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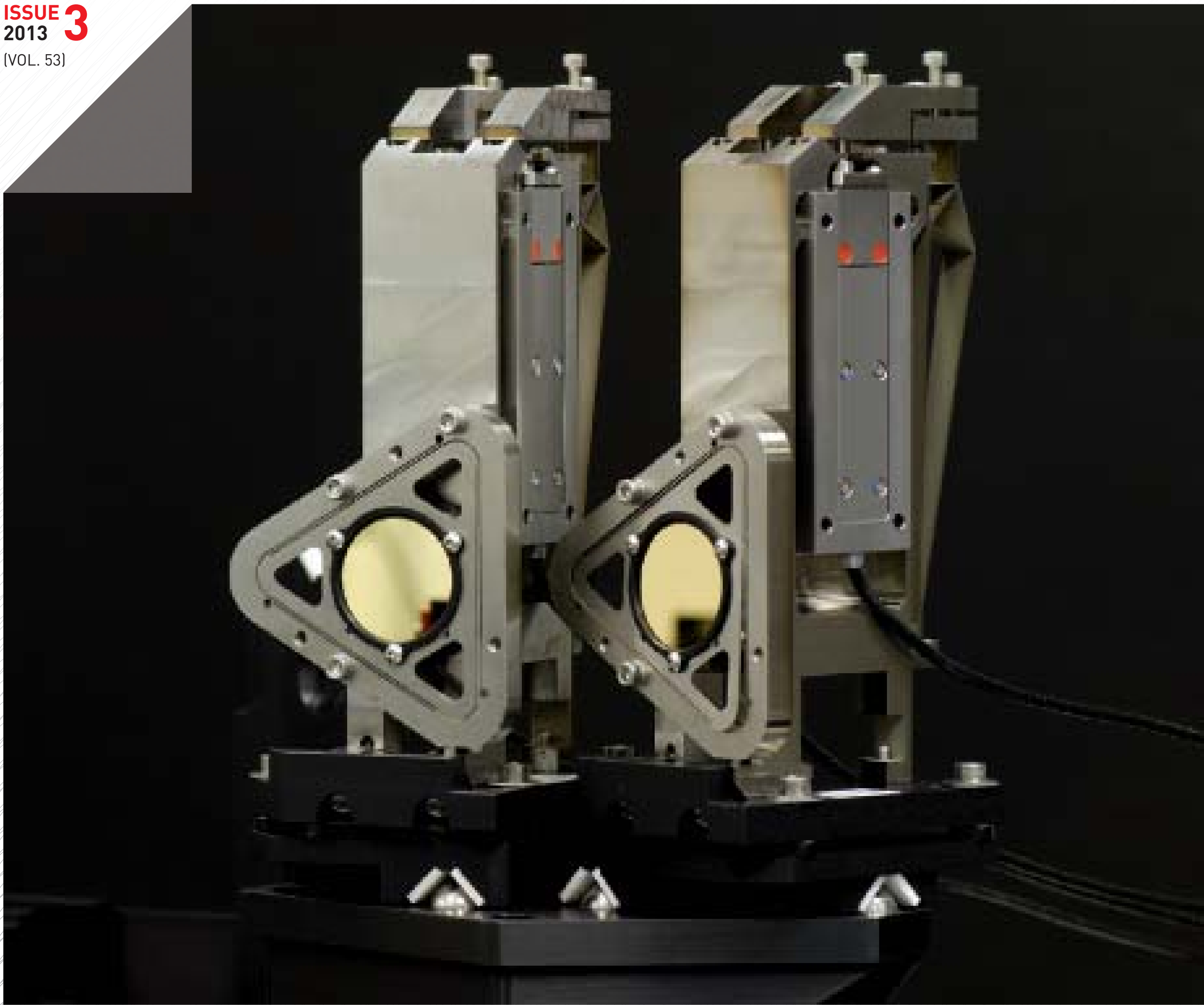
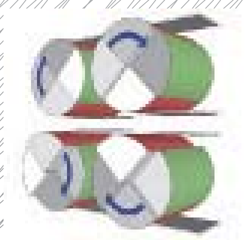


- **STAR SEPARATORS** FOR THE VLTI
- **ACTIVE** VIBRATION ISOLATION
- FAST **FREEFORM** PROCESSING
- **GENERIC SUBSTRATE CARRIER** DESIGN



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The main cover photo (Field Selector mechanisms for ESO's Unit Telescope Star Separator) is courtesy of Fred Kamphues/ TNO.

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FEATURES

SPECIAL INTEREST GROUP **OPTICS & OPTO-MECHATRONICS**

DSPE is an association that seeks to promote precision technology by connecting people and companies. So what do optics and opto-mechatronics have to do with DSPE? Everything, they're inseparable. Because specialists in research and industry are capable of creating increasingly complex and precise optical elements. Dimensions increase while retaining high levels of precision in terms of form and surface roughness. As a result, increasingly better optical systems can be developed. Good opto-mechatronics and precision mechanics are essential for this. After all, for an optical element to work, you always need a mounting to hold that element. Glasses need a frame to keep the lenses in front of your eyes…

A good example of the full integration of precision mechatronics in an optical element is the wafer stages manufactured by ASML, the global market leader in lithography machines, which is based in Veldhoven, the Netherlands. The mechanical interfaces are integrated into the optics. The top of the stage consists of a thick plate of glass-ceramics (Zerodur), all sides of which are polished and coated so that they can act as mirrors for the interferometers which ensure the precise positioning. The top of the stage also has recesses in the glass-ceramics in which optical sensors are placed. Given that everything is executed in a single block, very narrow tolerances can be achieved from the mirrors to the sensors.
Diamond turning technology makes it possible to turn precise mirrors from aluminium and copper. Mounting interfaces such as screw thread can be fitted straight onto the optical element. Depending on the precision of the optical system to be achieved, the latest cutting-edge mechanics or precision mechanics are required. These mechanics must ensure that the optics continue to work, often under the most extreme conditions. For instance, optics in satellites are exposed to major fluctuations in temperature. The mechanics must be executed in such a way that the optics do not warp because of thermal expansion or shrinkage. Furthermore, the optics and the mounting must be able to withstand large accelerations when the satellite is launched by rocket.

Precision mechanics is required to manufacture optical elements and for fixing them and adjusting their settings. This is how optics and mechanics come together, which is why DSPE has taken the initiative to provide a platform for optical and opto-mechatronical technology by connecting people and companies. The High-Tech Systems event in Eindhoven marked the launch of the DSPE Special Interest Group Optics & Opto-Mechatronics. DSPE wants to organise its first conference in this field in September/ October 2013 – optical companies in the Netherlands and Europe will be updated.
At DSPE, I'm the person behind this initiative. I've worked at ASML for 23 years, and during that time I've developed the opto-mechanics for a range of optical measuring systems. Such development projects are always carried out by multidisciplinary project teams, in which the mechanical engineer works directly with the optical engineer who came up with the optical concept. Together, they develop a sensor that works both optically and mechanically. We want to foster that collaboration with the new Special Interest Group.

Cor Ottens
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INCREASING SENSITIVITY FOR DISTANT PLANETS AND SUPERMASSIVE BLACK HOLES

Dutch research institute TNO has provided ESO (European Southern Observatory) with a series of so-called Star Separators. These sophisticated optical and mechanical systems will make ESO's Very Large Telescope Interferometer (VLTI) 200 times more sensitive. This will allow the VLTI to explore the material around supermassive black holes at the centre of the Milky Way and also in other galaxies. It also offers the potential to study giant planets around nearby stars.

JAN NIJENHUIS AND FRED KAMPHUES

The Very Large Telescope array (VLT) is operated by the European Southern Observatory (ESO) and is located on Cerro Paranal in a remote region of the Atacama desert in Chile; see Figure 1. The VLT is the world's most advanced optical astronomical observatory, consisting of four Unit Telescopes with main mirrors of 8.2m diameter and four movable 1.8m diameter Auxiliary Telescopes. The telescopes can work together, to form a giant interferometer, the Very Large Telescope Interferometer (VLTI).
In interferometer mode astronomers can see details up to 25 times finer than with the individual telescopes. The light beams are combined in the VLTI using a complex system of mirrors in underground tunnels where the light paths must be kept equal within a few nanometers over hundreds of meters. With this kind of precision the VLTI can reconstruct images with an angular resolution of milliarcseconds, equivalent to distinguishing the two headlights of a car at the distance of the moon.

But a further improvement is planned. ESO has recently taken delivery of the last of a series of sophisticated optical and mechanical systems called Star Separators. These systems from the Dutch research institute TNO will allow the VLTI's future instruments to observe even much fainter objects than currently possible.

AUTHORS' NOTE

Jan Nijenhuis is senior project manager/system engineer at TNO Mechatronics Equipment, and Fred Kamphues is a project manager and AIT (Assembly, Integration & Test) manager and owner of Millhouse Consultancy.

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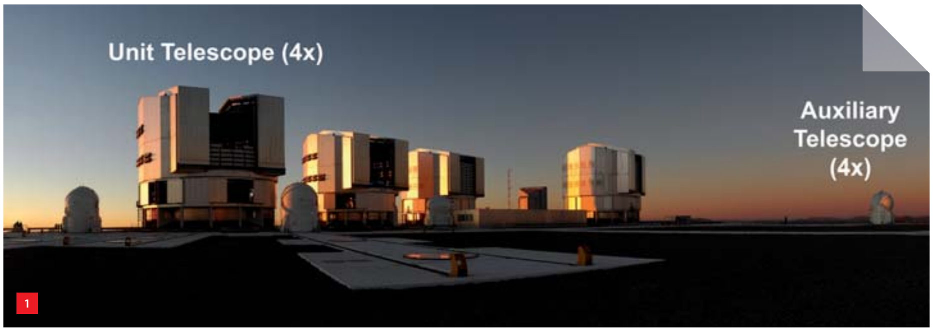
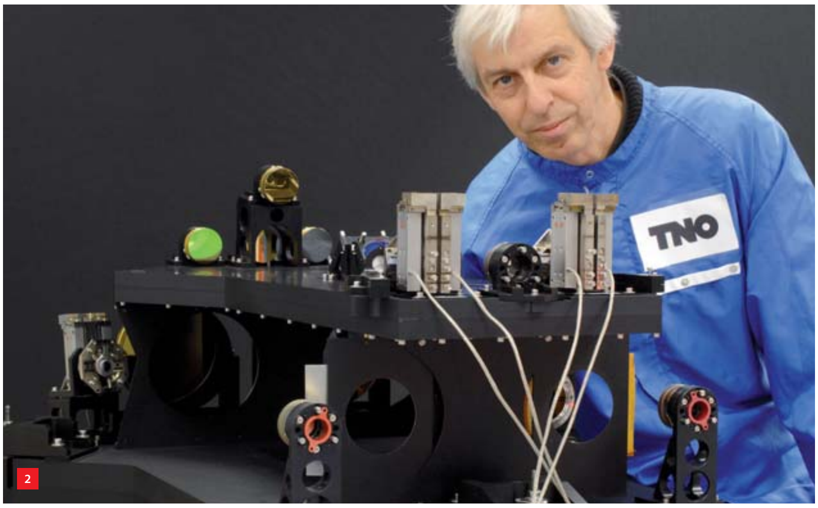


1 *The ESO Very Large Telescope array in Chile. (Photo: ESO/Fred Kamphues)*



2 *Star Separator for the VLTI Auxiliary Telescopes.*
3 *Principle of operation of the Star Separator.*

Thanks to this development the VLTI will become two hundred times more sensitive. This will allow the VLTI to explore the material around supermassive black holes at the centre of the Milky Way and also in other galaxies. It also offers the potential to study giant planets around nearby stars and measure the positions of objects to far higher accuracy than is possible at present.
TNO has worked in close cooperation with ESO for almost a decade and has delivered four Auxiliary Telescope (AT) and four Unit Telescope (UT) Star Separators.

Functional description

Light coming from the telescopes is combined using constructive interference, which can be obtained for telescope viewing angles of up to Ø 120”. However, the field of view of the interferometer (Coude focal plane) is only Ø 2” (on sky for UT). Hence, much of the individual telescope capabilities would remain unused. Furthermore, within the Ø 2” a bright star must be present as a reference, so the VLTI can correct for the constantly changing atmospheric conditions by use of adaptive optics. Often this bright star is not present, resulting in a considerable portion of the hemisphere that cannot be observed with the VLTI. Therefore, the Star Separator (STS) must enable the simultaneous observation of two objects that are separated by as much as 120”.

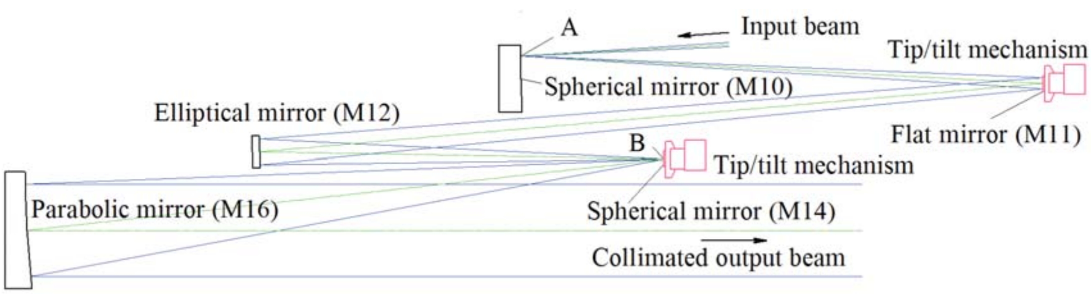
The main requirements for the Star Separators are:

- Simultaneous observation of two objects in the Coude focal plane sized Ø 2” (on sky)
  The objects are located within 0-120” (on sky) of each other. One of the objects should be bright enough to enable interferometry.
- Pointing and tracking of stars
  The Star Separator must compensate for the Earth’s movement with an accuracy 0.01” and 0.002” resolution (for the STS-UT only; for the STS-AT this is realised with a separate de-rotator).
- Chopping on a star
  Pointing at an object and its dark background with 1-5 Hz frequency provides the option to subtract the background from the object. This greatly enhances the signal-to-noise ratio.
- Tip-tilt control
  The output should be controlled in tip-tilt to align it with the delay lines and subsequently the detectors.
- Pupil alignment
  The output pupil must be carefully aligned with the input pupil, to avoid vignetting and to ensure a proper overlap for the metrology system.

Due to the fact that there are two rather different telescopes, also two different mechanical solutions for the Star Separator had to be developed. Both types of Star Separator are identical from an optical point of view.

Optical principle

Figure 3 shows the principle of operation of the Star Separator. The spherical mirror (M10) coincides with the Coude focal plane, meaning that the hemisphere is reimaged on this mirror by the telescope. This image rotates around the optical axis as result of the earth rotation (a so-called de-rotator in front of the STS for the AT compensates for this rotation and creates a stationary image). The mirror size corresponds to Ø 120” field of view of the telescope.



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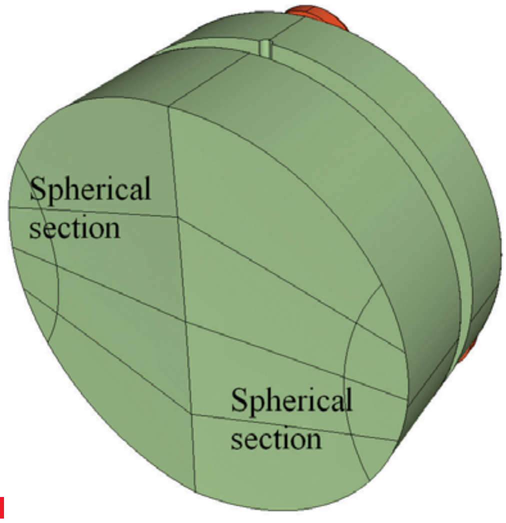

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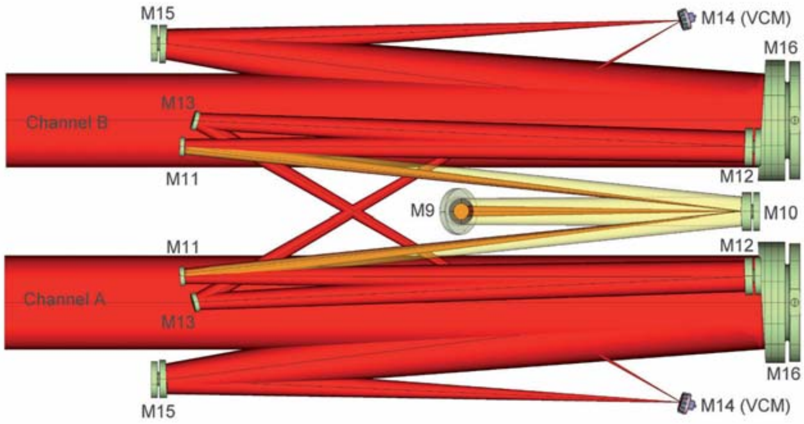

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4 *M10 rooftop mirror.*
5 *Optical lay-out for the STS-AT.*

A small portion of this image (Ø 2”) is reimaged by the M12 elliptical mirror (for the AT this is a toroid mirror) on another spherical mirror (A is reimaged on B). The latter coincides with the focal plane of the parabolic mirror, hence the image is transferred as a set of parallel beams to the output pupil of the STS. All parallel beams have a common circular intersection at that point.
The axial position of the output pupil is determined by the radius of the spherical mirror that is mounted on top of a tip/tilt mechanism. Rotation of this mirror around its vertex allows adjustment of the lateral position of the output pupil.

The radius of curvature of mirror A is such that the telescope pupil (conjugated plane of telescope primary mirror) is reimaged on the flat mirror M11 (intermediate pupil location). The radius of curvature of mirror B is variable for the AT, because the required axial position of the output pupil relative to the STS varies (the AT has no fixed position on the platform while the location of the output pupil is fixed). For the UT fixed-curvature mirrors are used.

The STS has to provide two output beams. This is done by copying the optical system of Figure 3. The input spherical mirror (M10) then becomes a rooftop mirror (Figure 4) with two spherical sections. The image on M10 of the hemisphere is split in two sections this way. One will contain the guide star, while the other section will contain the scientific object.

The mechanical limitations of the STS environment necessitate the introduction of additional folding mirrors to reduce the size of the STS (Figure 5). This is particularly true for the AT, where only a cylinder of Ø 1 m is available to house the STS (Figure 6). Here also a hyperbolic mirror had to be introduced just before the parabolic mirror, because the focal distance of the latter is > 1 m.

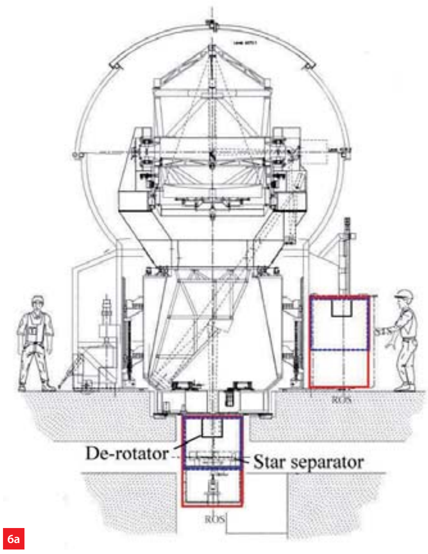
Mechanical features of the STS-AT

The structure and mirrors of the STS are made of the same aluminum alloy to minimise its sensitivity for temperature changes. An aluminum structure quickly adapts to the environmental temperature, which is important at the beginning of the night when temperature drops quickly.

The scientific object and the guide star can be imaged on the individual sections of M10 by use of the de-rotator. The tip/tilt mechanism that operates the M11 folding mirror determines which Ø 2” section of M10 is reimaged on the detector. The chopping function of the STS is also provided by this mechanism. The technical requirements are summarised in Table 1.

The mechanism is shown in Figure 7. Clearly visible are the two monolithic parts. The guidance mechanism part provides the tip/tilt function of the mirror around its vertex. The other part provides the gearing between the piezo actuators and the actuating struts for the guiding mechanism. The piezo provides a maximum stroke of 38 μm with a repeatability of 3 nm and a resolution of 2 Å. These performances are possible because of the capacitive sensor that is built into the piezo actuator. The equivalent mirror rotations are: 16 mrad, 1.3 μrad and 0.08 μrad. This is better than the required values as given in Table 1.

The combination of a standard piezo stage from PI and hysteresis/friction-free mechanisms enables control of the mirror position without the need for optical feedback control on the mirror position. This reduced the cost of the



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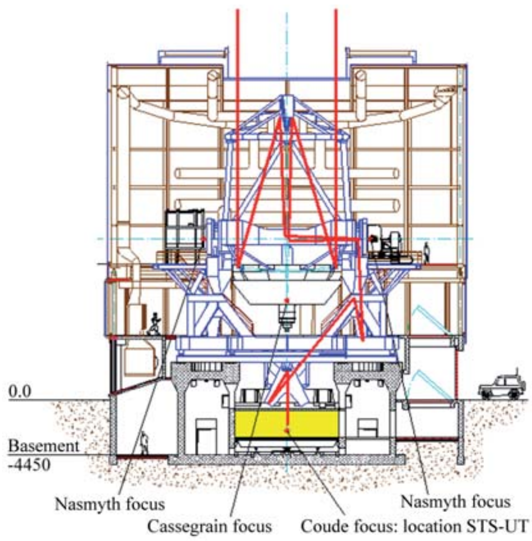

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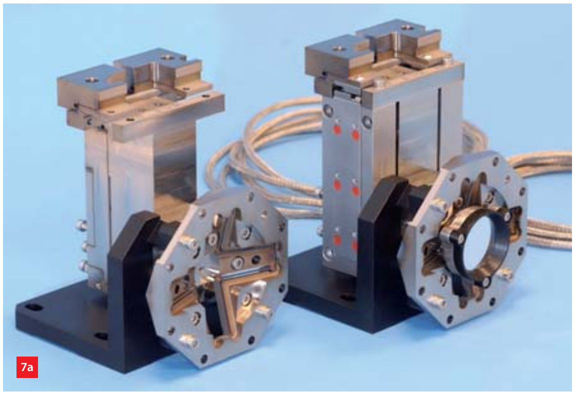

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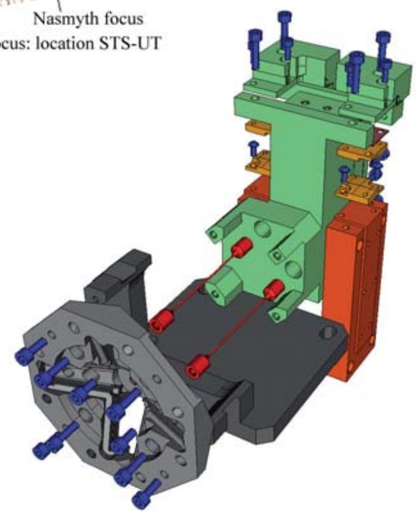

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6 *Telescope cross-section with location of Star Separator indicated.*
(a) Auxiliary Telescope (AT). (Courtesy of ESO/AMOS)
(b) Unit Telescope (UT). (Courtesy of ESO)

7 *M11 mechanisms for the AT Star Separator.*
(a) Realisation.
(b) Schematic.

mechanism at the time of the development of the STS-AT (2003) considerably.

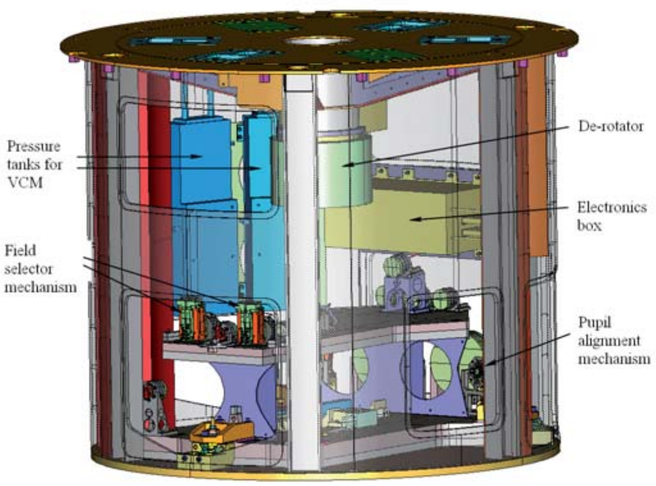
Each STS-AT is equipped with four of these mechanisms. Two are used to provide the Field Selector function (M11 rotation), while the other two are used to provide the control of the lateral output pupil position (M14 rotation). The M14 mirror is actually a Variable Curvature Mirror (VCM). This mirror has been developed by ESO and consists of a thin membrane mirror with pressure chamber. Changing the pressure changes the mirror curvature. An overview of the assembled Star Separator and the Upper Relay Optics Structure (UROS) is given in Figure 8.

To verify the performance of the mechanism, it was mounted on a flat table with a fixed autocollimator in front of it. The resolution of this collimator is 0.1 µrad with an accuracy of 0.5 µrad. The chopping features of the mechanism were tested as well. Chopping at 5 Hz proved to be no problem. Even faster actuation is possible. For pointing correction during observations ESO would like to correct at 50 Hz. The limit of the mechanism is > 100 Hz.

Each STS-AT is equipped with 19 mirrors in total; 16 are mounted using a kinematic mount with its thermal center coinciding with the optical axis. This was done to enable that these mirrors could be dismounted and remounted without affecting the alignment. The other mirrors are mounted in a different way but with identical qualities on (re)mounting.

Table 1 *M11 mechanism requirements.*

Requirement	Required value
Pointing range	14.6 mrad (both axes) ≈ 1°
Pointing accuracy	2.1 µrad
Pointing resolution	0.43 µrad
Pointing correction frequency	50 Hz
Chopping frequency	1 Hz (5 Hz goal)
Chopping accuracy	94 µrad



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The structure and the mirrors are transported in separate boxes to provide optimal transport safety.
All mirror brackets are mounted on two parallel platforms. These platforms consist of two hollow sections that are bolted together to keep mass down and stiffness as high as possible.

Mechanical features of the STS-UT

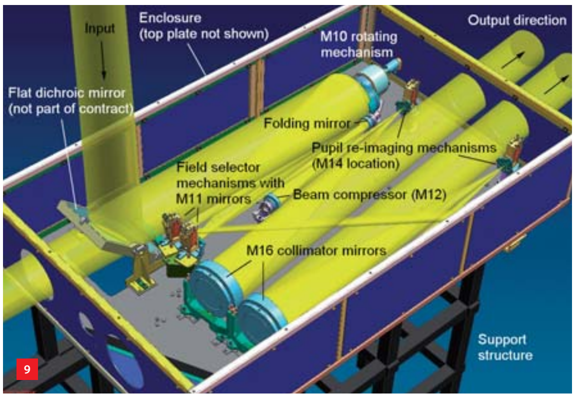
The UT Star Separator works along the same principle as the STS-AT, but has its own de-rotator mechanism (on M10) and a Field Selector (FS) mechanism with extended travel; see Figure 9. The available space is considerably larger compared to the STS-AT (Ø 8 m versus Ø 1 m). However, the required optical components are also bigger, because of the much bigger size of the UT. The available space allowed mounting all optical components on one level. An aluminum honeycomb plate is used for this. This plate was specially designed and manufactured by Airborne International in the Netherlands. The particular optical lay-out of the UT does not allow realising a symmetric Star Separator. Both output beams are located on the same side of the input beam.

FS mechanism

The Field Selector mechanisms (Figure 10) of the STS-UT are very similar to that of the STS-AT. However, based on the experiences with these mechanisms they have been considerably improved; see Table 2. This was necessary to realise much larger mirror rotation angles. Manufacturing has also much improved because of the identical actuator lever design for both rotation axes. All parts are made from a titanium alloy (Ti6Al4V), because this material provides the best elastic performance.
Further enhancements of the STS-UT mechanism relative to the STS-AT version are:

- Both rotation axes of the mirror coincide with the mirror surface, hence no OPD (optical path difference) effects.
- The actuating direction of the actuator lever has reversed. Instead of pushing, the lever is pulling on the actuator struts.
- A tension spring provides a 5N hysteresis-free preload on the piezo.
- The adjustments of the mechanism are simplified.

The actuator levers to which the struts are connected, have been lightweighted as much as possible. This is for dynamic reasons. The gear ratio obtained through these levers is 11. The other levers provide a gear ratio of 5, giving a total gear ratio of 55. These upper levers have been split in two sections allowing to adjust the angular position of the mirror for a given piezo position. The piezo pushes against the lever. To make sure that contact between the piezo and the lever is never lost, a small preload spring is added. The FS actuators are equipped with magnetic dampers to avoid internal resonances; see Figure 11. The realisation is shown in Figure 12.



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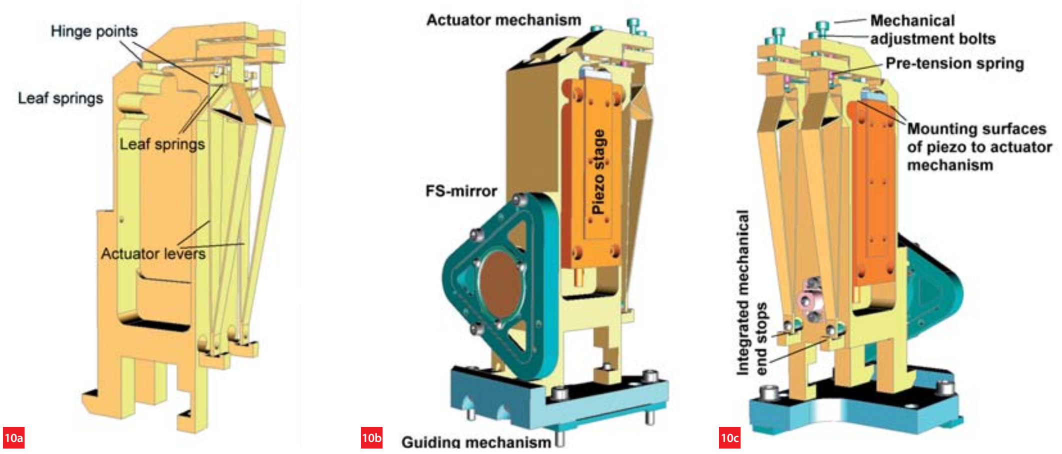
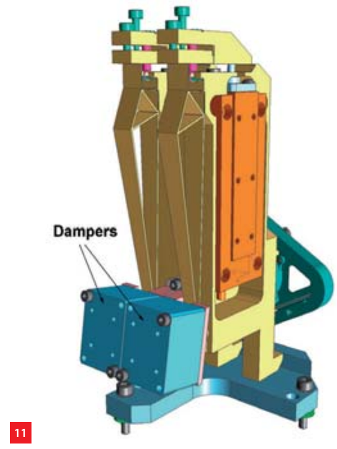
8 *The Upper Relay Optics Structure (UROS) with integrated STS-AT.*
(a) Schematic (sideview).
(b) Realisation.
9 *The UT Star Separator.*





The dynamic performance of the mechanisms has not changed. This means that chopping the mirror at 50 Hz is still possible. Please note that the gear ratio of 55 between piezo actuator and mirror causes that 7 g of moving mass is felt by the piezo as being 21 kg when operating the mirror.

M10 pointing and tracking mechanism

Contrary to the situation with the STS-UT, no de-rotator is present in the STS-UT. That means that the reimaged hemisphere on M10 rotates slowly as result of the earth rotation. The guide star and scientific object will exchange position in time on the M10 mirror sections as a result of that (Figure 13). This will interrupt the scientific observation. It actually means that the two spherical mirror sections should follow their part of the reimaged hemisphere while maintaining their rooftop configuration. The distance between the two centres of curvature is determined by *R* and *α*. The gap between the two must be minimised to allow minimal distance between guide star and scientific object. For proper optical functioning the two mirrors should maintain their centres of curvature and their point of ‘contact’. Hence mirrors A and B should rotate around axes defined by their centres of curvature and the point of contact between the two mirrors. Rotating the mirrors will not cause a change in optical configuration, because the mirror surface will always be a subsection of the same sphere.

10 *STS-UT Field Selector mechanism.*
(a) Schematic.
(b) Front view.
(c) Rear view.
11 *STS-UT scan mirrors with magnetic dampers.*
12 *Realised STS-UT Field Selector mechanisms.*

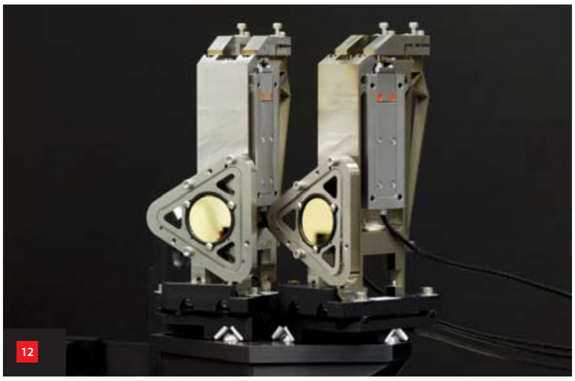


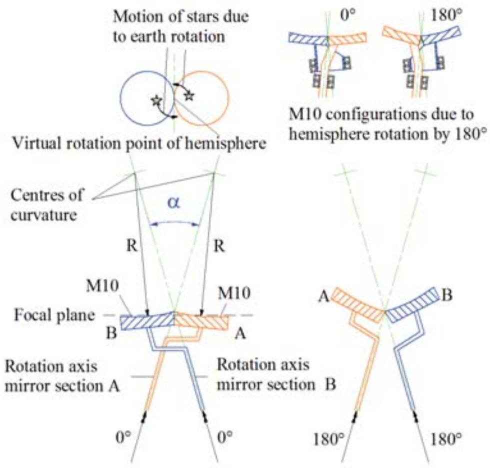
Table 2 *Comparison between mechanisms for AT and UT.*

Characteristic	STS-AT	STS-UT
Mirror rotation angle	16 mrad	129 mrad
Rotational stiffness in plane of mirror		90x smaller
Thickness of struts	Ø 0.8 mm	Ø 0.4 mm
Moment of inertia of mirror assembly		6x smaller
Moving mass of actuator lever	42 g	7 g
Stiffness of actuator lever		5x smaller

Both mirror sections have to rotate at equal speed to avoid a collision between the mirrors. Rotating the mirrors will cause relative motions as shown in Figure 13. Another reason to minimise the gap between the mirrors is to allow one star to be imaged by the telescope on the intersection of the two mirrors for calibration reasons.
The rotation function is provided by an ultrasonic (acoustic wave) motor because it is self-locking and has no backlash. The actual mechanism is shown in Figure 14.

Other important features of the mechanism are:
- The gap between the two mirrors will be about 30 μm. About 10 μm is used for the actual gap, while the mirror edge’s radii are limited to 10 μm.
- Protective ring sections are fitted around the mirrors for safety reasons. The mirror is razor sharp at the edge.
- The mirrors are mounted on a kinematic mount and held in position with bayonet-type pins. This is of particular importance for transport reasons. The mirror can now be packed separately without the need for re-alignment when the instrument is assembled at Cerro Paranal.

The fully assembled UT Star Separator is shown in Figure 15.



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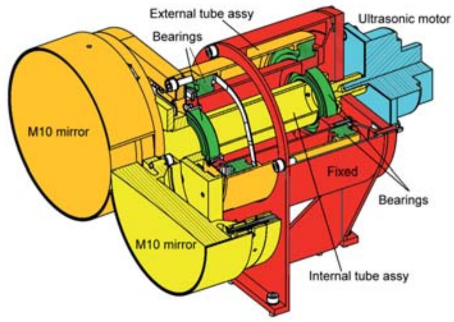

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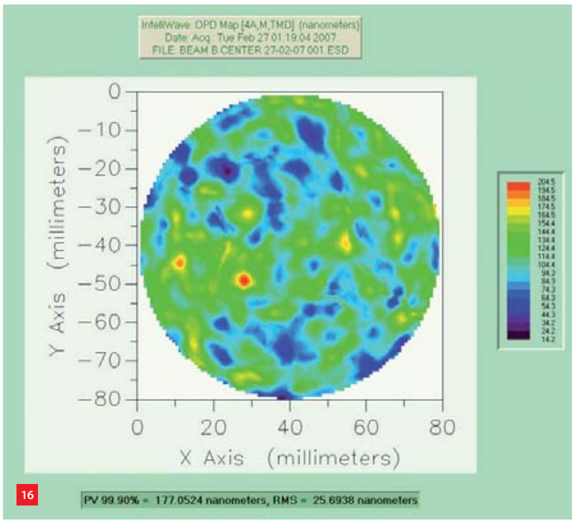
13 *Principle of operation of M10 mechanism.*
14 *UT M10 pointing and tracking mechanism.*
15 *STS-UT with M10 pointing and tracking mechanism in foreground.*
16 *WFE of Beam B of AT Star Separator #2.*



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Conclusions

TNO has successfully developed the Star Separator subsystems for the AT and UT telescopes. The Star Separators meet or surpass the requirements (Table 3). It has been demonstrated that elastic mechanisms can operate very predictably and that there is no need for control feedback on such mechanisms. Reproducibility of mirror mounting has also been demonstrated. Isostatic mirror mounts ensure precise and repeatable positioning at submicron level.

The measured Wave Front Error (WFE) of the Star Separators ranges from 25 to 30 nm rms (Figure 16). The required value is 35 nm rms. This performance is independent of the environmental temperature due to the athermal design of the STS.

The sharp edge of the M10 mirrors gives a much better split of the optical beam than predicted, with also much less stray light than expected. OPD stability is around 9 nm rms for all UT Star Separators and even less for the AT Star Separators. Four AT and four UT Star Separators have been delivered to ESO for integration in the VLTI facility at Cerro Paranal.

Acknowledgement

The work reported in this article was conducted at TNO under a contract with ESO in Garching (Germany). The authors would like to thank Frederic Derie and Francoise Delplancke at ESO, for their input during the design and development of the Star Separator subsystems. TNO also wishes to thank their subcontractors Airborne, Axsys (mirrors), Brandt, FMI, Gimex, Instrumek, Jagema, KMWE, MPP, PI, Vacutech and West End for their excellent contributions. ■

Table 3 *Star Separator performance.*

Requirement	Required value (on sky)	Obtained value (on sky)
Pointing range	120″	149″ (vertical) 130″ (horizontal)
Pointing accuracy	±0.01″	±0.01″
Pointing resolution	±0.002″	±0.002″
Pointing correction frequency	50 Hz	100 Hz
Chopping frequency	1 Hz (5 Hz goal)	63 Hz
Chopping accuracy	±0.44″	±0.01″

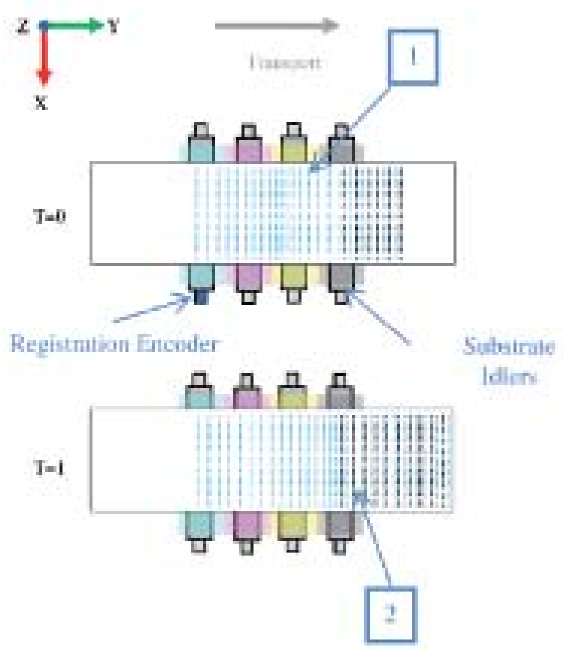
IMPROVED INK REGISTRATION THROUGH ADVANCED STEEL BELT STEERING

In single-pass digital printing, requirements for the relative registration accuracy may exceed 10 micrometers over a distance of more than a meter. In order to eliminate the mechanical (e.g. elasticity) properties of the substrate, CCM introduced a steel belt conveyor using vacuum technology for substrate clamping. Actuated Axially Movable Segmented Rolls (AMSRs) allow continuous control of the two surface orientations (X, Rz), without deformation of the belt. A demonstrator was built to validate the actuated AMSR technology.

AREND-JAN BELTMAN, RONALD PLAK, JOHN HAZENBERG, ROB PULLES, BERT BRALS AND GERT VAN OOIK

Manufacturing equipment for single-pass digital printing faces an interesting challenge to deal with the growing productivity demand in combination with rising droplet registration accuracy. Although the administration speed of print heads is still increasing, high-throughput speeds and/or increased print resolution can only be achieved by using multiple heads in series. Given at least four different inks, the distance between the first and last print head can become more than a meter. If the relative registration accuracy over such a distance has to be below 10 micrometers, an intense fusion of multiple engineering disciplines becomes essential.

With the continuous improvement of the print head's jetting accuracy, registration deviations of subsequent droplets from independent heads must also become smaller. CCM is well acquainted with the mechatronic challenges that are encountered during the development of inkjet printing equipment for customers. It became clear that a generic solution for accurate transport of substrates is mandatory to reach the next level of jetting quality. 1



1 *Drop alignment artefacts due to substrate transport; registration error after substrate tension variation (1) results in 'banding' (2).*

AUTHORS' NOTE

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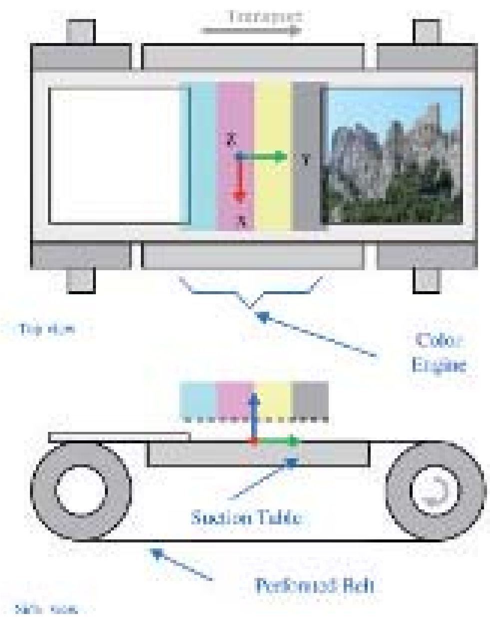

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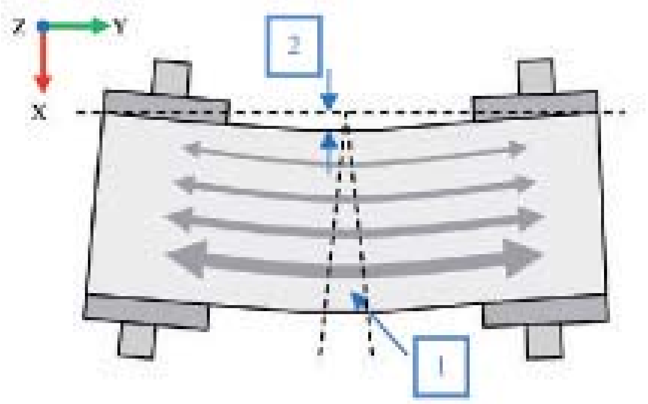

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2 *Conveyor belt transport concept, also showing the applicable coordinate system.*
3 *Conventional steering mechanisms introduce both stretch of the belt (1) and deflection in the printing area (2).*

For applications with a fixed array of print heads there is a distance between independently generated droplets. In conventional systems, the substrate is manipulated directly along the print heads, as illustrated in Figure 1.
During transport from the 'first' droplet location to the 'last' adjacent droplet location, the combination of limited substrate stiffness and all kinds of forces will introduce lateral and longitudinal (illustrated in Figure 1) disturbances in colour registration. In other words, when the substrate can move freely, exceptional precautions regarding substrate steering and driving should be taken, although in many cases the results are still unsatisfactory.

Approach

Prior to finding an improvement for colour registration, different 'target' materials for printing have to be inventoried. These could include sheet-to-sheet transport of paper, cardboard, plastic, MDF and other semi-rigid materials. For roll-to-roll applications, paper, plastic and other non-rigid materials have to be looked at.
A commercially available conveyor system with a suction area right below the colour engine (that is, the subsequent series of colour bars, each holding multiple print heads), as illustrated in Figure 2, seems an obvious (cost-effective) concept for carrying the list of substrate types given above.

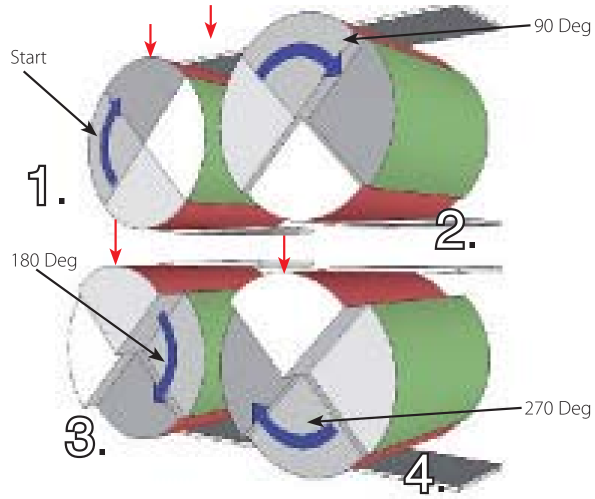
Based on CCM experiences and measurements, the motion accuracy of a mandatory transport concept should meet a planar accuracy of less than 10 μm over a length of 1 m at a transport speed up to 2.5 m/s. That is why the high Young's modulus value of inert and easily cleanable stainless steel made this material attractive as a carrier.

Conventional conveyor systems

Due to the high material stiffness, steel belt conveyors have excellent motion accuracy properties in the transport direction (Y). However, achieving high motion accuracy in the lateral direction (X) proved to be the greatest challenge in steel belt transport. CCM had already done research in belt steering systems [1] before becoming involved in inkjet equipment development. This research showed that geometric imperfections of a belt or its rollers cause internal stresses in a conveyor belt. Partly due to these internal stresses, the belt will move in the lateral direction when transported. Eventually it will run off its transport rolls. Therefore, a steering mechanism is mandatory. Currently available steering systems introduce lateral translation in the printing area, as illustrated in Figure 3. Furthermore, conventional steering concepts introduce stresses in the belt that cause longitudinal deviations.

Axially Movable Segmented Roll

In [1] it is explained that an infinite belt motion will introduce infinite (lateral) belt translation. In order to compensate for this effect, the rolls in Figure 4 are deliberately cut into segments. Each segment can move independently in a lateral (X) direction by means of mechanical guides. By introducing these Axially Movable Segments (AMS), the existing infinite lateral motion will be chopped into steps per active segment – active means that



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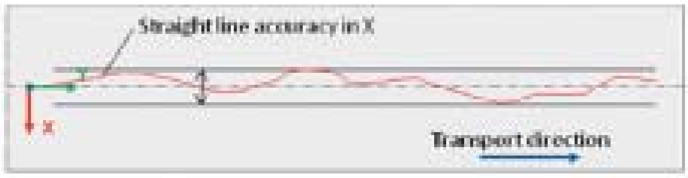

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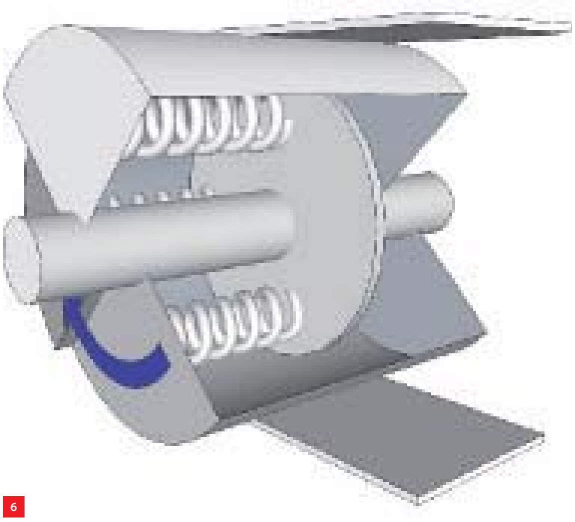

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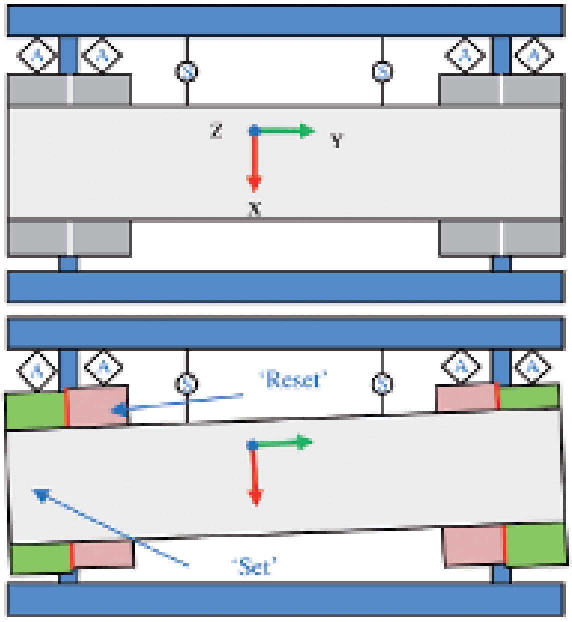

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4 Axially Movable Segments during rotation.
5 Definition of straight-line accuracy.
6 Visualisation of AMS guiding stiffness.
7 Preferred actuation concept: using actuators (A) the belt can be controlled in Rz and X. Measurement through (S).

the segment is physically in contact with the steel belt. In Figure 4, this principle is visualised in four steps of rotation, starting with an inactive roll.

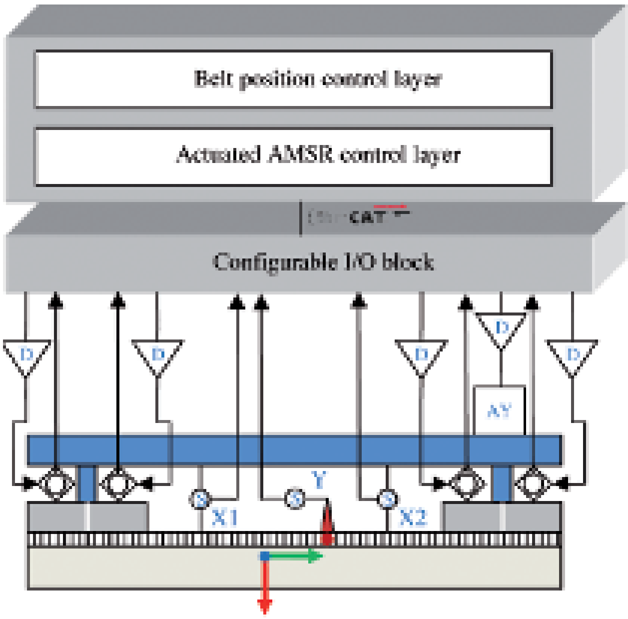
The sole introduction of an Axially Movable Segmented Roll (AMSR) can prevent undesired belt behaviour as illustrated in Figure 3. However, it does not improve belt straightness performance, defined in Figure 5. The guide for the axial motion of the segment has a relevant stiffness, see Figure 6. During the active part of the rotation, this spring is tensioned by the segment movement. At the location marked with a red arrow in Figure 4, this tension disappears almost instantaneously when the segments become inactive. The energy stored in the spring is suddenly released. Integral axial stiffness of the remaining active segments will be preloaded at once, thus introducing undesired lateral vibrations.

Actuated AMSR

As in other motion control systems, direct measurement and actuation of the belt edge in the printing area is preferred, since it allows continuous control of the belt position and subsequently the substrate position. Figure 7 illustrates how relevant degrees of freedom can be controlled without indirect relations with transport velocity.

When an actuator system for the 'set' (green) segment is introduced, accurate control of the belt position is possible. An additional actuator for the 'reset' (red) segment can be used to control the release of stored energy in the guides, as described in the previous paragraph.

A comparison of Lorentz- and reluctance-type actuators showed that the latter offered the best integral compromise



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9

8 *Control architecture, visualising drives (D), the Y actuator (AY) and different layers.*
9 *Generic Substrate Carrier demonstrator.*

of non-recurring costs and performance. It must be said that the nonlinear properties of a reluctance actuator required extended research.

Motion control

Figure 8 gives an overview of actuators, sensors and the controller. The SAXCS-inspired [2] control architecture mainly consists of two parts. The first part controls the force mechanism of Figure 4. The lateral motion of the segments is measured by gap sensors that are required for the force control loop of the reluctance actuators. This information, combined with the known stiffness of the segment guiding, can be used to predict the lateral force at any moment.

Through pretensioning ('biasing') of the segment that will almost become free from the belt, an undesirable step force is avoided. However, this partly model-based approach cannot cope with variations in mechanical properties of the segment guiding or the force constant of the actuator. Therefore, an additional repetitive control algorithm was added. During every revolution of the roll it gradually 'learns' model mismatches and compensates for them by means of slightly adjusted force feedforward.

The second part of the control architecture controls the X, Y and Rz positions of the belt. The X and Rz positions are both calculated from the combined output of two belt edge sensors X1 and X2. A transformation matrix is used to derive X and Rz. Due to the manufacturing process of the belt, the belt edge contains reproducible artefacts with amplitudes beyond the accuracy budget. An identification sequence is performed for each new belt to determine the relation between longitudinal and lateral belt information. The resulting lookup table is then used to compensate for all belt edge artefacts.
The Y controller can either use position information directly measured at the belt (marked Y in Figure 8) or position information derived from the rotational encoder that is part of the driving roll. Sensor Y is optical and interprets a laser-engraved bar pattern on the steel belt.

Demonstrator results

In order to test the feasibility and the accuracy to be expected from the proposed solution with actuated AMSR rolls, the Generic Substrate Carrier (GSC) demonstrator was built; see Figure 9.

To determine lateral accuracy, the position difference of the belt edge between the two sensor positions, spanning the work area of 900 mm, was measured. By using the output of both belt edge sensors, shifted over the work area length, a power spectral density analysis (PSD) can be performed to visualise the 3σ value of the lateral accuracy.

First, the accuracy of the actuated AMSR control was measured without compensating for the previously described 'reset' segment vibrations. Next, the measurement was repeated with the proposed spring stiffness compensation and the learning controller activated.

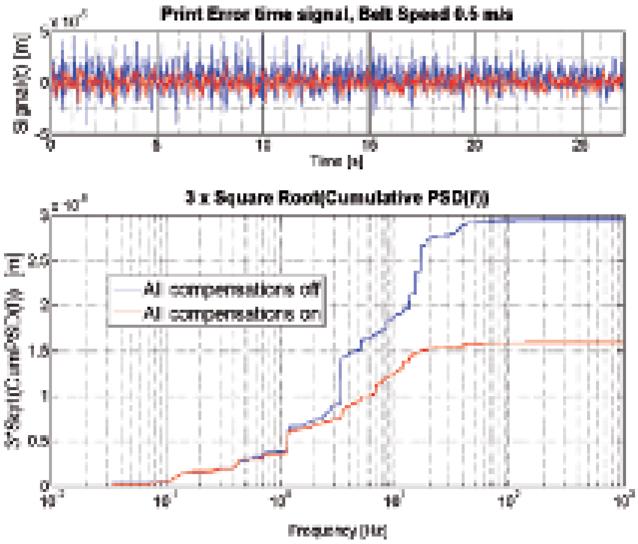
Figure 10 shows the PSD analysis results for both situations. As can be seen in the figure, the accuracy has improved drastically by using these compensation techniques, using which a lateral accuracy of almost 15 µm was achieved with this first demonstration prototype. In the longitudinal direction, an accuracy far below 5 µm has been measured! Also, print tests have been performed with a full-colour inkjet module installed onto the GSC. The results of the output prints are significantly better than those of conventional systems, even with speeds up to 2.5 m/s.

Together with DJM, a company specialised in research and development of industrial inkjet printing solutions, CCM exhibited the demonstrator during the Drupa 2012 fair in Düsseldorf, Germany. Motivated by the enthusiasm of interested parties, CCM is now designing a Generic Substrate Carrier for series production. With the lessons learned from the demonstrator, the successor will be able to achieve a lateral accuracy below 10 µm. In parallel, CCM will deploy a roll-to-roll application to serve single-pass substrate printing.

In conclusion

Substrate tension variation and external disturbances become a major problem due to the limited stiffness of the substrates. To overcome this problem, a steel belt conveyor has been introduced on which the substrate is fixated with vacuum clamping during the complete printing process. An advanced belt steering concept has been developed based on actuated Axially Movable Segmented Rolls (AMSRs).

On both sides of the rolls there are reluctance force actuators for segment manipulation. During rotation, the belt will (always) translate axially with respect to the segments that are in contact due to given limitations in belt and/or roll manufacturing (e.g. accuracy of weld perpendicularity). The actuated AMSRs compensate this translation, based on the measured belt position. Once per revolution, when the segment is not in contact with the steel belt, it will be actively positioned back to its 'centre' position to minimise disturbances in the system.



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A demonstrator has validated the AMSR technology and has been successfully exhibited at the Drupa fair 2012. A series product is now being designed. ■

10 *3σ cumulative PSD of lateral accuracy.*

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[2] Smart And fleXible Control Solutions, www.saxcs.nl

CCM, CENTRE FOR CONCEPTS IN MECHATRONICS

Product development company CCM was founded in 1969 by Professor Alexandre Horowitz. CCM's core competence is transforming fundamental technologies into custom turnkey mechatronics systems. CCM participates in the entire product development process: from elaborating product concepts, design, assembly, testing and installation to after-sales support. CCM employees are highly educated and experienced technical specialists, in the fields of mechanical engineering, physics, electrical engineering, electronics and software engineering.

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THE NATIONAL METROLOGY INSTITUTE OF THE NETHERLANDS

On 28 March 2013, a Precision in Business (PiB) day was held at VSL, the Delft-based national metrology institute of the Netherlands. VSL conducts research and provides metrology services aimed at enabling reliable measurements for business and society. The PiB day was organised by DSPE and its Young Precision Network (YPN), and attracted some 35 attendees. The day included presentations and a lab tour, under the overall theme of "the ultimate in accuracy".

VSL consultant Marijn van Veghel kick-started the day with an introduction. VSL is the national metrology institute appointed by the Dutch government to maintain and develop national measurement standards. It was named after Dutch mathematician and physicist Jean Henri van Swinden, who presented the original meter to the French government in 1799.

Scope

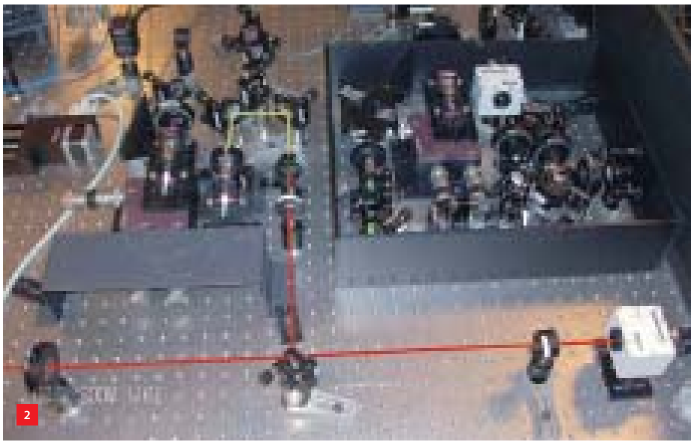
In many industries, product development and optimisation processes require very accurate measurements. Sound and reliable measurement is VSL's core business, as can be seen from an overview of its main activities:

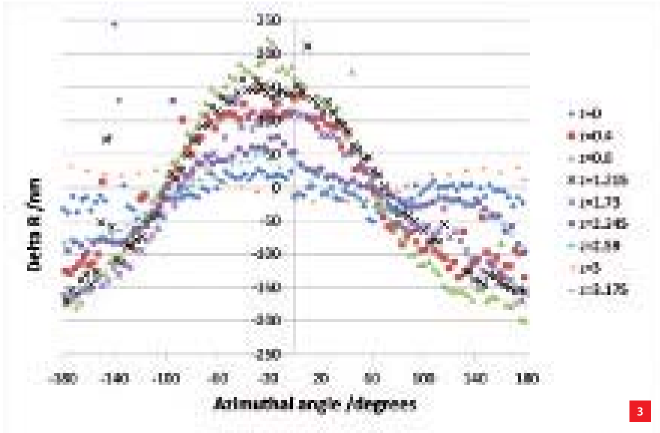
- maintaining national measurement standards;
- developing new standards (for example for LEDs);
- representing the Netherlands in the international metrology community;
- providing industry and society with the opportunity to trace their measurement results back to the national standards.

The metrological fields covered include length, mass, optics (photometry/radiometry, radiation thermometry), temperature, and time and frequency. VSL is closely involved with EMRP (European Metrology Research Programme), the coordinated research programme for European national metrology institutes. The total budget for the 2009-2016 period amounts to 400 M€. VSL participates in 33 projects and coordinates six of them.

One of VSL's internationally recognised specialties is length metrology, including optical frequency standards, classical geometrical measurements, vibrations, land surveying equipment, dynamic length measurements, and micro- and nanometrology, see Figure 1. Geometrical measurements include size, position, angle, form, roughness, etc., from one dimension up to six degrees of freedom. Topics in micro- and nanometrology are micro-coordinate metrology, Atomic Force Microscopy, sub-nanometer interferometry and in-line metrology.

1 *One of VSL's specialties is micro- and nanometrology. VSL, Carl Zeiss and Eindhoven University of Technology were partners in developing and realising the F25 micro-coordinate measuring machine. The diameter of the probe shown here is 300 μm.*





Length metrology

Next, VSL's Steven van den Berg elaborated on the topic of length metrology. After motivating the need for universal measures and the origin of the meter, he introduced the relationship between the meter and the second, two of the seven base units within the SI. According to the official definition, the meter is the length of the path travelled by light in vacuum during a time interval of 1/299,792,458 of a second.

These days, the wavelength of (laser) light is used as a reference for length measurements, with the iodine-stabilised helium-neon laser as primary standard. In practice, the meter is related to the second by measuring optical frequencies relative to an atomic clock. The underlying equation is the well-known $\lambda = c/\nu$ (with λ wavelength, c velocity of light and ν frequency of the light).

Laser frequency is measured using a 'frequency comb', which represents the spectrum of a pulsed laser. The comb spectrum features equidistant peaks (the distance being the pulse repetition frequency); a feedback loop can lock the repetition frequency to a frequency standard. VSL built its own frequency comb using a Ti:Sapphire laser (810 nm, 40 fs pulses, 1 GHz repetition rate) and achieved stabilisation of the repetition frequency to a 10^{-12} relative uncertainty in 1 second averaging time.
In essence, the frequency comb bridges the gap between radio frequencies (the domain where atomic clocks operate) and optical frequencies in a single step, bringing the accuracy of atomic clocks into the optical domain. Hänsch and Hall won the 2005 Nobel Prize in Physics for this achievement, sharing it with Glauber. Following this procedure, traceability from the meter to the second is provided by a phase-locked frequency comb laser, allowing for optical frequency measurement, see Figure 2.

2 Set-up in VSL's lab for measurement of optical frequency standards.

*3 Study of the static tactile probing behaviour of VSL's F25: radius deviation as function of azimuth and height (**z**) on a reference sphere.*

The step from laser wavelength to dimensional measurements, either absolute length or displacement, can now be made by interferometry, based on fringe counting and phase interpolation. At VSL, methods such as Michelson or Fabry-Pérot interferometry are applied for calibration of the F25 micro-CMM, line-scale measurements, diameter measurements using a CMM and a laser interferometer, and distance measurements. One of the practical problems concerns variations of the refractive index in air. When the complete spectrum of the femto-second laser is used, information about this refractive index (variations) may be obtained. This is a topic of ongoing research.

Form metrology

Leaving behind the 1D world of length metrology, on behalf of his VSL co-workers, Rob Bergmans presented work on ultra-accurate form characterisation of optical surfaces. This is part of an EMRP project on form metrology, aimed at improving the uncertainty of optical components, such as flat mirrors, aspheres and freeforms. The rationale for this project was the observation that metrology is the limiting factor in the manufacturing of advanced optical components, where Europe is facing heavy competition from East Asia.

Compared to conventional, spherical optics, aspherical and freeform optics offer more design freedom and the same optical performance with less elements. For instance, this is ideal for designing lenses for mobile phone cameras. These optics demand absolute 3D measurement of entire lens form/shape with an uncertainty of a few tens of nanometers. Besides ultra-precise flatness metrology, the EMRP project covers single-sensor as well as multi-sensor techniques (for example Tilted-Wave Interferometry combined with the Traceable Multi-Sensor technique).

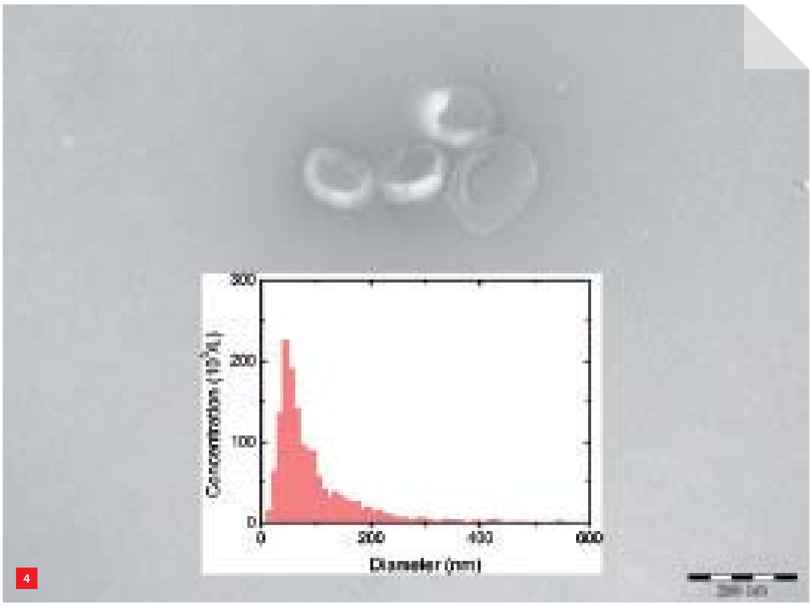
VSL's contribution to the EMRP project included tactile freeform measurements using the F25 micro-CMM. Bergmans elaborated on the geometric error model of the F25 and the (tactile and optical) probing systems on the F25. VSL has also worked on (non-contact) single-sensor scanning; it participated (with TNO and Eindhoven University of Technology) in developing the NANOMEFOS (Nanometer Accuracy Non-contact Measurement of Freeform Optical Surfaces) instrument.

Next, task-specific uncertainty calculations based on the Virtual CMM approach were addressed. The analytical approach no longer suffices because of correlations between measurement points. The solution is to perform Monte-Carlo calculations/simulations using a software model of the measurement, representing all relevant aspects, ranging from measurement strategy and machine geometry to environmental factors. Random variation of the input parameters generates a large number of measurement results (virtual probings), which can then be statistically processed to yield the desired uncertainty.

To conclude, Bergmans presented the results of international comparisons of sphere measurements; see Figure 3 for a typical VSL result. Overall, good agreement was obtained between the participating labs for the sphere diameter, within an estimated uncertainty at VSL of 70 nm. There also was a good agreement between static and scanning results. However, the uncertainty of sphericity measurements turned out to be much higher, ~ 250 nm, and differences were observed between scanning and static probing. First measurement results on an aspherical lens, using the F25, were also presented, coming as error maps for lens shape.

Biology

The last presentation offered an interesting excursion into the world of biology. Rienk Nieuwland, Principal Investigator at Amsterdam Medical Center, talked about metrological characterisation of microvesicles in body fluids. These vesicles contain a so-called Tissue Factor that plays a role in blood coagulation. Clinical relevance of vesicle research can be found for instance in the fact that in cancer patients the second largest cause of death is thrombosis.
The size distribution of vesicles displays a peak below 100 nm, see Figure 4. However, routine detection of ultra-small vesicles (< 100 nm) in body fluids is impossible with currently available optical technology. For example, Flow Cytometry only detects the 1-2% of vesicles that are larger than 400 nm in size. Up to now, different methods yield different answers for vesicle counts.



4 *Size distribution of vesicles.*

Therefore, last year an EMRP project was started that aims to standardise the detection of vesicles between laboratories and improve their detection. In this METVES project (www.metves.eu), coordinated by Nieuwland, AMC collaborates with VSL and three other national metrology institutes. The detection methods investigated include Atomic Force Microscopy, Small-Angle X-ray Scattering (SAXS) and Anomalous Small-Angle X-ray Scattering. One of the challenges of the METVES project, Nieuwland said, is the collaboration between the worlds of biology and metrology, concerning differences in scientific approach as well as practicalities. For example, where in the metrology institute is the fridge for storing biological samples?

But when it came to offering cool drinks, after an extensive lab tour, VSL did a good job. It was a fitting close to a rewarding Precision in Business day organised in a fruitful DSPE-YPN-VSL collaboration. ■

INFORMATION
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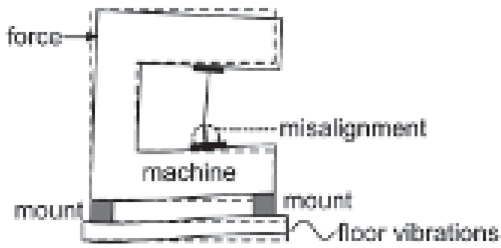
A HARD-MOUNT TWO-SENSOR CONTROL STRATEGY

A single-axis active hard-mount vibration isolator was developed using a two-sensor control strategy. The hard mount provides a stiff support for a precision machine while an active control system is used to get the desired vibration isolation performance. With this hard-mount two-sensor control strategy three performance objectives are realised simultaneously: isolation from floor vibrations, a low sensitivity for direct disturbance forces, and damping of internal modes. It was successfully validated on an experimental set-up.

MICHIEL BEIJEN, DIRK TJEPKEMA, JOHANNES VAN DIJK AND HERMAN SOEMERS

Environmental disturbances such as floor vibrations and disturbance forces may cause vibrations inside precision machines. This leads to internal deformations of the equipment and therefore reduces its performance. This is shown schematically in Figure 1.

To reduce the effects of floor vibrations, the equipment is usually mounted on a vibration isolator. A vibration isolator can be considered as a mechanical low-pass filter for floor vibrations: low-frequency floor vibrations are still being transmitted onto the equipment while isolation is provided for floor vibrations with a frequency above √2 times the so-called suspension frequency. This suspension frequency is calculated as the square root of the suspension stiffness divided by the mass of the suspended equipment. Most industrial vibration isolators are designed as a soft mount with a low suspension stiffness to aim for a low suspension frequency (typically 0.5-3 Hz) and therefore provide a low transmission of floor vibrations. An active control system can be added to artificially increase the damping of the suspension mode. Examples of such active vibration isolation systems have been described in recent Mikroniek articles [2] [3].
However, a low suspension stiffness introduces problems with leveling of the equipment and it worsens its response to disturbance forces acting directly on it (e.g. reaction forces due to stage motion, forces due to acoustic excitation or cable-transmitted forces). Both problems can be circumvented by using active hard mounts, which provide a much higher suspension stiffness. Due to the higher suspension stiffness, the suspension frequencies will be higher (typically 5-20 Hz). Therefore, the transmission of floor vibrations will also be higher. An active control system is then required to improve the response to floor vibrations.



1. *Schematic view of an internal deformation causing misalignment in a precision machine.*

AUTHORS' NOTE

Michiel Beijen worked on two-sensor control of active hard-mount vibration isolators for his M.Sc. thesis in the department of Mechanical Automation and Mechatronics (WA) at the University of Twente, Enschede, the Netherlands. This work is part of Dirk Tjepkema's Ph.D. thesis [1], which was produced in the same department under the supervision of Johannes van Dijk and Herman Soemers. Dirk Tjepkema now works at Demcon in Enschede, Herman Soemers at Philips Innovation Services in Eindhoven, the Netherlands.
The authors gratefully acknowledge the support of the Smart Mix Programme of the Dutch Ministry of Economic Affairs and the Dutch Ministry of Education, Culture and Science.

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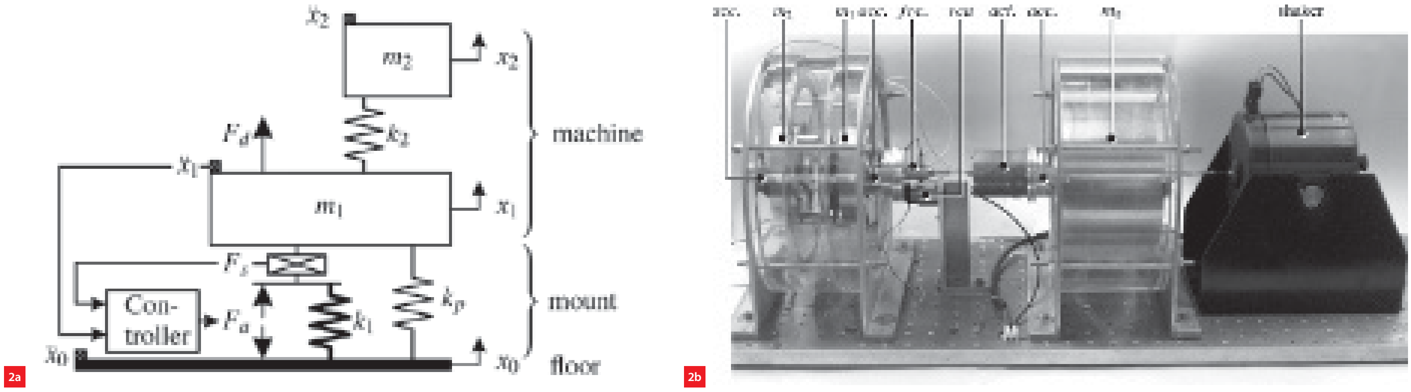


Another recent Mikroniek article [4] describes an active hard-mount vibration isolation approach in which the active control system is based on a combination of acceleration feedback and adaptive acceleration feedforward control. With this approach it is possible to provide a stiff suspension, to improve the response to floor vibrations and, at the same time, to artificially increase the damping of both the suspension mode and relevant structural modes of the precision machine. However, adaptive feedforward control requires a large computational effort of the controller's digital signal processor, even for a vibration isolation system with only one dominant direction of motion. For reduction of the computational effort, this article presents an approach based on the combination of acceleration feedback and force feedback. Compared to adaptive feedforward control, this results in a similar performance of the active hard-mount vibration isolation system.

Active vibration isolation set-up

Figure 2a shows a mass-spring model for a precision machine suspended by an active hard-mount vibration isolator with suspension stiffness k_1. For modeling of an internal mode, the precision machine is split into two separate masses m_1 and m_2 connected by a spring with internal stiffness k_2. The position of the machine is disturbed by a floor vibration x_0 and a direct disturbance force F_d. The actuator force is denoted as F_a. Since practical vibration isolators contain parasitic stiffness paths (e.g. from cables and guidances), a small parasitic stiffness k_p is taken into account. The parasitic stiffness is set at about 1% of the value of suspension stiffness k_1. Measurements can be taken from an accelerometer on mass m_1 and from a force sensor F_s located between the spring with stiffness k_1 and mass m_1. The stiffness of the force sensor is considered to be infinite. No physical damper is present since the suspension mode is actively damped and the mechanical damping of a physical spring is assumed to be negligible.

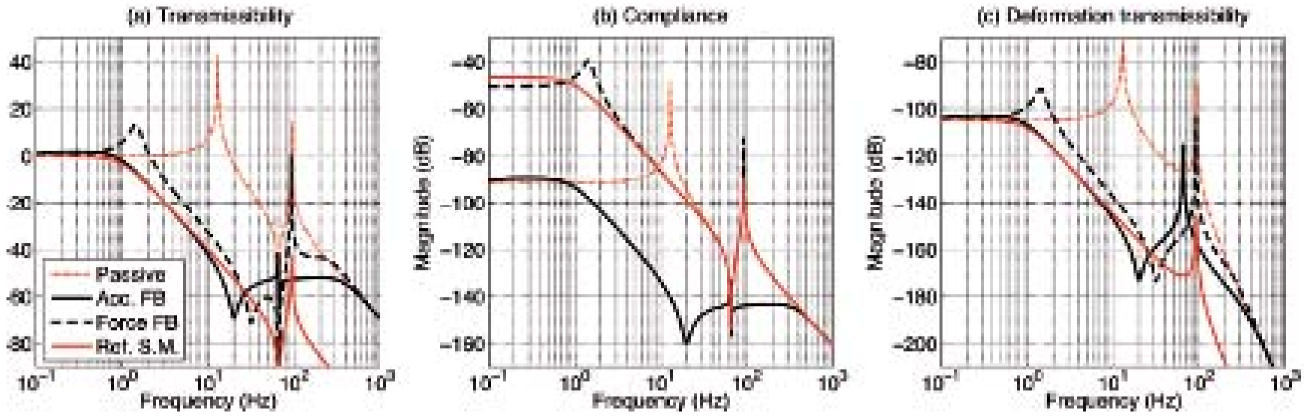
Figure 2b shows the corresponding experimental set-up for the active hard mount. The devices *acc.* are piezoelectric accelerometers at masses m_0 (representing the floor), m_1 and m_2. A piezoelectric force sensor *frc.* is mounted between actuator *act.*, which includes mount stiffness k_1, and mass m_1. An additional voice-coil actuator *vca* is used to apply direct disturbance forces to the system. So, the active hard mount consists of the actuator *act.*, two accelerometers *acc.* at masses m_0 and m_1, and a force sensor *frc.* The bodies are mounted in a linear guidance to allow motion in one direction only. To prevent gravity compensation the set-up is placed horizontally. The mass and stiffness values are chosen such that the set-up has a passive suspension frequency of 13 Hz, which is a typical value for hard-mount vibration isolators. The internal mode of the set-up is 90 Hz.

Three performance measures are defined for analysis of the vibration isolator performance:

- The *transmissibility* describes the transfer of floor motion x_0 to machine motion x_1. A low transmissibility implies a strong isolation of floor vibrations.
- The *compliance* describes the transfer from direct disturbances F_d to machine motion x_1. A low compliance results in a stiff support and thus a good rejection of direct disturbance forces.
- The *deformation transmissibility* describes the internal deformation $(x_2 - x_1)$ due to floor motion x_0. Internal modes are well-damped if the deformation transmissibility plot contains no resonance peaks.

These performance objectives are all functions of the frequency. It will be shown that all three performance objectives can be satisfied simultaneously using two-sensor control, while this is impossible when only a single sensor is used for feedback control. To determine the (deformation) transmissibility in the experiments, the floor body is excited by a shaker such that the velocity spectrum of body m_0 is

2 *Active vibration isolation.*
(a) Mass-spring model.
(b) Experimental set-up corresponding to the model.

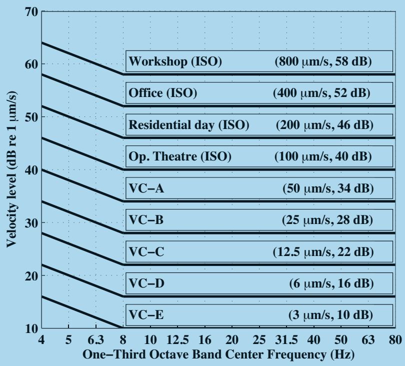


4 *Performance of active hard-mount vibration isolators by feedback control using a single sensor. The Ref. S.M. line corresponds to the performance of a reference soft-mount system with a suspension frequency of 1 Hz and 70% skyhook damping of the suspension mode. All other lines correspond to hard mounts.*

25 μm/s rms per 1/3 octave. This is comparable to VC-B curve excitation (see the box for more information). To determine the compliance, a random disturbance force is applied by the additional voice-coil actuator *vca*. This actuator provides a random signal of 0.3 N rms. The voltage provided to this additional voice-coil actuator is a measure of the applied direct disturbance force.

Vibration Criteria (VC) curves

Floor specifications for precision machines are based upon standard curves, known as vibration criteria (VC) curves [5]. The curves are indicated as VC-A (least quiet) to VC-E (most quiet), see Figure 3. The vibration level is expressed in terms of velocity and the rms value for 1/3-octave bands is used to assess the vibration level. Although it is common to use VC-D excitation in experiments with precision machines [2], here VC-B excitation was used for the floor, because it leads to a better representation of the effectiveness of two-sensor control. Since floor vibrations are of a stochastic nature, the VC-B curve is converted to a Power Spectral Density (PSD) function. In the experiments described in this article, floor vibrations are evaluated using the PSD.



3 *Floor specifications for precision machines are specified in so-called VC-curves [5].*

Single-sensor control

Because a hard mount is used, a control system is needed to artificially lower the system's suspension frequency and to add damping to its suspension mode. To realise this, the following controller action is used:

$$F_c = -(K_a \ddot{x}_1 + K_v \dot{x}_1)$$

This controller implements proportional acceleration feedback and integral acceleration feedback (velocity feedback) using the sensor signal $\ddot{x}_1$. A physical interpretation of this PI controller is the addition of a virtual mass K_a by the proportional (P) action to lower the suspension frequency, and a virtual skyhook damper K_v by the integral (I) action to damp the suspension mode [6]. The numerical values for K_a and K_v depend on the desired transmissibility, i.e. the closed-loop suspension frequency and its relative damping. State-of-the-art soft-mount systems typically have a suspension frequency of 1 Hz with 70% skyhook damping [1]. Therefore, K_a and K_v will be tuned such that a similar performance is obtained for hard-mount systems.

Another single-sensor control strategy is using force feedback. From Newton's second law, which states that force and acceleration are proportional by mass, it follows that the same controller action can be used for force feedback when dividing the numerical values for K_a and K_v by the total machine mass.

For both acceleration feedback and force feedback, the controller actions are filtered with a second-order low-pass filter at 20 Hz to limit the controller bandwidth.

Results

In Figure 4 the performance of hard-mount systems is compared with a state-of-the-art soft-mount system. This soft-mount system has a suspension frequency of 1 Hz and is equipped with a velocity feedback controller to realise 70% active skyhook damping of the suspension mode. No virtual mass is added to the soft mount.

Figure 4a shows the transmissibility. The transmissibilities of the active hard-mount system with acceleration feedback and the active soft-mount system are comparable in the frequency range up to 20 Hz, which is the low-pass filter frequency of the controllers to limit the bandwidth. The transmissibility of the active hard-mount system with force feedback is not as desired, because with force feedback the achievable suspension frequency is limited by the parasitic stiffness.

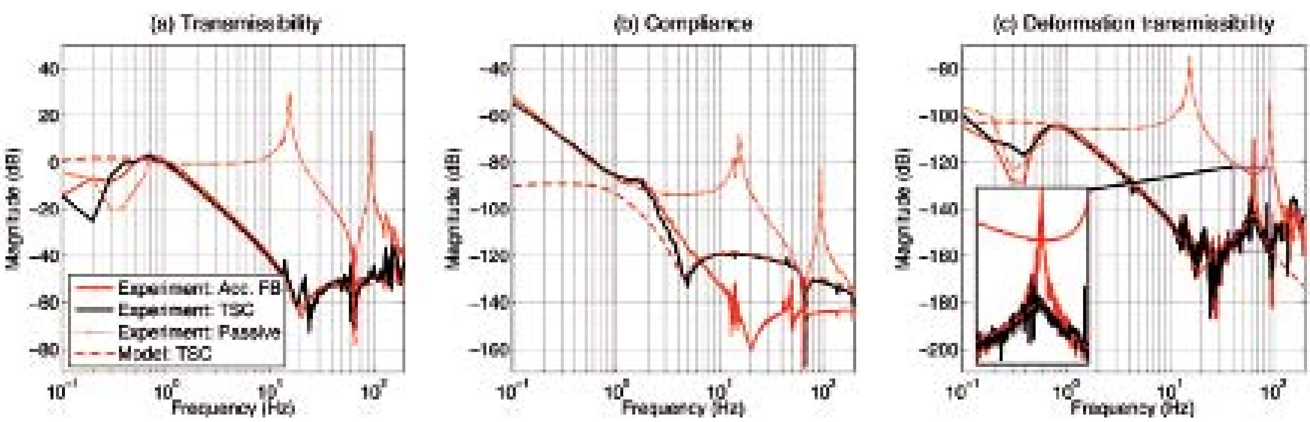
Figure 4b shows the compliance. The static compliance is the inverse of the support stiffness and should be as low as possible. Using acceleration feedback, the static compliance is $1/k_1$, which is as desired. Using force feedback, the static compliance is $1/k_p$, which is much higher since the parasitic stiffness is small compared to the suspension stiffness k_1, and therefore less beneficial. The static compliance of the reference soft mount is about 170 times higher than that of the hard mount, which is the major disadvantage of soft mounts with respect to hard mounts.

Figure 4c shows the deformation transmissibility. Compared to the soft mount, the resonance peak of the internal mode of active hard mounts is much higher for both acceleration feedback (at 66 Hz) and force feedback (at 92 Hz). For acceleration feedback, the internal mode is lowered in frequency, which is undesired. Both feedback strategies fail to damp the internal mode.

Two-sensor control

Figure 4c shows that poorly damped resonance peaks, caused by the presence of internal modes, show up when feedback control with a single sensor is used. It appears that the frequency of the internal mode corresponds with an anti-resonance frequency in the loop gain of the feedback loop. At an anti-resonance frequency the sensor cannot provide useful information to the control system. According to Figure 4c, the loop gains for both acceleration feedback and force feedback have an anti-resonance frequency, because the deformation transmissibility plots of both control strategies display a poorly damped resonance peak. However, the frequencies at which the anti-resonance occur, is different for both control strategies. This means that for any frequency there is always at least one sensor with no anti-resonance at that frequency, which therefore can provide useful information to the control system. Hence, the internal resonance can be damped using two-sensor control.

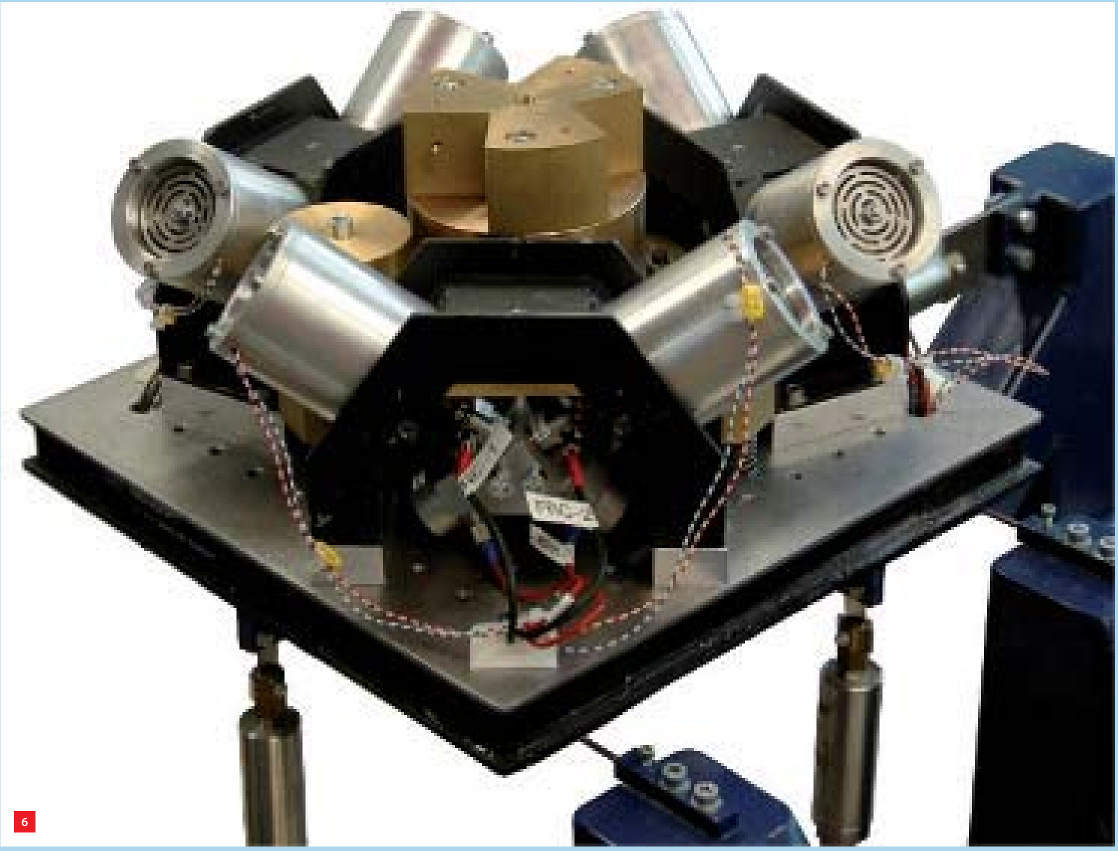
The two-sensor control strategy is designed as follows. At low frequencies, only acceleration feedback will be used, because the analysis of Figure 4 shows that acceleration feedback performs better than force feedback at low frequencies. At higher frequencies, a combination of acceleration feedback and force feedback is used. This combination of controllers has to be designed carefully. On one hand, the combination of two separate controllers may not lead to an unstable system. On the other hand, both controllers should not cancel out each other's controller output. It appears that the controllers can be successfully combined by using different low-pass filter structures for the two controllers in the high-frequency range, which is the range where internal modes occur. With such a combination, the three performance objectives described above can be achieved simultaneously. This is shown in



5 *Experimental results for active hard mounts with acceleration feedback and two-sensor control (TSC). With TSC, the internal mode is damped with 30 dB with respect to acceleration feedback, while still a low transmissibility and a low compliance are achieved.*

Two-sensor control in multiple directions

This article focuses on two-sensor control for single-axis set-ups, but it appears that the described strategy is also well-suited for multi-axis systems. For the set-up shown in Figure 6, two-sensor control is successfully applied by using modal decoupling of the system. Modal decoupling reduces the multiple-input multiple-output (MIMO) system to a set of single-input single-output (SISO) systems. Subsequently, two-sensor control is applied to each SISO system.



6 *Six-axis hard-mount vibration isolator.*

Figure 5, where the modeled and experimental results for two-sensor control are compared. The experimental results are obtained using the set-up shown in Figure 2b and the experimental conditions as described in the section "Active vibration isolation set-up".
Figures 5a and 5c show the (deformation) transmissibilities. It is observed that these measurements become noisy at frequencies above 100 Hz. This is because sensor noise dominates over the actual acceleration level at these high frequencies. At frequencies below 1 Hz the results become unreliable because the piezoelectric sensors cannot provide reliable measurements below 1 Hz. In the mid-frequency range (1-100 Hz) the measurements fit well with the modeling results. Around 20 Hz some additional peaks due to resonance modes are visible. These modes originate from motion of the table on which the experimental set-up is mounted. In the deformation transmissibility, the internal mode is poorly damped when acceleration feedback is used, while with two-sensor control the mode is damped significantly. Using two-sensor control, the resonance peak of the internal mode drops 30 dB with respect to acceleration feedback.

Figure 5b shows the compliance plots. It is observed that for high frequencies (> 5 Hz) the compliance is very well estimated by the model. At low frequencies, the measured compliance is not constant, but has a certain slope due to the unreliable piezo-electric sensor measurements at low frequencies. One can observe that in the mid-frequency range the compliance for two-sensor control is higher than that for acceleration feedback. However, the compliance level is, for both acceleration feedback and two-sensor control, much lower than that of the passive hard mount, which already provides a sufficient stiff support. So two-sensor control is the best control strategy, because damping of the internal mode is more beneficial than obtaining an extremely low compliance using acceleration feedback.

Conclusions

Two-sensor control is a promising strategy for adding damping to internal modes in active hard-mount systems. The frequency of the suspension mode is lowered from 13 Hz to 1 Hz and 70% skyhook damping is added to this mode, while the high static stiffness of the passive hard mount is not affected. Using two-sensor control, damping is added to the internal mode and the peak value of this resonance is decreased with 30 dB as compared to single-sensor control using acceleration feedback. The two-sensor control strategy was successfully validated on an experimental set-up. ■

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MASTERING X-RAY DIFFRACTION AND FLUORESCENCE

According to Bragg's law, in physical research unknown crystal lattices can be determined by studying the diffraction of X-rays. In materials research a crystal that has already been examined can then be used to analyse the fluorescence peaks in an X-ray spectrum. The position and intensity of these peaks correlate with elemental concentrations in a sample. PANalytical in Almelo, the Netherlands, has turned the principles of X-ray diffraction and fluorescence into a range of precision instruments for materials research and industry.

FRANS ZUURVEEN

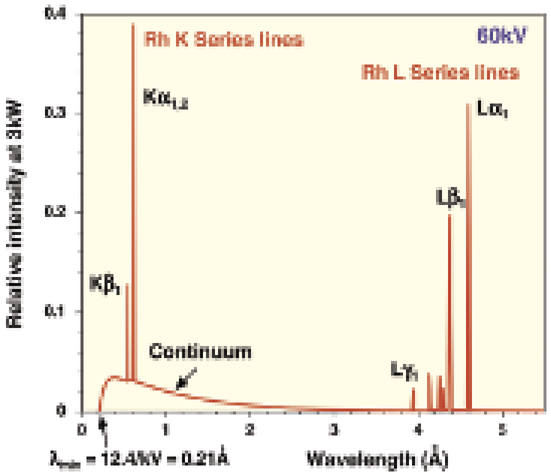
PANalytical, which is part of the Spectris company in Egham, UK, continues the X-ray diffraction and fluorescence work of the former Science and Industry division of Philips Electronics in Eindhoven, the Netherlands. Work in this field started in the Mount Vernon laboratories of Philips Norelco in the US shortly after World War II. It was there that physicists developed a vertical diffractometer with a Geiger-Müller counter tube. In Eindhoven, this instrument was followed by more sophisticated diffractometers with a series of X-ray fluorescence materials analysis instruments as spin-outs. In 2002, Philips sold its X-ray diffraction and fluorescence activities to Spectris.

Since it was founded, PANalytical has had a strong innovative influence on both the former diffraction and fluorescence product lines at Philips (see Figure 1), encouraged by the emerging analytical needs for advanced materials research and production in several sectors, including the semiconductor, pharmaceutical, nanotechnology and minerals industries. These industries required instruments that could analyse the composition and properties of materials faster and more accurately. Diffraction and the range of fluorescence equipment for industrial materials analysis underwent considerable growth. Just like at Philips before, the X-ray tube factory in Eindhoven, which got new premises last year, is an integral

1 *The PANalytical Empyrean X-ray diffraction instrument.*

AUTHOR'S NOTE

Frans Zuurveen is a freelance text writer who lives in Vlissingen, the Netherlands. In his engineering career, he has worked at Philips Electronics on scientific equipment, including X-ray fluorescence and electron optics.



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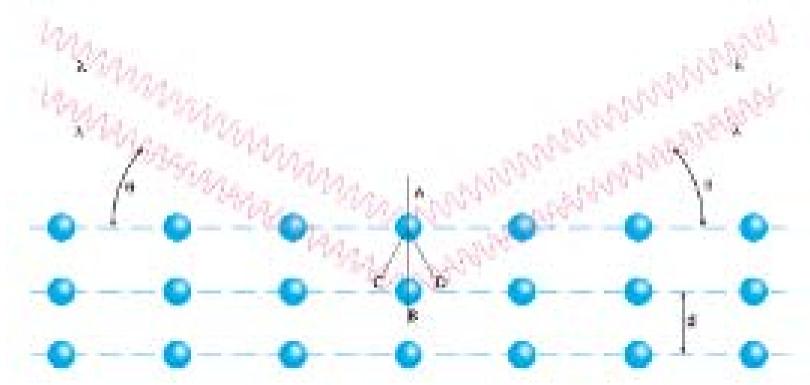

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part of the PANalytical organisation. As such, PANalytical has become the only manufacturer of X-ray analysis equipment with its own plant for dedicated tubes.

X-rays

In 1895, Wilhelm Conrad Röntgen discovered that a previously unknown radiation was emitted when fast electrons ejected from a heated cathode hit the metal anode in a cathode ray tube. This tube would later be developed into a wide range of specialised X-ray tubes. The spectrum of radiation emitted proved to be a superposition of a continuous spectrum, the so-called Bremsstrahlung, with peaks that could be attributed to the individual elements in the anode material (see Figure 2).
Bremsstrahlung (braking radiation) is caused by the speed reduction of electrons entering the anode material. According to Kramer's law, the spectral intensity of the X-rays initially increases with increasing wavelength, from zero at λ_{min} (see Figure 2), which corresponds with the energy of the incident electrons, which in turn corresponds with the voltage between cathode and anode in the tube.

What is more relevant to this article are the peaks in the X-ray spectrum, which are called characteristic radiation. As said, their wavelength depends on the kind of anode material. Electrons are scattered from the inner shell of their atom and replaced by electrons from shells with higher energy. The latter emit photons with a clearly defined energy, and hence wavelength, typical of the respective chemical element.

The above explains why X-ray tubes with different anode materials operated at specific high voltages are applied, depending on the wavelength aimed at. Another aspect of

2 The spectrum emitted by an X-ray tube is a superposition of continuous Bremsstrahlung with peaks from individual elements in the anode material.
3 Principle of Bragg's law.

this is the principle of X-ray fluorescence instruments: the peaks in the spectrum of the X-ray radiation emitted by an irradiated sample are typical of the composing elements. The wavelength characterises the element; the height of the peak is proportional to its concentration.

Bragg's law

Bragg's law (father and son, William Lawrence Bragg and William Henry Bragg, Noble Prize Physics, 1915) is formulated as:

$$n\lambda = 2d \cdot \sin\theta$$

Here a crystal is modelled as a set of discrete parallel planes, each separated by a distance d (actually, in a crystal, a number of such sets can be discerned, each characterised by a specific value of d). Incident X-ray radiation produces a so-called Bragg peak if reflections off the various planes interfere constructively (see Figure 3). This is the case when the phase shift is a multiple of 2π, corresponding with a path difference of a whole multiple n of the wavelength λ of the incident radiation. This condition is fulfilled when this multiple is equal to the actual path difference of $2d \cdot \sin\theta$, with θ the angle between the incident ray and the scattering planes.

In crystal lattice analysis instruments – based on diffraction – the distance d is unknown and, therefore, the principal subject of the analysis. This is possible because λ is a known parameter from the X-ray tube. Conversely, in material analysis instruments – based on fluorescence – λ is unknown. This analysis is possible when a crystal with known parameter d is used.

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4 *The goniometer of an Empyrean X-ray diffraction instrument, showing X-ray tube (left) and detector (upper right).*

5 *Curved, multi-layer mirrors.*

Clearly, the angle θ is unknown in both cases, i.e. diffraction as well as fluorescence. This requires the use of a so-called goniometer, in which this angle can be varied and defined with high precision. It explains why, in principle, one or more goniometers always form the basic assembly in the instruments produced by PANalytical (with one exception, to be explained later). In general, the sample stays static while the X-ray tube and the detector move at the same angle θ relative to the sample or lattice plane; the tube is for incident radiation, while the detector is for emitted radiation. In some cases, the tube remains static and the sample moves at an angle θ and the detector at an angle 2θ.

Precision technology

When designing a goniometer, precision technology is key. Not only because the peaks in an X-ray spectrum are very narrow and therefore limited to a small angular window, but also because background noise (small- and wide-angle X-ray scatter) is of certain importance. Not so long ago, this noise used to be a nuisance, but nowadays new techniques make it possible to extract data from background noise. Another precision aspect to consider is the arrival of computed tomography imaging (CT) in the field of materials analysis technology, which means that the interior of a sample can be 'looked into'.

From a purely mechanical point of view, three goniometer design items are important: accurate bearing, reproducible angular driving and precision angle measuring with high-resolution encoders (see Figure 4). Details of the mechanical design cannot be revealed, but it can be noted that PANalytical does not use ball bearings in its goniometers, but sleeve bearings with extremely small bearing slits. The shaft and sleeve are made of steel, not bronze and steel as an old-fashioned designer could suppose. The bearings are lubricated, but the exact details of what lubricants and steel compositions are used remain a company secret.

The driving mechanisms are based on pre-tensioned, hence playless, worm and worm-wheel or tooth-wheel combinations, coupled with highly accurate DC motors, operated using advanced servo-control algorithms. Angular positioning is realised by using integrated high-precision Heidenhain encoders in the feedback loops. To produce an optimised integral system, PANalytical developed its own control software.

The angular encoder used the most is the Heidenhain ERA 4000 with an accuracy of ± 2 arcsec. The graduation substrate of this encoder is steel. The grating structure consists of several layers of gold, a transparent spacer and chromium on a cylindrical surface. A laser is used to shape the chromium layer into an angular scale. For even more accurate rotations in calibration and test devices, PANalytical uses the Heidenhain RON 905 encoder. This high-accuracy angle encoder with integrated stator coupling is able to see steps of 0.00001° (0.035 arcsec) and measures with an accuracy of ± 0.2 arcsec. For X,Y-translations of samples, Heidenhain linear scales LIF 400 on Zerodur substrate are used, with 10 nm resolution. For sample rotation and tilt, the ERA 4000 is used in most cases.

X-ray precision

Not so long ago, the common thinking on X-rays was that, unlike visible light, they could not be focused. The only available device to create a more or less parallel X-ray beam

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6 *The PIXcel X-ray detector.*
7 *A PANalytical ceramic X-ray tube.*

was the collimator, which consists of a set of parallel metal sheets. One of the disadvantages of the collimator, however, was the loss of intensity due to absorption.

Nowadays, thin-layer technology has made it possible to really focus X-rays. Several institutes have succeeded in creating multi-layer X-ray mirrors, consisting of alternating layers of light and heavy material, e.g. Si and Mo; see Figure 5. In the Netherlands, the associated design and manufacturing skills can be found in Prof. Fred Bijkerk's group at the University of Twente (i.e. the MESA+ Institute for Nanotechnology) and at the FOM Institute DIFFER. The individual layers have a thickness from 0.5 to 5 nm. By giving such a set a well-defined curvature, a parallel beam of X-rays can be converged to one single point or to a line focus. Both PANalytical and lithography machine manufacturer ASML use this promising new technology.

Another method of making X-rays converge in one point, is by using a set of hollow glass fibres no more than a few micrometers thick. This is accomplished by arranging the fibres in a conical configuration aimed at one point – a real precision technological achievement.

Another precision innovation is the PIXcel X-ray detector (see Figure 6), developed as part of the Medipix2 collaboration project headed by CERN in Switzerland. PANalytical has secured the exclusive rights to use this technology in its analytical instruments. A PIXcel detector such as this consists of a matrix of pixels, each comprising a Si column of about 0.3 mm thick and 55 μm across. Each pixel column converts the X-ray quanta hitting its upper surface into electrons. The electron quantity is proportional to the X-ray intensity on one detector pixel. Connected to each Si column is an integrated AD converter in CMOS IC technology, which creates a digital signal representing the X-ray intensity on one pixel.

A somewhat older precision technological achievement is the creation of extremely thin windows to be used in an X-ray optical path, for example in X-ray tubes. As said, the anode material in the tube is responsible for the main wavelength of the X-ray radiation. But this radiation arises in a vacuum and should pass the exit window with as little loss as possible. That's why those windows are created from an extremely thin sheet of beryllium, which is relatively transparent to X-rays thanks to its low density and atomic mass. Such a window has to be as thin as possible, only a few dozen micrometers or even less. Moreover, the window has to withstand the pressure difference of at least one bar and to be sealed vacuum-tight to the ceramic outer wall of the tube; see Figure 7. (Ceramics are increasingly replacing glass in X-ray tubes.)

Diffraction instruments

PANalytical came up with the name Empyrean from the Aristotelian world view of concentric spheres surrounding Mother Earth, where the Empyrean sphere represented the element of fire. The name is being used for a range of

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8 *Wafer sample manipulation in the goniometer of an X'Pert PRO MRD diffractometer.*

9 *An Axios X-ray fluorescence spectrometer with mechanised sample handling in universal holders.*

PANalytical diffraction instruments, all of which have one universal platform that can be fully customised. This means that different elements – X-ray tube, sample holder and detector – can be added to the always identical goniometer stage. At the heart of this systematic approach are universal mechanical adapters, which are designed in such a way that subsequent alignment is superfluous. Other parts of the system include the X-ray-optical components and semiconductor detectors mentioned above.
There are a range of samples that can be used in Empyrean instruments, e.g. monocrystals, polycrystals, polycrystalline powders or thin-film objects. The application area is very wide and aims to serve scientific and industrial goals in materials research.

Other series of diffraction instruments are X'Pert PRO MRD and MRD XL. These instruments are dedicated to research in the semiconductor industry, for examining silicon wafers up to 12 inches in diameter. Those instruments are equipped to handle large samples, which can be displaced, rotated and tilted, thanks to X,Y-stages, rotation tables and tilting cradles (Figure 8). The user can manipulate the samples from behind a monitor. The PreFIX concept of adapters means that components can be swapped without any time-consuming alignment procedures.

Fluorescence instruments

X-ray fluorescence equipment – also known as X-ray spectrometers – is being used in various industries (e.g. the cement, oil, plastics, mining and steel industries) for product and process control. The instruments can be divided into two categories: sequential and simultaneous. In sequential instruments the goniometer moves along the various peaks present in the X-ray spectrum emitted by the sample when hit by an X-ray beam from the source, i.e. the X-ray tube. This is a more versatile, but somewhat time-consuming approach to materials analysis.

Simultaneous X-ray spectrometers, meanwhile, are faster but focus more on one analysis task at a time. Several detector channels (wavelength- or energy-dispersive), each tuned to a specific X-ray wavelength, are arranged around the sample, each connected to a port in the sample measurement chamber. Each channel is adjusted to the frequency of one of the spectrum peaks in the emitted X-rays. This means that such an instrument is adapted to a specific analysis task, for example finding concentrations of nickel, chromium, vanadium, manganese, silicon or phosphorus in stainless steel. This parallel measuring of elements means that analysis data are available in one minute or less, which is an important advantage to the industrial sector.

One of the PANalytical X-ray spectrometer product lines is called Axios (see Figure 9). This line has the nickname

10 *A turret for robotic sample handling in an Axios spectrometer.*

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instruments for elemental analysis for industry process control and for research and development.

To conclude

Wilhelm Conrad Röntgen was rather astonished by his discovery that radiation could penetrate objects, even human organs. His first publication aroused much public interest and encouraged scientists to repeat his investigations, unfortunately with many untimely deaths due to the previously unknown danger posed by these rays. Besides their later use in medical diagnostics, these X-rays appeared to be of great benefit in materials research. Initially, this only concerned physical disciplines, but the activities of Philips Analytical – which PANalytical has successfully and innovatively continued with – showed a fundamental mechanical and instrument control aspect, featuring real precision technology. ■

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FAST for simultaneous equipment. These instruments are equipped with special sample loading equipment, using universal sample holders (see Figure 10). This optimised sample handling system guarantees brief and accurate composition measuring.

Another series of instruments, dedicated to the semiconductor industry, are the Semyos spectrometers. These have been specially designed to measure the composition of elements in layers deposited on wafers, together with their corresponding thicknesses. The instruments use standardised containers for wafers of up to 300 mm in diameter (12 inch).

The instruments mentioned above are wavelength-dispersive spectrometers. PANalytical's portfolio also includes another kind of spectrometer: X-ray energy-dispersive instruments (EDXRF). These are characterised by a cooled semi-conducting germanium or silicon detector, which records the X-ray spectrum: energy as a function of frequency or wavelength. These PANalytical instruments are called Epsilon. The Epsilon 5 series comes with an automatic sample-loading system. These instruments provide high-performance trace element analysis for industry, research and development applications. They are also a cost-effective option for commercial analytical laboratories. The Epsilon 3 energy-dispersive spectrometers are designed as bench-top

TEACHING WITH A PROFESSIONAL PARTNER

Wouldn't it be ideal to bring the expertise of a professional partner into the classroom? Upon graduation, students often do not know what to expect when starting to work for a company. The Leidse instrumentmakers School and TNO Optomechatronics are collaborating, bringing together years of experience and the eagerness of youth into one multidisciplinary project, so that students can gain experience in solving real-life engineering problems.

MARC FRIEDHEIM, TOM DUIVENVOORDE AND ALEXANDER EIGENRAAM

AUTHOR'S NOTE

Marc Friedheim is a teacher in electronics and physical computing, with a mechanical background, in the Mechatronics and Laser technology department at the Leidse instrumentmakers School (LiS). During the fourth-year projects at the LiS, he is an internal supervisor. Potential external partners in the supervision and tutoring of fourth-year students are invited to contact him.
Tom Duivenvoorde and Alexander Eigenraam are mechanical designers at TNO Optomechatronics and external supervisors of this year's LiS students. They both completed the LiS programme before acquiring a bachelor degree in mechanical engineering.

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The Leidse instrumentmakers School (Leiden Instrument Makers School, LiS) was founded by Professor Heike Kamerling Onnes (Nobel Prize in Physics, 1913) in 1901 as a school to educate precision craftsmen for the production of research instruments. The school keeps up with new developments in precision technology and offers a one-year specialisation course in mechatronics.

During the first half-year of this specialisation, students learn by working on a project. By using a practical example and mentorship (provided by TNO Optomechatronics), the LiS aims to prepare their students as well as possible for the precision industry. In this article a small breakdown is given of the first semester, with an example of this year's project conducted with TNO.

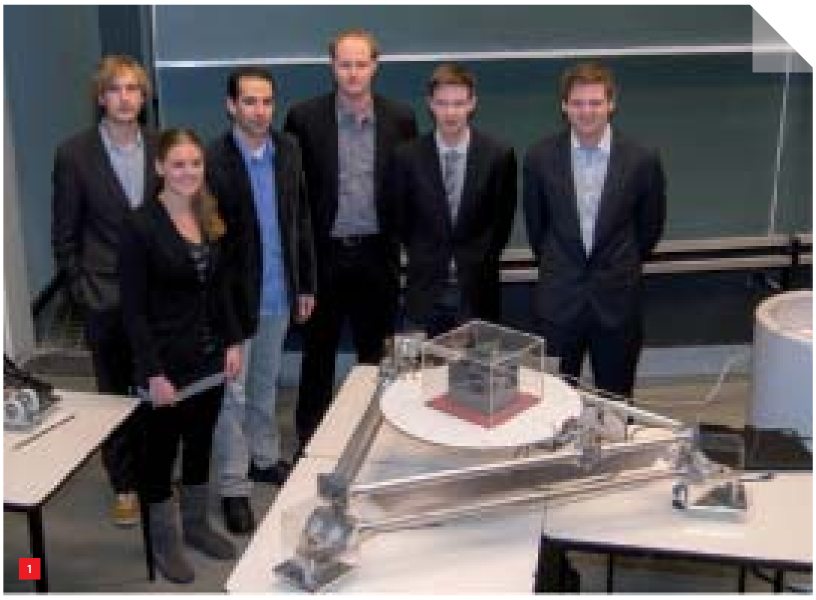
First-semester project

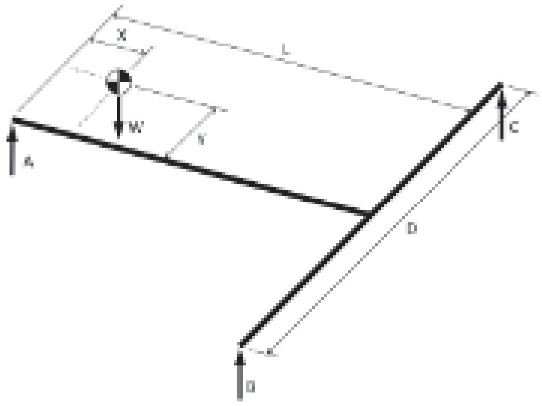
The goal of the project is to develop, build and test a multidisciplinary instrument. Working together in small project groups of up to four students, their assignment is a real-life problem from the field of precision engineering. During this period the external partner functions as the customer, providing hands-on experience and the project assignment. The project has a hard deadline and after five months a functional model, including detailed production drawings, a design report and a presentation that explains the design process, are to be delivered.

Center-of-gravity measurement device

When developing and building space-flight hardware, it is often required to measure the position of the center of gravity of the instrument. This can be done by using three separate weighing scales to measure the center of gravity in the horizontal plane and rotating the instrument 90 degrees to measure in the perpendicular plane. This method is time consuming and sensitive to mistakes and has limited accuracy.

1 Students and supervisors with the instrument at the final presentation to the public in January 2013, with from left to right: Alexander Eigenraam (TNO), Floor Groen (student), Marc Friedheim (LiS), Tom Duivenvoorde (TNO), Lars Eeuwijk (student) and Tim Vermeulen (student).





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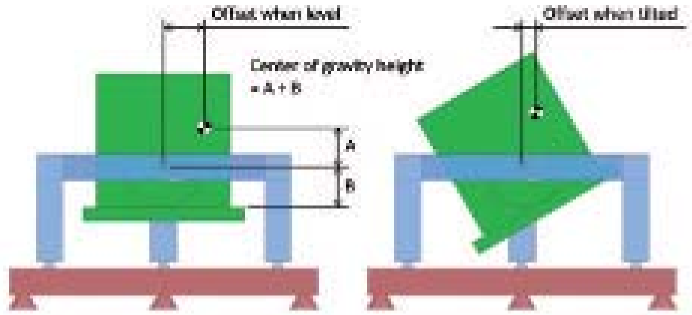

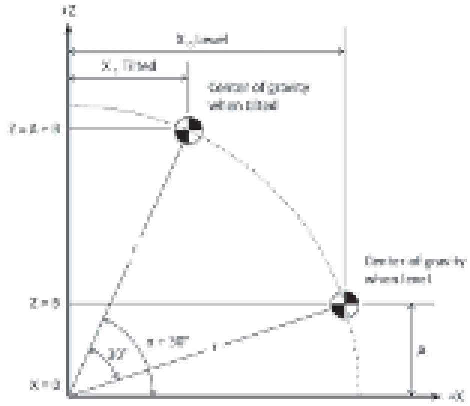

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Increasing instrument complexity and the wish to become more cost-effective, resulted in the idea at TNO Opto-mechatronics to build a dedicated device for a simple center-of-gravity measurement. See Figure 1.

Mechanics

The instrument developed by the LiS students consists of a measurement frame with a rotation platform on which the object is placed. The frame distributes the weight of the object over three loadcells. With the known position of each loadcell and the measured forces, the center of gravity can be calculated in the horizontal plane using the sum of the moments (Figure 2) [1]:

$$\Sigma M_x = (B + C)L - WX = 0$$
$$\Sigma M_y = C(D/2) - B(D/2) - WY = (D/2)(C - B) - WY = 0$$
$$X = (B + C)L/W$$
$$Y = (C - B)D/(2W)$$

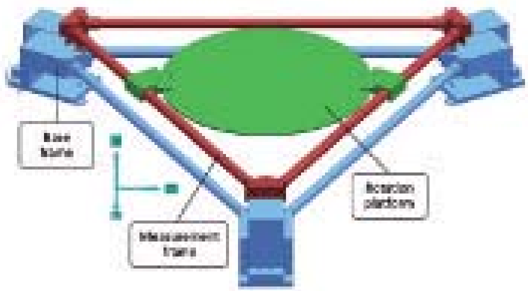
This principle is the same as using three separate weighing scales.
Tilting the object inside the measurement frame will result in an offset in the position of the center of gravity when this is measured again in the horizontal plane. Together with the tilt angle and the additional height of the rotation platform, the position of the center of gravity in the perpendicular plane can be calculated (Figure 3) [1]:

$$A = 2X_0 \cos(30) - 2X_1$$
$$Z = A + B = \text{center-of-gravity height from reference plane}$$

The realised instrument (Figure 4) [3] consists of the following main structures:

- The base frame, which supports the loadcells and guides the forces to the fixed world.
- The measurement frame, which defines the position of the three weight measurement locations with respect to each other.

2 *Using the sum of the moments to determine the center of gravity in the horizontal plane.*
3 *Determining the center of gravity in the remaining direction after tilting the rotation platform.*
4 *Simplified 3D CAD model indicating the main structures.*



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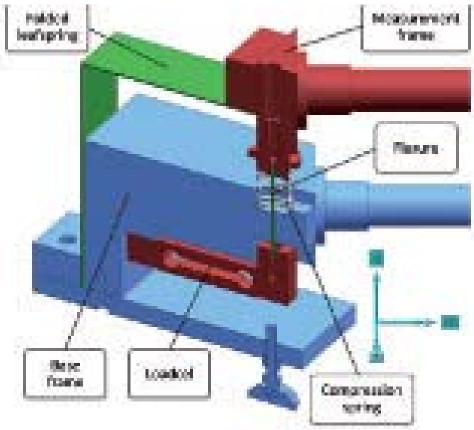
- The rotation platform, which provides a mounting surface for the instrument and enables tilt for the measurement.

The measurement frame is connected to the base frame and the loadcells with elastic elements.
Three folded leafsprings under 120 degrees mount the measurement frame to the base frame, constraining three degrees of freedom (DoFs): Tx, Ty, Rz. Three flexures mount the measurement frame to the three loadcells constraining the other three DoFs (Tz, Rx, Ry). These DoFs are required for the measurement and are free within the stroke of the loadcells.

The elastic elements are integrated within three corner blocks. These corner blocks are connected with tube



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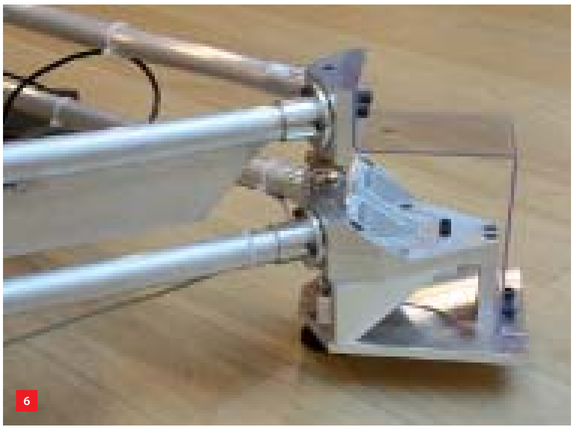

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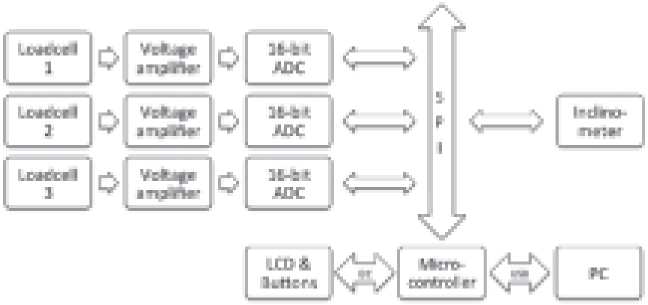
5 *Section view of the 3D CAD model of a corner block indicating the main components.*
6 *One of the three corner blocks.*
7 *Simplified electronics and software flowchart.*

profiles to form the base frame. Figures 5 [3] and 6 display one of the instruments corner blocks, connecting the measurement frame with the base frame and the loadcells. The compression spring is used for mass compensation of the measurement frame and the rotation platform.



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Mechatronics at the LiS

Since 2003, the fourth-year students at the LiS have the option to specialise in the field of mechatronics. During the one-year specialisation, the students apply their practical and theoretical knowledge about precision mechanics within a multidisciplinary project. Such a project requires wider knowledge, so apart from the regular lessons in conventional machining, students learn about a range of new topics including physical computing (electronics and embedded software) and advanced mechanics.

The impact on the student's development as a result of the cooperation between the LiS and an external partner is substantial. Working together with an external partner and preparing for a weekly review meeting changes the students. They are focused on solving this specific problem and are taken out of the day-to-day teaching routine. Students are stimulated to apply and expand their technical knowledge and are eager to do so. During the project, important decisions have to be made that influence the course and the final results. Every choice has to be backed by a solid argument or a back-of-the-envelope calculation.

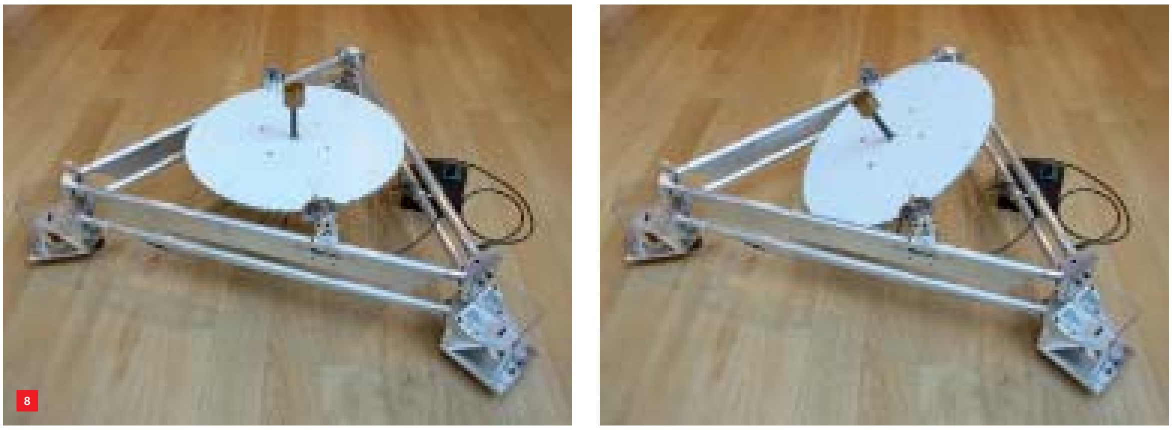
In the second semester of the fourth year, the students follow an individual internship at a precision-oriented company or institute, during which the same project format is applied. One of this year's students has started at TNO Optomechatronics to develop and build an instrument for measuring thermal contact resistance.

Electronics and software

To control the instrument and the measurements, the students designed dedicated electronics and software. The loadcells measure the weight distribution and an 8-bit microcontroller performs the calculations and communication with the external hardware. The Arduino microcontroller [2] is used because of its function as a multifunctional device providing the interface between the computer and numerous possible devices.

The electronics hardware configuration (Figure 7) consists of three analog sensors (the loadcells) and three voltage amplifiers. The amplified voltage is converted with a 16-bit Analog-to-Digital Converter (ADC) with integrated Serial Peripheral Bus (SPI). An inclinometer measures the angle of the rotation platform. The readout is performed continuously and displayed on a small LCD display through the I2C communication bus.

During the measurement program, the required adjustment actions to be preformed by the operator, such as tilting the rotation platform, are displayed on an attached PC. The complete user interface consists of a PC, LCD display and three push buttons.



8 *The completed instrument during measurement of a test weight in horizontal (left) and tilted (right) orientation. The electronics cabinet containing the microcontroller, LCD and control buttons can be seen on the right.*

Conclusion

Three students from the LiS, mentored by designers from TNO Optomechatronics, successfully built and tested an instrument that measures the center of gravity of a space instrument. All design choices have been backed with the necessary calculations and the whole process was carefully documented in writing and detailed production drawings. The students made a huge effort to complete the instrument within the set time frame and budget.

Near future

The LiS education programme is becoming more focused on the mechatronics project in the fourth year due to the growing demand for multidisciplinary instrument makers. In time, the course is likely to become a mandatory part of the programme. To succeed in providing all the students with a demanding assignment and high-quality supervision from people in the field of precision engineering, the LiS will need more industrial partners like TNO. ■

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HIGHER THROUGHPUT, HIGHER EFFICIENCY

Record deposition rates for alumina of up to 1 nm/s were reached using spatial Atomic Layer Deposition (ALD). One interesting application enabled by this disruptive improvement is passivation of crystalline silicon solar cells, which can increase solar cell efficiency and enable the use of thinner wafers. After the successful introduction of a process development tool, start-up company SoLayTec developed a high-volume tool, based on the same concept, targeting throughput numbers of up to 3,600 wafers per hour.

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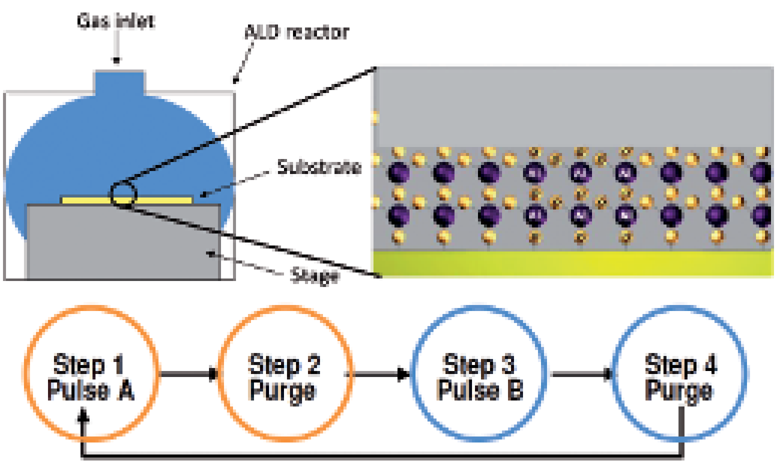
AD VERMEER

Atomic Layer Deposition (ALD) is a gas-phase deposition technique for depositing high-quality thin films. It is done by sequential exposure of a substrate to at least two precursor gases, interrupted by purging with inert gas (Figure 1). Both precursor exposures cause a self-limiting deposition effect that stops after an atomic-scale layer has been deposited. The self-limiting process enables unsurpassed layer thickness control and layer conformance on textured surfaces and even in very deep trenches.



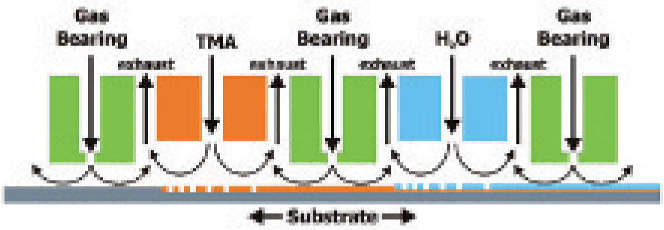
1 *ALD principle.*

One atomic layer has a thickness in the order of magnitude of 0.1 nm and the filling and purging of the reactor space is a slow process giving rise to the main drawback of ALD, the very low deposition rate (~ 1 nm/min). ALD was first developed and patented in the 1970s by Prof. Suntola in Finland, but has only found wide-scale application in the last decade in front-end semiconductor production. Here, the extreme layer control is instrumental in miniaturisation. Batch reactors are used to solve the speed issue. The cost per wafer is acceptable because of the high added value.

Spatial ALD

Three years ago, record deposition rates for alumina (Al_2O_3) of up to 1 nm/s (60 times faster than usual for single-wafer ALD) were reached at TNO using a different approach called *spatial* ALD (Figure 2), while maintaining the typical assets regarding layer quality as obtained by conventional ALD [1] [2]. In spatial ALD, the precursor gases are confined in fixed areas through which the substrate passes, thus eliminating the purge steps. This allows for ALD at high throughput numbers without using a batch process, opening up the possibilities of using this technique for lower-cost products.

The first test set-up was equipped with a rotating wafer table under a deposition head with two precursor segments separated by a nitrogen-fed gas bearing (Figure 3). The gas bearing conveniently combines the functions of contactless positioning at close range and precursor gas separation. Any mixing of the precursors trimethylaluminium (TMA)



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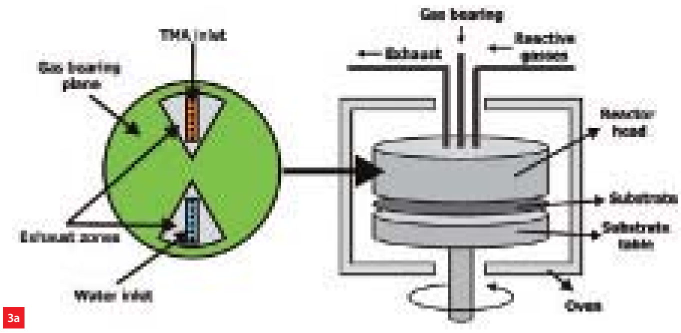
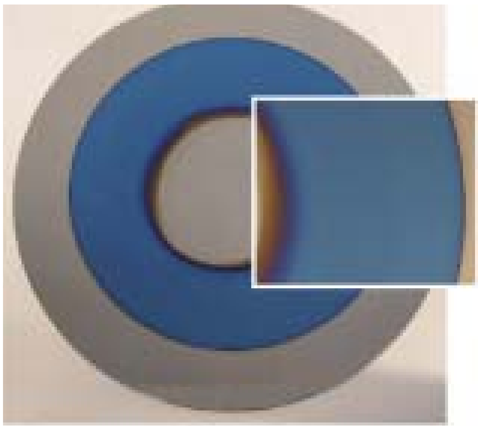


3a

and water vapour causes serious contamination with Al_2O_3 powder. This unit was placed in a simple oven with a hole drilled in the bottom for the wafer table axle, which means an expensive heated wafer table did not have to be used. The process temperature is typically 175-225 ºC. The growth rate of 1 nm/sec was reached at 10 rev/s. The same set-up – with some upgrades – is still in use at TNO and has since been utilised for a range of tests, also with different materials.

The homogeneous layer thickness typical for ALD is recognisable in the ring-shaped deposition pattern; the blue colour is caused by light interference at the thin layer. The constant growth-per-cycle is illustrated in the graph, confirming true ALD.

2 *Spatial ALD principle.*
3 *First, rotating test set-up.*
(a) Schematic.
(b) Sample with 90 nm ring-shaped deposition.
(c) Growth-per-cycle (GPC) graph.
4 *Improved backside passivation of solar cell with additional Al_2O_3 layer.*



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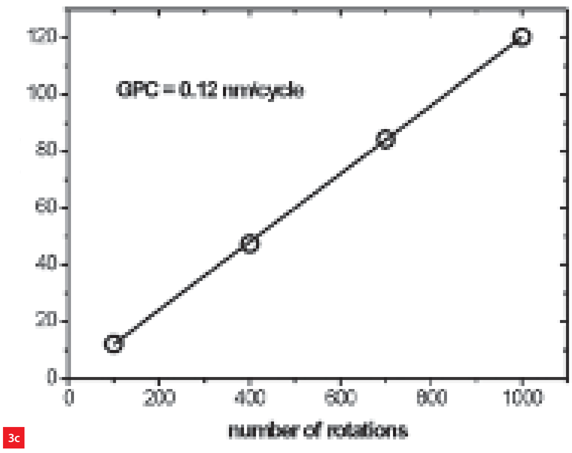

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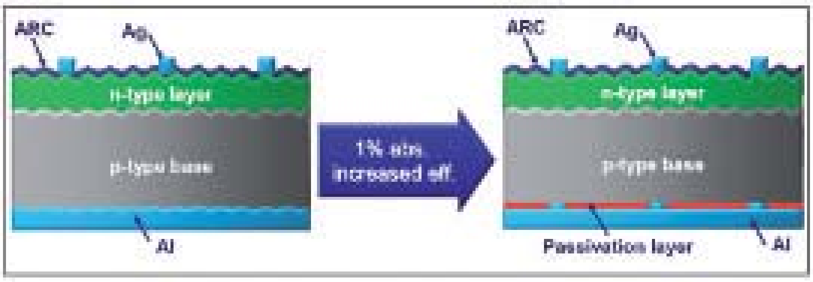
Solar cells

While searching for interesting applications based on these encouraging results, it was found that the speed breakthrough could benefit the passivation of crystalline-silicon solar cells. These are low-cost products produced in high volume, which was a no-go area for ALD before because of the low speed and high cost. Applying a thin alumina layer on the backside was reported to increase solar cell efficiency (Figure 4) and enables the use of thinner wafers, thus reducing the amount of silicon required, which is the main cost factor [3]. Using the Dutch ‘Kenniswerkersregeling’ (Knowledge Workers’ Scheme), a team was assembled to develop a system that would achieve full-area single-sided deposition of alumina on 156 x 156 mm^2 crystalline-silicon wafers [4].

Carrier-free, flexible concept

The concept chosen was aimed at industrial application. Reliability, throughput and flexibility are all important requirements. This leads to the ‘double floating’ concept: handling wafers without any mechanical contact and not using carriers in a spatial ALD reactor (Figure 5a). The injector head has two water chambers surrounding the TMA chamber, so the process will work in both directions resulting in two layers per full cycle. The injector head has the same width as the square or semi-square 156 x 156 mm^2 wafers. The reciprocating movement of the wafer is



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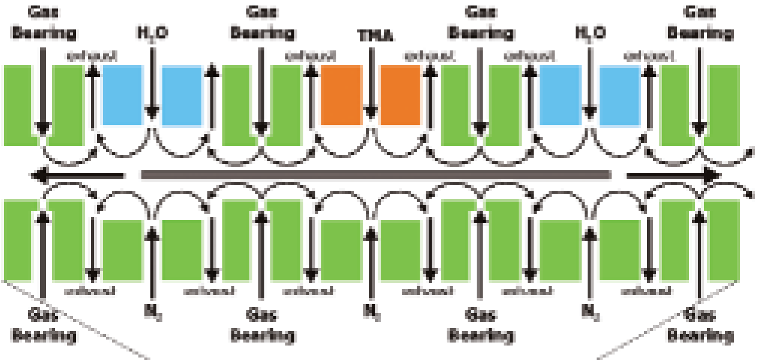

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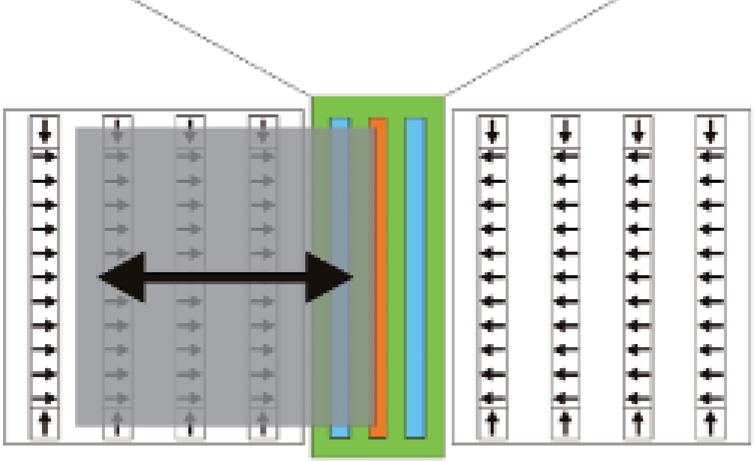

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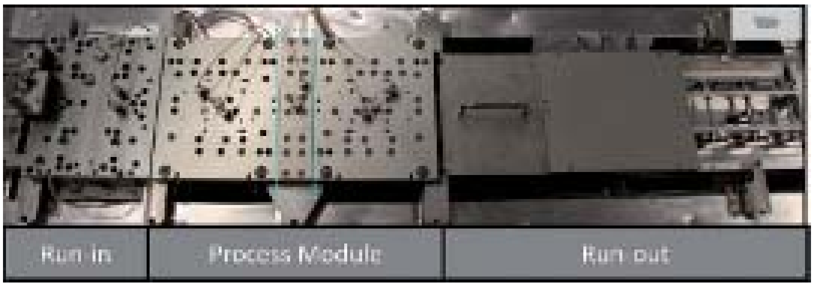


5c

5 *Double-floating spatial ALD reactor.*
(a) Schematic, in which 156 x 156 mm² wafers are transported back and forth, in a reciprocating motion underneath a spatial ALD injector head with the same width as the wafer.
(b) The injector head is surrounded by wafer drives that supply the reciprocal motion of the wafer on pulses of air.
(c) Experimental set-up with, from left to right, run-in, left-hand drive, injector head, right-hand drive and run-out.

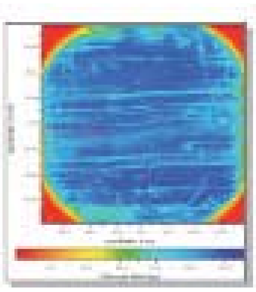
achieved by pulsing flows of air in the substrate drives next to the injector head (Figure 5b). The wafers are centred by flows of air perpendicular to the movement direction, on both sides of the wafer.

When the desired number of ALD cycles – and, correspondingly, the desired layer thickness – is reached, the wafer is ejected from the reactor. The next wafer can be processed in the reactor immediately after that because preheating, typically to 200 °C, is already done in a parallel step in a run-in section (Figure 5c). The cycle speed of the prototype was 2 Hz, resulting in a deposition rate of four monolayers per second or ~30 nm/min.

Homogeneous depositions (2-4% thickness variation) with minimal backside deposition are obtained over the entire area of the wafer (Figure 6). The passivation effect is measured by determining 'effective lifetime' τ_{eff} of electron-hole pairs that are triggered by (sun)light. These pairs fall back into a lower energy state after a certain time, a loss factor called recombination. Al_2O_3 was deposited on both wafer surfaces, and the samples were subsequently annealed at 350 °C for 30 min in a nitrogen ambient to activate the passivation. Excellent lifetime values were measured, although highly dependent on type, quality and pre- and post-treatment of the Si wafer.

These results are in line with earlier reports on the rotating tool and beyond practical requirements for the application. It is quite remarkable that these excellent results compare with much slower existing plasma-assisted ALD.

The project resulted in a new, independently operating OEM company being set up, named SoLayTec. The first customers were research institutes that further developed the solar cell concept including backside passivation with



6a

6b

6 *Deposition results.*
(a) Semi-square 156 x 156 mm², p-type CZ-Si, 1-3 Ω·cm. Lifetimes in the same range as achieved with the rotating tool.
(b) 156 x 156 mm² solar cell wafer with full area coverage, ~ 100 nm Al_2O_3 layer thickness variation (max – min)/(2·average) < 2%.

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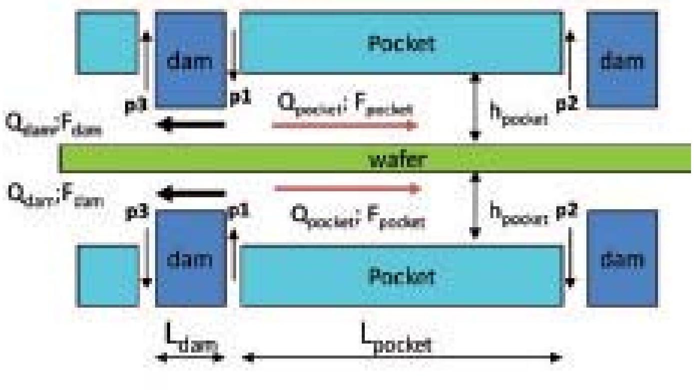

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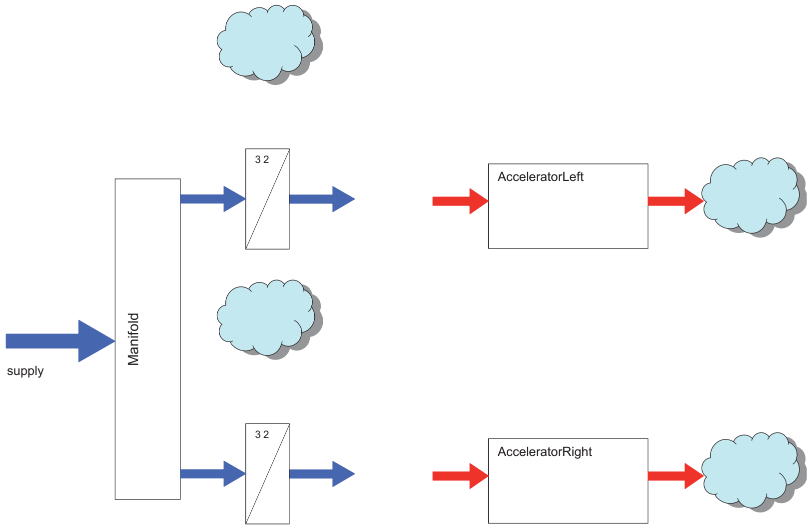

8b

7 *PDT with deposition unit (left) and gas supply unit (right).*

8 *Pneumatic drive pockets.*
(a) Shear forces on wafer result from flow Q_{pocket} *from* p_1 *to* p_2.
(b) Air heated up downstream of cold valves before entering the pockets.

alumina. For these users, a Process Development Tool (PDT) has been developed capable of processing at throughput numbers up to 150 wafers per hour based on a passivation layer thickness of 10 nm (Figure 7). This includes a gas supply unit, where liquid TMA and H_2O are evaporated before routing it to the deposition unit. Based on the same concept, a high-throughput ALD deposition tool – the High Volume Tool (HVT) – has subsequently been developed, targeting throughput numbers of up to 3,600 wafers/hr. Both products use the same core process modules to ensure a smooth transition from lab to fab.

High Volume Tool

The throughput needed to be drastically increased for mass production. The total deposition rate depends on the number of TMA and water slots that are integrated in the injector head, in combination with the number of passages of the substrate per second. It was feasible to integrate two TMA and three water sections in the injector head to achieve two layers per wafer passage instead of one, within the same footprint, increasing the throughput accordingly. Further scaling up to industrial requirements could be achieved by placing six or even ten injectors in parallel use, as a modular system (Figure 8). Still, that did not deliver the target throughput of more than 3,600 wafers/hour. For that, an upgrade of the motion solution was also required.

The motion challenge

With the growth per ALD cycle of 0.125 nm and a two-cycles-per-wafer passage through the injector head, the required layer thickness of 10 nm is reached after 40 passages. Since the system layout is based on pass-through, this is rounded off to 41 passes. With ten deposition units in the system and 3,600 wafers per hour system throughput, one wafer should be processed in 10 seconds. With 0.5 seconds transport time (the time between the last deposition of one wafer and the first deposition of the next), 9.5 seconds remain for the 41 passes. The process requires a constant speed, but is forgiving in the speed accuracy because of the self-limiting nature of ALD. The speed value was established at 1.2 m/s, 20% higher than in the PDT. After passing through the TMA slots, the motion should reverse as fast as possible. The total stroke is circa 200 mm. The chosen target acceleration (and deceleration) is 24 m/s^2. The moving mass is 10 g, leading to a required driving force of 240 mN.

The driving force is realised by shear forces of hot air floating symmetrically alongside the top and bottom plane of a section of the wafer through drive pockets (Figure 8a). It has taken considerable effort to come up with the detailed design and optimisation of these pockets, but these have

9 *High Volume Tool with ten deposition units. Every DU (shown in the inset) has one injector head and all DUs connect to a main conveyor belt. If one DU fails, all others continue. Repairs can be done offline.*

now become SoLayTec's area of expertise. The requirements have indeed been met in the latest improved drive pocket design. One of the improvements was to switch from one pocket per side to two parallel, shorter pockets. In the end, the design is a trade-off between air consumption and cycle speed.

The wafer position is measured at discrete points to keep the hardware simple and robust. The actual position and speed at intermediate points is calculated; depending on the position, that information includes some latency. All input flows have to be preheated to the process temperature to ensure an isothermal process. Standard pneumatic valves have been chosen for cost and availability reasons. These valves cannot withstand the heat of the air fed into the reactor. Therefore, the air passes through heaters downstream of the valves before entering the reactor (Figure 8b). This means there is also a time lag between the switching of the valves and the actual realisation of the force, even on top of the switching time of the valves.

To further complicate things, each subsequent wafer can have significant total thickness deviations that influence the pocket forces and the actual moving mass. The control algorithm to make the motion work reliably under these circumstances was one of the challenging aspects of the design. It is based on iterative learning control; during every cycle, the actual movement is measured, evaluated and used as input for the control signals of the next cycle.

The process speed variation actually achieved is less than 5%, which is quite satisfactory for the ALD process.

Reliability and serviceability

Selling a technically innovative new machine incorporating a new process for a new solar cell design to a customer on the other side of the globe that needs to produce 24/7 is more than challenging for a start-up company. In the product architecture domain this has led to a highly modular concept (Figure 9). It is in fact a cluster tool with a fully independent asynchronous operation. Every deposition unit (DU) performs the full process with each wafer passing through only one of the DUs. If one DU fails, the wafers simply pass this DU, while all the other DUs continue. In the rare case that the problem cannot be solved on the spot, the DU can be taken out and replaced within minutes. Including preheating, less than an hour (partial) downtime is needed.

Compared to other machines in the same production line, the total footprint of the system is not too big. As such, a spacious layout has been chosen because it provides good accessibility for service.
Recent system tests have confirmed system performance on all major performance aspects. One of the remarkable results concerned the wafer breakage rate, which was more than ten times better than the specified 0.1% at system level, confirming the rationality of the challenging motion concept.

Conclusion

A successful launch of a new OEM company based on a new promising technology has been achieved in a relatively short time. The first High Volume Tool was recently shipped to Asia. The HVT concept has been well received in the market and system performance is satisfactory. ■

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SUMMER SCHOOL ON MANUFACTURABILITY

The Summer School on Manufacturability, a DSPE initiative, is organised by and held at the Leidse instrumentmakers School (LiS, Leiden Instrument Makers School). The five-day course (27-31 August 2013) in Dutch is aimed at young professional engineers with limited manufacturability know-how. Milling, turning, grinding, Electrical Discharge Machining (EDM), casting and sheet metal working are the technologies presented and discussed.

Stainless steel frame made by metal sheet working. (Photo courtesy of Suplacon)

Day	Tuesday 27 August	Wednesday 28 August	Thursday 29 August	Friday 30 August	Saturday 31 August
Location	LiS (Leiden)	LiS (Leiden)	Hittech Gieterij (Nunspeet)	Suplacon (Emmeloord)	LiS (Leiden)
Technology	Milling and turning (introduction)	Milling, turning and grinding (advanced)	Metal casting	Metal sheet working	EDM (Electrical Discharge Machining)
Morning	Marco van der Velden (Hittech MPP) elaborates on the essence of CAD/CAM-based production engineering and planning for machining complex and high-precision components. Additionally, the LiS introduces milling and turning.	TNO highlights the functional and technical aspects of micro-milling. Next, Bart Venhuis and Jan Willem Zierikzee (Hembrug) discuss the developments and practicalities of hard-turning. Jaco Saurwalt (ECN) shares the concept and practicalities of grinding.	Bart Meijnen gives a tour of the basics of metal casting to the point of current technologies. The advantages of casting are discussed, as well as the limitations, so that well-considered choices can be made regarding the casting process.	Frank ten Napel elaborates on metal sheet working, covering separating operations (e.g. laser cutting), transforming processes (e.g. deburring and tapping) and bending operations, including tolerance aspects. Also, cost-efficient design for sheet metal working is introduced.	Gerrit ter Hoek (Ter Hoek Vonkerosie) offers an in-depth overview of EDM, covering different EDM technologies and capabilities of EDM in terms of e.g. micro-precision. Tacx is visited, where Ramon van der Stel shows EDM in practice.
Afternoon	Fabrication illustrations and practice are offered by LiS professionals, including Hessel Dolman and Gerko van Veelen. Participants will design and fabricate a product with conventional turning. Next, CNC-machining (programming and fabrication) is demonstrated interactively on the basis of different product designs (e.g. details, dimensions, accuracies).	The participants are offered practical experiences in the LiS workshop. The LiS professionals provide training regarding the process from CAD/CAM to CNC-machining. This training reflects on various designs. Additionally, the participants experience quality control by measuring CNC-fabricated objects.	The foundry is shown more extensively. The participants are involved in the process of making their own casting product. With the given theory and practice, the participants are informed about good formability of casting, cost aspects of metal casting, possibilities such as reverse engineering and basic design rules with respect to metal casting.	The lecture continues, including reflection on the participants' sheet metal assignment. This assignment is given to the participants before the course (more details will follow). Next, the fabrication process of sheet metal working is shown at Suplacon. Piet van Rens (Settels Savenije van Amelsvoort) reflects on construction principles related to sheet metal.	Gerrit ter Hoek continues his lectures. He discusses production engineering and cost aspects of EDM, based on various examples. EDM practice is shown at the LiS location.
Evening	Informal group discussions facilitated by senior experts in research instrument making, production engineering etc. Participants are inspired to share examples from their daily work.	Informal group discussions facilitated by senior experts.	Visit of "Nacht van Nunspeet" (Night of Nunspeet), including street theatre performances.	Informal group discussions facilitated by senior experts.	

REGISTRATION

Participants can register online. The course will be held in the Dutch language. Participants can make usage of the LiS's hotel deals for the nights in the Leiden region (27, 28 and 30 August) and in the Nunspeet region (29 August).

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HIGH-TECH SYSTEMS 2013: SUCCESSFUL DEBUT

The High-Tech Systems international conference and exhibition in Eindhoven that focused on high-tech innovation and mechatronics was a resounding success. The conference attracted nearly 2,400 visitors and over 100 exhibitors, and especially the lectures on various high-tech topics were very well received. The event was an initiative by Brainport Industries, DPSE, Syntens and Techwatch.

EDITOR'S NOTE

This review was contributed by Techwatch.

www.techwatch.nl

The event was held in the Klokgebouw, which is part of the Philips heritage. (Photos: Bart van Overbeeke/Techwatch)

The mayor of Eindhoven, Rob van Gijzel, opened High-Tech Systems 2013.

The opening sessions included lectures on co-development and cooperation by high-tech giants such as ASML/Zeiss, Philips/Süss and Mapper/Leti. Business, networking and commercial partnerships were high on the agenda of the exhibiting companies. The Europe Enterprise Network matchmaking went very well with 60 participants and 100 matchmaking meetings.

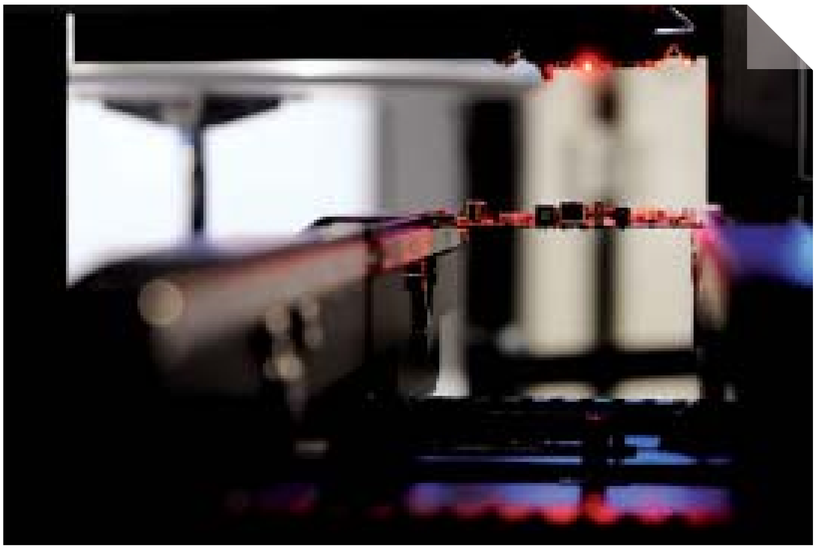
The event was also particularly lively because of its side events on sensor developments, piezo systems, service business, and model-driven development. On Tuesday, 23 April, one day before the main event, more than 60 international visitors had the opportunity to visit the best

The 2014 event will be held on 7 and 8 May 2014 near Eindhoven at the 's-Hertogenbosch 1931 heritage conference facilities. High-Tech Systems 2014 aims to have an even stronger international focus in terms of participants, visitors and lectures. High-Tech Systems has enjoyed an incredible start and is now on track to become a recognised leading event in Western Europe on high-tech systems. Information on commercial opportunities is already available. ■

high-tech players from the industry and academia in and around Eindhoven, such as the High Tech Campus, Eindhoven University of Technology, ASML, Imec and TNO. This opportunity was much appreciated, and the day finished with a 'tech dinner' in the *De Machinekamer* restaurant.

Visitors from twelve nations attended the High-Tech Systems event, with Germany being especially well-represented; German participants came from Silicon Saxony, North Rhine-Westphalia and Hessen. Approximately 10% of the visitors came from abroad, which is a very good start to build on for High-Tech Systems 2014.

Next year, the event will once again take high-tech innovation and engineering as a theme, focusing on advanced high-tech co-development and co-engineering as well as advanced and close cooperation models to bring systems to market on time and on budget, and with the required specs and features. High-Tech Systems 2014: 'Complex Systems, Close Cooperation'.



INFORMATION

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SPREADING THE **PIEZO** GOSPEL

Piezo technology has come of age and in the Netherlands the Applied Piezo foundation is its messenger. 2013 saw the closure of the successful SmartPie research programme at a High-Tech Systems 2013 seminar and the publication of a comprehensive piezo textbook. Applied Piezo is now working to increase its international visibility and develop a full-blown training programme.

Examples of piezo components for high-tech applications.

Piezoelectric materials are among the 'invisible' materials that are all around us, although they are unknown to the public at large. Mobile phones (camera focus), automotive electronics (airbag, parking sensor) and medical technology (foetal ultrasound) are just a few of the application areas in which 'piezo' is indispensable. High-tech systems are increasingly dependent on mechatronic solutions, using piezo-electric mechatronic systems to enhance accuracy and cut prices. Piezoelectric actuators – devices that convert an electrical signal into an 'action' such as a physical displacement – play an important role in such high-tech systems, and also in high-tech manufacturing technology. So do piezoelectric sensors, which are devices that convert a mechanical action into an electrical signal. Applications range from inkjet printers and loudspeakers to scanning tunnelling microscopes (STMs) and wafer scanners for making integrated circuits (ICs).

Piezo-based parking sensors.

Applied Piezo

The aim of the Applied Piezo foundation is to facilitate industry access to promising and indispensable piezo technology. Applied Piezo is a group of companies (including Océ, TNO and Bosch Rexroth Electric Drives & Controls) and universities (the three Dutch universities of technology and K.U.Leuven in Belgium) that provide complementary piezo expertise. Their collaborative goals are:

- to create new business for piezo actuators and sensors;
- to promote piezo technology;
- to stimulate knowledge development and innovation;
- to provide a network for exchanging knowledge, expertise and products.

SmartPie

In 2007, Applied Piezo initiated the SmartPie research programme ("SMART systems based on integrated PIEzo"). SmartPie research was aimed at strengthening the innovative position of the Dutch high-tech industry by generating new piezo-based technology. This research programme was funded by the participating companies and universities as well as by the Dutch government through the SmartMix programme.

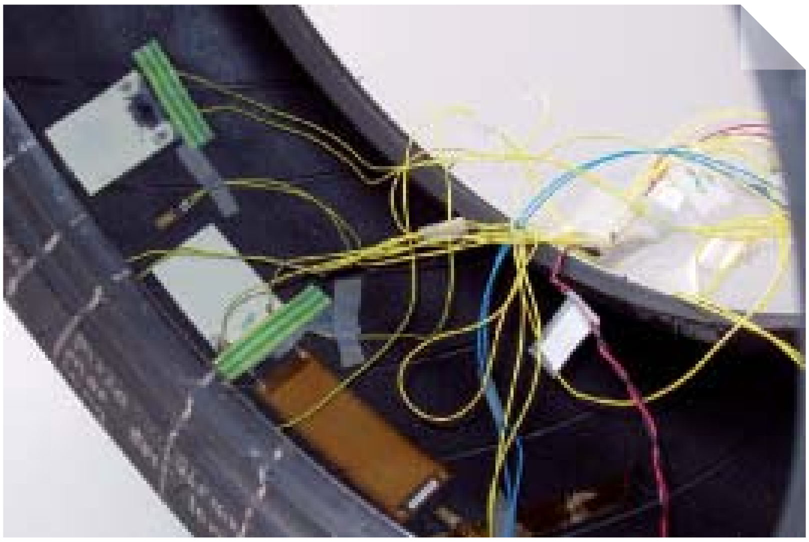
The research focussed on two lines:

- Integrated Manufacturing
  Technology transfer for manufacturing piezo systems via alternative and integrated production routes. The research concentrated on thin-film systems via a silicon technology route (MEMS, Micro Electro Mechanical Systems), post-formable systems via polymer injection and or blow moulding and robust systems via metal forming technology.
- New applications
  Innovative piezo applications for high-tech systems, including a set of mechanical, measurement and control design principles to be used for a variety of systems. The application research was concentrated around vibration control in precision equipment and touch-based man-machine interfaces.

The programme now has come to an end, and this was marked by a closing seminar at High-Tech Systems 2013 (see the report on the event in this issue of Mikroniek, page 42 ff.) and presentations at the Materials 2013 trade fair & conference in Veldhoven, the Netherlands.

International audience

Building on the results of the research programme and continuing its community building activities, Applied Piezo strives to strengthen its international visibility as the piezo portal to the Dutch piezo-related industry. The Electroceramics XIII conference held at the University of Twente in Enschede (the Netherlands) in June 2012 was a milestone in that respect. The Applied Piezo LinkedIn group is an important tool in the foundation's internationalisation strategy.



A piezo-based energy-harvesting car tire.

The 2012 and 2013 highlights of the publication of the piezo technology introductory books (see the box on the next page) have laid the foundation for extending the piezo course that was developed under the auspices of SmartPie to provide a common ground for researchers. The extended course will be aimed at a wider audience, as part of Applied Piezo's ongoing efforts to spread the piezo gospel.

Active vibration isolation

The final SmartPie report will be published this summer. For a preview of SmartPie output, please read the article on active vibration isolation in this Mikroniek issue, page 20 ff.

INFORMATION

WWW.APPLIED-PIEZO.COM
WWW.SMARTPIE.NL
WWW.LINKEDIN.COM/GROUPS?GID=49032

☞ Continue

An Introduction to **Piezoelectric Materials** and **Applications**

The SmartPie seminar at High-Tech Systems 2013 concluded with the presentation of *An Introduction to Piezoelectric Materials and Applications*. The book is an extended version of *An Introduction to Piezoelectric Materials and Components* (2012) by the same authors, Jan Holterman and Pim Groen. This initiative from the Applied Piezo foundation was part of the SmartPie research programme's dissemination activities and was welcomed as a broad overview of the field by the international piezo community, which prompted the authors to expand the book to include chapters on application fields and practical considerations.

The new publication, containing over 200 full-colour illustrations (most of which are brand new), is aimed at creating a basic understanding of the piezoelectric effect and its use in a wide variety of applications. It is useful for students and engineers who want an introduction to the world of piezoelectric materials and the broad scope of electromechanical transducers in which piezoelectric components are used.
The book provides:

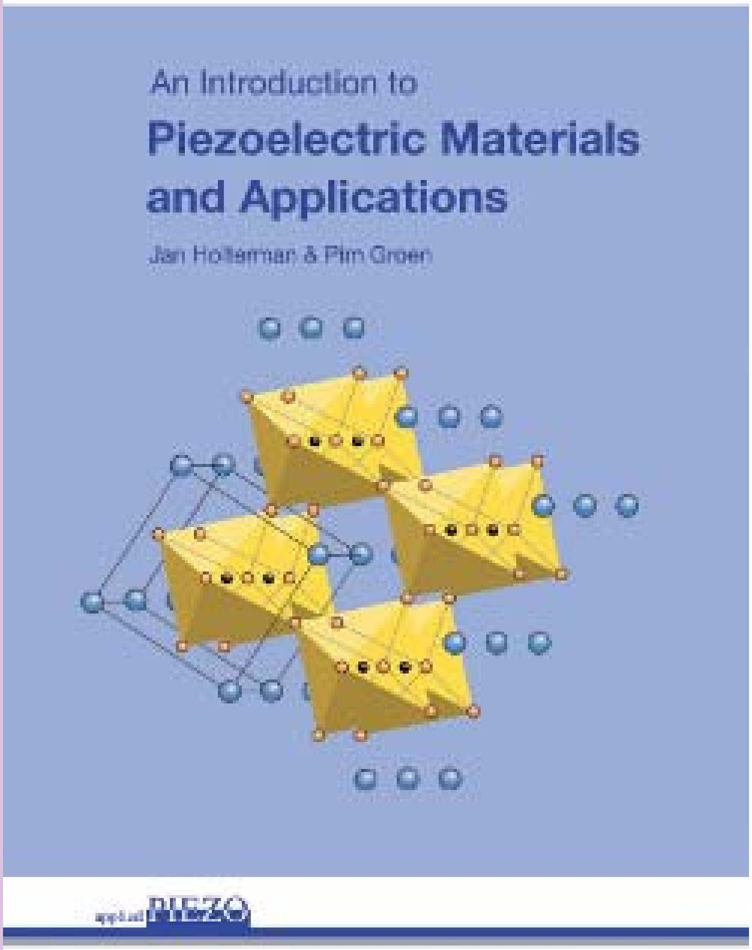
- general modelling tools for understanding and describing the behaviour of piezoelectric materials and components;
- an overview of piezoelectric materials, piezoelectric ceramic components, piezoelectric thin films and the manufacturing thereof;
- an introduction to the use of piezoelectric components in four distinct application fields:
  a) sensors,
  b) generators and energy harvesters,
  c) actuators and motors,
  d) acoustic transducers;
- an overview of measurement techniques and practical tips for using piezoelectric components.

Besides the basics of piezo technology and a broad overview of application fields, the book includes various results from the SmartPie research programme, e.g. energy harvesters, piezoMEMS and composites (multiphase materials for variation of electrical and physical properties).

Jan Holterman obtained his Ph.D. on active vibration control using smart materials from the University of Twente (the Netherlands). He is currently working for Imotec, a mechatronic engineering company in Enschede (the Netherlands), and he specialises in engineering piezoelectric applications. Pim Groen joined Philips Research in Eindhoven in 1987 and obtained his Ph.D. in the field of cuprate superconductors in 1990. In 2002, he moved to Morgan Electroceramics to continue his work on piezoelectric ceramics. He is currently working at Holst Centre as a programme manager and at Delft University of Technology as a professor in the field of smart materials & sensors.

A preview of the book and an order form can be found on the Applied Piezo website.

WWW.APPLIED-PIEZO.COM



Jan Holterman & Pim Groen, ***An Introduction to Piezoelectric Materials and Applications****, hardcover, 307 pages, ISBN 978-90-819361-1-8, € 58.50 (handling and shipping not included, special rate for students)*

SUMMER SCHOOL
OPTO-MECHATRONICS 2013

The Summer school 2013 is jointly organised by DSPE, The High Tech Institute and Mechatronics Academy, from June 24 to June 28, 2013. It will be hosted by TNO at its premises on the TU/e campus in Eindhoven. The summer school is the place to be for anyone working in the field of precision engineering and wanting to learn and experience from expert designers how to design opto-mechanical instruments that are actively controlled, operating in the non-perfect environment.

24 June – "The BIG picture" & Systems Engineering
Rob Munnig Schmidt (Delft University of Technology) & Friso Klinkhamer (ASML)
The first day will focus on the systems engineering aspects of product development and discuss the optical delay line of ESO's Very Large Telescope (see page 5 ff.) in terms of requirement management, conceptual system design, first elaboration of preferred concept, system breakdown/budget flow, and verification.

25 June – Optical Design
Stefan Bäumer & Eddy van Brug (TNO)
The optics day will consist of two parts: an overview of the optical aspects of a delay line followed by an introduction to optical design approaches. These will be put into practice, when the participants will design an optical delay line. Finally, they will work with the optical design programme Zemax. A detailed discussion on the simulation results will be given.

26 June – Control Design
Pieter Nuij (Eindhoven University of Technology) & Adrian Rankers (Mechatronics Academy)
In control technology terms the optical delay line can be seen as a linear motion system. A tutorial of principles and methods of motion control will be given, with special attention paid to the typical control challenges of delay lines: servo behaviour, vibration disturbance rejection, sensor noise and closed-loop stability. The participants will put motion control theory into practice by undertaking design exercises for a delay line.

27 June – Opto-Mechanical Design
Jan Nijenhuis & Fred Kamphues (TNO)
Apart from putting things together, high-quality mechanics will guarantee best performance in terms of optical quality/stability and control performance. Lightweight and stiff structures are therefore crucial in achieving this goal. Emphasis will be put on the interactions with the other key technologies needed (optics, control and electronics) and on the mechanical design itself. Participants will design a specific part of the cat's eye (optical section of the delay line).

28 June – Actuation, Sensing & Dynamics
Rob Munnig Schmidt (TU Delft) & Adrian Rankers (Mechatronics Academy)
Some still missing elements will be presented that are necessary to realise high-performance active positioning and control systems for optics. An overview is given on electromagnetic and piezoelectric actuators, optical position measurement systems and capacitive sensors. Further, attention will be given to the performance-determining mechanical system dynamics and vibration isolation. The new field of adaptive optics will shortly be touched upon.

Evening programme
The evening programme during the week will feature experiences with the Very Large Telescope (Frederic Derie, ESO), systems engineering and wafer steppers (Frank de Lange, ASML) and an active informal summer programme. ■

WWW.SUMMER-SCHOOL.NL

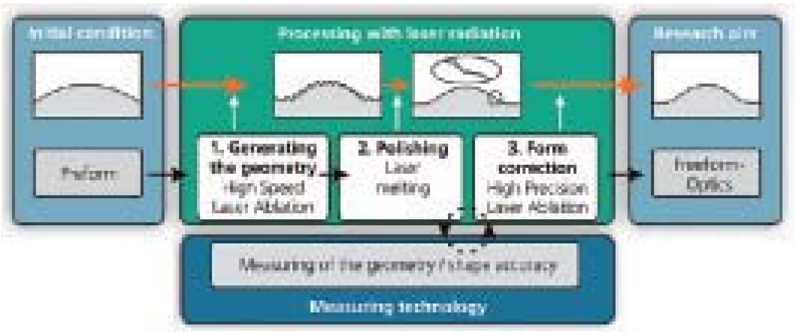
Special Interest Group Optics & Opto-Mechatronics

At the High-Tech Systems event in Eindhoven, the Netherlands, – a concise report can be found on page 42 ff. in this issue – the DSPE Special Interest Group Optics & Opto-Mechatronics was launched. In his Editorial, on page 4, DSPE board member Cor Ottens introduces this new DSPE initiative. in September/October 2013, DSPE wants to organise its first conference on optics and opto-mechatronics.

FAST **FREEFORM** PROCESSING

When it comes to optics with aspherical or freeform surfaces, conventional optics manufacturing methods require long processing times. At the Fraunhofer Institute for Laser Technology ILT in Aachen, Germany, a laser-based process chain especially for manufacturing these kinds of optics is in development.

SEBASTIAN HEIDRICH



1 *Illustration of the laser-based process chain for manufacturing freeform optics.*

Optics with an aspherical surface form improve image quality and moreover can replace several pieces of spherical optics and help to reduce the size and weight of optical components. On the other hand, they are expensive to produce with conventional manufacturing methods and thus can only be applied in high-priced systems. Furthermore, freeform optics with no symmetrical axis may give rise to completely new optical systems, but at even higher manufacturing costs.

For that reason, a laser-based optics manufacturing process is in development at the Fraunhofer Institute for Laser Technology ILT. With laser radiation, a tool is used that can be adjusted to the surface form in nearly no time and is thus especially suitable for aspherical and freeform surfaces. The aim of this new manufacturing method is to increase the flexibility and individualisation in the manufacturing of optical components by using laser radiation. This includes the processing of the geometry as well as the polishing, especially of aspheres and freeform optics which can be manufactured with high flexibility and short lead time.

To reach the surface roughness and form accuracy needed for optics, the laser-based optics manufacturing process is divided into several single steps, which are then combined within a process chain (Figure 1). Starting from an easy-to-manufacture glass preform, a first processing step removes redundant material with High Speed Laser Ablation. A second step involves polishing the resulting surface and reduces the roughness generated by the High Speed Laser Ablation step, without removing any material. An optional third step locally removes remaining redundant material with high precision and leads to the desired (freeform) optics. During and/or between these steps, a measurement of the geometry and shape accuracy is executed in order to match the actual with the targeted result.

AUTHOR'S NOTE

Dipl.-Ing. Sebastian Heidrich is a member of the Polishing group within the Fraunhofer Institute for Laser Technology ILT in Aachen, Germany.

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Compared to conventional manufacturing methods, one great advantage of this process chain is the decoupling of tool and workpiece geometry. This leads to a great amount of flexibility and a short processing time, which is nearly independent of the surface geometry, but only varies with the optics size and the amount of material to be removed. One more advantage is the modular design, which allows the isolated development of each process step. Moreover, single process steps can also be applied within conventional manufacturing methods, thereby leading to a shorter processing time.
For the Laser Polishing, CO_2 laser radiation is needed because of its high absorption coefficient in a thin surface layer of the glass material. For that reason, CO_2 laser radiation is also used for the two ablation processes. Compared to ultra-short pulse laser radiation, which can also be used for the ablation processes, it moreover exhibits higher laser powers, which results in a shorter manufacturing time.

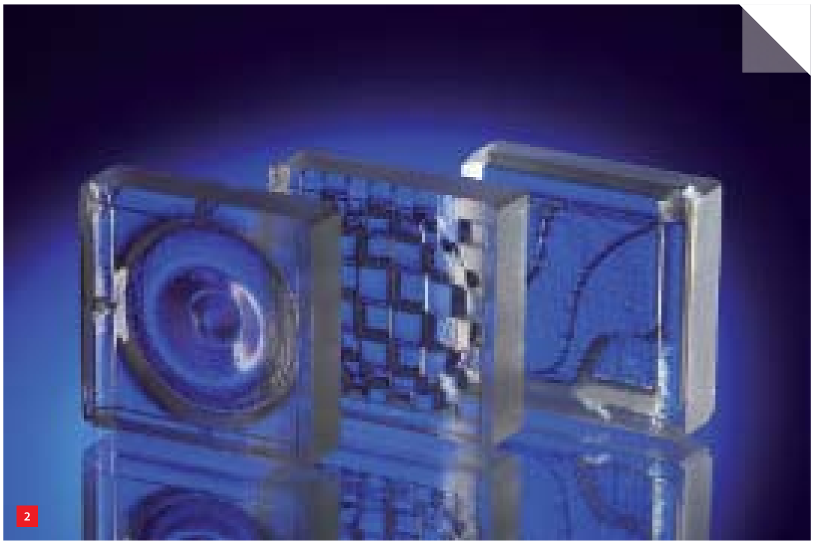
Generating the surface form

In order to generate the optics surface shape, glass material is removed with High Speed Laser Ablation. For this purpose, high laser powers are used to heat up and vapourise the glass surface. The resulting glass vapour is removed from the working area with an extraction system. With a constant high laser power, high ablation rates and thus short processing times can be reached, comparable to the times of conventional grinding methods on plane glass material. With a variation of the process parameters, different ablation depths, resulting in curved surfaces, can be realised without increase of the processing time. With this method, nearly any desired surface form can be generated. Examples are displayed in Figure 2. It shows the high flexibility concerning the surface shape. Moreover, starting from a glass sample with a conventionally polished plane surface, generating any surface form with the High Speed Laser Ablation requires less than 30 seconds.

Reducing the surface roughness

After generating the surface form, its roughness has to be reduced for use as an optical component. This is done by Laser Polishing. In this process step, the optics surface is heated up with laser radiation to temperatures just below its vapourisation temperature. As a result, the glass viscosity is reduced and the roughness can be smoothened without removing any material or changing the generated surface shape. In order to reach the desired temperature everywhere on the surface without exceeding the vapourisation temperature, the process has to be adapted towards the surface shape (Figure 3). This is done without changing the tool itself, but just by adaption of process parameters via a graphical software interface. These adaptions then are used to calculate the required movement of the laser beam on the glass surface.

With these adaptions, the Laser Polishing – just like the High Speed Laser Ablation – is very flexible concerning the surface shape to be processed. Again, the processing time does not depend on the surface shape itself but on the glass material and the size to be polished, so spherical, aspherical and freeform optics of the same material and size can be polished in nearly the same time. Starting from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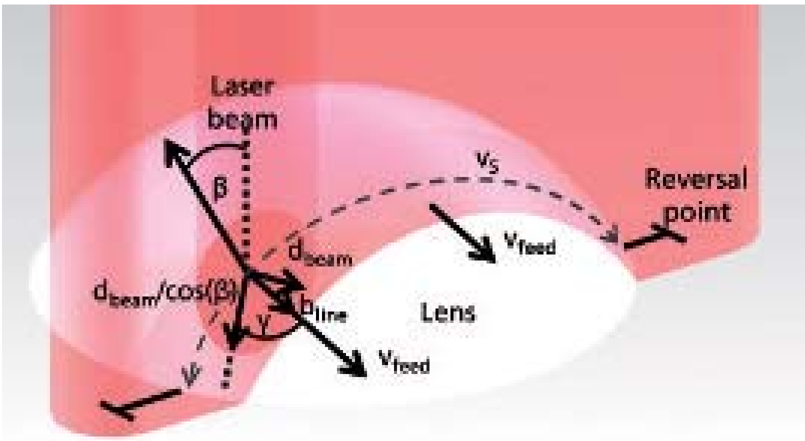

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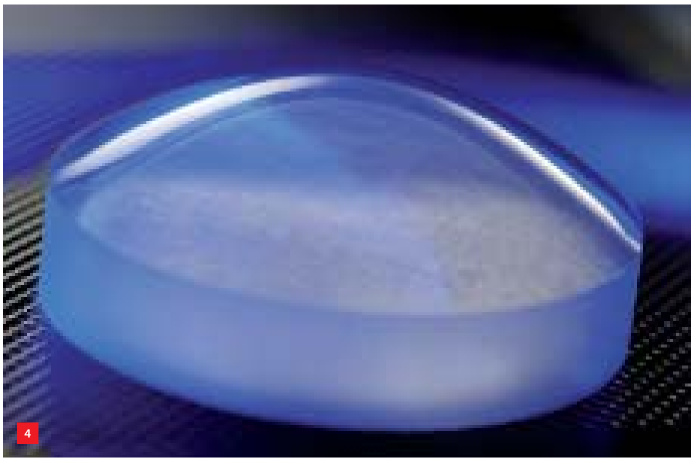
2 *Demonstration of the High Speed Laser Ablation; processing time for each sample (20 mm edge length) < 30 s.*
3 *Description of the main process parameters for Laser Polishing.*



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4 *Laser Polished optics with aspherical surface (Ø 64 mm); processing time < 40 s.*

5 *Demonstration of the High Precision Laser Ablation; processing time < 30 s.*

6 *Demonstration of the whole process chain; processing time (20 mm edge length) < 2 minutes.*
From left to right:
- *Initial material*
- *High Speed Laser Ablation*
- *Laser Polishing (front side)*
- *Laser Polishing (rear side)*

conventionally ground surfaces, a surface roughness sufficient for illumination optics can already be achieved by Laser Polishing (Figure 4).

Applying form correction

For a surface roughness which is sufficient for imaging optics, the Laser Polishing will be optimised in the future. In addition, a High Precision Laser Ablation step for reducing the roughness and for form correction can be applied. The requirements for this step directly emerge out of the Laser Polishing: material removal with high lateral as well as vertical resolution and moreover selective material removal without changing surface areas is necessary. For this, the surface has to be measured in order to identify the areas with material to be removed. After that, the measurement data has to be transferred into instructions for the laser processing machine. Especially the vertical resolution with values < 10 nm for reducing the roughness can be achieved with laser radiation. When applied to a conventionally polished surface, selective ablation depths < 10 nm can be reached, as witnessed by Figure 5. It shows the capability of selective material removal as well as the high vertical resolution.

Combination of the process steps

For manufacturing optical components, the process steps have to be combined into the described process chain. First results are presented in Figure 6, showing the combination of High Speed Laser Ablation and Laser Polishing. Starting from a conventionally ground flat glass sample, the desired surface form is generated with High Speed Laser Ablation. Subsequently, the resulting surface roughness is reduced by Laser Polishing. To get a transparent optical sample, the ground rear side is also Laser Polished. The combination of Laser Polishing and High Precision Laser Ablation is investigated in a separate process. After Laser Polishing, the surface is measured with white-light interferometry. Based on the measurement data, the surface is processed with High Precision Laser Ablation.

Further development

In conclusion, the presented laser-based optics manufacturing paves the way for a revolutionary new approach to manufacturing nonspherical optical components in shorter time and with lower costs. Nevertheless, more development has to be conducted in order to meet the demanding requirements for optical components. For example, the form deviation has to be reduced to smaller values. Moreover, the process steps have to be adapted towards each other for efficient use within the laser-based process chain. ■

UPCOMING **EVENTS**

24-28 June 2013, Eindhoven (NL)

International Summer school Opto-Mechatronics 2013

Five days of intensive training, organised by DSPE, The High Tech Institute and Mechatronics Academy.

WWW.SUMMER-SCHOOL.NL

26-30 June 2013, Eindhoven (NL)

RoboCup 2013

International event with 2,500 participants, featuring the robot soccer world championship (in three leagues, including the Humanoid League) and the RoboCup Rescue and RoboCup@Home challenges.

WWW.ROBOCUP2013.ORG

27-31 August 2013, Leiden (NL)

Summer School Manufacturability

A joint initiative of DSPE, LiS Academy and the Hittech Group. See page 41 for a detailed schedule.

(Photo courtesy of Hittech Group)

WWW.LISACADEMY.NL

7 November 2013, Den Bosch (NL)

Bits&Chips 2013 Embedded Systems

Twelfth edition of the conference on embedded systems and software, organised by Techwatch.

WWW.EMBEDDED-SYSTEMEN.NL

21 November 2013, Utrecht (NL)

Dutch Industrial Suppliers Awards 2013

Event organised by Link Magazine, with awards for best knowledge supplier, best logistics supplier and best customer.

WWW.LINKMAGAZINE.NL

3-4 December 2013, Veldhoven (NL)

Precision Fair 2013

Thirteenth edition of the Benelux premier trade fair and conference on precision engineering. Some 260 specialised companies and knowledge institutions will be exhibiting in a wide array of fields, including optics, photonics, calibration, linear technology, materials, measuring equipment, micro-assembly, micro-connection, motion control, surface treatment, packaging, piezo technology, precision tools, precision processing, sensor technology, software and vision systems. The conference features more than 50 lectures on measurement, micro-processing, motion control and engineering. The Precision Fair is organised by Mikrocentrum.

WWW.PRECISIEBEURS.NL

11-12 December 2013, Ede (NL)

Netherlands MicroNanoConference '13

Conference on academic and industrial collaboration in research and application of microsystems and nanotechnology. The ninth edition of this conference is organised by NanoNext.NL and MinacNed.

WWW.MICRONANOCONFERENCE.NL

7-8 May 2014, Den Bosch (NL)

High-Tech Systems 2014

The second edition of this event around mechatronics and precision technology; see the report on the first edition on page 42 ff.

WWW.HIGHTECHSYSTEMS.EU

CPE COURSE CALENDAR

COURSE	CPE points	Provider	Starting date (location, if not Eindhoven)
BASIC			
Mechatronic System Design (parts 1 + 2)	10	HTI	30 September 2013 (part 1) 11 November 2013 (part 2)
Construction Principles	3	MC	29 October 2013 (Utrecht) 19 November 2013
System Architecting	5	HTI	4 November 2013
Design Principles Basic	5	HTI	25 September 2013
Motion Control Tuning	6	HTI	20 November 2013
DEEPENING			
Metrology and Calibration of Mechatronic Systems	2	HTI	18 November 2013
Actuation and Power Electronics	3	HTI	23 September 2013
Thermal Effects in Mechatronic Systems	2	HTI	to be planned
Summer school Optomechatronics	5	DSPE + HTI	24 June 2013
Dynamics and Modelling	3	HTI	25 November 2013
Specific			
Applied Optics	6.5 6.5	MC HTI	12 September 2013 29 October 2013
Machine Vision for Mechatronic Systems	2	HTI	26 September 2013
Electronics for Non-Electronic Engineers	10	HTI	3 September 2013
Modern Optics for Optical Designers	10	HTI	13 September 2013
Tribology	4	MC	30 October 2013 (Utrecht) 27 November 2013
Introduction in Ultra High and Ultra Clean Vacuum	4	HTI	28 October 2013
Experimental Techniques in Mechatronics	3	HTI	to be planned
Design for Ultra High and Ultra Clean Vacuum	4	HTI	25 November 2013
Advanced Motion Control	5	HTI	7 October 2013
Cooling of Electronics	3	HTI	6 November 2013
Iterative Learning Control	2	HTI	4 November 2013
Advanced Mechatronic System Design	6	HTI	to be planned

DSPE Certification Program

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

WWW.DSPEREGISTRATION.NL/LIST-OF-CERTIFIED-COURSES

Course providers

- The High Tech Institute (HTI)
  WWW.HIGHTECHINSTITUTE.NL
- Mikrocentrum (MC)
  WWW.MIKROCENTRUM.NL
- Dutch Society for Precision Engineering (DSPE)
  WWW.DSPE.NL

Piezo expert HEINMADE takes over wire-EDM specialist CVT

In the promising and growing field of piezo technology, Heinmade started distributing high-performance piezo components from international manufacturers such as Noliac and Piezomechanik in 2005. Over the years, the company developed into a supplier of piezo-ceramic solutions, particularly for the semi-conductor and medical technology industries. Heinmade is based on the High Tech Campus Eindhoven, the Netherlands, and has a staff of ten. With its in-house piezo knowledge and production technology, the company can develop and supply customised piezo-based systems for high-tech clients, from prototypes to medium-sized series. The company outsources the production of components while assembling and testing systems itself, if necessary in a cleanroom environment. Piezo technology is often used in casings or so-called stages (positioning systems) that can be manufactured to high accuracy using wire Electrical Discharge Machining.

Controlled Vonk Technologie (CVT) in Hoogeloon near Eindhoven has been a specialist in the field of wire Electrical Discharge Machining (wire-EDM) for over 35 years. This machining process is described as the "electrical fret sawing of metals using a thin wire". CVT has two staff and six machines, four for wire-EDM and two for sinker-EDM. Using these high-performance machines that can operate unstaffed 24/7, the company offers flexibility, quality and high delivery reliability at a competitive cost price. CVT serves clients in the high-tech mechanical engineering and medical industries in various countries, including the Netherlands, Belgium, Germany and Switzerland.

Given the exact tolerances (to a few micrometers) and the high-quality finishing (low surface roughness) wire-EDM can achieve, Heinmade has been one of CVT's clients for five years now. EDM is the best solution for manufacturing flexure hinge assemblies, which are frequently used in high-precision stages that require exact tolerances. Low surface roughness reduces the risk of notching (and hence material failure) during high-frequency movements in stages. All in all, EDM is crucial to the success of Heinmade's piezo systems.

When owner manager Albert van Heugten indicated last year that he wished to sell CVT at some point in time, Heinmade director Hein Schellens seized the opportunity to get hold of this crucial production technology. Heinmade took over CVT on 1 January of this year. Schellens: "The most important reason was chain management. With the takeover of CVT, we now have this manufacturing knowledge in-company and can reduce our lead times even further. That is particularly important during the product development stage to ensure that prototypes can be made quickly. The precision that clients demand in their systems for positioning and for manufacturing parts just keeps increasing. That's why we need CVT's expertise in wire-EDM." This helps Heinmade to increase the reliability of its delivery.

CVT will be operating as an independent unit in the Heinmade holding company, continuing to serve existing and new clients. Albert van Heugten will stay with the company for another three years to transfer his knowledge to his successor, who has already been appointed, and to familiarise him with the business. For the time being, CVT will stay in Hoogeloon, and following recent investments in 2010 and 2011, it will be working with up-to-date machinery. In the longer term, however, Hein Schellens envisages a merger of both companies at a single location.

WWW.HEINMADE.COM WWW.CVTBV.NL

DEMCON acquires minority interest in Qmicro

High-end technology supplier Demcon (HQ in Enschede, the Netherlands) has acquired a minority interest in Qmicro, which is an off-spring from Concept to Volume (C2V), a University of Twente (UT) spin-off. C2V focused on MEMS for analytical equipment, such as micro gas chromatographs. In 2009, C2V was taken over by the American company Thermo Fisher Scientific, which decided to close its office in Enschede this spring.

Qmicro Director Mark Kok comments: "We develop products based on MEMS (Micro Electro Mechanical Systems, ed.) chips. For Demcon, we can now develop such things as micro-actuators." Demcon Director Dennis Schipper: "We saw the opportunity to more actively engage in the world of micro- and nanotechnology. Qmicro's expertise complements our service offering, for example, for miniaturising components for the mechatronic systems we design."

WWW.DEMCON.NL

Growth at PM-Bearings

In May, PM-Bearings, a manufacturer of high-precision linear bearings and positioning systems, in Dedemsvaart, the Netherlands, opened a new cleanroom (ISO class 6). Given the increasing demand and new developments, especially among international customers, PM-Bearings foresees a further increase in demand for cleanroom-assembled sub-micron positioning systems and linear slides. To be able to meet the increasing demand, the existing cleanroom has been extended to a total surface area of 400 m^2.

For the next six months, PM-Bearings will be able to manage thanks to the new capacity, but in 2014 this will no longer be sufficient. To address this, PM-Bearings expects to be able to use the expansion of the existing Dedemsvaart office in Q3 2013. This 6,500 m^2 expansion will bring the total surface area to 13,000 m^2. This new building will house a new 1,000 m^2 (ISO class 6) cleanroom and 'cleaning street'.

The accompanying photo is an example of the systems that PM-Bearings assembles in the cleanroom, i.e. an advanced positioning table with micro-precision that was developed for a customer in the semicon industry. The biggest challenge was to maintain that precision over the entire range of the XY-table, which moves 150 mm in both directions. To that end, certain matters such as the thermal conduction had to be taken into account, because there are various expansion coefficients at play. PM-Bearings developed and engineered the solution entirely in-house. Given that the company manufactures the linear slides and all the product parts themselves, they can ensure the products all fit each other and that the high precision requirements can be met.

Assembly of an advanced positioning table in the PM-Bearings cleanroom.

KMWE investing

■ *The first Makino A81M in the Netherlands is in operation at KMWE.*

KMWE, key supplier for the high-tech equipment industry and aerospace (for example, Boeing B787 and Airbus A350), continues in 2013 with investment and expansion, for both units Precision Components and Precision Systems. Against the general market trend at this moment, this is the largest investment in the history of KMWE, which has headquarters in Eindhoven, the Netherlands. The investment of M€ 5 is the result of the continued growth of titanium and steel parts and the ever-increasing complexity and size of the products.

Now, the first Makino A81M in the Netherlands is in operation at KMWE. This is a new, very accurate, 5-axis machining center that is specially equipped for machining large, complex titanium parts. This investment is in line with the strategy of KMWE to acquire a leading position in the machining of titanium. Additionally, KMWE has developed new clamping and fixture methodologies and milling strategies. Together with special cutting tools a substantial reduction in production time is realised.

Due to the increasing complexity and high quality standards further enhanced measurement capability for larger products is needed. In April 2013, the eighth coordinate measuring machine from Mitutoyo was installed. The partnership with Mitutoyo will be underlined by a visit from the CEO/President of Mitutoyo Japan to KMWE later this year.

KMWE Precision Systems recently started with the expansion of the current cleanroom. An additional cleanroom will be built of approx. 500 m^2, which will increase the total cleanroom area to approx. 1,000 m^2. The new cleanroom is according to Class ISO 6 specifications with ISO 5 workstations. With this new cleanroom KMWE will meet the latest requirements for high-tech EUV products.

WWW.KMWE.COM

New Institute for Nanolithography

ASML, the Foundation for Fundamental Research on Matter (FOM), the University of Amsterdam (UvA), the VU University Amsterdam and the Netherlands Organisation for Scientific Research (NWO) have announced their intention to establish the Institute for Nanolithography (INL). The initial research programme of the INL will focus on physical and chemical processes that are key for future extensions of Extreme Ultraviolet (EUV) lithography. This technology is at the forefront of chip manufacturing and is indispensable for innovation in the global semiconductor industry.

ASML will provide more than one third of the institute's annual budget, investing roughly M€ 30 over ten years. FOM and NWO will contribute M€ 25 over ten years and UvA/VU will make a contribution of M€ 12.5. The City of Amsterdam has committed M€ 5 million as start-up funding. The institute is expected to benefit from the government incentive for public-private partnerships (TKI) and plans to raise M€ 25 million from various other funding instruments such as European programmes. The overall initiative amounts to M€ 100 for ten years.

The institute will be launched in the third quarter of 2013 under the management of the FOM Institute AMOLF. By 2015, it will become an independent institute managed by FOM in collaboration with UvA and VU, and employ about 100 highly qualified scientists and staff. The institute will be located at the Science Park Amsterdam, and it will be linked to the education programmes of the joint science faculties of UvA and VU.

WWW.ASML.COM

WWW.FOM.NL

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