.

GIHIN MOK

AUTHOR'S NOTE

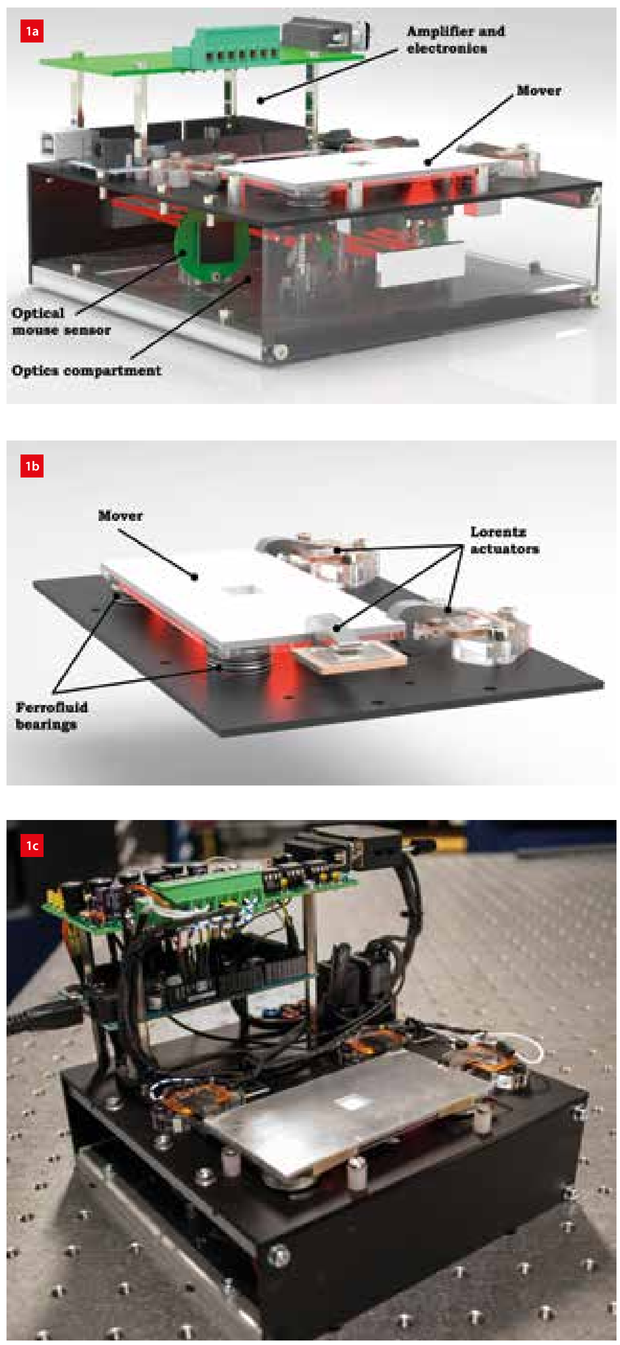
Gihin Mok obtained his M.Sc. degree in mechanical engineering at the Precision & Microsystems Engineering department of Delft University of Technology, the Netherlands. He was awarded the 2015 Wim van der Hoek Award for his M.Sc. thesis on the design of a planar precision stage using cost-effective optical mouse sensors, and is currently working as a process control engineer at Shell.

The goal was to demonstrate that a cost-effective planar precision stage can be developed, with optical mouse sensors as measurement system. This positioning system is designed for the microscope industry with applications such as automated blood cell counting or region-of-interest tracking in mind, where an accuracy of 10 micrometer is sufficient.

The main focus was on using a measurement system based on optical mouse sensors for motion control at microscopic scale. The main contribution resides in overcoming the sensor's major shortcomings even when regarding it as a black box. In addition to already investigated methods to improve the sensor's performance (such as error reset and illuminating the measured surface with an external light source), two new techniques (optical magnification and sensor dynamics compensation), which increase the sensor's resolution and control bandwidth while providing uniform sensitivity over a larger stroke, are proposed and validated.

Stage design

The design of the stage is shown in Figure 1 and consists of two main parts; the mover and the base. The mover positions a sample such that it can be observed with the microscope. Three Lorentz actuators actuate the mover in three degrees of freedom: in-plane (X, Y) and a rotation. These actuators have a moving-magnet configuration (coils on the base and magnets on the mover) such that heat and thermal expansion due to losses in the coil will not influence the region of interest. The magnets and coils were designed to provide a linear motor constant over the entire operating area. The mover's in-plane movement should have no non-linear Coulomb friction (for better controllability), whereas any out-of-plane movement should be avoided (to maintain constant sensor sensitivity and focus for the mouse sensor and the microscope). In order to achieve these two requirements, the mover is suspended on three ferrofluid bearings.



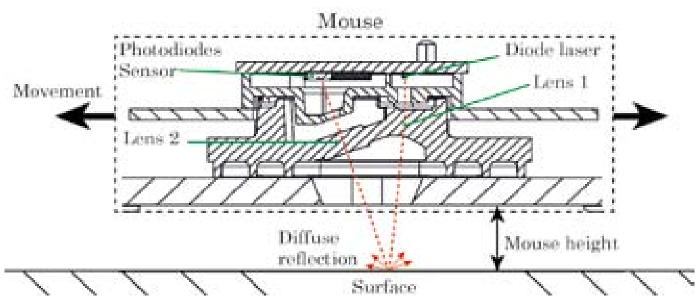
1 *The completed prototype of the positioning stage. The base only measures 160 mm by 168 mm.*
(a) Render of the complete stage.
(b) Render of the base.
(c) Picture of the complete stage.

The base contains two optical mouse sensors, 'looking' at the bottom of the mover via optical elements, measuring the in-plane movements of the mover. The rotation of the stage can be obtained by translating the position measurements of the two sensors into one coordinate system. In order to reduce measurement errors, the sensor is placed directly below the mover in line with the field of view of the microscope. The position controller, actuator amplifier control, and sensor read-out are all implemented on a self-developed PCB, which is controlled by an Arduino Due microcontroller. The stage can be programmed and operated with standard open-source software and is powered by a standard 12V DC adapter.

Sensor design

Working principle

Figure 2 shows the working principle of an optical mouse sensor. The light emitted by the source reflects diffusively on the surface and part of it goes through a lens. The lens projects this light onto a photodiode array (PDA) to create an image of the surface. Using digital image correlation, the patterns in different frames are compared to determine how much the object has moved. Optical mouse sensors can generally acquire and process images at frequencies of several kilohertz, with the limiting factor being the exposure time required by the photodiodes to acquire an image with enough surface details. This means that an adequate irradiance on the sensor is needed to achieve a high frame rate to track high-speed movements.



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Ideally, the surface should be uniform, such that the sensitivity of the sensor (the number of counts per unit of displacement) is not influenced by local patterns. In addition, a rough surface will provide the sensor with enough details in its field of view to detect motion. Finally, a surface with ideal diffuse reflection is desired to make effective use of the available irradiance of the light source. Combining all requirements, a ceramic aluminium oxide (alumina) was selected for the measurement surface.

Sensor selection

The most important criterion when selecting an optical mouse chip for the planar stage is its resolution; specifications are shown in Table 1. Besides these performance indicators it is important that they are commercially available. The selected sensor is the ADNS-9800, an infrared laser mouse sensor chip with a 30 mm by 30 mm PDA and an enhanced resolution of 3.1 µm (using interpixel interpolation). The sensor is sold including all peripheral electronics and can be read out with a microcontroller using the SPI protocol.

Table 1. Manufacturer specifications of the ADNS-9800 optical mouse sensor.

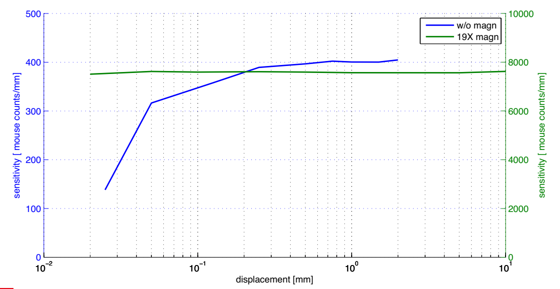
Resolution	3.1 µm
Maximum speed	3.8 m/s
Maximum acceleration	300 m/s^2
Frame rate	12 kHz

Sensor characterisation

The ADNS-9800 was characterised by performing a series of relative displacements between the sensor and the measuring surface. A motion-controlled stage was used to conduct these displacements with different motion profiles, while using the internal sensor as a reference for the optical mouse sensor.

The results show that smaller displacements have a decreasing sensitivity, whereas larger displacements have a more uniform sensitivity. This behaviour is highly undesirable in a positioning system because the sensor will not have the same sensitivity over the full stroke. A hypothesis for this is that the sensor has some sort of noise rejection filter which prevents drift when the mouse is standing still. With small steps this 'constant' loss of incremental counts has a larger impact on the average sensitivity than with larger steps.

Figure 3 shows the non-constant sensitivity in relation to the displacement. Small steps have a relatively large deviation in sensitivity, while larger steps are uniform. Introducing magnification will make the mouse sensor measure a larger step, thus moving the mouse sensor into the constant-sensitivity region.



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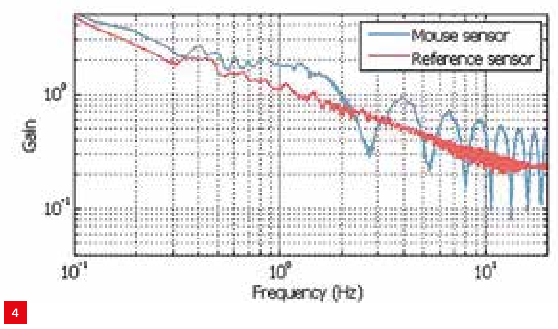
2 *Cross-section of an optical mouse sensor, demonstrating the working principle of an optical mouse.*

3 *Sensitivity of the mouse sensor as a function of displacement.*

In addition to unwanted steady-state behaviour, there are also undesired dynamics in the sensor's measurement signal. By performing an open-loop sine sweep the unwanted dynamics could be extracted; see Figure 4. The dynamics correspond with a digital finite-impulse response (FIR) filter (moving average) with a frequency of 3.5 Hz, which is considerably slower than the frame rate of 12 kHz and the sensor read-out at 200 Hz.



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Sensor improvements

So far, non-constant sensitivity and slow sensor dynamics are the main drawbacks of using an optical mouse sensor as a position sensor in a planar stage. In addition to this, the sensor's resolution of 3.1 μm is quite impressive for an ordinary mouse application, but not good enough for micrometer positioning. In this section, two improvements to address these shortcomings are proposed.

Optical magnification

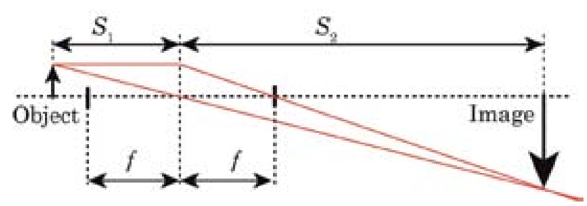
A method to increase the mouse sensor's resolution is to magnify the image of the measurement surface which is projected on the PDA with the use of an extra lens. In this case, a positive (i.e. biconvex) lens can be used to create a larger image of an object. However, this will require some extra design considerations.

First, the irradiance on the sensor will decrease quadratically with the magnification factor. This issue can be solved by adding a more powerful (external) laser source. A 630 nm red diode laser was selected which matches the spectral sensitivity peak of the sensor.

Second, the speeds and accelerations sensed by the optical mouse will increase proportionally with the magnification factor, effectively decreasing the maximum speed and acceleration of the stage that can be sensed given the maximum speed and acceleration specified for the sensor. This drawback will be addressed by the stage's motion controller.

The magnification is determined by S_2/S_1 and is a function of the focal length *f*. The focal length determines how long the total optical path needs to be. A higher focal length *f* is preferred to increase the length of S_1, such that small variations (i.e. caused by external vibrations) have a lower relative impact on the magnification factor and therefore ensure a more constant sensor sensitivity. On the downside, S_2 becomes massively longer. However, by folding the optical path it is still possible to keep the whole system compact; this is shown in Figure 5.

With a magnification factor of 19 times, the sensor resolution increases to 0.13 μm. In addition, the sensor's sensitivity with magnification remains uniform even for small stage displacements, as shown in Figure 3.



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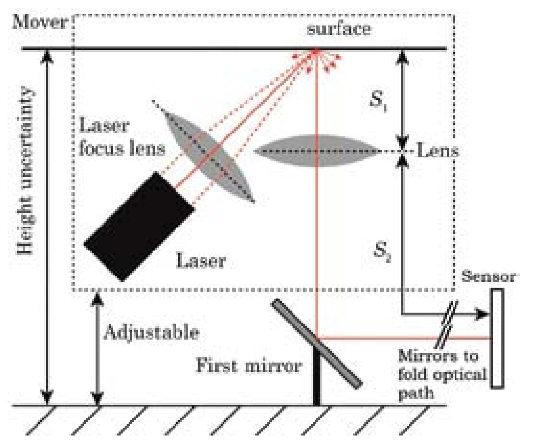

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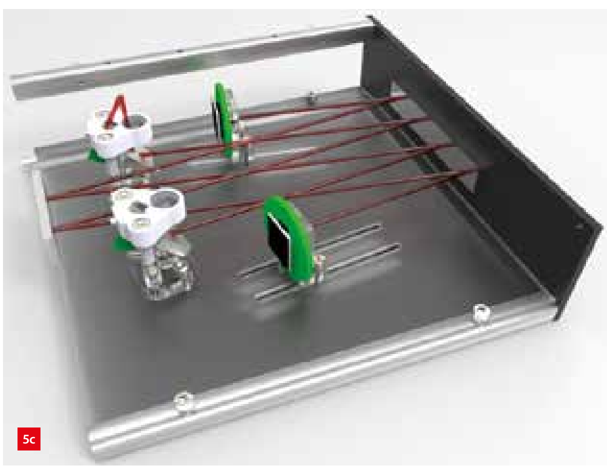
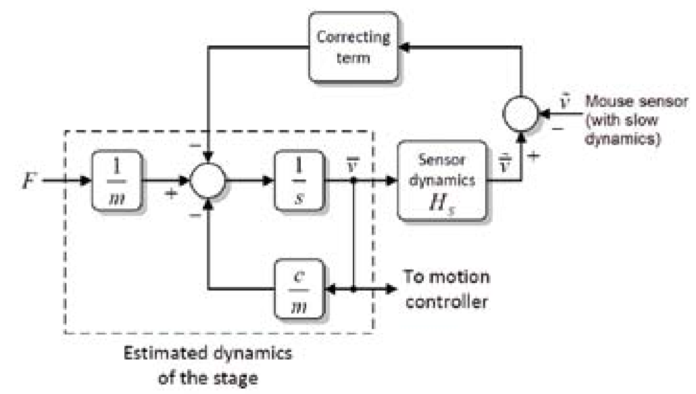

5c

4 *Sensor gain as a function of frequency.*

5 *Optical magnification for increasing the mouse sensor's resolution.*
(a) Key parameters.
(b) Implementation in the design.
(c) Application of mirrors for folding the optical path to keep the system compact.



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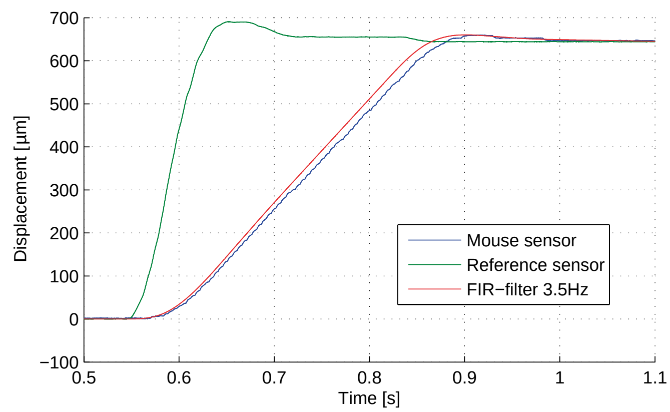

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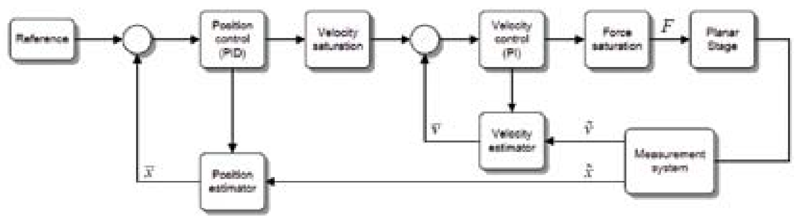
Sensor dynamics compensation

To increase the control bandwidth, a predictor-like state estimator was designed. A block diagram representation of this estimator is shown in Figure 6. The idea is to construct a model of the system to estimate the velocity of the stage. Without modelling the sensor dynamics it is impossible to correct the estimation of the observer. The mouse sensor will be slower because it is affected by the digital filter, this would be equivalent to correcting the observer with the difference between the green and blue line in Figure 6b.

By superimposing the model of the sensor dynamics on top of the estimator output, $\bar{v}$ (red line), it will be possible to use the mouse sensor for feedback. As the correcting term brings the states $\tilde{v}$ and $\tilde{\bar{v}}$ together, it is expected that $\bar{v}$ will approach v if the model of the system is accurate enough. The motion controller is then driven at the estimated velocity, which is not affected by the slow sensor dynamics in the mouse sensor. The addition of this estimator increases the control bandwidth from 1 to 10 Hz.

Controller design

Since the maximum velocity and acceleration of the stage are limited due to the optical magnification used for the optical mouse sensor, a cascaded position-velocity controller with velocity saturation was designed to control the mover's position. The final controller design is shown in Figure 7, depicting an outer position control loop (PID) which provides a target velocity for an inner velocity control loop (PI), with a velocity saturation at 30 mm/s. The inner loop (controller and plant) should follow the target velocity profile as closely as possible. Two state estimators as described in the previous section are used to estimate the position and velocity of the mover. These estimated states are used to control the stage, effectively compensating for the slow sensor dynamics.



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Experimental results

The experiments presented here illustrate the positioning performance of the planar stage. In the first experiment, the precision of its measurement system was determined by comparing the displacement measured by the mouse sensor and an external reference sensor; the set-up is shown in Figure 8. A series of consecutive displacements (100) of the same length (1 mm) were performed in order to determine the stage's repeatability. By comparing the reference sensor with the desired reference position, the servo error was determined which includes all error sources in the loop. The 3σ positioning error is 9.7 µm with a settling time of 1.0 s.

In the second experiment, the mover was positioned at a target location for a long period of time to assess the positioning stability of the stage. This includes measurement stability, servo stability and stability against disturbance. The 3σ positioning stability is 3.1 µm. In the third experiment, steps of different lengths were performed in order to determine if the sensitivity of the sensor is constant over larger displacements. The result is shown in Figure 8, where steps ranging from 1.0 to 4.0 mm are performed, showing uniform sensitivity.

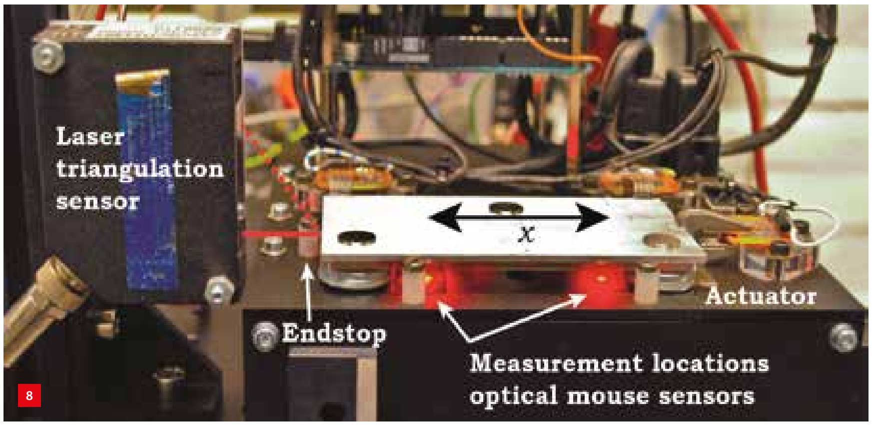
6 *Coping with slow sensor dynamics.*
(a) Block diagram of the velocity estimator.
(b) Step response; the extracted dynamics can be subtracted from the reference signal / estimator output for feedback purposes.

7 *Block diagram of the cascaded position-velocity controller, including the state estimators.*

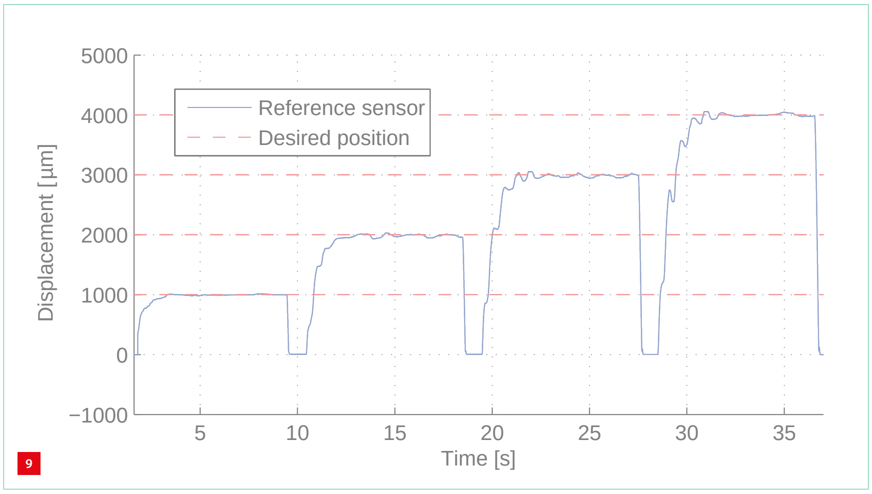
Table 2. Experimental results; see text for explanation.

	Experiment 1 (servo error, 1 mm step)	Experiment 2 (positioning stability)
Resolution (μm)	0.13	0.13
Positioning error (μm, 3σ)	9.7	3.1
Settling time (s)	1.0	-

These results show that the system performs well enough for the intended application of blood cell counting and region-of-interest tracking. Table 2 shows the results of the experiments. Positioning accuracy below 10 μm was achieved. Figure 9 shows step responses of varying sizes; the sensor sensitivity remains uniform over a large range of displacements.



8 *Experimental set-up. A secondary external reference sensor was used to compare the displacements measured by the optical mouse sensors. This sensor was not used in the control loop.*



9 *Step responses in the experiments.*

Conclusions

The position measurement system of a cost-effective planar precision positioning stage is presented in this paper. This measurement system is based on a commercially available and accessible optical mouse sensor chip. The focus has been on improving some of the most significant shortcomings of the sensor system which result from using the chip as a black box.

First, the resolution of the measurement system has been increased and its non-constant sensitivity removed by means of optical magnification using an external lens. Since the light intensity of the sensor decreases with magnification, an externally focused diode laser is used to illuminate the measurement surface. An additional consequence of the optical magnification is that the maximum tracking speed of the stage decreases. In order to address this, a cascaded position-velocity controller was designed such that it is possible to saturate the speed.

Second, experiments with the sensor system revealed that a digital filter integrated in the mouse sensor chip reduces the control bandwidth to only 1 Hz. To overcome this issue, an observer-like predictor was designed to estimate the state of the mover. The predictor uses information about the model, sensor dynamics, system inputs and optical mouse sensor output so that, instead of controlling the stage with delayed information from the sensor system, the 'predicted' state of the mover is used to drive the controller. By doing so, the control bandwidth was successfully increased by a factor of 10.

With these methods, the demonstrator was able to achieve a high positioning accuracy down to 9.7 μm, fulfilling the requirement for microscopy purposes. The planar precision stage has a component cost of only €200 and was conceptualised, designed and validated within a time frame of just one year. ■

ACHIEVING OPTIMAL PERFORMANCE

In the field of micro and precision engineering, the ability to measure at every stage of the production process is key: "If you can't measure it, you can't make it". On 15-16 March 2017, euspen will be hosting the 12th International Conference and Exhibition on Laser Metrology, Coordinate Measuring Machine, and Machine Tool Performance (Lamdamap), looking at aspects of metrology when applied to machine tools. In advance of the event, this article looks at the key issues related to advanced machine tool metrology.

CHRIS YOUNG

The production of more and more accurate and smaller and smaller components relies on and indeed is underpinned by advanced machine tool metrology, which facilitates the assessment of performance of machines. This requirement becomes more pressing as the drive in industry towards the greater use of nanoscale surface finishes and features gathers pace.

The Lamdamap event, organised by euspen (European Society for Precision Engineering and Nanotechnology), is a leading source of relevant knowledge. It allows the next generation of manufacturers to use all available advances in measurement techniques to meet tomorrow's production challenges. The 2017 edition will take place on 15-16 March at the Renishaw Innovation Centre in the UK.

Increasing requirements

The efficiency and capability of a machine tool is influenced by a number of factors including its system configuration, its operating environment, and its performance output requirements. Designers constantly drive increases in product performance as they specify more and more exacting manufacturing tolerances. In addition, constrained design specifications, increased product geometry complexity, and the use of higher-performance materials, all effectively result in products that are getting more and more difficult to machine.

From a manufacturing process perspective, engineers are continuously trying to improve machine tool capability in respect of availability, performance, and quality, with the goal of reducing the amount and seriousness of process breakdowns, as well as increasing machine uptime, material removal rates, and automation.

AUTHOR'S NOTE

Chris Young, Managing Director & CEO of UK-based Micro PR & Marketing, is media partner of euspen.

Because of this, a paradoxical situation arises wherein more severe conditions are being imposed on the machine tool while at the same time greater performance is expected but with reduced levels of process interruption.

It is reasonable to view a machine tool as a subsystem within a larger manufacturing system, where changes in its performance can have a significant impact on product lifecycle characteristics such as cost-to-market, final product conformance, and lifespan. Machine tool improvements can be made through optimisation of elements contained within its system, and these include its geometry, mechanical components, electrical components, electronic components, the CNC controller, part fixturing, and cutting tools amongst many others.

Calibration

To produce conforming products at a high level of process capability it is vital that a machine tool is demonstrably accurate. However, even a relatively simple 3-axis machine has numerous (in excess of 20) potential sources of geometric error, including squareness, straightness, and linearity to name but a few. If you were to add one or more rotary axes, this significantly increases the complexity further. Each of the errors needs not only to be fully understood, but also either corrected or compensated for before parts can be machined.

There are numerous devices that have been used over the years to calibrate machines, but in some instances it can take as much as five days to fully calibrate a machine. This extent of downtime is massively costly and therefore not generally acceptable, so within the area of precision engineering there is a huge push to attempt to drive to down calibration time drastically and put in place rapid and non-intrusive verification systems to confirm on-going equivalence and prevent catastrophic failures.

Metrology research

Looking at it in a broader sense, metrology is essentially the art of measurement, and it is a fundamental and underlying capability without which products cannot be manufactured. Today, a massive amount of research is focussed on developing new methods, techniques, and tools (be they software, instruments, or processes) to support the adoption of in-process dimensional and surface metrology for high-value, precision-manufactured components such as those found in engine components for aeroplanes, medical implants, optical components, and microelectronics. Some call this drive to manufacture, measure, and correct in-process the “factory on the machine”.

Much recent research (for example at the University of Huddersfield, UK, see the impressions in Figure 1) has expanded industry’s understanding of the factors that contribute to machine tool inaccuracy. This has led to predictive methods for assessing the capability of machines to produce specific components and the development of a low-cost electronic compensation system that can increase machine tool accuracy by a factor of ten, with significant cost savings for factory temperature control. Such rapid calibration techniques have been developed, for instance, by

1

Huddersfield University in collaboration with a UK-based aerospace OEM, reducing timescales from days to less than one hour. It is these sorts of initiatives that provide the core of the euspen Lamdamap event.

The accuracy of machine tools is fundamental to the quality of the products they make. A better understanding of why errors occur and how to minimise them is vital to ensuring higher standards of manufacturing and increased productivity. All machine tools and coordinates measuring machines (CMMs) inevitably develop intrinsic deviations resulting from the inexact manufacturing of the machine components, from wear of functional parts, from ruler reading errors, as well as from elastic deformations of the structure.

Trend

At the euspen-hosted Lamdamap event, all the latest developments in this area of metrology will be discussed. Chris Pockett, Head of Communication at Renishaw explains his perspective on the state of the sector. “There is a clear trend towards higher speed and increased richness of information about machine and process — providing a greater depth of measurement data to enable more advanced forms of production control.”

“Clear recent examples of this are Renishaw’s XM-60 Multi-Axis Calibrator for machine tool production and service, and the Sprint On-Machine Contact Scanning System. In the case of XM-60 — a tool for machine tool producers and service companies — this system provides six channels of measurement data for each captured point, versus only one channel for the established systems. In other words, six times improved throughput to capture the same data. Similarly, the SPRINT system brings a step change over individual discrete point measurement by introducing a full 3D stream of measurement data during probing.”

Lamdamap 2017

At Lamdamap, attendees will find on the exhibition floor an array of technology solutions targeted at the refinement of metrology techniques when applied to advanced machine tools from leading companies in this field. In addition, at the conference, papers will be presented on such topics as novel manufacturing technologies and machine tools, new developments in measurement techniques, performance evaluation for machine tools and CMMs, roughness and machine tool standards, and metrology in new fabrication techniques.
Two keynote presentations already have been confirmed for the event, the first by Prof. Xiangqian Jiang from the University of Huddersfield, UK, looking at surface metrology for future manufacturing, and the second by Dr Josef Mayr from IWF, ETH Zurich, Switzerland, on thermal error compensation of machine tools. ■

1 *Impressions of machine tool performance research at Huddersfield University.*

INFORMATION
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Connect 2 Cleanrooms – leading bespoke modular cleanroom specialists

Connect 2 Cleanrooms is an award winning industry leader, creating modular cleanroom solutions for critical environments, both in the UK, Europe and globally. The company designs and manufactures bespoke monobloc, hard- and soft-wall cleanrooms in house and delivers quality cleanroom solutions to meet the ISO 14644-1 standard required. Its consumables division, Cleanroomshop.com, supplies a full range of consumables, equipment and furniture to the cleanroom industry worldwide.

Although the diverse ranges of industries Connect 2 Cleanrooms serves have different needs and priorities, they all have one shared need. Each organisation has a critical process that requires protection. Their cleanrooms become an integral part of their client's processes, supporting innovations across the UK, Europe and the rest of the world, impacting on electronics, energy, engineering & manufacturing, healthcare & pharmaceutical as well as laboratory sectors.

They understand the importance of placing products in mission-critical environments and the requirement of technical support at varying stages. Connect 2 Cleanrooms is happy to support their clients with their URS (User Requirement Specifications) and will provide additional technical support to meet various qualification stages.

Connect 2 Cleanrooms, the modular cleanrooms experts, has further expanded into mainland Europe with the opening of a new office in Utrecht, the Netherlands. After many successful years serving this market from its UK Head Office, this new local office now provides Dutch clients with the advantage of having Connect 2 Cleanrooms' expertise and full technical support close at hand.

Joe Govier, Connect 2 Cleanrooms' MD, is excited by the opportunity created from the synergy between the Netherlands' market and Connect 2 Cleanrooms' own vision; "The Netherlands is a hot-bed for world-leading and innovative, high-tech, precision industries, with state-of-the-art facilities and cutting-edge research and development. The Netherlands' talent for creativity and entrepreneurship is one that is shared by us and we are excited to now be in a position to offer an improved service and collaborate with like-minded companies."

Clients are able to work together with this office for new cleanroom or laminar flow requirements, as well as for on-going support and cleanroom validations for their existing clean environments. As part of their offering, Connect 2 Cleanrooms also offers full after sales support including validation and service contracts, along with full cleanroom training, and regular open days. Its new office is within walking distance of Utrecht Centraal Station, ideally located to be accessible across the whole of the Netherlands.

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ACCLAIM FOR CONTROL ENGINEERING AND PRECISION DESIGN TALENT

DSPE presented two awards at the sixteenth edition of the Precision Fair, held 16 and 17 November in Veldhoven, the Netherlands. Wouter Aangenent, senior architect and project leader at ASML, received the Ir. A. Davidson Award for his leading role as a specialist in control engineering/mechatronics and his enthusiastic commitment to knowledge transfer. The Wim van der Hoek Award was presented to Niels van Giessen for the smart design of a robot arm in the project for his bachelor's degree in mechanical engineering at Avans University of Applied Sciences.

DSPE board member Toon Hermans, the managing director of Demcon Eindhoven, presented the Ir. A. Davidson Award on the afternoon of Wednesday 16 November. The purpose of the prize is to encourage young talent by recognising the efforts of a precision engineer with several years of experience working at a company or institute and a proven performance record which has been acknowledged internally and externally. Candidates must also have a demonstrated enthusiasm for the field that produces a positive effect on young colleagues.

IR. A. DAVIDSON AWARD

The biennial prize, which was established in 2005, is named after an authority in the field of precision mechanics who worked at Philips in the 1950s and 1960s. The prize comes with a certificate, trophy and sum of money. The trophy was created by the Leiden Instrument Makers School (LiS) in the form of the handbook in precision mechanics that Davidson used as a foundation when forming the constructors community at Philips.

Enthusiastic champion

This year the field of nominees in contention for the Ir. A. Davidson Award was considerable. The panel of judges, however, was unanimous in its decision to honour Wouter Aangenent as the winner. He studied mechanical engineering at Eindhoven University of Technology (TU/e), the Netherlands, and obtained his Ph.D. in control engineering in 2008 at the same university. He subsequently joined TMC, a high-tech engineering company that encourages its employees to develop their entrepreneurial skills, where he worked on a project for ASML. In 2010 he was hired by that Veldhoven-based lithography machine builder, where he now serves as a control architect and project leader.

Wouter Aangenent has grown to become one of the leading specialists in control engineering/mechatronics. In that capacity he has become a champion of an ASML-wide Way

1 *2016 Ir. A. Davidson Award winner Wouter Aangenent (right) receiving the award certificate from DSPE board member Toon Hermans. (Photos: Mikrocentrum)*

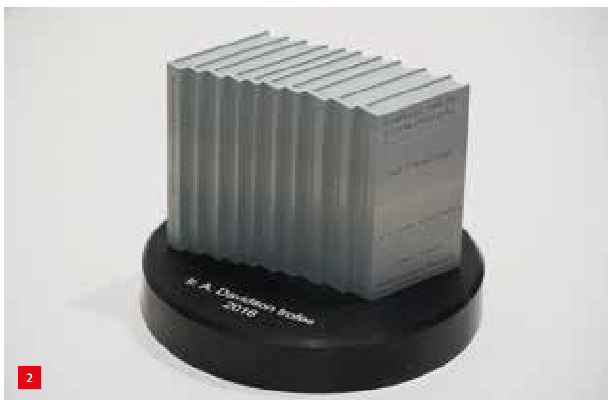
of Working for control design aimed at guaranteeing high performance and robust controller implementation in all machine modules. Wouter Aangenent is very active in transferring his knowledge and inspiration to new, upcoming talent. He regularly delivers presentations at conferences and encourages colleagues to do the same. He was one of the initiators of the ASML Servo Control training programme and provides this training to both new and existing employees in the Netherlands and the US.

He also promotes knowledge transfer beyond ASML, for example through the Mechatronic Systems Knowledge Exchange working group for explicit mechatronics knowledge-sharing in the Eindhoven region. In addition, he maintains close contacts with TU/e, supporting students' master's and Ph.D. projects. Finally, the Ir. A. Davidson Award judges recognised the enthusiasm with which Wouter Aangenent has participated in special projects over the years, such as the TU/e RoboCup team and the design of a table-top hockey robot at TMC.

New concept

The next day of the Precision Fair, Thursday 19 November, featured the presentation of the Wim van der Hoek Award. This award (also known as the Constructors Award) was introduced in 2006 to mark the 80th birthday of the Dutch doyen of design engineering principles, Wim van der Hoek. This design engineering award is presented every year to the person with the best graduation project in the field of design in mechanical engineering at the Dutch universities of technology and applied sciences. This award includes a certificate, a trophy made by LiS and a sum of money (sponsored by the 4TU federation).

The 2016 Wim van der Hoek Award was presented to Niels van Giessen, who studied mechanical engineering at Avans University of Applied Sciences in Den Bosch, the Netherlands. He graduated last summer and his graduation project involved the design of a robot arm in which special attention had been devoted to the construction of the 'wrist'. The panel of judges called his design an excellent example of the application of well-known precision design principles and praised his clear formulation of the assignment and conclusions, which he substantiated with experiments and suggestions for improvement, including in relation to cost price. With his bachelor's project, Niels van Giessen has laid the foundation for a new robot arm concept that can be deployed for handling purposes in production environments. ■



2 *The trophy that comes with the Ir. A. Davidson Award represents the handbook in precision mechanics Davidson had compiled.*

3 *2016 Wim van der Hoek Award winner Niels van Giessen.*
(a) *Receiving the award certificate from DSPE board member Jos Gunsing.*
(b) *Receiving Wim van der Hoek's congratulations.*

IN THE HEART OF THE HIGH-TECH 'SILICON FOREST'

This year, Portland, Oregon was the host city of ASPE's Annual Meeting in late October. Portland is in the heart of the high-tech 'Silicon Forest' which has a deep appreciation for precision engineering. This report features highlights of the 31st edition of the event.

TON PEIJNENBURG, MARIJN NIJENHUIS AND DANNIS BROUWER

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Technical Leadership Committees

ASPE (American Society for Precision Engineering) has constituted a number of Technical Leadership Communities (TLCs) in an effort to enhance the technical strength of the society and promote increased participation of the members in charting ASPE's technical directions. Six distinct fields now have such a committee, managed by a senior member in combination with one of the six directors-at-large of the society. These fields are Precision Manufacturing, Metrology Systems, Characterization, Precision Design, Micro & Nano Technologies, and Controls and Mechatronics.

For the Annual Meeting in Portland (Figure 1), each TLC had formulated an oral session and was responsible for its technical content. For the first time, each oral session had an opening paper delivered by one of the TLC leaders to describe developments in the field: what is 'hot', how is this technical area evolving, what should the membership know about its state-of-the-art (and a little beyond). The nice thing about this concept was that it was not a 'dive in deep' in a technical area, but more an overview for all attendants to follow and to get a feeling of what's going on in each of the six TLC areas. It worked out really well.

Tutorials

As always, the ASPE Annual Meeting had a strong slate of tutorials including Dutch and Belgian input. Gerrit Oosterhuis (VDL ETG) and Martijn Vanloffelt (LayerWise)

delivered their "Applications of Additive Manufacturing to Precision" with selected case studies to illustrate specific aspects of additive manufacturing (AM) and their impact on part performance within the context of precision-engineered systems. Part design, AM process settings and post-processing of the parts were extensively discussed.

"Dynamics and Control of Precision Motion Systems" was given by Stephen Ludwick (Aerotech) and Theo Ruijl (MI-Partners), focussing on the use of frequency-domain techniques. Piet van Rens (Wienes Product Development/ Settels Savenije van Amelsvoort), Marijn Nijenhuis and Dannis Brouwer had a full-day tutorial "Design Principles for Precision Engineering" (Figure 2), about the conceptual approach to designing precision mechanisms like manipulators, scientific instruments, precision equipment, etc. They focussed on the mechanical aspects of precision in a mechatronic system context. Extra attention was devoted to essential 'details' that make the difference between a good and bad design.

1 *Portland by night. (Photo: Eric Baetscher, Wikimedia Commons)*

2 *Piet van Rens delivering his part of the "Design Principles for Precision Engineering" tutorial. (Photo: Vivek Badami)*

Student Competition & Mentoring Event

At the same time there was also a Student Competition & Mentoring Event. This year, the student teams had to design, simulate and control a beam steering device with two degrees of freedom. The teams comprised three to six B.Sc. or M.Sc. students. The competition included mentoring by various precision engineering experts who were available for one-on-one consulting. Teams would draw upon their precision engineering skills to solve a multidisciplinary challenge covering mechanical, electrical, metrology and control aspects.

The contest consisted of two phases. First, at their own school, the participants received a set of parts (CAD models) and could use modelling tools to understand the challenges and set out a strategy. In the second phase, at the meeting in Portland, the teams assembled and tuned the devices to project a given pattern on the wall. The philosophy behind the challenge is to get more students involved in precision engineering as early as possible so they can appreciate how exciting it is to pursue a career in precision mechatronics. Funding from local companies and the National Science Foundation helped over thirty students attend the conference.

Keynote address

Marv White from Sportvision, Inc. delivered a keynote on precision in augmented reality. Sports broadcasts, streaming video and rendering sporting events for mobile devices now routinely include virtual effects like the '1st & Ten' in American football, K-Zone and pitch trajectories in baseball (Figure 3), advantage lines and virtual flags in sailing competitions and driver markers in motorsports, in short: augmented reality.

Conveying the illusion that the virtual effects are part of the scene and truly augment reality requires true precision measurements and fast calculation routines to get the effects real time on the screen at the right position. Using several examples, Marv White showed measuring camera characteristics, car and boat position and orientation, flying camera tracking, and player tracking. Based on such measurements, changing just the right pixels in each image 60 times per second (or so) creates the illusion that lines, smoke trails, tracks on the turf and virtual video screens really exist at the event. It was a most entertaining opening talk.

Presentations

The first session was on precision design, where Mark Stocker from Cranfield Precision introduced the eleven principles for precision equipment design. Some of these overlapped with other TLC topics. The idea of the principles was a compelling one. For precision machining, John Ziegert gave an extensive overview of the state of the art and upcoming manufacturing technologies such as AM. The third session addressed reducing the cost of precision, with a powerful introduction by Alex Slocum from MIT. For the full programme, see the ASPE website, aspe.net.

Poster sessions and exhibit

For the second time, all conference participants were asked to help judge the posters. A web-based application was used that (randomly) assigned five posters to each participating judge. Scores could be easily entered on certain criteria. Especially the random allocation of posters to judges stimulated looking at posters that one otherwise would have missed. The exhibit was a good meeting place (Figure 4), with a special mention of MI-Partners who managed to ship their through-the-wall magnetic levitation stage from the Netherlands to the Far West!

To conclude

On the final day of the conference, participants visited FEI Company and CoorsTek – Oregon Operations. FEI Company designs and manufactures focussed ion beam workstations, scanning electron microscopes and transmission electron microscopes. Tour participants viewed their products and the manufacturing cleanroom. CoorsTek manufactures ceramic air-bearing guideways, and precision structural components and assemblies.

All in all, the ASPE 2016 Annual Meeting has proven to be a worthwhile event. ■

3 *Augmented-reality pitch trajectory in baseball. (Illustration: Sportvision, Inc.)*

4 *Impression of the exhibit. (Photo: Vivek Badami)*

GOOD VIBRATIONS NEAR ABSOLUTE ZERO

Experiments in cryostats at very low temperatures, for example as performed at Leiden University, have to be protected against vibrations arising from the cooling equipment. A multi-disciplinary team comprising Dutch research institutes, engineering agencies and external experts designed and realised a double-frame vibration isolation solution. A primary frame supporting the experiment is mechanically isolated from the outer, secondary, frame which supports the vibration-generating pulse tube refrigerator. As a result, the dominant vibrations are suppressed.

TJERK OOSTERKAMP, MARK BEKER, EVERT HOOIJKAMP, MARTIN DE WIT, GESA WELKER, DIAN VAN DER ZALM AND GIJS AKKERMANS

The Leiden Institute of Physics has a long tradition of researching all kinds of phenomena at very low temperatures. It was in Leiden that Heike Kamerlingh Onnes, with his co-workers, became the first physicist in the world capable of liquefying helium. He quickly realised that for a scientist it is not enough to work with one's own ideas and inventiveness. It is wiser to surround oneself with people that have the technical expertise and knowledge of materials and production. Therefore, he founded the Leiden Instrument Makers School (LiS), which to this day has been engaged in educating world-class instrument makers.

Now, more than one hundred years later, much has changed in cryogenics. Reaching a temperature of 4 K, when helium liquefies, has become much easier. Today, 4 K is the starting point to reach even lower temperatures, just 0.01 degree above absolute zero. After going to 4 K with a first cooling stage, the second cooling step is performed by a machine called a dilution refrigerator (see Figure 1) [1].

Pulse tube refrigerator

For a long time, the only option to perform the first cooling stage was a 'wet' cryostat, which relies on liquid helium for its cooling power. The helium is boiling and thus remains at a constant temperature as long as the helium bath is periodically refilled. In fact, it can consume approximately 100 litres of liquid helium every week. Since this is rather expensive, 'dry' cryostats, or cryogen-free refrigerators, have been developed in the past ten years. Combined with a dilution refrigerator, they can also reach

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www.physics.leidenuniv.nl
www.innoseis.com
www.hittech.nl
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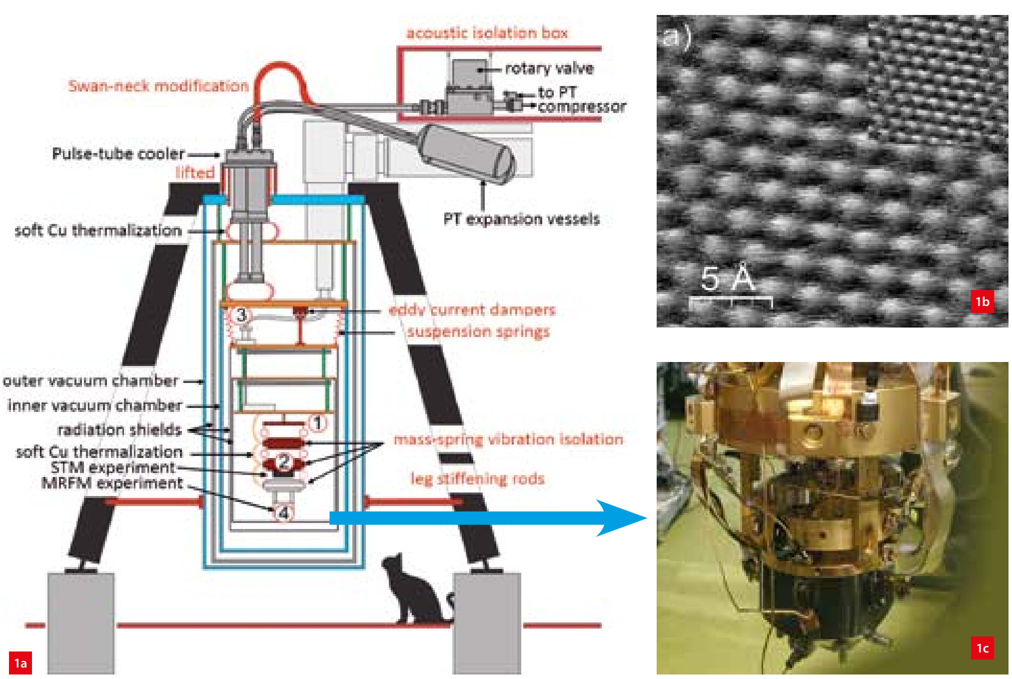


1 *The commercial pulse-tube-cooled, cryogen-free dilution refrigerator.*
(a) *Schematic representation with vibration-reducing modifications in red. The various vibration measurements are indicated by the numbers:*
1: SQUID at the mixing chamber plate.
2: SQUID at the second mass.
3: Geophones at the 3 K plate.
4: MRFM (magnetic resonance force micoscopy) vibration measurement inside MRFM set-up (aluminium box in the order of 10 x 10 x 10 cm³).
(b) *First scanning tunnelling microscope (STM) image with atomic resolution of graphite.*
(c) *Close-up of MRFM set-up*

0.01° above absolute zero, but the first cooling step is not derived from the boiling of pre-cooled liquid helium. Instead, a pulse tube refrigerator (PTR) is used [2].

The PTR uses a closed circuit of helium gas that is periodically compressed in the warm part of the system and subsequently expanded in the cold parts of the PTR, which are located inside the cryostat. This makes the cryostat cold enough for operating the actual dilution process in the second cooling step. In contrast to the wet cryostats, no helium is consumed because of the closed circuits, resulting in low(er) operating costs and theoretically unlimited time for experiments at temperatures close to absolute zero.

A 7 kW helium compressor, in combination with a PTR, can provide a PTR cooling power of 1.5 W at 4 K. Compared to this, the dilution refrigerator's cooling power is minute, only a few milliwatts. And with decreasing temperature, this small power decreases even more, resulting in a cooling power of only a few microwatts at the cryostat's base temperature of 0.01 K. These extremely low temperatures are so useful when performing scientific research that many tens of these cryostats are built every year. The Netherlands can be proud that many of these are built in Leiden, by the Dutch company Leiden Cryogenics and the Finnish company Bluefors, that both were founded, unsurprisingly, by Dutchmen who were educated at Leiden University and LiS.

Not only do the PTR-pre-cooled cryostats have lower operating costs and unlimited operating time, another advantage is that their volume for the experiments is much larger (by a factor of 10 to 100) than in cryostats that are cooled through the consumption of liquid helium. This allows for the design of experiments at low temperatures that are much more complicated as there simply is much more space to build complex apparatus.

Vibration isolation

So, for research on the quantum materials of the future through the use of scanning probe microscopes (SPMs) such as the AFM (atomic force microscope) [3] or the STM (scanning tunnelling microscope) [4], it is now possible to use more complex cryogenic motors needed for the microscope's (nano)positioning, which is quite difficult at these very low temperatures.

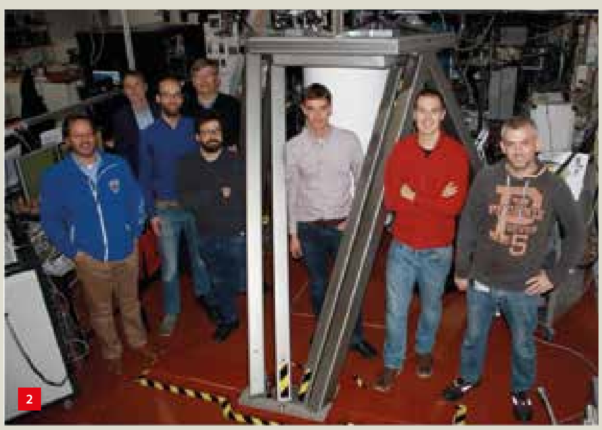
In order to perform the envisioned experiments on the nanoscale it is of course of utmost importance that the vibrations which originate from the compressor and the PTR will not disturb the experiments. Until recently it was not possible to create images with an STM inside a pulse-tube-cooled cryostat at atomic resolution as shown in Figure 1. In addition, as was recently demonstrated in Leiden, science continues to demand that technology further stretches its limits with ever lower temperatures, better nanopositioning and even lower vibration levels.

The time that an individual researcher could move the boundaries of technology, only aided by technicians employed by the university, seems to have passed. In order to proceed with more accurate SPM research at low temperatures, the Leiden researchers needed to improve the design of their cryostat. They looked for new solutions to block the vibrations generated by the compressor in order to prevent them from reaching the vibration-sensitive microscope, located inside the cryostat. It turned out to be very important for the scientists to cooperate with various experts from different companies. But how do you find the people with the required expertise willing to collaborate? Using a research subsidy from NWO, the Dutch Organisation for Scientific Research, a project team was constituted (see the box).

Project team

Multidisciplinary collaboration between research institutes, engineering agencies and external experts in the Holland Instrumentation network was created to achieve something that none of the individual partners would have been able to do on their own. The project team (see Figure 2) consisted of:

- Project leader: Philson Consulting, Philip Sonneveldt
- System engineering/dynamics/thermal: Hittech Multin, Pieter Kappelhof and Evert Hooijkamp
- Construction: ACE ingenieurs & adviesbureau, Gijs Akkermans, Joep Braam, Joao Ribeiro and Ben van Essen
- Mechatronics and seismic vibration measurement and isolation: Innoseis, Mark Beker and Alessandro Bertolini
- Realisation: Fine Mechanical Department Leiden University, Fred Schenkel
- Low-vibration cryogenic systems: Leiden Spin Imaging, Dian van der Zalm
- Scientific input: Leiden University, Martin de Wit and Gesa Welker
- Fabrication: Kasteel Metaal
- Customer: Leiden University, Tjerk Oosterkamp



2 *Team members with the new double frame of the cryostat.*

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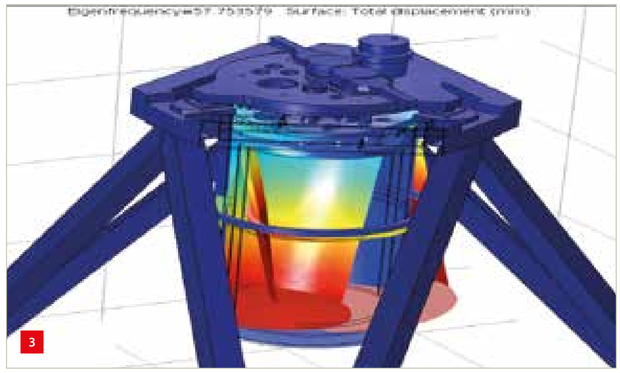
Design

The first idea of Leiden University was to make an improved design of the heat-links (copper braiding) between the pulse tube and the cryostat. The rotation of the valve switching the pulse tube back and forth between the high-pressure output of the compressor to the low-pressure input of the compressor, as well as the expansion of the gas in the pulse tube results in undesirable vibrations of several micrometers of absolute motion in the cryostat, thereby compromising the accuracy of the experiments (STM and MRFM, i.e. magnetic resonance force micoscopy).
In order to overcome this issue, the following goal was formulated: design a vibration isolation solution to mitigate the influence of the pulse tube on the measurement probes, by means of an improved heat-link. This can be done passively or actively.

Further studies proved that due to the multi-stage plate design of the cryostat, vibrations coming from the pulse tube should be considered as the main contribution. Isolating the pulse tube from the rest of the cryostat was considered to be of primary concern rather than redesigning the heat-links. This would be achieved by creating a high-stiffness secondary support structure or frame on which the pulse tube could be mounted.

To close the cryostat's vacuum chamber, there was still a need for a flexible, though vacuum-tight, connection between cryostat and pulse tube, an edge-welded bellow in this case. Due to the forces arising from the pulse tube and the desired reduction of vibration levels, the team determined that the frame and vacuum connection would need to meet the following requirements: the pulse tube frame's stiffness in all translational directions needs to be as high as $1 \cdot 10^8$ N/m and the stiffness of the bellow in all translational directions would have to be lower than $1 \cdot 10^3$ N/m.

The dynamic behaviour can be described by the modes of the structure and is a key factor in the reduction of the vibrations. Here, the modes were obtained by numerical modal analysis performed on a finite-element model in COMSOL Multiphysics (see Figure 3) [5]. The mode shape of the inner structure showed a movement similar to that of two, out-of-phase, pendula. The combination of the first modes, including the mode shape shown in the figure, was used to compute the frequency response functions belonging to the loading of the pulse tube. By modifying the design parameters (e.g. contact stiffness values) and studying the resulting dynamics obtained via the modes, the effect of different design concepts could efficiently be quantified.



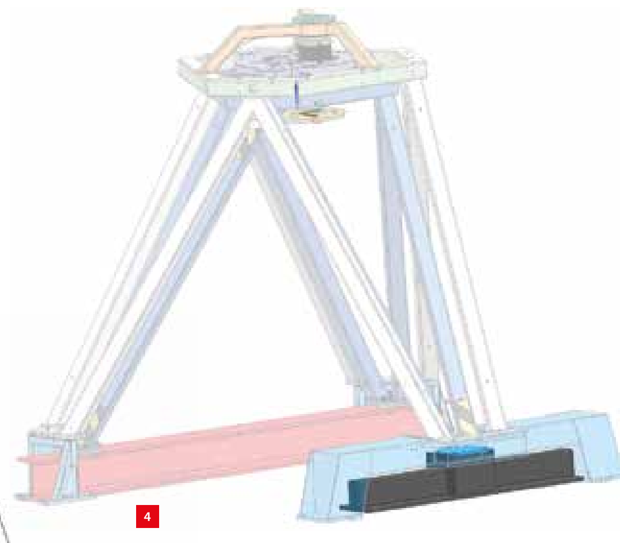
3 *The mode shape of the inner structure similar to two out-of-phase pendula.*

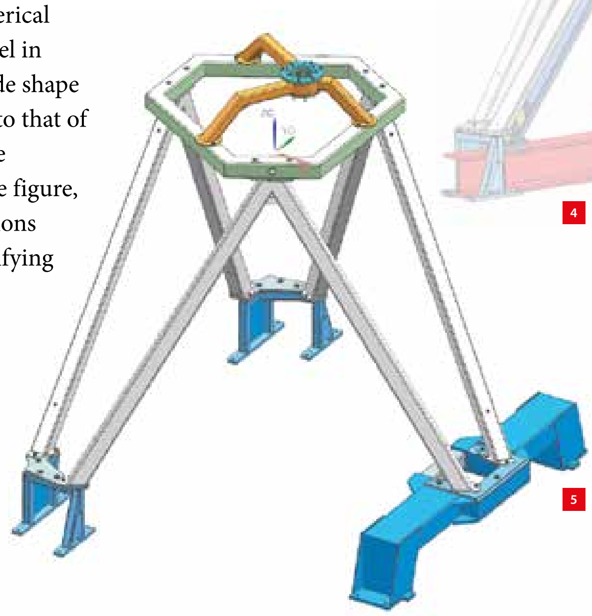
4 *Bridge-like construction of the primary and secondary frame.*

5 *CAD layout of the cryostat's external structure.*

The end result was an outer secondary frame, with structural design similar and parallel to the one already holding the cryostat, but mechanically isolated from the primary frame. The primary frame was the result of an earlier phase of the project that together with several other improvements resulted in achieving atomic resolution inside a dry cryostat at 15 mK [6].

Because of volume constraints, due to the floor and the instrument foundation layout at Leiden University, a welded bridge-like construction was designed to support the primary and secondary frames without any mutual mechanical connection (see Figure 4). The new frame which reaches over and around the cryostat has the sole purpose of holding the pulse tube (see Figure 5). This frame was designed to be sufficiently stiff to eliminate the motion of the pulse tube despite the high forces exerted on it by the high-pressure line coming from the compressor.





This result, along with Leiden Spin Imaging's profound knowledge and know-how [7], was used for the new secondary frame that has an alternative hexagonal ring welded ring on top (see Figure 6), in which the pulse tube is mounted. Its stiffness is as high as required. The edge-welded bellow, however, is still ten times stiffer than desired.

As a result, the vibrations generated by the pulse tube are constrained by the secondary frame, as the pulse tube is being held by this frame and is only weakly connected to the primary frame. Consequently, the vibrations generated by the pulse tube no longer enter directly into the primary frame, which is supporting the cryostat.

Results

Kasteel Metaal has produced and delivered the secondary frame to Leiden University. First results show a significant improvement. Physical proof of the isolation of the vibration is obvious when you put your ear to the frames. In the secondary frame you can hear the pulse tube 'sing'; on the primary frame, right next to the other frame, you hear nothing.

The improvement through vibration isolation is demonstrated in Figure 7 by comparing the accelerations of a geophone before and after the new frame was installed. In the figures a cumulative number (integrated value) is presented as a function of the frequency; the accelerations are presented as a root-mean-square figure by integrating up to the frequency on the x-axis. Most important is that the steps that were previously present at 1.4 Hz and 2.8 Hz (the frequency of the pulse tube) are no longer observed. The vibration level now appears to be limited by the vibrations present in the laboratory.

To conclude

The researchers are looking forward to repeating their measurements in the new Leiden University measurement laboratory, which is expected to open in July 2017. Then they will know whether the vibrations have improved by a factor of ten in amplitude or whether they may have reduced even more.

The results from this multi-disciplinary collaboration have helped Leiden University to acquire additional funding for investments in equipment for future research projects. Part of these investments will fund the development and implementation of improved vibration isolation solutions.

6 *Top view showing two hexagonal rings, one holding the pulse tube tripod and another holding the cryostat itself.*

7 *Improvement of vibration isolation performance.*
(a) Acceleration.
(b) Motion.

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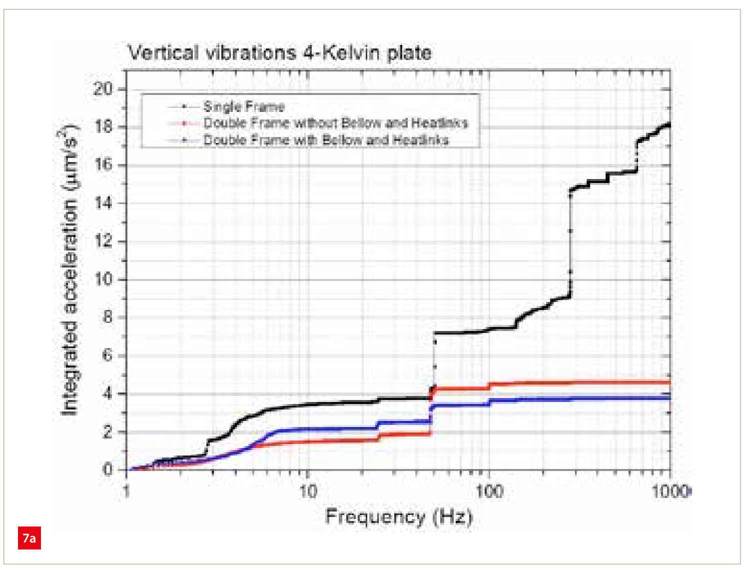

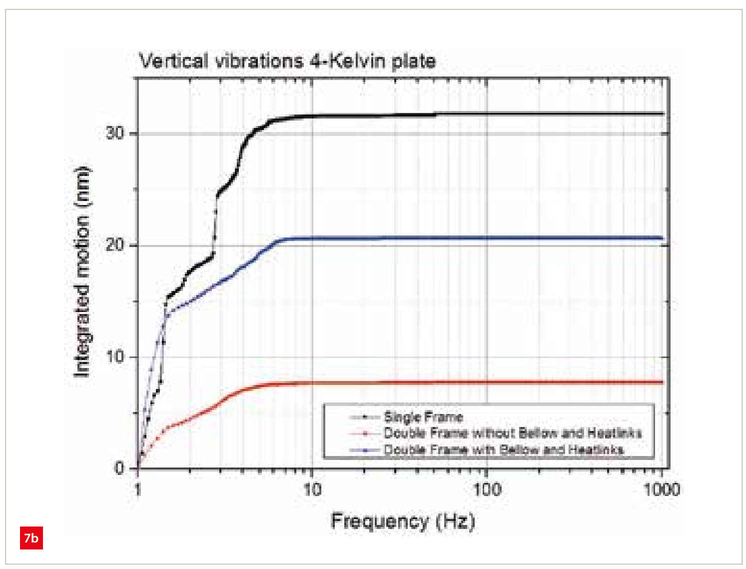

Ter Hoek takes the next step in precision engineering

This autumn, Ter Hoek Vonkerosie signed a partnership agreement with the German company PEMTec. From now on, Ter Hoek will be known as PEM Application Center (PAC) in the Benelux. In doing so, the company from Rijssen, the Netherlands, is taking the next step towards further specialisation in the field of precision engineering technologies. PEMTec is an internationally operating organisation that develops equipment for Precision Electro Chemical Machining (PECM). With the partnership, Ter Hoek becomes part of a select group of specialists that make this new, highly advanced technology available to manufacturers.

"The big advantage of this new technology is that it results in virtually no wear to tools", says Director Gerrit ter Hoek. "This means that we can manufacture large production series at exactly the same level of precision using a single tool. Components can be machined at a micron level, making very low tolerances and, therefore, extreme accuracy possible."

Over the past quarter of a century, Ter Hoek has developed into a specialist in the precision engineering industry, through such technologies as spark erosion and LaserMicroJet. The partnership with PEMTec is the next logical step for the firm. Ter Hoek makes test tools for PECM equipment, from which prototypes are developed. Once a product is ready for serial production, Ter Hoek also delivers the final tool. "In addition, as PAC, we have the know-how needed to support the client during every stage of development and in each choice of process. And we ourselves can also perform PECM for our clients, using our own PEM800 machine."

Technical specifications of the PEM800 include tool dimensions of 800 x 640 x 400 mm^3 and a tolerance of 2 µm and R_a of 0.03 µm for finished products.

WWW.TERHOEK.COM

The smallest parallel-kinematic piezo system from PI

The new P-616 NanoCube® from PI (Physik Instrumente) is extremely compact and offers identical dynamics, precision and velocity on all three motion axes with loads of up to 50 g. This makes it suitable, for example, for use in fibre alignment, microscopy or precision manufacturing. The dimensions of the P-616 are only 40 × 40 × 40 mm^3 and its mass is only 80 g. The travel range on all three spatial axes is 100 µm and the resolution is 0.3 nm, which is realised directly by using non-contact capacitive sensors.

The NanoCube features a parallel-kinematic design with three lever-amplified PICMA® actuators and friction-free flexures. The drive concept makes the compact form and the high stiffness of the system possible. PICMA actuators are also distinguished by a high lifetime under extreme ambient conditions.

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Zeiss and ASML strengthen partnership

ASML and Carl Zeiss SMT, a business group of Carl Zeiss AG, have agreed to strengthen their long-standing and successful partnership in the semiconductor lithography business, through ASML's acquisition of a 24.9% minority stake in Carl Zeiss SMT. The main objective of this agreement is to facilitate the development of the future generation of Extreme Ultraviolet (EUV) lithography systems due in the first few years of the next decade.
This technology will enable the semiconductor industry to produce microchips delivering much higher performance at lower costs.
The next generation of EUV optics will offer a higher numerical aperture (NA), making it possible to further reduce critical dimensions in the lithography process. The current EUV systems have an optical system with NA of 0.33 whereas the new optics will have NA larger than 0.5, enabling several generations of geometric chip scaling.

"High-NA is the logical next step for EUV, as it circumvents complex and expensive 0.33 NA EUV multiple patterning. High-NA EUV is a robust way for chips to scale all the way down to the sub-3 nanometer logic node in a single exposure with high productivity and reduced cost per feature. That is several generations from where we are today and underlines our commitment to propel Moore's law," said Martin van den Brink, President and CTO at ASML.

WWW.ASML.COM
WWW.ZEISS.COM

New initiative: Dutch Optics Centre

Dutch companies in the optical manufacturing industry can strengthen their position in the global market by joining forces in a consortium with research institutes and the government. Therefore, Delft University of Technology and TNO have launched the Dutch Optics Centre. Some 20 industrial SMEs engaged in the development and/or manufacturing of high-tech optical and optomechanical products and tools such as satellites, telescopes, microscopes and measuring instruments, are involved in the initiative, six of which are now also a partner in joint R & D projects. The city of Delft, the Province of South Holland and the Ministry of Economic Affairs support this initiative.

The centre will focus on developing and marketing – in small consortia – optical products for applications in aerospace, medical sector and semiconductor industry. For that purpose research and production facilities are shared and scientific talent is recruited and trained. In addition, the partners intend to start a joint research programme and joint promotion of the Dutch optical science and industry abroad.

Detail of the Gaia BAM space interferometer; also read the article on page 28 ff. (Photo: TNO/Fred Kamphues)

WWW.DUTCHOPTICSCENTRE.COM

GE acquires Concept Laser

GE has reached an agreement to acquire a 75% stake in Concept Laser GmbH. The agreement allows for GE to take full ownership in a number of years. Privately-held Concept Laser has more than 200 employees and is headquartered in Lichtenfels, Germany, with significant operations in the United States (Grapevine, Texas), China, and a global network of more than 35 distributors and agents. Concept Laser is a pioneer in the field of metal additive manufacturing.
Earlier this year, the attempted takeover of SLM Solutions Group, another German supplier of additive manufacturing equipment, by GE failed.

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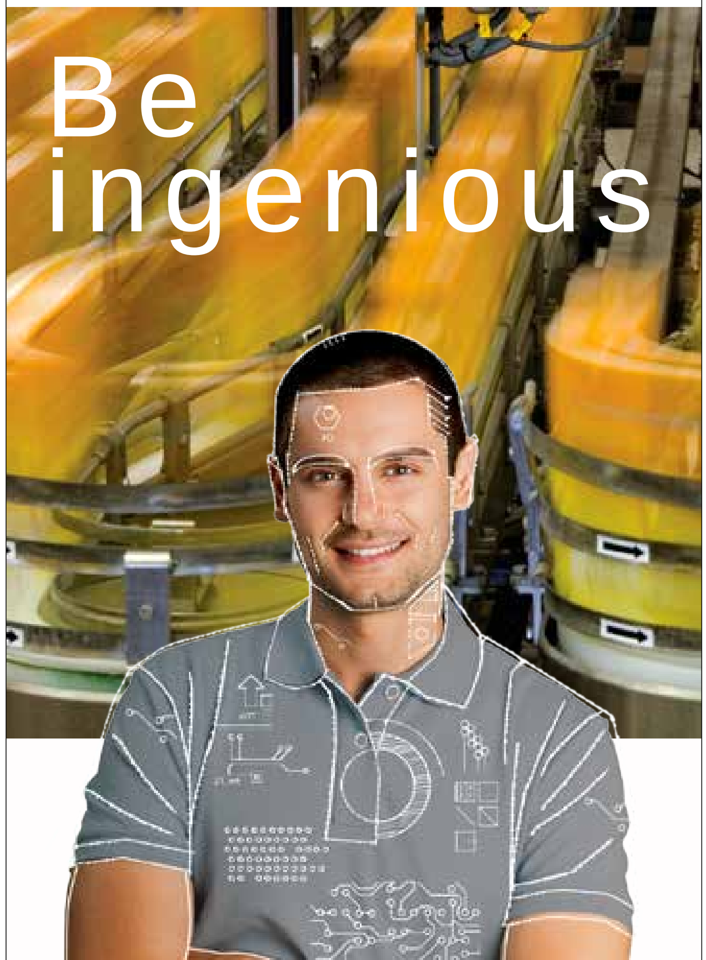

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Mechatronics System Design - part 2 (MA)	5	HTI	3 April 2017
Design Principles	3	MC	8 March 2017
System Architecting (Sioux)	5	HTI	3 April 2017
Design Principles Basic (SSvA)	5	HTI	to be planned (Spring 2017)
Motion Control Tuning (MA)	6	HTI	15 November 2017
ADVANCED			
Metrology and Calibration of Mechatronic Systems (MA)	3	HTI	7 November 2017
Actuation and Power Electronics (MA)	3	HTI	-
Thermal Effects in Mechatronic Systems (MA)	3	HTI	to be planned (September 2017)
Summer school Opto-Mechatronics (DSPE/MA)	5	HTI	-
Dynamics and Modelling (MA)	3	HTI	to be planned
Summer School Manufacturability	5	LiS	to be planned
Green Belt Design for Six Sigma	4	HI	22 February 2017 19 April 2017 (Enschede, NL)
RF1 Life Data Analysis and Reliability Testing	3	HI	6 March 2017
SPECIFIC			
Applied Optics (T2Prof)	6.5	HTI	23 February 2017
Applied Optics	6.5	MC	2 February 2017
Machine Vision for Mechatronic Systems (MA)	2	HTI	11 October 2017
Electronics for Non-Electronic Engineers – Basics Electricity and Analog Electronics (T2Prof)	6	HTI	9 October 2017
Electronics for Non-Electronic Engineers – Basics Digital Electronics (T2Prof)	4	HTI	6 February 2017
Modern Optics for Optical Designers (T2Prof)	10	HTI	19 January 2018
Tribology	4	MC	14 March 2017 31 October 2017 (Utrecht, NL)
Design Principles for Ultra Clean Vacuum Applications (SSvA)	4	HTI	to be planned (Spring 2017)
Experimental Techniques in Mechatronics (MA)	3	HTI	2 May 2017
Advanced Motion Control (MA)	5	HTI	6 November 2017
Advanced Feedforward Control (MA)	2	HTI	on request
Advanced Mechatronic System Design (MA)	6	HTI	to be planned (Spring 2017)
Finite Element Method	5	ENG	in-company only
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Precision Engineering Industrial Short Course	5	CRANF. UNI.	to be planned (Cranfield, UK)

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Publication dates 2017

nr.:	deadline:	publication:	theme (with reservation):
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2.	24-03-2017	28-04-2017	Robotics
3.	26-05-2017	30-06-2017	Flexures / mechanisms
4.	04-08-2017	08-09-2017	Optomechatronics
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