# Mikroniek

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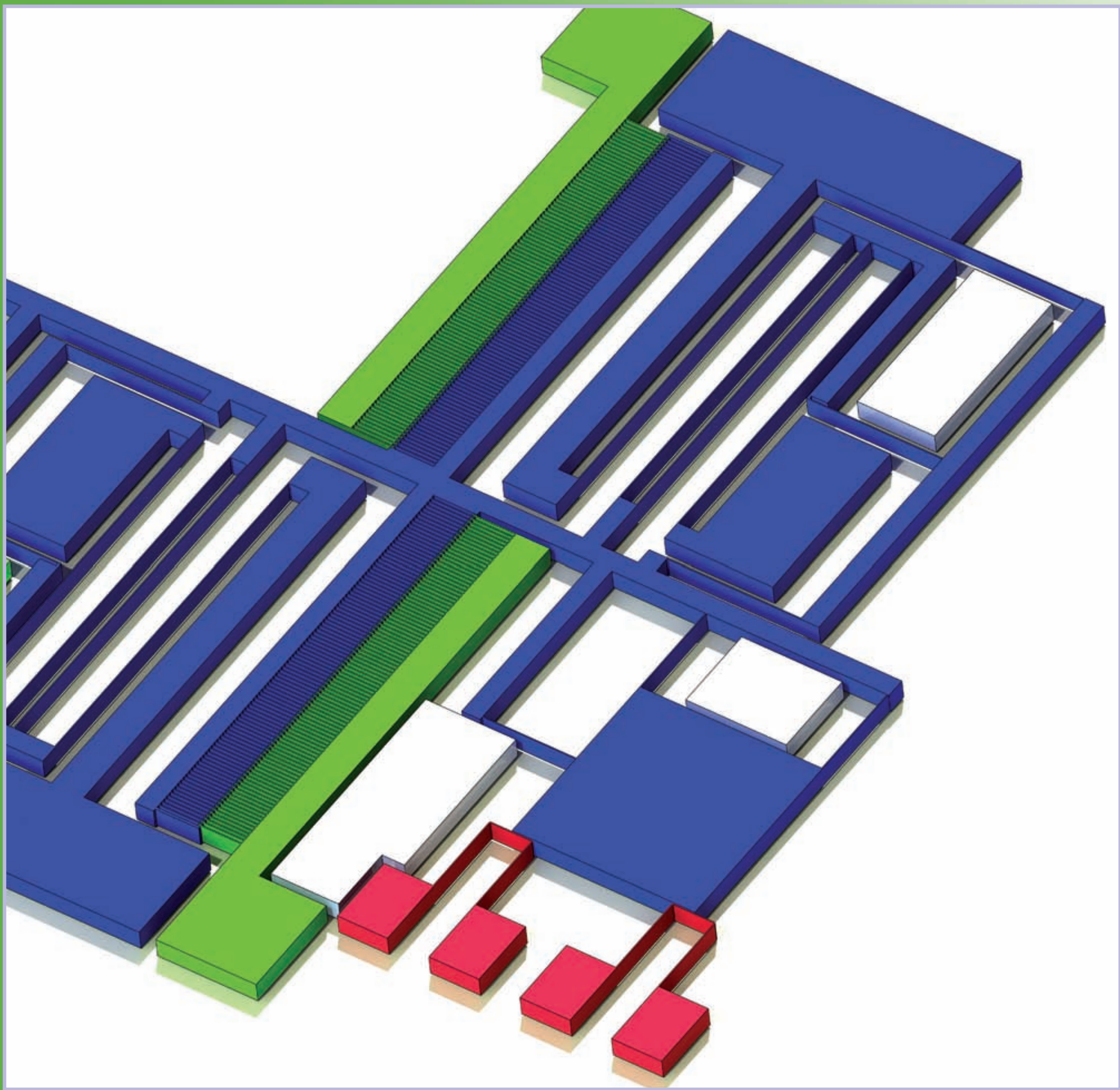

Towards accurate small-scale manipulation • On the use of compliant design
Thermal expansion under control • Euspen 2011 conference report
Atomic-scale resolutions in TEMs • More control over motion control
Second Symposium on Compliant Mechanisms • Artists in micro-EDM

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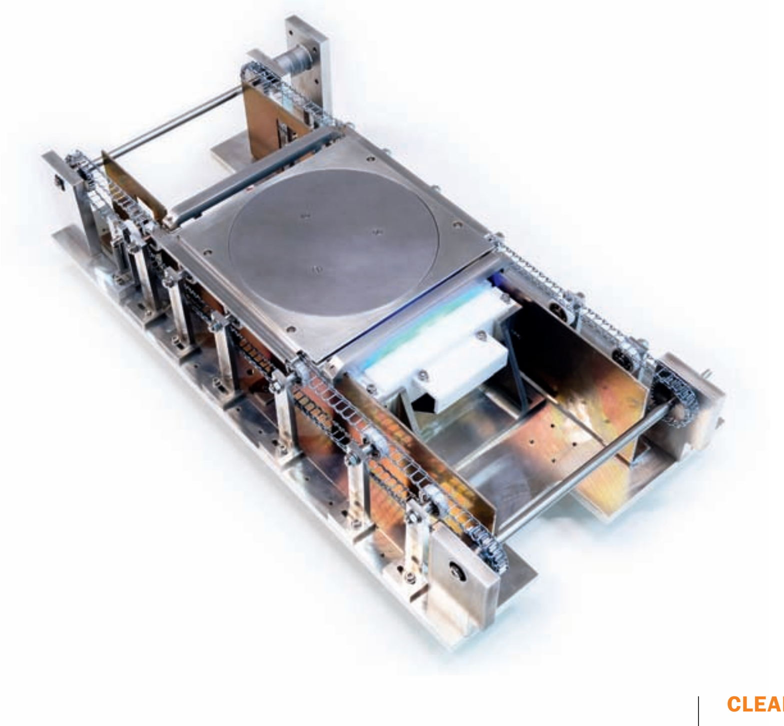
# THE DEVIL IS IN THE DETAILS



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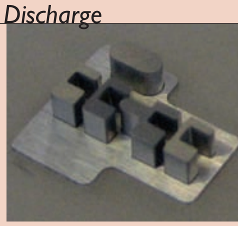
Mikroniek - 2011

# In this issue



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The cover photo (system overview of a MEMS thermal displacement sensor) is courtesy DEMCON and University of Twente.

editorial

# Eindhoven / Franche-Comté: promising exchanges

Initial contacts between organisations from Eindhoven, the Netherlands, and Franche-Comté (East of France area), such as DSPE and the organisers of Micronora, the International Microtechnology Trade Fair, were made last year at the fair in Besançon, France. This resulted in a visit to Eindhoven on 8 June 2011 by a delegation from Franche-Comté. The delegation included representatives from local companies, FEMTO-ST, the Pôle des Microtechniques and the Microtechnology science park (Temis). The valuable meetings, organised by our Enterprise Europe Network's counterpart, led to promising exchanges.

Franche-Comté is an industrial region with strong know-how in microtechnology and precision engineering that goes back to the watch-making industry. The Pôle des Microtechniques, one of the French national industrial clusters, has defined priority technology areas and is willing to stimulate collaborative projects with other clusters in Europe. The challenge of developing complex devices integrating multiple functions requires the combination of different kinds of expertise. The Franche-Comté's orientation towards micromechanics is complemented by Eindhoven's know-how in micro-electronics, which provides an excellent basis for mutually beneficial collaboration.

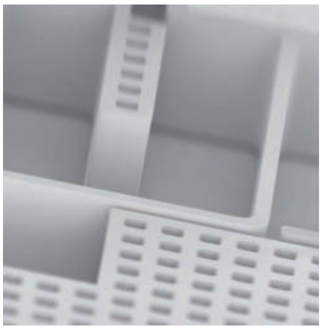
The French public research laboratory FEMTO-ST works in several domains where collaboration could be especially beneficial. Firstly, smart structures are being developed based upon massive integration of sensors into mechanical structures. Automated prognosis and "health monitoring" systems allow these structures to perceive and modify their environment in order to achieve higher levels of safety and technical performance. Secondly, FEMTO-ST is a world leader in high-precision micro-assembly, a crucial step in smart systems fabrication and packaging in all fields of microsystems technology, including 3D stacks in micro-electronics, MEMS and MOEMS. Thirdly, research is carried out on the integration of miniaturised WiFi chips into small medical systems and on flexible and stretchable circuits for wearable systems.

Indeed, the visit to the Eindhoven campus enabled FEMTO-ST to present specific know-how and to start collaboration, especially in the domain of MOEMS micro-assembly. Connecting people in this way so that they can discover their complementary areas of specialisation and competence is a first step. Experience proves that the more we create opportunities for such meetings and discussions, the more we get tangible results. I am very pleased to see that the exchanges have already generated ways for concrete collaboration.

Anne-Marie Vieux
Enterprise Europe Network - Chamber of Commerce and Industry of Franche-Comté (ARIST)

# Towards accurate small-scale manipulation

*Accurate manipulation of small objects is becoming more and more important. Besides accurate manipulation, the demand for small manipulators is also increasing. Some examples are high-density data storage, (digital) light processing, accelerometers, rate sensors, and the use of cantilevers in atomic force microscopy. Another example where small and accurate manipulators are beneficial is inside an electron microscope, for sample as well as beam manipulation. This work presents the design, fabrication and experimental validation of a thermal displacement sensor for accurate measurement of the position of a MEMS stage. The sensor was integrated with the manipulation stage in a single-mask production process.*



• *Bram Krijnen, Richard Hogervorst, Jan Willem van Dijk, Johan Engelen, Léon Woldering, Dannis Brouwer, Leon Abelmann and Herman Soemers* •

**Authors' note**

Bram Krijnen is a mechatronic engineer at DEMCON Advanced Mechatronics in Oldenzaal, the Netherlands, and a Ph.D. student in the field of micromechatronics in the group of Mechanical Automation and Mechatronics at the University of Twente (UT), the Netherlands. The work described in this article is part of the CLEMPS project (Closed-Loop Embedded MEMS-based Precision Stage) and was in part laid down in the Master theses of Richard Hogervorst (work done at DEMCON and Delft University of Technology, Delft, the Netherlands) and Jan Willem van Dijk (work done at DEMCON and UT). Johan Engelen (Ph.D., now at IBM Zürich), Léon Woldering (postdoc) and Leon Abelmann (associate professor) are (past) members of the MESA+ research group Transducer Science and Technology at UT. Dannis Brouwer is assistant professor in the UT group of Mechanical Automation and Mechatronics and project manager at DEMCON. Herman Soemers is technology manager mechatronics at Philips Innovation Services in Eindhoven, the Netherlands.

In MEMS (Micro-Electro Mechanical Systems), thermal or electrostatic actuators [1, 2] in combination with flexure-based stages are able to reach positioning accuracies of several nanometers. However, accurate positioning is limited by many factors, such as drift, external disturbances and load forces. Adding feedback control, and thus position sensing, can enhance the performance of MEMS positioning systems. The object of the CLEMPS research project was to develop a closed-loop MEMS-based precision stage for in-plane positioning in three degrees of freedom (DoFs). The combination of three single-DoF stages into a 3-DoF manipulator was already shown in [3], but feedback was not integrated in this design and the system has to be extended for larger strokes.

## Sensing principle

Position sensing in MEMS is often based on the varying capacitance between the fixed world and an actuated stage [4]. Some alternative position sensors use integrated optical waveguides, the piezo-resistive effect, or varying thermal conductance. Lantz et al. [5] demonstrated a thermal displacement sensor achieving nanometer resolution over a 100 μm range. However, a multi-mask production process and manual assembly were needed to fabricate this displacement sensor together with its stage.

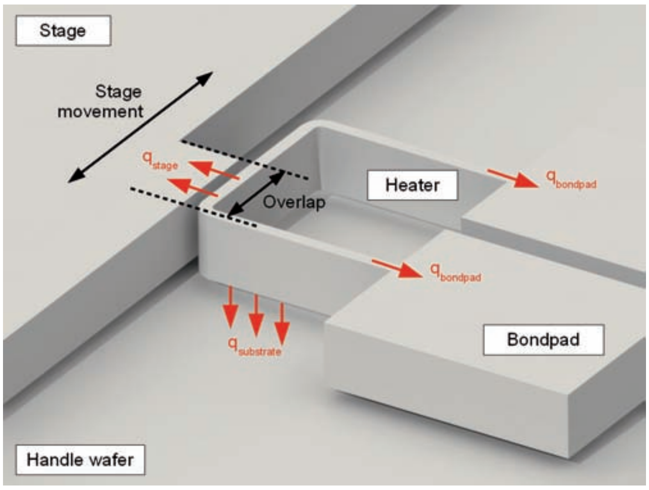


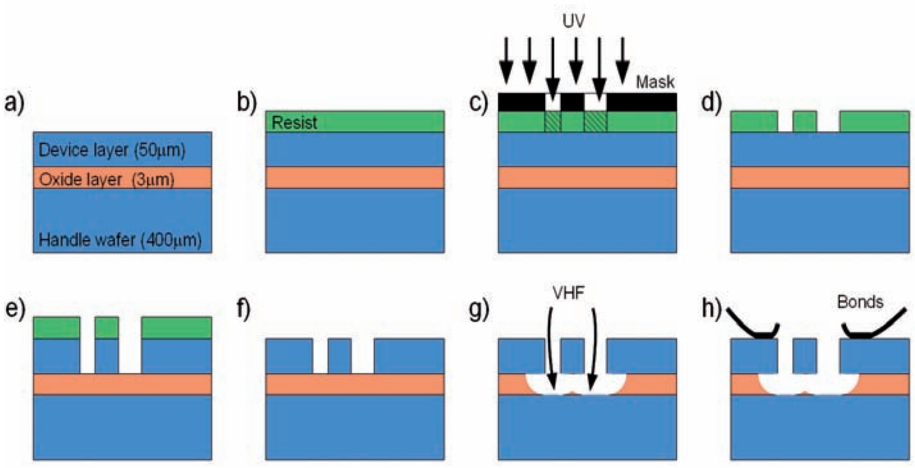

Figure 1. Schematic overview of a single heater and the main conductive heat flows (red arrows). On this scale, conduction is dominant over radiation and convection. The heater consists of two parts, the sensing part parallel to the stage, and the heater legs perpendicular to the stage. The conductive heat flow through the thin layer of air towards the stage ($q_{stage}$) is highly dependent on the overlap. The heat flows towards the underlying handle wafer through air ($q_{substrate}$) and towards the bondpads through the heater legs ($q_{bondpad}$) are also indicated.

This work presents the design, fabrication and experimental validation of a thermal displacement sensor integrated with an actuated stage in a single-mask production process. Integration of all subsystems in a single fabrication process is a great advantage, since in MEMS the design of a system is largely restricted by limitations on the fabrication process. Development and optimisation of a new fabrication process is expensive and time-consuming.

The thermal displacement sensor consists of two heaters in a differential configuration. The heater actually is a thin silicon structure that is resistively heated due to the supplied electrical power. When the stage is overlapping the heater, heat is transferred due to conduction from the heater towards the stage through the thin layer of air ($q_{stage}$). An increasing stage overlap results in more efficient cooling of the heater and therefore a decrease in heater temperature. Since the electrical resistivity of silicon is highly dependent on its temperature, the electrical resistance of the heater will also decrease at increasing overlap. Thus, the electrical resistance of the heater is a measure for the stage position. A differential heater configuration is chosen to make the sensor less sensitive to changes common to both heaters, such as ambient temperature and air humidity changes. Thin aluminum wires are bonded to the bondpads in order to apply an electrical voltage or current to the heaters. One of the heaters of the thermal displacement sensor is shown in Figure 1. In the image the bondpads, heater and stage can be clearly identified.

## System design

To be able to focus on the design of the closed-loop system, a relatively simple and reliable fabrication process was chosen. The fabrication process is schematically shown in Figure 2. The fabrication process is based on a Silicon-On-Insulator wafer (SOI-wafer). A SOI-wafer consists of three layers: a silicon handle wafer, a thin insulating silicon dioxide layer and a low-resistant silicon device layer. Deep Reactive-Ion Etching (DRIE) is used to achieve anisotropic (directional) etching through the device layer of the SOI-wafer with a high aspect ratio [6]. Aspect




(a) A SOI-wafer consists of three layers: a silicon handle wafer (~400 µm), a thin insulating silicon dioxide layer (3 µm) and a low-resistant (=highly doped) silicon device layer (50 µm).
(b) A layer of photoresist is spin-coated on top of the wafer.
(c) The resist is illuminated through a mask.
(d) The resist layer is developed.
(e) The device layer is anisotropically etched by deep reactive-ion etching; the process stops at the silicon dioxide layer.
(f) The remaining photoresist is removed.
(g) Vapour phase HF is used to isotropically etch the silicon dioxide layer.
(h) The structures that are fixed to the handle wafer through the oxide layer can be bonded for electrical contact.

Figure 2. Schematic drawing of the SOI fabrication process.

ratios up to 25 are common nowadays, which means that for a minimum feature size of 3 µm structures with a height up to 75 µm can be etched reasonably well. After deep reactive-ion etching the device layer is released from the handle wafer by isotropic HF vapour phase etching of the silicon dioxide layer [7]. Thin structures (width < 10 µm) are released from the substrate in this way. Large structures will stay mechanically fixed to the substrate (anchor points), while being electrically isolated from the handle wafer due to the silicon dioxide layer. Large moving structures are perforated in order to release them from the handle wafer.

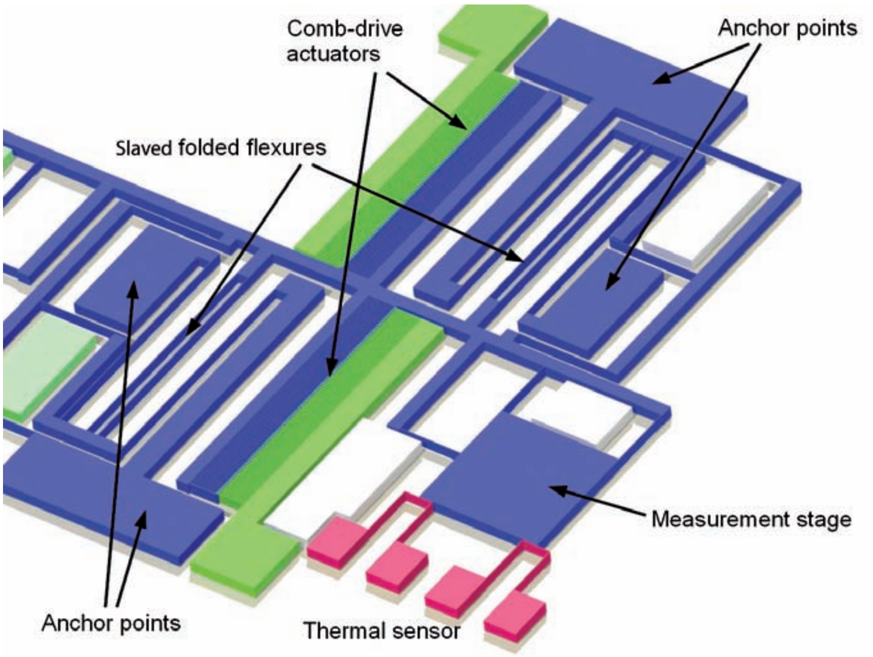
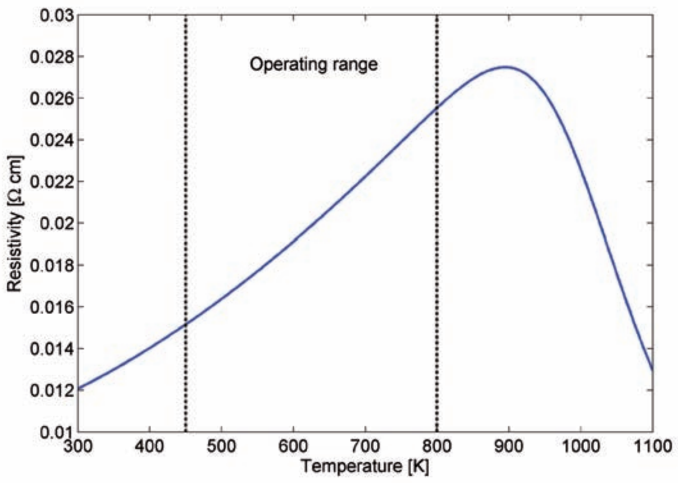



Figure 3. An overview of the complete microsystem. The stage is moved by electrostatic comb-drive actuators. The moving stage is constrained to one DoF by two slaved folded flexures. A measurement stage is added to thermally decouple the stage from the sensor. The thermal sensor is shown in the bottom of the figure (red). The thermal sensor consists of two heater structures, as shown in Figure 1. Anchor points are large structures that stay mechanically fixed to the handle wafer. The parts that are electrically insulated from each other are depicted in different colours.



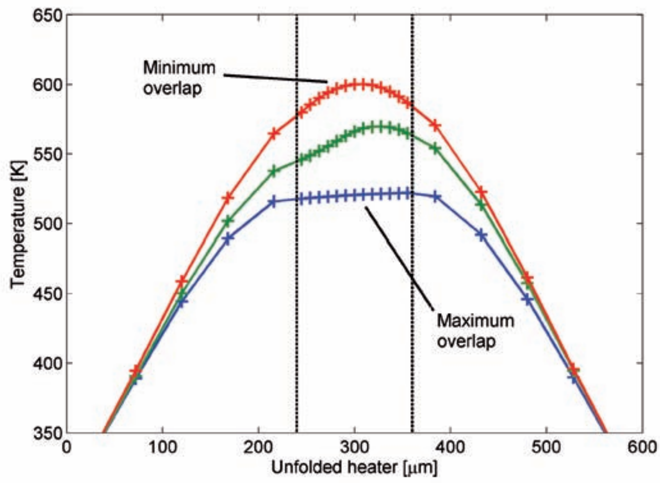




Figure 4. The electrical resistivity of silicon is highly dependent on the temperature. The heaters are used on the positive slope of the resistivity curve, which means that a higher temperature results in a higher electrical resistance. The theoretical curve shown in this graph is for a boron doping concentration of $4.7\times10^{18}$ $cm^{-3}$.

Figure 5. The temperature profile over the heaters is modeled for various stage overlaps. The heater is unfolded over the x-axis; the sensing part is in between the vertical dashed lines, the heater legs are left and right of the vertical dashed lines. The maximum temperature is 600 K at minimum overlap and 522 K at maximum overlap.

The integration of sensor and actuator in a single layer of silicon also has mechanical advantages. It obeys several design principles for precision manipulation [8]; contactless sensing and actuation do not introduce friction and hysteresis, and without assembly misalignments are avoided and overconstraints in a monolithic device layer are unlikely to lead to unpredictable system behaviour.

The complete design of the actuated stage with thermal displacement sensor is shown in Figure 3. The system consists of electrostatic comb-drive actuators to move the stage. The stage movement is constrained to one DoF by so-called slaved folded flexures. The slaved folded flexures ensure parallel movement with respect to the heater structures over a range of 2x100 µm (in positive and negative direction). Slaved folded flexures are used instead of 'normal' folded flexures, since the sideways stiffness of the 'normal' folded flexure is insufficient to prevent snap-in due to electrostatic forces [9]. A measurement stage is added to the design to thermally decouple the stage from the sensor.

## Modeling

A lumped capacitance model was generated in 20-sim (www.20sim.com) to predict the temperature profile over the heaters and the heat flows in the sensor. An important property of the lumped capacitance model of the sensor is the electrical resistivity of silicon as a function of the temperature; see Figure 4. A theoretical model can be found in [10].

The temperature over the heater for different stage overlaps is shown in Figure 5. At minimum stage overlap the heater structure will reach its maximum temperature. In this simulation the maximum temperature is limited to 600 K. When the stage partially overlaps the heater structure, the heater will cool down and the temperature profile becomes asymmetric. Eventually, when the stage is completely in front of the heater, the maximum temperature of the heater has decreased to 522 K and the temperature profile is roughly symmetric again. As a result of this temperature change, the heater resistance will decrease from 840 Ω to 790 Ω.

The power dissipation of a single heater is roughly linear with its stage overlap, as shown in Table 1. Due to the differential configuration, when one of the heaters has maximum overlap, the other heater has minimum overlap. Therefore the total power dissipation of the sensor as a function of the stage position is more or less constant and the thermal equilibrium of the complete system will hardly change.

The lumped capacitance model of the sensor was able to predict the heater resistance and the dissipated power within 10%. More information on the lumped capacitance model and the results in this paragraph can be found in [10]. There, the lumped capacitance model is also used for optimisation of the sensor sensitivity as a function of the doping concentration of the device layer of the SOI-wafer, the geometry of the heaters and the operating mode of the sensor, i.e. whether a constant voltage or a constant current is applied to the heaters. Some of these simulation results have been validated using measurements on fabricated sensors.

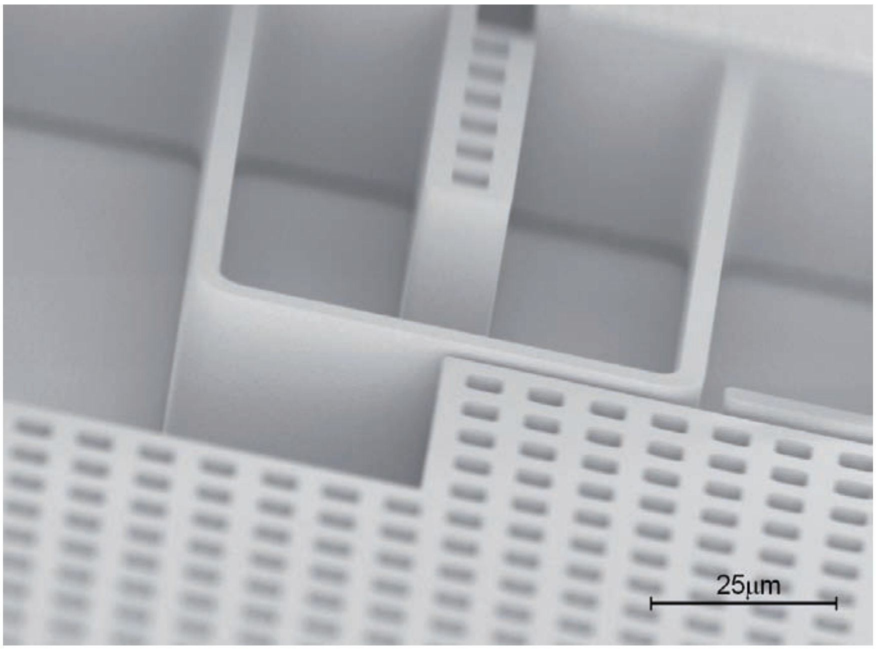


Figure 6. Scanning electron micrograph of one of the heaters. In this production run the height of the device layer was only 25 µm. Perforation of the moving stage (bottom) is also shown in this image.

Table 1. Power dissipation as simulated for maximum, half and minimum stage overlap of a single heater. A constant voltage of 8.3 V was applied to the heater, which resulted in a maximum temperature of 600 K at minimum overlap.

| | Maximum overlap (mW) | Half overlap (mW) | Minimum overlap (mW) |
|---|---|---|---|
| Bondpads | 55 | 56 | 57 |
| Stage | 14 | 8 | 2 |
| Substrate | 15 | 18 | 21 |
| Radiation | 0 | 0 | 0 |
| **Sum** | **84** | **82** | **80** |

## Experimental validation

The fabricated devices were diced, glued and wire bonded to a PCB for measurement. A scanning electron microscope image of one of the heaters is shown in Figure 6. A secondary measurement setup was used to calibrate the stage displacement as a function of the actuation voltage on the comb drives. Stroboscopic video microscopy was used for this purpose, performed with a Polytec MSA-400 and its Planar Motion Analyzer software. The measured data provide accurate information about the stage position at a specified actuation voltage. The 1σ value of the noise roughly corresponds to 20 nm.

A constant current of 9.8 mA was applied to the heaters and the voltage difference over the heaters was measured. The voltage output of the sensor as a function of stage displacement is shown in Figure 7 (top). The current was chosen such that a maximum temperature of 800 K could be expected at minimum overlap. The stage displacement in this experiment was from –55 µm to +55 µm. The resulting output voltage increased from –0.807 V to +0.758 V. The average sensitivity of the heaters was 2.9 Ω/µm. A

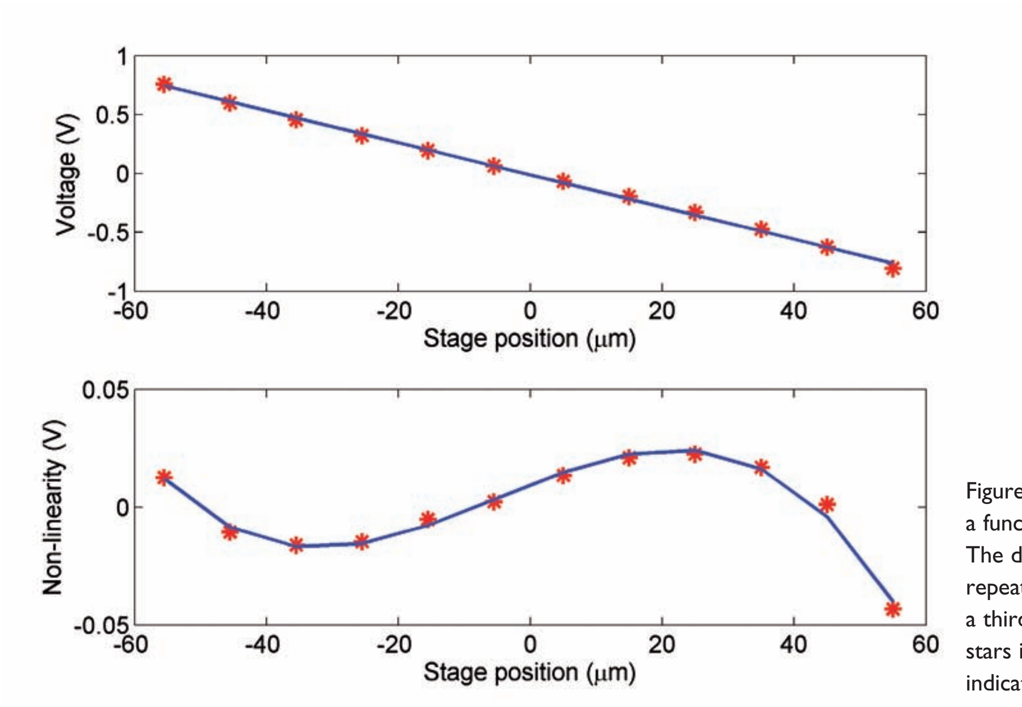



Figure 7. The sensor output voltage as a function of the stage position (top). The deviation from the linear fit is highly repeatable and can be approximated by a third-order polynomial (bottom). Red stars indicate measured data and blue lines indicate the linear and polynomial fit.

linear fit was made of the sensor output voltage and the deviation from this linear fit is also shown in Figure 7 (bottom). Considering all non-linear effects in the sensor, the differential sensor is surprisingly linear. The remaining non-linearity is highly repeatable. The voltage output of the sensor was filtered at 25 Hz and had an RMS noise value of 22 µV, which corresponds to a resolution of 1.7 nm (0.33 nm/Hz$^{1/2}$). The sensor noise is dominated by the noise of the A/D converter.

A major drawback of thermal systems in the macro-world is the low bandwidth due to high thermal time constants. By downscaling thermal sensors or actuators to MEMS, much higher bandwidths can be achieved. The thermal capacitance ($C \sim r^3$) decreases much faster due to miniaturisation than the thermal resistance increases ($R \sim r^{-1}$). Therefore, the time constant will decrease quadratically with decreasing size ($\tau = RC \sim r^2$). In order to measure the time response of the thermal sensor, a step voltage was applied to one of the heaters of the sensor and the resistance of the heater was measured. The result is shown in Figure 8 (top). The heater structure has a time constant of 522 µs, which means the sensor has a bandwidth (-3 dB) of 305 Hz.

Two more time constants can be distinguished in the complete system, also shown in Figure 8 (bottom). A time constant of 51 ms was found that can be attributed to the time constant of the measurement stage. Furthermore a time constant of 1.3 s was found that is caused by heating of the complete system and substrate. Since the sensor dissipates a constant amount of power, the time constant of the complete system will only show up at start-up of the sensor. The time constant of the stage is hard to suppress. The sensor position history can be used to compensate for this effect. For position control of the stage, the relatively large time constant of the measurement stage does not lead to instability; therefore the control bandwidth is fortunately not limited by the stage time constant.

## Conclusions

We have designed, fabricated and tested an integrated thermal displacement sensor for accurate measurement of the position of a MEMS stage. Due to the small scale of MEMS structures a thermal sensing principle can still achieve reasonably high bandwidths, in contrast with many thermal systems in the macro-world. The sensor has a high resolution (1σ noise < 2 nm) over a range of 110 µm and requires only a small wafer surface area (< 0.5 mm$^2$). The sensor can be easily integrated in the same straightforward and single-mask fabrication process that is used for the actuated stage.

## References


[1] S.L. Paalvast, “Thermal Actuation for Precision Micro Motion and Positioning”, Ph.D. thesis, Delft University of Technology, Delft, the Netherlands, 2010.

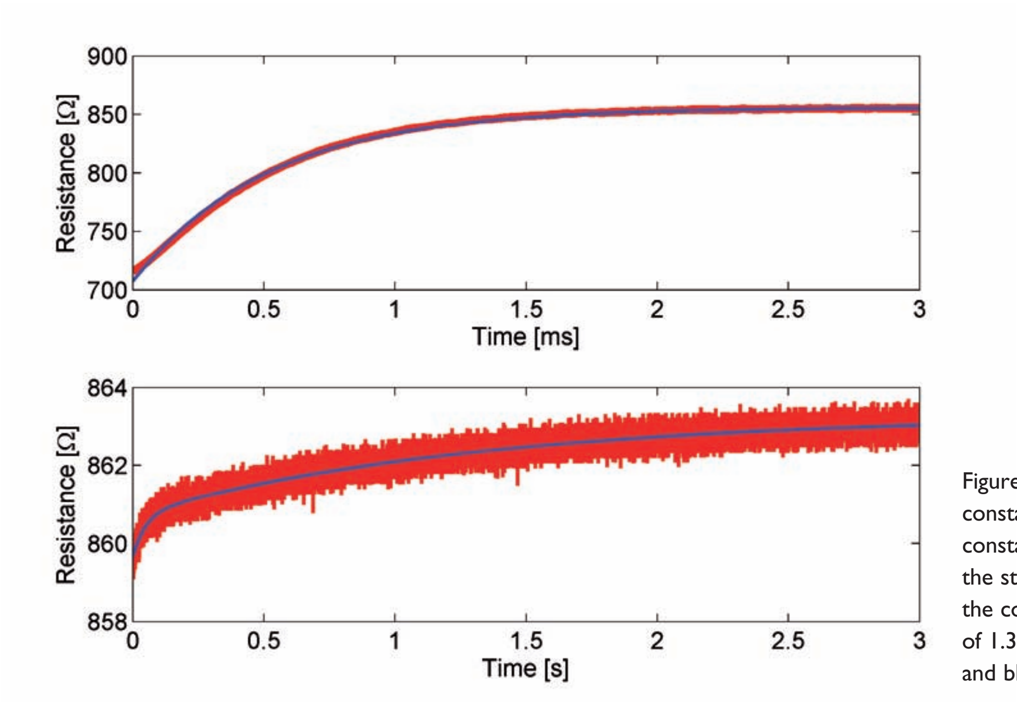



Figure 8. The heater structure has a time constant of 522 μs (top). Two more time constants can be distinguished (bottom); the stage has a time constant of 51 ms and the complete system has a time constant of 1.3 s. Red lines indicate measured data and blue lines indicate the exponential fit.


[2] R. Legtenberg, et al., “Comb-drive actuators for large displacements”, *J. Micromech. Microeng.*, Vol. 6 (1996), no. 3, pp. 320-329.

[3] B.R. de Jong, et al., “Design and Fabrication of a Planar Three-DOFs MEMS-Based Manipulator”, *J. Microelectromech. Syst.*, Vol. 19 (2010), no 5, pp. 1116-1130.

[4] A.A. Kuijpers, et al., “A micromachined capacitive incremental position sensor”, *J. Micromech. Microeng.*, Vol. 16 (2006), no. 6, pp. S116-S134.

[5] M.A. Lantz, et al., “A micromechanical thermal displacement sensor with nanometre resolution”, *Nanotechnology*, Vol. 16 (2005), no. 8, pp. 1089-1094.

[6] H.V. Jansen, et al., “Black silicon method X: a review on high speed and selective plasma etching of silicon with profile control: an in-depth comparison between Bosch and cryostat DRIE processes as a roadmap to next-generation equipment”, *J. Micromech. Microeng.*, Vol. 19 (2009), no. 3, pp. 1-41.

[7] P.J. Holmes, et al., “A vapour etching technique for the photolithography of silicon dioxide”, *Microelectronics Reliability*, Vol. 5 (1966), no 4, pp. 337–341.

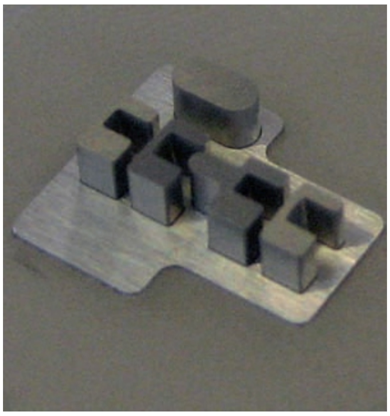
[8] H.M.J.R. Soemers, “Design Principles for Precision Mechanisms”, T-Pointprint, Enschede, the Netherlands, 2010, ISBN: 978-90-365-3103-0.

[9] D.M. Brouwer, et al., “Long-Range Elastic Guidance Mechanisms for Electrostatic Comb-Drive Actuators”, Proc. 10th euspen Conf. (2010), Delft, the Netherlands, Vol. 1, pp 47-50.

[10] S.M. Sze, et al., “Physics of Semiconductor Devices”, Wiley, Hoboken, NJ, USA, 2006, ISBN: 978-04-711-4323-9.

[11] B. Krijnen, et al., “A Single-Mask Thermal Displacement Sensor in MEMS”, *J. Micromech. Microeng.*, Vol. 21 (2011), no. 7, pp. 074007-074019.

# Artists in micro-EDM



*In 1990, Gerrit and Gerrie ter Hoek began machining electrically conductive materials with a single spark erosion machine in the back garden of their home in Rijssen, the Netherlands. Today, Ter Hoek Vonkerosie (approx. 20 staff members) claims to be the EDM (Electrical Discharge Machining) market leader in north-western Europe. For Mikroniek readers, the most important part of their success story is the fact that they specialise in the fast delivery of spark-eroded precision products. The convincing evidence of their skills is a punch-die combination with a clearance of only one micrometer.*

• *Frans Zuurveen* •

Ter Hoek Vonkerosie's machinery consists of about twenty Charmilles and Makino spark erosion machines and two Sarix SX 200 micro wire erosion machines; see Figures 1 and 2. One of Ter Hoek's key qualities is the company's continuous consultation with customers, the aim of which is to translate product demands into an efficient design, and its consultation with its operators, the aim of which is to achieve an efficient machining sequence; see Figure 3.

**Author's note**

Frans Zuurveen is a freelance text writer who lives in Vlissingen, the Netherlands.

Figure 1. A part of Ter Hoek's spark erosion machinery.

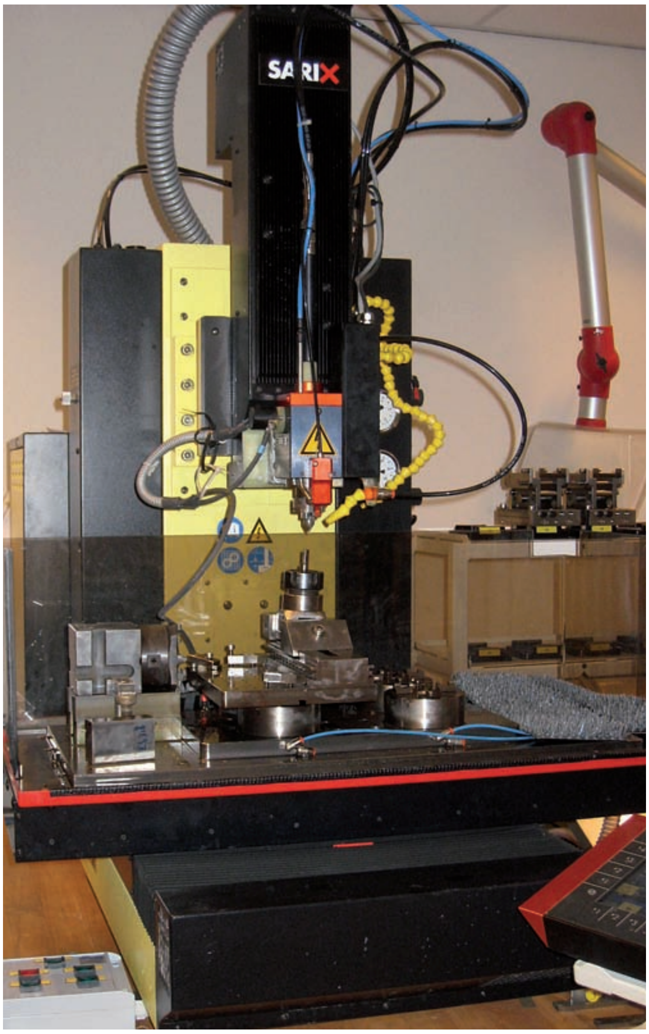



Figure 2. A Sarix SX 200 micro wire erosion machine with a robot arm for workpiece exchange in the background.

More often that not, such consultation results in a cheaper product that is better suited to the spark erosion machining processes. In extreme cases, Ter Hoek discourages customers to spark erode their product, when it is better suited to conventional cutting, i.e. turning, milling or grinding.

Theoretically, spark erosion, which is also called EDM or Electrical Discharge Machining, is a slow process of machining electrically conductive materials. Therefore, one could be inclined to think that EDM always results in an expensive product. This is not quite the case, however. On the one hand, machining times are long, especially for products with tight tolerances and high surface quality. On the other hand, however, EDM machines are generally able to run unmanned. Moreover, Ter Hoek has robot mechanisms at its disposal for changing tools or products. Therefore, Ter Hoek's spark erosion machines are able to continue 24 hours a day without any human interference, thereby helping to reduce costs. What's more, small

Figure 3. Gerrit ter Hoek (right) discusses the machining of a product with operator Marco Slot.

products weighing just a few grammes can be handled, as can heavy products up to 3,000 kilogrammes.

## EDM drilling

Ter Hoek is equipped to perform four kinds of spark erosion processes. The first process concerns spark drilling. A rotating hollow electrode makes holes with a diameter:length ratio of up to 1:700 with a maximum depth of 700 mm. The smallest holes, spark eroded on the Sarix SX 200, are a mere 0.02 mm in diameter.

Disposing of eroded material is a major problem, especially when drilling blind holes. Therefore, a maximum pressure of 110 bar is necessary to force the dielectric fluid, i.e. deionised water, to the bottom of the hole to carry away the eroded particles. To avoid getting a 'pole' at the centre of the hole, electrodes with two eccentric holes are often applied.

## Wire EDM

The second process is wire spark erosion; see Figure 4. This could be regarded as a simple 'fret-sawing' process, but making real precision products requires intelligent process control and a lot of experience. Ter Hoek is able to wire erode sheet metal with a maximum thickness of 500 mm. The wire thickness ranges from 30 µm (!) to 0.3 mm. The wire electrodes are made of electrolytic copper or brass. The zinc in the latter material evaporates, thereby providing some kind of cooling and an improved way of disposing of eroded material. All of Ter Hoek's wire eroding machines are equipped with an automatic wire insert into the indispensable starting hole.

The maximum wire transport speed that can be reached is 10 m/min. The wire cannot be used a second time and it


Figure 4. A Makino UH2 advanced wire spark erosion machine for ultrathin wire, 0.03-0.2 mm.


Figure 5. A Roboform die sinking spark erosion machine with control cabinet on the right.

has to be scrapped because of its roughness after use and its unreliable strength, which is due to the tension during machining – up to 90% of the ultimate tensile strength. When wire eroding sheet metal, the wire curves out in the opposite direction of the movement across the material. This effect is due to the forces between the wire and the workpiece and can amount to 0.3 mm. The software of Ter Hoek's machines compensates for this effect.

It is very important to apply a dielectric medium with sufficient insulating properties. The deionised water has to have a conductivity coefficient of less than 20 μS/cm$^2$, for extremely small gaps and maximum smoothness (0.1 μm $R_a$ is attainable!), or even 10 or 5 μS/cm$^2$. Ter Hoek uses special deionising equipment to reach such a low conductivity.

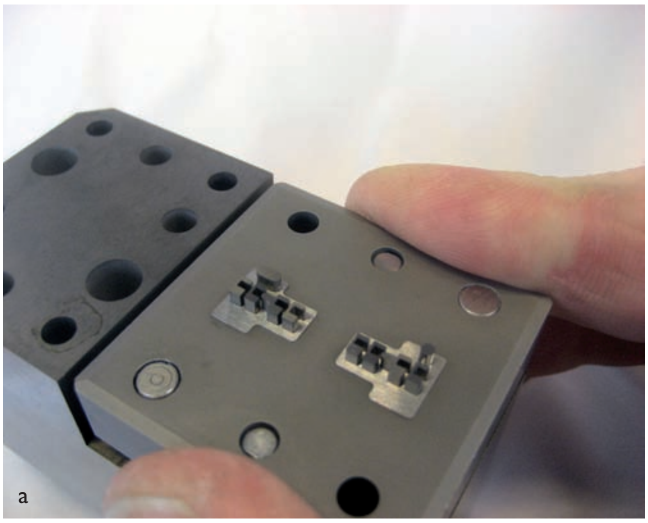
The last wire eroding item is four-axes machining, which deviates from the 'simple' fret-sawing principle. In that process, the wire guidance mechanisms above and below the workpiece are independently controlled. This is called XY-UV control. The XY axes relate to the movement of the lower head in the X and Y directions. The UV axes relate to the movement of the upper head in the U and V directions. Using the appropriate software, rather complicated three-dimensional products can be machined this way.

## 'Conventional' die sinking

The oldest EDM process is 'conventional' die sinking. An electrode that is the negative of the cavity to be made moves slowly downwards into the electrically conductive material. As in all EDM processes, the speed of this movement is not constant; it is servo controlled by measuring the ohmic resistance across the gap between tool and workpiece; see Figure 5. The electrode is made of electrolytic copper or carbon. Milling has previously produced the shape of the electrode. In general, the dielectric medium is paraffin.

## Micro-spark milling

Micro-spark milling is a rather new EDM process for producing '2.5-D' products by stacking successive horizontal spark erosion cut-outs. They are produced by an XY-controlled cylindrical electrode, which rotates around its own axis. Every cut-out that follows has to be equal to or smaller than the previous one. Together they form a cavity that is comparable to a die sinking cavity, but a higher precision can be attained.



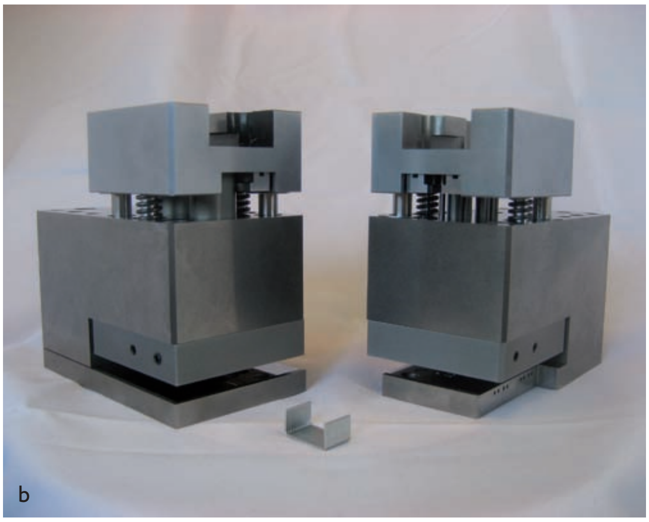


Figure 6. A punch tool for a hearing aid component from 20 μm thick sheet metal.
(a) A close-up of the tool with a 1 μm gap width.
(b) The complete tool; note the staples below, illustrating the small dimensions.

The precision and good surface quality of micro-spark milling is due to the vertical distance of the successive machining steps, which amounts to no more than a few μm. This small vertical distance is also necessary to guarantee exclusive material removal from the underside of the electrode. Sideways material removal would affect the shape of the electrode and, therefore, the final precision of the workpiece.

## A few examples

Many of the examples of Ter Hoek's precision products are related to medical uses. For instance, a tool for producing a miniature component for a hearing aid, punched from sheet metal with a thickness of only 20 μm; see Figure 6. For accurate and burr-free punching, the clearance between cutter and die should not be more than 5% of the thickness of the sheet. This means a gap width between punch and die hole of 1 μm. Superior control and knowledge of the wire erosion process on a Sarix SX 200 ensured that tolerances could be obtained for cutter and die that were a fraction of this gap width.

Another fine example of a Ter Hoek precision product is a micro-precision tool for die casting a small-toleranced medical product made of plastic with metal inserts. Three EDM processes are successively combined in this tool, i.e. micro-spark drilling for the holes, wire spark erosion to produce the contours and, finally, micro-spark

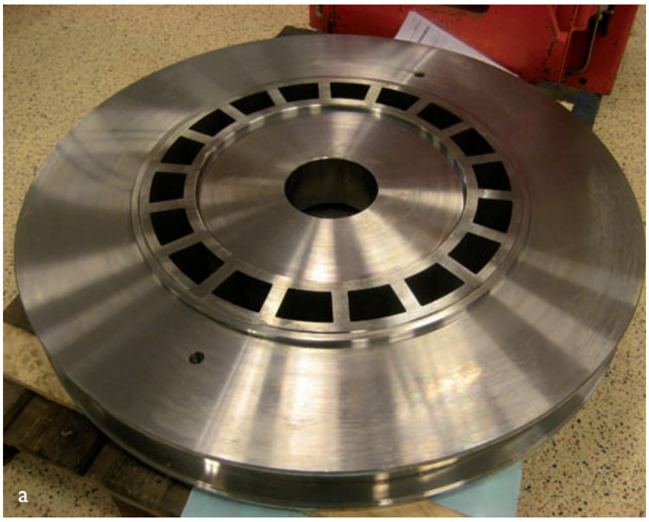


Figure 8. Examples of spark erosion contract orders for Ter Hoek.
(a) A rotor with 1 m outside diameter, in which the rectangular recesses are spark eroded with narrow angular tolerances.
(b) A torsion bar (to be applied in fatigue experiments) with spark eroded slots, 0.55 mm wide, made with a tolerance of only 20 μm.

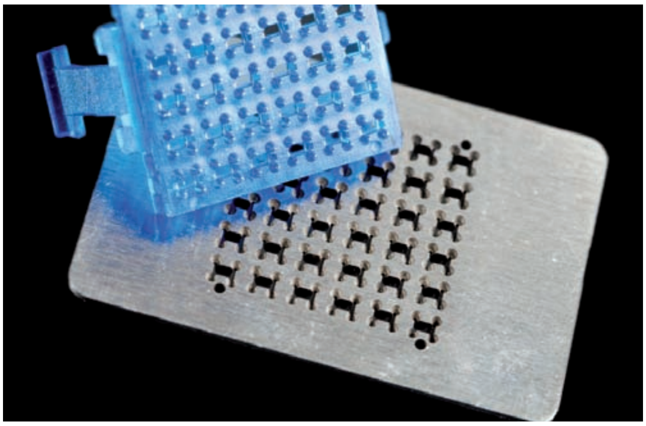


Figure 7. A metal die for a precision medical product. On top, the ultimate die-cast plastic product. The holes in the die have a diameter of 0.08 mm, with a tolerance of 2 µm.

milling for making the conical surfaces around each hole. Figure 7 shows the final die with the ultimate die-cast product in blue, without the metal inserts. The holes in the die have a diameter of 0.08 mm, with a tolerance of only 2 µm.

Finally, Figure 8 shows (see previous page) examples of spark erosion contract orders. In these cases, Ter Hoek does not manufacture the complete product, but only makes EDM recesses in already finished workpieces made of hard metals, according to customer specifications and drawings.

## To conclude

Electrical Discharge Machining seems to be a well-defined and well-developed machining process. It is regarded as rather expensive, but everybody is well aware of the advantage of handling ultra-hard metals without any force between workpiece and tool. Ter Hoek Vonkerosie's added value to this widely adopted technology is to listen carefully to customers so as to fully understand their problems. Moreover, Ter Hoek brings twenty years of experience to the table for optimising the use of state-of-the-art machinery.

**Information**

www.hoekvonkerosie.nl

# A steerable medical for minimally

*A meniscal lesion can be treated surgically in a minimally invasive procedure called a meniscectomy, which involves the removal of ruptured meniscal tissue from within the knee joint. However, given that there is limited access to the knee joint and conventional cutters are rather stiff, it is difficult to reach the entire meniscus. This has resulted in the design and evaluation of a cutter with a laterally steerable tip, which gives increased dexterity to the cutter in the knee. This design will render the use of different instruments unnecessary and also speed up the operation. The use of compliant design for the mechanical instrument joint decreases the part count and the complexity of manufacturing the instrument.*

• *Tim Nai* •

A player accidentally twists his knee: something that happens all too often during a football match. In pain, the player is carried off the field and not seen again for the rest of the football season. There's a significant possibility that a meniscal lesion is part of the injury. The menisci play an important role in how smooth our knee joints work. They are composed of cartilage-like tissue and located in the knee joint. Not only do they act as lubrication, but they also play an important role in the distribution of load on the knee joint; see Figure 1. Meniscal lesions usually occur during sports activities when the upper leg twists in the opposite direction of the load-bearing lower leg. More often than not, this results in a torn meniscus, which could cause pain and even immobility if left untreated. When meniscal tissue ruptures, it has very little or no capability of healing. Therefore, the aim of removing the lesion by surgery is to create a stable rim while removing as little tissue as possible.

## Difficult procedure

Meniscectomy, i.e. the surgical removal of meniscal lesion, is performed around 1.7 million times a year worldwide [1]. Thus, a small change in this surgical procedure could make a significant impact. The procedure is a difficult one because accessing the knee joint is difficult; see Figure 2. It is not only the bones and ligaments which limit access, but the veins, arteries and nerves surrounding the knee joint as well. To be able to reach any part of both menisci to correct the rim, a wide range of cutters is available with differently oriented instrument tips know as punches. These punches look like curved scissors, but they cut tissue like a perforator.

The limited space in a knee joint for manoeuvring an instrument towards a lesion means that quite a few punches

**Author's note**

Tim Nai obtained his M.Sc. in Mechanical Engineering at Delft University of Technology, Delft, the Netherlands. He was awarded the 2010 Wim van der Hoek Constructors Award for his M.Sc. thesis on the design of a compliant steerable arthroscopic punch. He is currently working as a business consultant with Accenture.

# instrument
# invasive surgery

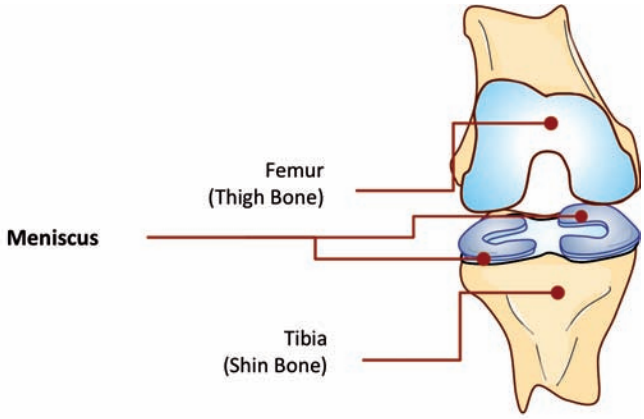



Figure 1. A schematic drawing of the knee showing the femur (thigh bone) and tibia (shin bone) with the menisci between them as two sickle-shaped tissue parts.

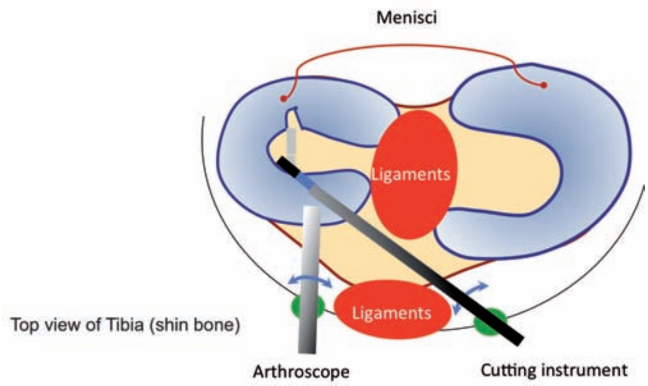



Figure 2. Top view of the tibia with an instrument inserted on either side of the knee. The arthroscope provides the image and the cutting instrument facilitates correcting the torn meniscus. As shown, a flexible tip at the end of the instrument would allow the surgeon to easily manoeuvre towards the tear.

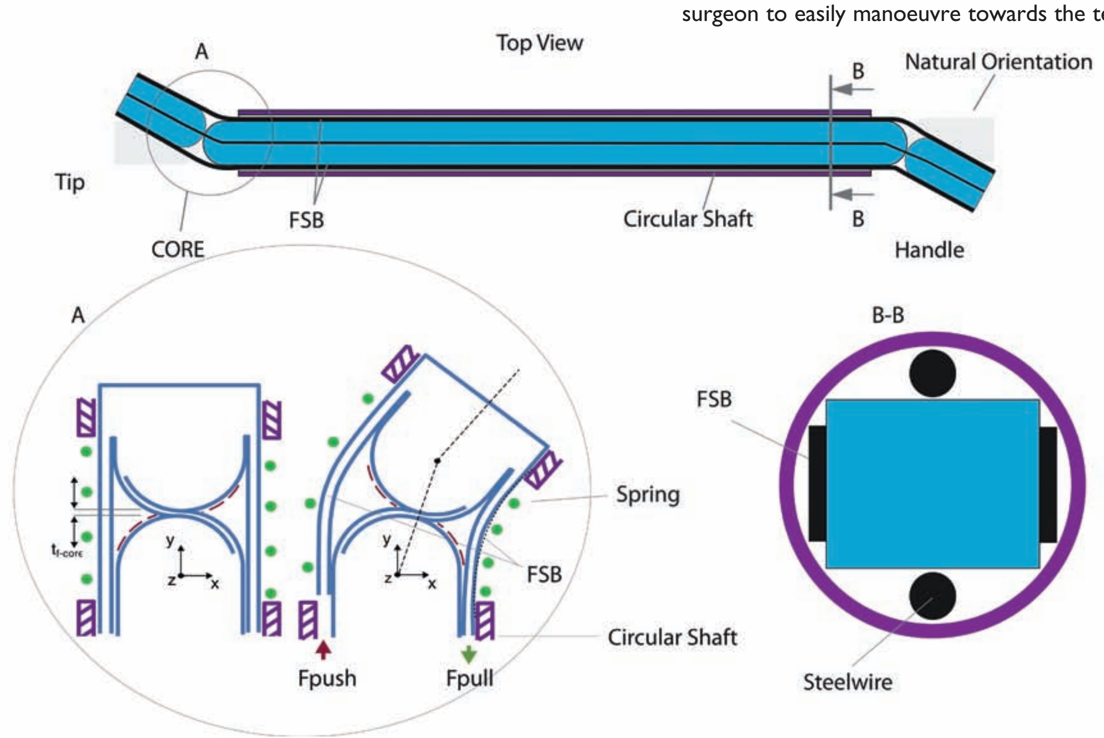



Figure 3. The circular shaft with handle and instrument tip demonstrates the concept of the laterally steerable instrument using a parallelogram configuration and two steerable flexible beams (FSBs). Magnification A shows one compliant rolling element (CORE) flanked by two FSBs and is surrounded by a spring. The B-B transverse cross section of the shaft shows a stacked pair of monolithic layers in the centre flanked by the two FSBs and surrounded by the circular shaft. The steel wires that enable the tip to be opened and closed run superior and inferior to the monolithic layers.

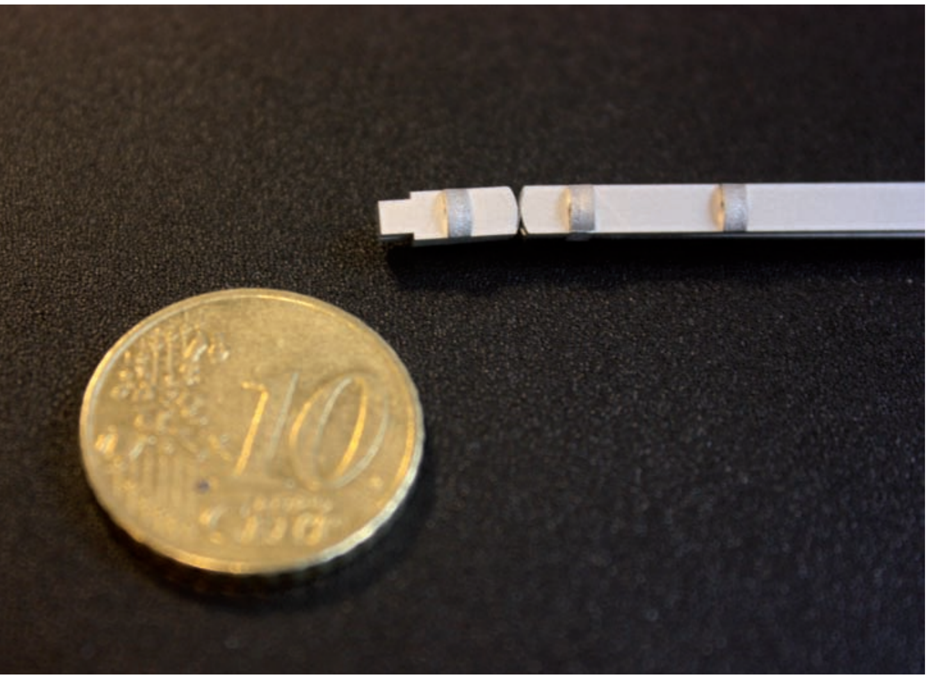
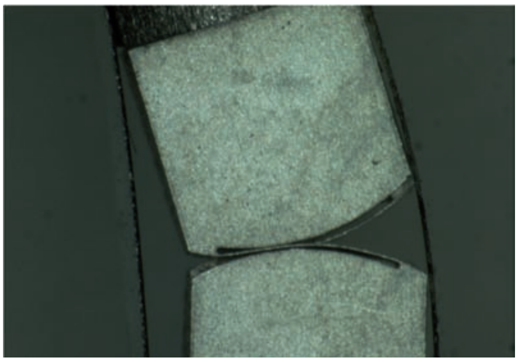


Figure 4. The inner structure without the surrounding tubes, handle or tip. The monolithic layers that form the CORE joint are locked in place by the clamps, placed in a perpendicular fashion along the length of these monolithic layers.

Figure 5. Magnified photograph of two stacked COREs with crossed flexures of 0.028 mm thickness.



have to be used intermittently to be able to perform the operation. Alternating instruments, however, increases the risk of infecting the knee joint. Furthermore, as surgeons try to work as efficiently as possible they try to limit alternating instruments, thereby posing a second risk, namely the application of excessive force on the knee joint to manoeuvre the instrument [2].

## Design

To overcome these disadvantages and increase the agility of the instrument in the knee joint, developing a laterally steerable punch was proposed; see Figure 3. Schematically, this punch comprises four parts: the handle, the shaft, the steering mechanism and the cutting mechanism. The design focus was on designing the steerable instrument joint, as it will be subjected to relatively high meniscal cutting forces (200 N axial load on the joint), yet needs to be small enough to enter the human knee joint through an access portal (smaller than 5 mm in diameter). Furthermore, an estimated range of instrument joint motion of –55 to +55 degrees was required. Thus, the goal was to design an integrated mechanism that facilitates the lateral steering of the instrument tip, while simultaneously allowing high loads to be transmitted towards the cutting mechanism at the tip.

The whole design process started by assessing the mechanisms used in the medical world, the conclusion of which was that traditional mechanisms where not suitable for meeting the requirements set for meniscectomy. Mechanisms using pin joints result in overly large constructions. Hydraulic and pneumatic solutions would be complex to seal. Non-conventional mechanisms using heat to activate shape memory metal or a current to activate electro-active polymer were shown to be unable to comply with required instrument robustness.

## Compliant mechanisms

Thankfully, compliant mechanisms did show potential. A compliant hinge generally consists of a relatively thin element connecting two solid parts. Deforming the material of the thin element within the elastic region allows for a relative displacement or rotation of the two solid parts. Traditional forms of compliant mechanisms are structured as thin beams that only allow small displacements in order to prevent buckling. In recent years, however, the development of non-conventional compliant hinges, which allow large displacements, has progressed rapidly.

The compliant rolling-contact element (CORE) is one of these non-conventional compliant hinges that can meet the requirements set for the intended design. The CORE is a rolling contact instrument joint in which two rounded solid parts are connected by a compliant crossed flexure, which keeps the solid parts at a constant distance from each other; see Figure 3. As a result, the contact surfaces of the solid parts can roll relative to each other without slipping, and from its neutral position, this allows the mechanical joint to rotate over 20 degrees in either direction. Moreover, the use of rounded contacts allows the mechanical joint to be subjected to the required compressive force, thereby meeting the requirement for cutting.

The steering mechanism was designed by first constructing a traditional mechanism, which was translated into a compliant counterpart using a pseudo-rigid body model. This model considered compliant hinges as traditional pin joints linked to a torsion spring, which allows for simple calculation of the dimensions of this compliant steering mechanism. Once the instrument joint had been designed, the next step was a steering mechanism. Given its simplicity, the compliant parallelogram mechanism was a promising steering solution. For the sake of construction, the instrument shaft and part of the handle had to be included in the design. The result is a shaft with two identical CORE joints at each end that are activated using a compliant parallelogram mechanism comprising two flexural steering beams (FSBs) located on either side of the shaft; see Figure 3. When the handle is rotated in the horizontal plane to the left, the instrument tip is counter rotated by the same angle because the length of the FSBs is fixed. The FSBs are guided in the shaft and can only bend at the level of both COREs, where they are guided by a helical compression spring.

## Construction

The second design phase was to ensure that this concept could be made. To that end, several design cycles were carried out to optimise the parts for construction and assembly. The principle was to build a construction that is nothing more than a simple puzzle to assemble. The symmetry of the two COREs means two identical monolithic layers can be made; see Figure 4. When these monolithic layers are stacked in a mirrored fashion, they form the inner rectangular shaft structure, with two COREs having flexures in alternating directions. Both ends of the stacked monolithic layers are identical and function as attachments for the instrument tip and the handle on either side. Using laser milling means that the thin flexure of 0.028 mm in the CORE joint can be made of stainless steel; see Figure 5. Circular clamps are placed along the length of the stacked monolithic layers to lock them together. Two holes with a diameter of 0.6 mm are made in each clamp to guide a steel wire that can activate a cutting mechanism at the tip. For the sake of convenience, the clamps are also made using laser milling.

The two FSBs are cut from a stainless steel foil with a thickness of 0.069 mm. They are welded on either side of a CORE using a micro-welding machine (THIN-LINE, Unitek Equipment, Monrovia, USA). A stainless steel tube of 5x4 $mm^2$ in cross-section functions as the outer shaft to provide structural rigidity at the centre of the prototype. Shorter

Figure 6. The prototype fitted with an end effector from a standard punch for presentation purposes. This end effector is activated using a steel wire connected to the jaw of the punch.

pieces of this steel tube are placed at each end of the stacked monolithic layers with two springs at the level of the COREs. These tubes house the clamps, the FSBs and the springs.

## Result

The prototype constructed (see Figure 6) was subjected to several tests to verify the calculated steering and robustness capabilities of the mechanical joint. The CORE joint proved itself capable of transmitting the 200 N, even when steered to its maximum angles of –22 and +25 degrees. To increase resistance towards torsion, the use of multiple stacked thinner monolithic CORE layers is recommended. Investigation into maximising the steering angle and the stiffness of this instrument is currently being carried out.

## Acknowledgments

The design of this steerable arthroscopic punch and all the related publications were only possible with the enthusiastic support of Gabriëlle Tuijthof and Just Herder from the Biomechanical Engineering Department of Delft University of Technology.

## References

[1] Baker, B. and Lubowitz, J. “Meniscus injuries”. eMedicine updated 22 November 2006, accessed 24 August 2007, available from www.emedicine.com/sports/topic160.htm.
[2] Tuijthof, G.J.M., “Technical improvement of arthroscopic techniques”, Ph.D. thesis, Delft University of Technology, Delft, the Netherlands, 2003.

# From particle physics to telescope technology

***From 23 to 27 May 2011, the euspen 11th International Conference was held in Cernobbio near Lake Como, Italy. The conference featured some 240 keynote, oral and poster presentations and over 30 exhibitors from all over the world. The three conference keynotes focused on particle physics, EUVL/X-ray optics and giant telescopes, respectively.***

• *Raymond Knaapen* •

**Euspen**

Founded in 1999 with funding from the European Community, euspen is a leading technical body in the field of ultra precision/nano manufacturing technologies. Linking leading industrialists and researchers worldwide, it has representation across more than thirty countries. Euspen strives to enable companies, research institutes and universities to more effectively develop and exploit leading edge precision, micro- and nanotechnologies, to promote their products and services, and to keep up to date with important developments.

Today, euspen is a self-sustaining non-profit organisation with individual as well as corporate members from industry and academia, collaborating with the American and Japanese societies for precision engineering, ASPE and JSPE, respectively. They jointly publish the journal of Precision Engineering. Euspen headquarters is located at Cranfield University in the UK. The largest annual euspen activity is the euspen conference. The past conferences were in Bremen (1999), Copenhagen (2000), Eindhoven (2002), Glasgow (2004), Montpellier (2005), Baden (2006), Bremen (2007), Zürich (2008), San Sebastian (2009), Delft (2010) and Lake Como (2011). The twelfth conference will be held in Stockholm from 21 to 24 May 2012.

www.como2011.euspen.eu
www.euspen.eu

The conference was held in the Spazio Villa Erba Congress Centre in Cernobbio (see Figure 1) and comprised a mix of presentations, poster sessions, technical workshops and a commercial exhibition (see Figure 6 at the end of this report) in which companies presented themselves and their products and services. The conference focus was on latest advances and market developments in precision processes and manufacturing, as well as fabrication, metrology and cutting-edge materials in the precision, micro and nano engineering sectors. This mix of research and industry, one of euspen's strengths, was reflected in the participant population.

The conference was opened by euspen president Dr Henny Spaan of the Dutch company IBS Precision Engineering. Euspen's presidency was transferred to Prof. Paul Shore of Cranfield University (UK) later during the conference. In the evening of the second conference day, a conference networking dinner was organised in Como's Palace Hotel, which has a beautiful setting and classical Italian ambiance. Another social activity was the 'tradition in the making' euspen soccer match; see Figure 2.

**Author's note**

Raymond Knaapen works as a system architect in the Precision Motion Systems department of TNO Science and Industry in Eindhoven, the Netherlands.


Figure 1. The Spazio Villa Erba Congress Centre in Cernobbio, near Lake Como, Italy, hosted the eleventh euspen conference.

## Keynote 1: Engineering for particle physics

The first conference keynote, “The Engineering Needed for Particle Physics”, was delivered by Mr Gianluigi Arduini of CERN, the European Organisation for Nuclear Research in Switzerland. Currently, he is senior accelerator physicist, deputy group leader of the Accelerator Beam Physics Group as well as machine coordinator for CERN’s flagship machine, the Large Hadron Collider (LHC). In his presentation, he explained why particle accelerators are used and what the engineering challenges are to build them. An accelerator can be considered as a microscope for particle physicists. To investigate the past of the universe, higher energy levels are needed to look further back in time.

The LHC is currently the largest particle accelerator in the world, having a magnetic energy of 10 GJ, which is comparable to the kinetic energy of an aircraft carrier at a speed of 30 knots. 37,000 tons of superconducting magnets are used to realise a magnetic field strength of 8.3 T, which is 40,000 times the earth’s magnetic field strength; see Figure 3. A temperature of 1.9 K is realised along 20 km length of the LHC to reach superconductivity conditions. RF fields with strength of 5.5 MV/m are used for particle acceleration, comparable to ‘surfing on a wave’, and a magnetic field is used for beam steering in a vacuum environment of $10^{-10}$ Torr. Beam trajectory control takes place with a bandwidth of 20 MHz to control the beam position within a few microns. The beam, with a cross section of approximately 16 μm, is steered through a large ring with a 27 km circumference at a depth of approximately 150 m under ground at the Franco-Swiss border near Geneva. The beam energy of 7 TeV is comparable to the kinetic energy of a 200 m train driving at a speed of 155 km/h.

One of the main LHC research themes is testing for the existence of the Higgs particle in the Standard Model of particle physics, in which it is used for explaining elementary particle masses. First collision experiments

Figure 2. As a growing tradition that started last year in Delft, a soccer match was organised between the local ‘national team’ and the ‘euspen all-stars’. The match was situated beautifully on the shore of lake Como, next to the conference centre. Both teams displayed high-quality soccer skills, but in the end the Italian team proved to have a bit more soccer genes and won the match.

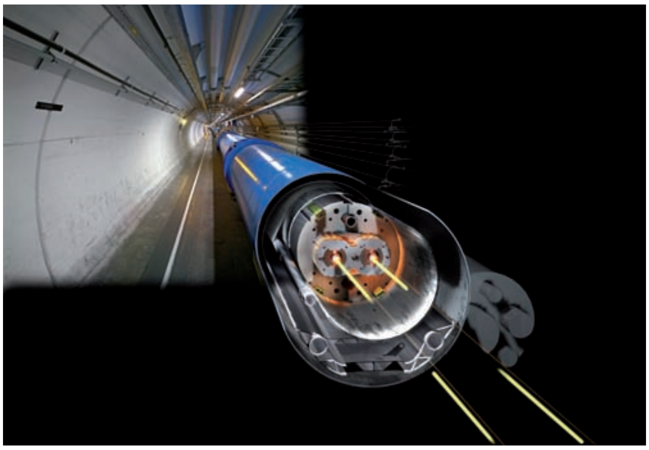


Figure 3. Cross section of an LHC dipole in the tunnel. (Photo courtesy CERN)

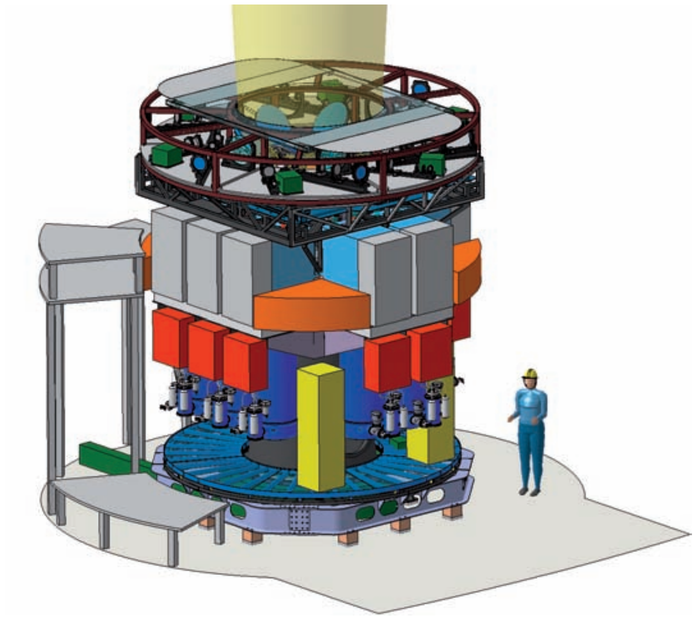


Figure 4. 3D design of the E-ELT instrument EAGLE (Extremely Large Telescope Adaptive optics for GaLaxy Evolution instrument), an adaptive optics-assisted multi-integral field near-infrared spectrometer. (Photo courtesy ESO)

were performed at half energy, being 3.5 TeV. Full-energy experiments are expected in a few years.

### Keynote 2: Manufacturing EUVL/X-ray optics

The second keynote, "Manufacturing of Precise Grazing Incidence EUVL/X-ray Optics by Means of Nickel Electroforming Replica Process", was held by Mr Dervis Vernani of Media Lario Technologies. The X-ray optics are used in X-ray telescopes for astronomy as well as in medical equipment. Media Lario is adapting the manufacturing technology to apply grazing incidence collectors for EUV Lithography (EUVL) equipment. There are many critical process steps in manufacturing of grazing incidence optics. Development is progressing in many of these process steps. One convenient manufacturing method for grazing incidence mirrors is based on galvanic electroforming replication from a master, where the mirrors can be manufactured in a monolithic structure.

Mandrel manufacturing is a critical step in the fabrication of the optics, because the initial shape accuracy and roughness highly determine mirror quality and accuracy. The replications of the mandrel surface are realised by nickel electroforming, after which the nickel shell is removed from the mandrel in a way that preserves optical quality. For astronomy, the shells have a thickness of e.g. 200 μm, while thickness in EUV applications is 3 to 4 mm because of the required cooling capacity. This thickness requires about two weeks of electroforming. Then, an optical coating is applied onto the nickel shell by a sputtering process (PVD), which is capable of achieving homogeneous layer thickness on curved surfaces. After manufacturing of the coated mirror shells, the optical elements have to be assembled in a special construction that provides sufficient stiffness, allowing for handling with minimal shell deformation. Shape and alignment measurements are conducted to enable assembly and corrections when needed.

### Keynote 3: The European Extremely Large Telescope

The third conference keynote, "Science and Technology of the European Extremely Large Telescope", was delivered by Dr Roberto Gilmozzi of ESO (European Southern Observatory). Finding earth-like planets in other solar systems is one of the rationales behind building large telescopes. To increase image resolution, which is needed to distinguish planets in telescope images, two trends can be pursued: increasing telescope diameter and increasing sensor sensitivity. The increasing diameter trend has been followed since 1990. The European Extremely Large Telescope (E-ELT), for instance, has a surface area of 1,200 $m^2$, with a diameter of almost 40 m. However, increasing telescope diameter is not enough for finding earth-like planets. Because of the expansion of the universe there is a brightness decrease, which leads to a contrast challenge in telescope imaging. Adaptive optics is used to correct for atmospheric turbulence; see Figure 4.

Additionally, numerical methods like Coronograph and spectral deconvolution are used to distinguish stars and planets.

## Sessions

The conference comprised a total of six sessions:

1. Ultra Precision Replication Techniques
2. Nano & Micro Metrology
3. Ultra Precision Machines & Control
4. High Precision Mechatronics
5. Ultra Precision Manufacturing & Assembly Processes
6. Important/Novel Advances in Precision Engineering & Nano Technologies

## Tuning fork stage

In session 2, an interesting presentation by Susumu Makinouchi of Nikon Corporation Japan on “An Interpolation Error Measuring System Using a Tuning Fork Stage” showed a very creative application of a tuning fork. A tuning fork is used for measuring interpolation errors. An encoder sensor is mounted to face one tuning fork arm, containing an encoder grid, while the tuning fork is excited by a low-distortion sound. Since a tuning fork has an extremely high resonance, the fork-arm motion becomes purely sinusoidal. The encoder sensor output, however, is contaminated with interpolation errors. Using FFT analysis, the interpolation errors can be extracted from the encoder measurement signal. Repeatability of the proposed measuring system was shown to be 0.33 nm, 1 sigma.

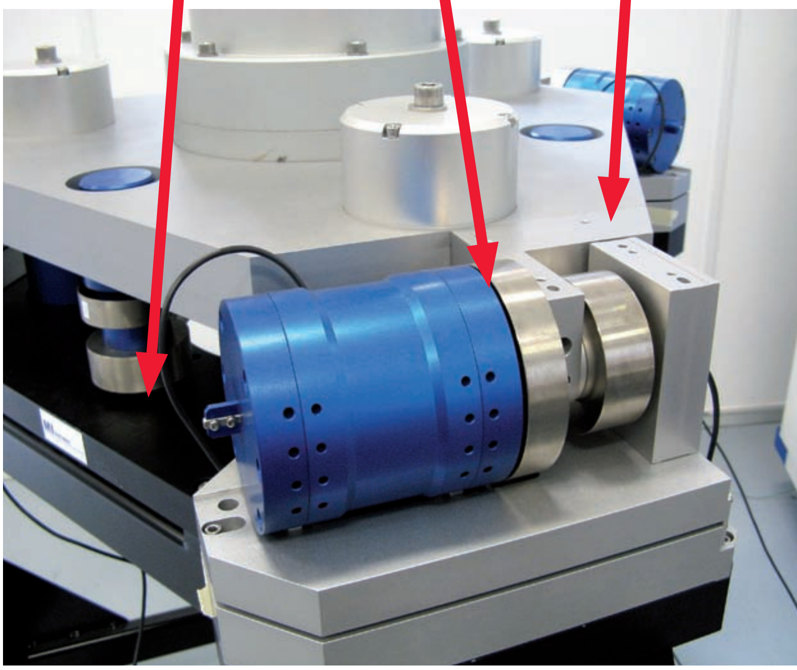



Figure 5. The MI-Partners Active Vibration Isolation system, developed for high performance, limited control complexity and high cost efficiency. Fundamental improvements concerned crosstalk (tilt-horizontal coupling) elimination and noise reduction. The positioning of horizontal and vertical geophones (the blue elements) is indicated. These sensors display excellent small signal behaviour. See also the article in Mikroniek 2011, no. 2.

## Increasing loop stiffness

The keynote presentation in session 3, “Elements for the Design of Next Generation, High Stiffness and High Accuracy Precision Machines”, was given by Prof. Alexander Slocum of MIT (Cambridge, USA). He focused on increasing loop stiffness in multi-axis precision grinding machines by applying stiff servo-controllable kinematic couplings, hydrostatic bearings and magnetic bearings. Cantilevers have to be avoided, because they are “the evil in the world”. Furthermore, closed-loop control was explained to obtain infinite stiffness at 0 Hz. Other design principles can be used as well in the grinding machine design to obtain high loop stiffness.

## ‘Dutch’ session

With some exaggeration, session 4 may be denoted as the ‘Dutch’ session. This session, chaired by Prof. Rob Munnig Schmidt of Delft University of Technology, Delft, the Netherlands, and Dr Wolfgang Holzapfel of German company Heidenhain, featured five Dutch poster presentations, as well as three orals: Rudolf Saathof (Delft University of Technology) with his keynote on “Evolving research on a non-contact adaptive optic actuation method for wavefront correction”, Maurice Teuwen (Janssen Precision Engineering) on “Advanced precision engineering in cryogenic environment”, and Dick Laro (MI-Partners) on “6-DoF active vibration isolation without tilt-horizontal coupling”; see Figure 5.

## Novel materials

In session 5, Dr Renato Jasinevicius of the University of São Paulo, Brazil, gave a keynote presentation on “Diamond Turning of Novel Materials”. He discussed different approaches to achieving and understanding the

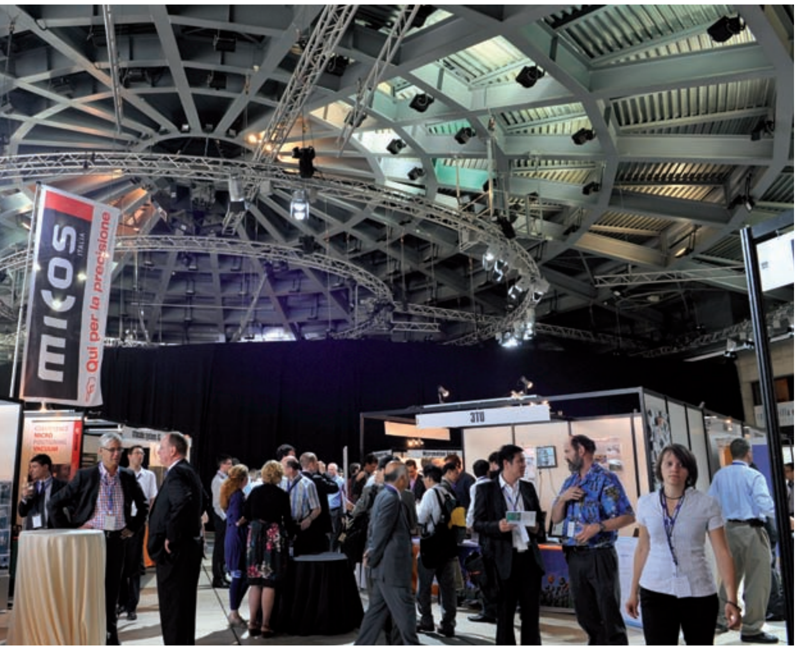


Figure 6. Impression of the commercial exhibition.
(Photo courtesy euspen)

ductile response to single-point diamond turning of novel materials. These – often brittle – materials, including tungsten carbide, indium antimonide and epoxy resin carbon nanotube composite, can be applied in, for example, precision glass moulding, diffraction optical elements and structural components.

## Nanotubes

Finally, the session 6 keynote was delivered by Ali Demir of Politecnico di Milano, Italy, on “Manufacturing and Characterisation of a Wettability Controlled Microvalve with Darkness/UV Actuation”. He presented the concept of contactless microvalve actuation through UV irradiation and darkness application, based on the control of the capillary pressures created in microchannels. The alternate application of UV and darkness allows commuting between hydrophobic and hydrophilic states of the microchannel surfaces functionalised with titanium dioxide nanotubes.

# Atomic-scale resolutions in TEMs

***The best resolution of FEI Company's most sophisticated transmission electron microscope (TEM) is the unimaginable distance of 80 pm, or less than 0.0001 μm. This Titan microscope works with 300 kV and this high voltage provides more specimen penetration power and a shorter equivalent electron wavelength of no more than 2 pm. At the DSPE PiB day on 16 June, FEI Company scientists presented some of the many challenges that have to be met when creating these extreme resolutions in TEMs.***

• *Frans Zuurveen* •

Perhaps unnecessarily, it is still worthwhile to first review the differences between a transmission electron microscope and a scanning electron microscope (TEM and SEM, respectively). A TEM's optical path slightly resembles a slide projector (see Figure 1), as it immediately provides a complete image of the specimen. In a SEM, an electron beam scans the specimen surface, while a detector simultaneously sends an electronic signal to modulate the local intensity of an image on a monitor screen; see Figure 2.

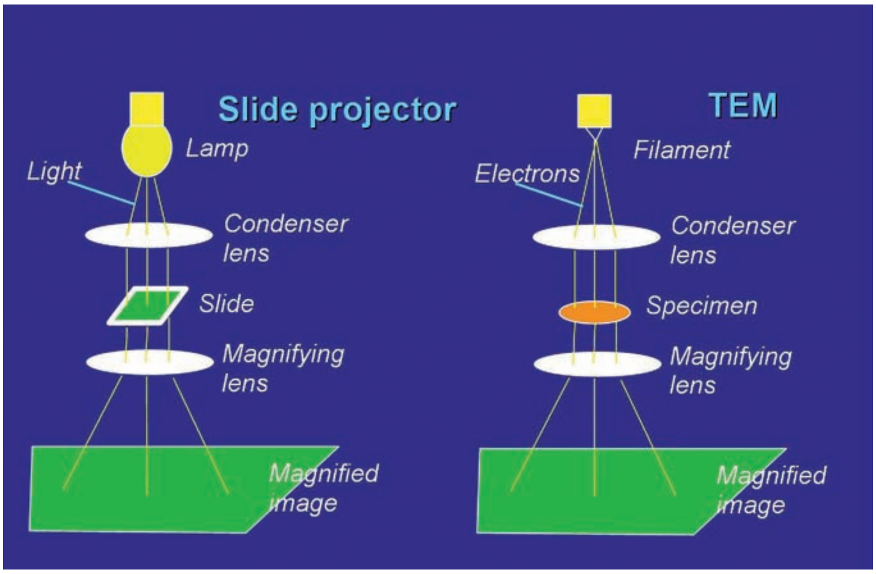



Figure 1. Comparison of a slide projector and a transmission electron microscope.

**Author's note**

Frans Zuurveen is a freelance text writer who lives in Vlissingen, the Netherlands.

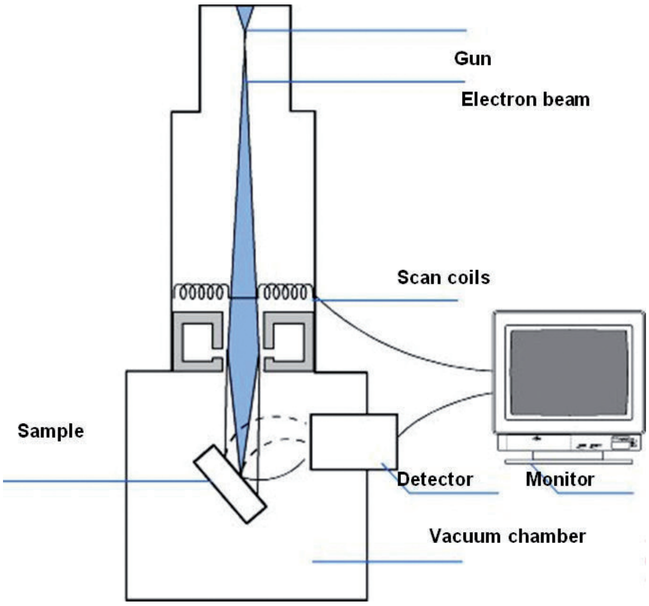



Figure 2. In a scanning electron microscope an electron beam scans the specimen surface. A detector sends an electronic signal to modulate the local intensity of an image on a monitor screen.

In the 1990s, Philips Electron Optics was a leading designer and manufacturer of TEMs and SEMs, fundamentally based on electron optics; see Figure 3. In this same period, the U.S. firm FEI was operating as a supplier of focused ion beam equipment. In 1997, the two companies combined their expertise by merging into FEI Company, with locations in Eindhoven (the Netherlands), Hillsboro (USA) and Brno (Czech Republic). FEI Company's current workforce totals 1,800 people, 550 of whom are based in Eindhoven, the Netherlands.

## FEI tools and markets

The first PiB-day speaker, FEI research director Frank de Jong, explained that FEI Company's main activities, besides TEM and SEM, are so-called DualBeam and focused ion beam equipment. A DualBeam (see Figure 4) has both an electron and an ion gun for observing and

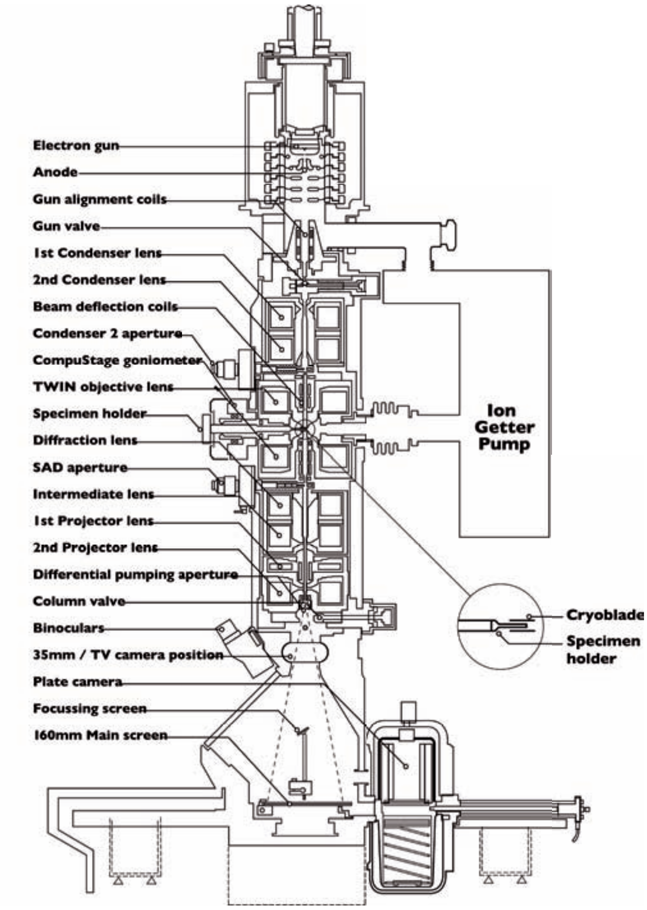



Figure 3. A cross section of the Philips EM 400 transmission electron microscope, developed in the late 1970s.

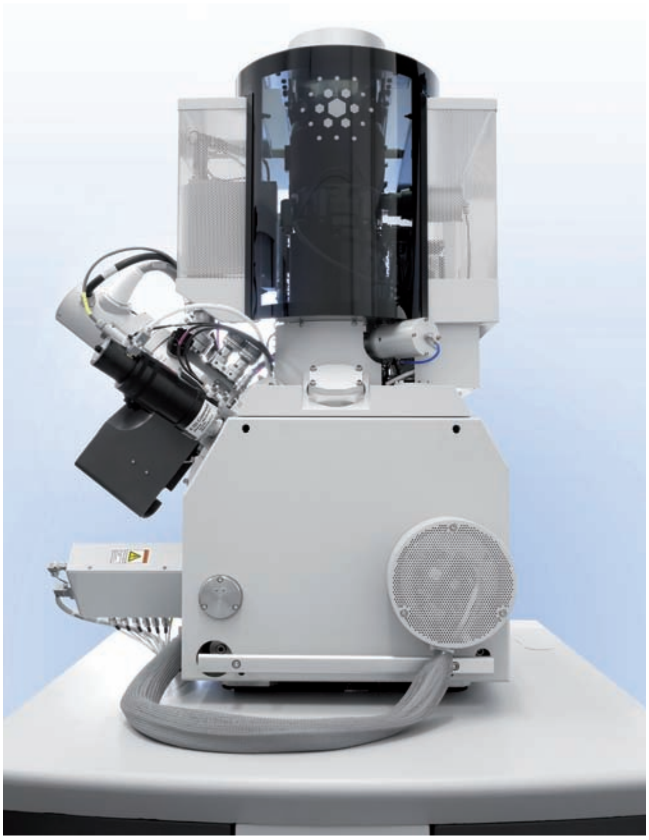


Figure 4. In an FEI DualBeam an electron beam (vertical) observes an object, whereas an ion beam (left) is able to modify it.

modifying a specimen, respectively. Focused ion beam instruments are purely intended for ‘machining’ specimen surfaces with high-speed charged particles. The main fields in which FEI products are used are fundamental research, life sciences, semiconductor design and manufacture, and the exploitation of the earth’s natural resources.

De Jong cited some convincing examples of recent FEI achievements, starting with the use of a TEM for recording optical spectra of gallium nitride LED materials. Secondly, a special version of the Titan TEM has been developed, together with the American DoE labs (Department of Energy), which has correction units above and below the objective lens for compensation of $C_s$, the imaging error resulting from spherical aberration. Another example is a newly designed, highly monochromatic SEM column with a significantly lower 1 V chromatic aberration. (The equivalent wavelength of an electron is inversely proportional to $\sqrt{V}$, with $V$ the voltage accelerating the electrons.)

Of course, detector design is of the utmost importance in scanning operations, both in SEM and in TEM (STEM: scanning TEM). Super X is a new STEM detector design, and it comprises a set of four X-ray detectors integrated into the objective lens. With Super X, an X-ray spectrum can be recorded in a much shorter time. De Jong also highlighted the use of TEMs in the life sciences to better understand the interaction of molecules and cells in structural biology, for instance in visualising organelles (specialised subunits within cells).

An extremely helpful instrument in life sciences research is the Titan Krios (see Figure 5), a TEM for studying frozen-hydrated samples. The electron beam and the vacuum environment of a ‘standard’ TEM damage or totally destroy living biological samples. Samples like these, e.g. viruses, can be studied on atomic level using a Titan Krios, as it freezes the specimen in amorphous ice.

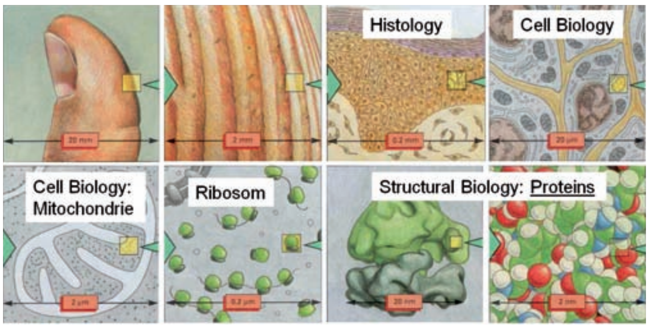
## The Cryogenic Autoloader

Jeroen van de Water’s PiB-day lecture was on the Autoloader, an accessory that may be hooked up to a Titan Krios to automatically load and unload frozen samples into and from the limited space within the objective lens. It facilitates contamination-free loading and analysing of up to 12 samples contained in a specially designed AutoGrid sample holder. In the life sciences, customers frequently ask for the unmanned analysis of large series of samples.


Figure 5. The Titan Krios, a TEM operating with 300 kV, for studying frozen-hydrated biological samples.

Van de Water firstly explained the ‘scale of life’ in biological research, from large to extremely small: histology → cell biology → mitochondria → ribosomes → protein molecules; see Figure 6. This scale corresponds with resolutions from 1 mm to 1 Ångstrom (1 Å = 0.1 nm), which can all be realised using a Titan TEM thanks to its significant magnification range (up to $10^7$, comparable to a photo camera with 10,000,000x zoom), and voltage range (60 to 300 kV).

Figure 6. The ‘scale of life’ in biological research, from the naked eye to a TEM resolution of 1 Å. With the latter, protein molecules can be studied on an atomic scale. The magnification range from upper left to lower right is 10,000,000x.



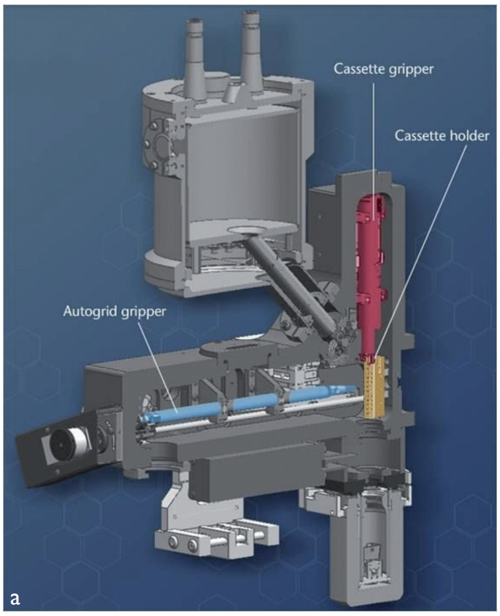
When studying biological samples, the following assessment always has to be made: a high voltage gives a better resolution but damages the specimen, whereas a low voltage saves the specimen but causes image noise. Embedding the biological specimen in a thin sheet of ice, however, relieves a researcher from having to make this difficult assessment because the vulnerable specimen is protected by frozen water. Ice crystals would cause image artefacts, so the ice has to be amorphous. To reach the required amorphous state, liquid ethane is used to cool down the hydrated specimen extremely quickly to 130 K or lower.

The AutoGrid sample holder (see Figure 7) can accommodate twelve copper grids of 3 mm in diameter with holes of 20 μm in diameter in each grid. The specimen can be observed through one of the holes.

Van de Water also explained that certain tricks can be used to minimise image degradation due to noise. He illustrated this with a 3D image of a KLH molecule (Keyhole Limpet Hemocyanin), a type of cell protein. The first trick is accumulating and averaging a series of images of the same molecule. Another one is a technique called electron tomography, whereby various 2D images from different points of view are manipulated in the microscope's computer to calculate a 3D image. This technique is similar to human X-ray computer tomography in medical systems.

## Demonstrations

PiB-day participants were shown how the mechanics of an Autoloader work. They could also observe the impact of heat from the human body on the performance of an electron microscope. When looking at a high-resolution image on a Tecnai TEM (see Figure 8) in a small demonstration room, the heat produced by a dozen people – for each of them about 200 W – was enough to cause significant specimen and image drift. The image of a graphite sample moved centimeters with each image update every 0.5 seconds, corresponding to a shift of a few nanometers at sample level.



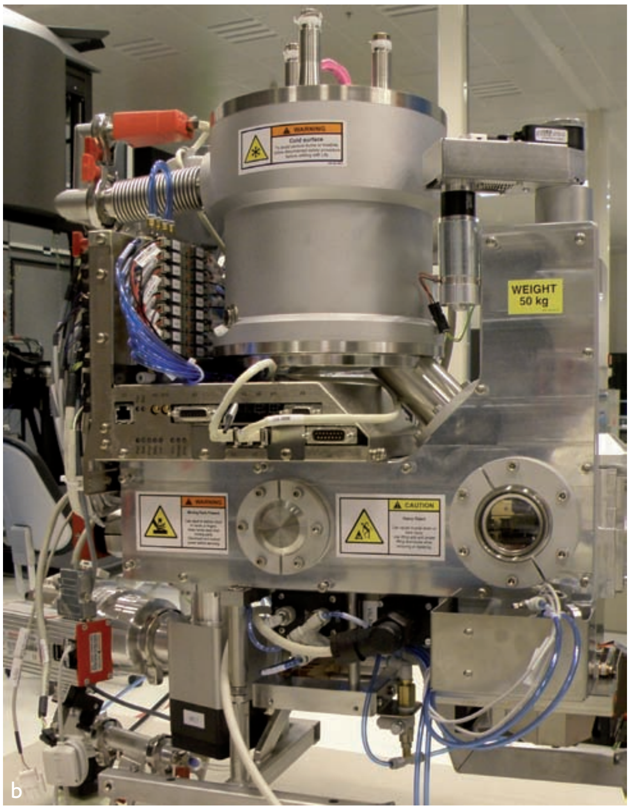




Figure 7. The Cryogenic Autoloader loads and unloads copper grids from an AutoGrid sample holder with twelve grids of 3 mm in diameter into the vacuum space within the microscope objective.
(a) Schematic drawing.
(b) Realisation: the lower right window shows how the specimen in the sample holder moves into the microscope.

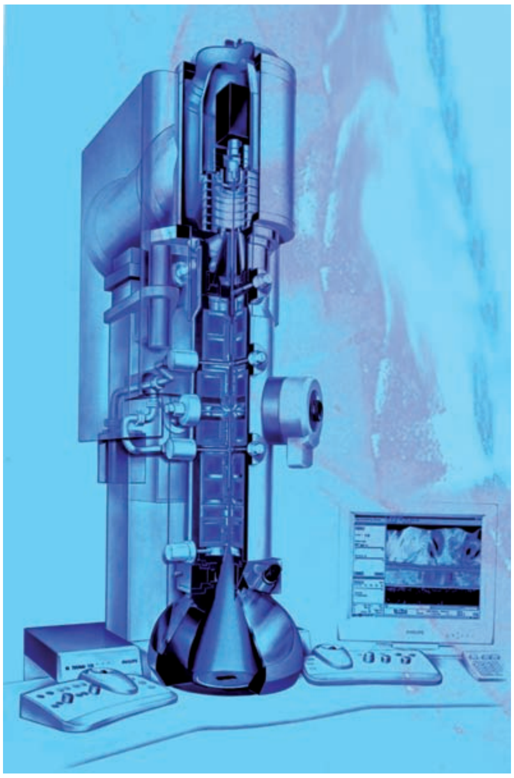


Figure 8. A schematic cross section of a Tecnai transmission electron microscope.

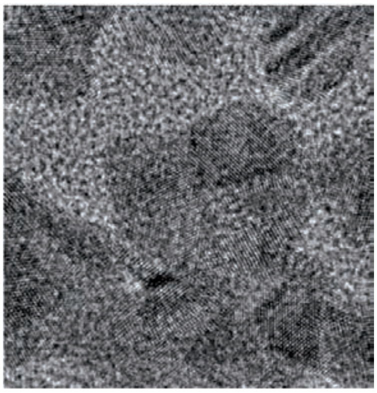


Figure 9. TEM image of crystallic gold palladium with lattice spacings of 0.23 nm. The image is 25 nm wide.

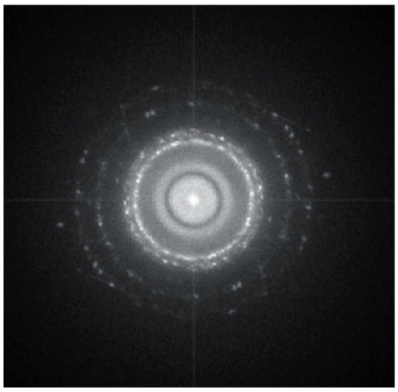


Figure 10. FFT (Fast Fourier Transform) image of the sample of Figure 9.

FEI microscopes are being assembled in clean rooms where protective clothing is mandatory. DSPE members were shown a huge Titan microscope shielded with an impressive cover (see Figure 5) for eliminating noise transmission via the air and for reducing heat transfer. Of course, the microscopes are insulated against vibrations; a Titan TEM column, for instance, is mounted on air springs.

## In search of a 10 pm vibration source

The quest outlined before to minimise influences in the microscope's environment explains Ab Visscher's endeavour to find the cause of the nearly undetectable vibrations initiated within an electron microscope itself. He has investigated instabilities with an amplitude of 10 pm inside a ChemiSTEM, a Tecnai STEM for material analysis with a cryo accessory. Visscher explained that such vibrations cannot be detected using a standard vibration accelerometer, but can only be visualised through the microscope itself by carefully observing high-resolution images.

As an example Ab Visscher showed an image with gold palladium crystal lattice spacings of 0.23 nm; see Figure 9. Figure 10 shows an FFT (Fast Fourier Transform) image of the same sample. Here the sample is imaged in the frequency domain. Each ring then corresponds to a defined lattice spacing, with a higher resolution at a larger radius. Each position in a ring corresponds to an angular orientation of a lattice in the original image. A continuous ring means that all orientations are present, whereas a point belongs to one orientation only, and an amorphous sample provides no rings at all.

Fourier analysis of the vibrations, which – despite their extremely low amplitude – influence the high-resolution performance of a microscope, showed a resonance frequency of about 270 Hz. Visscher found out that the temperature inside the microscope – environmental or near liquid nitrogen ($LN_2$) temperature – influences this frequency. Such low-amplitude vibrations may be related to the boiling effects in the $LN_2$ Dewar vessel. Even flexible elements in the microscope, like the copper braids that transport cold from the Dewar, may transmit such tiny vibrations. Needless to say, the outcome of Visscher's research has contributed to improvements in FEI products.

## To conclude

DSPE visitors were, of course, well aware of Philips Electronics' ongoing concentration on its core disciplines. In the Eindhoven-Veldhoven high-tech region this process has resulted in new businesses emerging that originated from earlier activities of the well-known 'incandescent lamps manufacturer'. A prime example of this is the birth of FEI Company. Its success testifies to the excellent fertile ground for existing precision technological skills. In short, FEI Company has proven to be a fruitful marriage of the arts of understanding the behaviour of electrons and ions.

**Information**

www.fei.com

# Thermal expansion

***With ever-decreasing workpiece tolerances, it has become more and more important to prevent thermally induced distortions in machine tools. This implies limiting the machine's thermal deformation or even tightly controlling its temperature. IBS Precision Engineering provides measurement technology to accurately measure this thermal machine tool behaviour.***

• ***Marianne Vincken and Guido Florussen*** •

The accuracy of many systems, like printers, wafer steppers, telescopes and precision lathes, is affected significantly by temperature changes. Machine tools like milling machines and lathes, for example, can drift significantly due to temperature changes. These changes result from environmental changes (day-night cycle) and from heat sources present in the machine itself. This causes the cutting tool to change its position relative to the workpiece, resulting in dimensional errors in the workpiece geometry. This error changes quite slowly over time, but can be quite large, e.g. > 100 μm. When workpiece accuracy is important, it is vital that this thermally induced drift is prevented. In principle, this can be achieved in two different ways, namely by preventing any temperature changes occurring (i.e. active cooling of the machine) or by modelling the machine's drift and compensating for it.

**Authors' note**

This article is an abridged and edited version of the report on the thermomechanics theme day organised last year by Mikrocentrum, which was published in the Dutch trade journal Metaal Magazine. Marianne Vincken of 1005 tekstproducties is a freelance text writer. The article is based on the theme day presentation given by Guido Florussen, metrology expert at IBS Precision Engineering in Eindhoven, the Netherlands.

## Basics

Thermal expansion is expressed by the basic equation:

$$\Delta L = \alpha \cdot L \cdot \Delta T$$

To limit changes in length ($\Delta L$) the terms on the right-hand side should be minimised. One way to do this is to use materials with a low expansion coefficient ($\alpha$), like Zerodur and Invar. Unfortunately, these materials are expensive and hard to machine. A more practical solution is to limit the temperature change ($\Delta T$) as much as possible. To determine the success of this method, measurements are required with increased precision, which is not an easy job.

## Probe nest

To do this, IBS Precision Engineering uses a combination of a well-defined Masterball with a roundness error smaller than 25 nm and capacitive sensors in a so-called probe nest; see Figure 1. This is used to measure the distance to the Masterball as a function of time. The probe nest should be firmly attached to the machine. If this is not the case, the device will soon start measuring primarily the vibrations in the stand to which the sensor is attached. Capacitance sensors are used in this case since they will result in more precise measurements compared to inductive sensors. This is because the signal of inductive sensors not only contains the distance to be measured, but also a signal resulting from inhomogeneities in the material, as the eddy currents penetrate about 0.1 to 0.3 mm into the target material. A capacitance measurement only concerns the

# under control

two outermost layers of atoms; the signal in question is therefore much cleaner.

A capacitance measurement is non-contact and very fast; the system's bandwidth equals 15 kHz using an oscillating electrical field at 1 MHz. The resolution is typically a few nm only (3.5 nm peak-to-peak). The change in capacity ($\Delta C$) is a function of the sensor surface ($A$), the dielectric constant ($\varepsilon$) and the change in distance ($\Delta d$) from the sensor to the Masterball:

$$\Delta C = A \cdot \varepsilon / \Delta d$$

The measured change in capacitance ($\Delta C$) is then a measurement of the displacement ($\Delta d$) by keeping $A$ and $\varepsilon$ constant. Now the displacement and the tilt error of the Masterball can be measured: the $x$, $y$ and $z$ coordinates and the $R_x$ and $R_y$ tilting error angles.

## Vibrations and noise

The distance measured between the sensor and the Masterball can be distorted by noise and/or vibrations. In that case, the measuring signal is corrupted by higher harmonics or noise. The source of these higher harmonics can be mechanical (low frequencies, < 500 Hz) and/or electrical (typically > 1 kHz). A system-integrated Fourier analysis tool enables the user to analyse the frequency power spectrum 'live'.

If this frequency is low (< 1 kHz), mechanical vibrations occur and this can be resolved by improving the stability of the measurement set-up. If, on the other hand, the frequency is high (> 1 kHz), then the sensor picks up electrical noise, possibly emitted by linear motors nearby. That problem is generally solved by grounding the target with a carbon brush, sliding cable, etc. This is often required when measuring spindles are equipped with air bearings or ceramic bearings, i.e. when the rotor is electrically isolated from the stator, which is not the case for steel ball bearings. Lubrication pumps are another potential source of distortion. They can generate a displacement that occurs at periodic intervals, which might seriously disrupt a high-precision measurement.

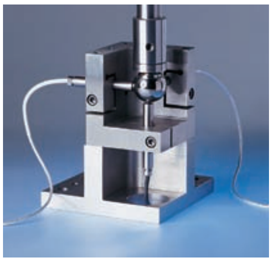


Figure 1. A Masterball is attached to the spindle. The probe nest, mounted firmly to the machine's table, is equipped with sensors. The capacitance sensors measure the (change in) distance to the Masterball.

## Quantifying thermal drift

Once the measurement set-up has been realised successfully, the machine's thermal drift can be determined. Before starting the experiment, the machine is first allowed to heat up. The machine manufacturer might prescribe a certain warming-up period, typically 15 minutes. After warming up, the thermal drift measurement

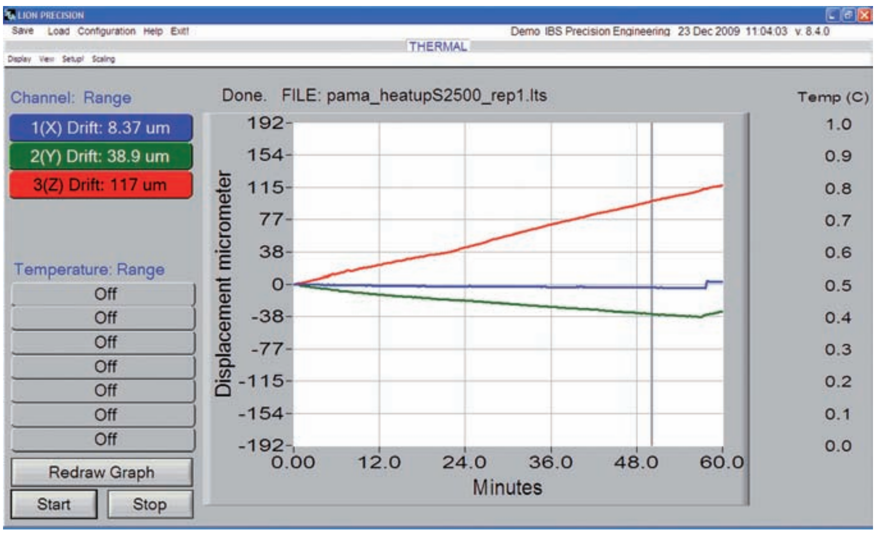



Figure 2. The drift in an uncompensated machine after an hour of warming up at a speed of 2,500 rpm.

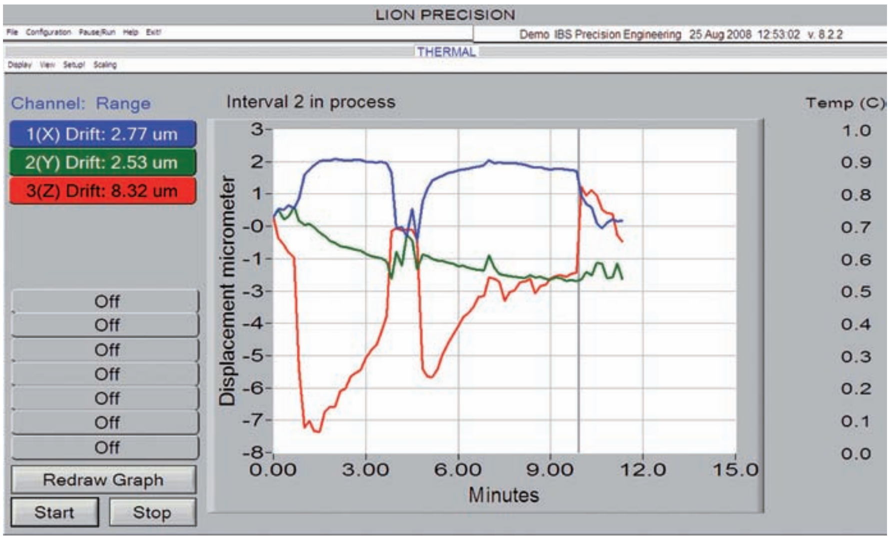



Figure 3. The drift in a properly compensated machine during a test measurement with an alternately high (35,000) and low (2,000) number of revolutions per minute.

can start. The machine's thermal drift in *x*, *y* and *z* direction is then recorded periodically, i.e. every minute, for a few hours. Figure 2 shows a typical measurement result for an uncompensated, large machine.

The major heat source in a machine tool is the spindle unit. Other heat sources present include hydraulic pumps, electronics, motors, gear boxes, the cutting process, etc., and, last but not least, the environment. The thermal displacement is nearly always greatest in the *z* direction (spindles do 'grow'), even exceeding 100 μm in extreme cases. In the *x* and *y* direction this drift is usually much smaller, in the order of several tens of microns, mainly due to symmetry.

The displacement in the *z* direction, however, is affected by a different mechanical effect. The bearings in a spindle unit are usually pre-tensioned to remove play and increase stiffness. As the spindle starts spinning, the bearing balls are subjected to large centrifugal forces, decreasing this pre-load. As a result, the rotor extends slightly from the stator. This shift is quantified as a function of RPM (revolutions per minute) in a separate measuring sequence, for which the spindle speed is very quickly varied over the entire spectrum, while monitoring the Masterball's displacement. The measurement set-up is identical.

## Compensation

Once the machine has been measured, an attempt can be made, if required, to prevent the expansion. One way of doing this is to ensure that the heat is immediately removed and that the spindle and the rest of the machine do not heat up. Alternatively, the expansion can be compensated for using a machine model. There are known examples at IBS Precision Engineering of cooled compensated machines with deviations in the *z* direction of less than 10 μm; see Figure 3. The best machine that was ever tested deviated even less than 2 μm. A practical tip from IBS: when compensating, pay close attention to the +/– sign for the compensation; when an incorrect selection is made, the issue is made twice as bad instead of being resolved.

Actively cooled machines can limit the drift to a few μm, a straightforward compensation to 20-80 μm and 10-50 μm is within the realm of possibility with an advanced compensation. These are figures from machines that were compensated for based on a model.

**Information**

IBS Precision Engineering
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# High-tech paperclips and tie wraps

***Last May, a group of prominent researchers from all over the world gathered for the Second International Symposium on Compliant Mechanisms (CoMe2011). The symposium was held at Delft University of Technology, Delft, the Netherlands, and promoted intense interaction among researchers interested in the field and exchange of their ideas. The main objective of the meeting was to discuss fundamental issues and future directions in compliant mechanism research and design.***

• *Sérgio Pellegrini* •

Compliant mechanisms, also known by the name of compliant structures or flexure mechanisms, are mechanical devices that accomplish their motion due to deformation of slender segments instead of relying exclusively on rigid links with relative motion lumped in joints. Compliant mechanisms benefit from numerous advantages such as compactness, cheap production, no assembly, no maintenance and no friction or backlash. Everyday examples include paperclips, tweezers, snap-fits and tie wraps, while high-tech applications are present in micromirrors for beamers, in a variety of measurement systems, and in stages for micropositioning in microscopes for instance.

The symposium in Delft followed up on the First Symposium on Compliant Mechanisms, which was held in Bangalore, India, in 2007, and was organised by Prof. G.K. Ananthasuresh, who is one of the pioneers of the field, and Dr Anupam Saxena. The goal of the first meeting was to make an inventory of methods and approaches and consisted of twelve invited presentations. It was a highly motivating meeting that deserved a sequel.

**Author's note**

Sérgio Pellegrini studied mechanical engineering at the Universidade de São Paulo, Brazil, and now is a student at Delft University of Technology.

From the awareness of the multidisciplinary challenges faced in compliant mechanism research, one objective of the Second Symposium was to bring together researchers of several relevant fields who are all working on compliant mechanisms but from a different angle, and who publish and meet in different journals and conferences; see Figure 1.

In particular, the symposium targeted the following areas:
1. Precision engineering, perhaps the most classical field where typically precise motion is achieved by small elastic deflection of leaf springs and other slender parts of a structure;
2. Compliant mechanisms and robotics, where large deflections are used to achieve functions such as path or motion generation;
3. Topology optimisation, where algorithms are developed to distribute material in a design space to perform a predefined function;
4. Structural mechanics, where structures are studied that turn into compliant mechanisms if the stiffness is reduced.

Figure 1. Participants of the Second International Symposium on Compliant Mechanisms.

It was most interesting to see top representatives from all of these fields and observe the differences and similarities in their approaches, some of which will be briefly discussed below.

The event started with a tutorial on the design of flexure mechanisms given by Dr Simon Henein, from CSEM (Centre Suisse d'Electronique et de Microtechnique). The tutorial provided an extensive overview on the state of the art in compliant mechanisms. Many real-life examples were given, and some methods and practical issues in design were also discussed. A very interesting discussion took place on the association of the concepts of degrees of freedom (DoFs) and Grübler's mobility to the degree of hyperstaticity, typically used in structural mechanics, for the design of mechanisms. For mechanisms, a positive degree of hyperstaticity indicates that there will be difficulties in the assembly, having to control different tolerances simultaneously.

Next day, the event proceeded with five keynotes and thirty very dynamic presentations of papers, which were presented as a combination of so-called fast-forward podium presentations that were followed by interactive presentations in a separate room. This format allows ample time for in-depth discussions with the authors, as well as excellent opportunity for networking and meeting the top scientists in the field in person. Also, this way of presentation avoids parallel sessions and allows everyone to visit the presentations of their interest.

In the fast-forward sessions, the authors were invited to present their work in 180 seconds. They were encouraged to respect the time limit by a sonorous bell, which proved to be important and very effective. Longer explanations and discussions were encouraged in the interactive sessions, in which the authors exhibited posters, laptop videos and physical demonstrators.

In the field of precision robotics, nicely following up on Dr Henein's tutorial, Murielle Richard, from the Swiss Federal Institute of Technology Lausanne, expanded on the design of 3D mechanisms using a building block approach. The complex tri-dimensional problem is split into a series of two-dimensional problems, simpler and well-mastered. Defining sets of active and passive building blocks, she presented a 5-DoF ultra-high precision robot as application example. Another example from precision robotics was presented by Dr Dannis Brouwer from the University of Twente. He brought a table-top 2-DoF positioning stage for large displacements based on cross-flexural hinges; see Figure 2.

Figure 2. Interactive presentations with posters, videos and demonstrators gave the authors (amongst them Dr Dannis Brouwer, second from the right) an excellent opportunity to present their ideas and discuss these extensively with the audience.

On the basic research level, some papers added to Dr Simon Guest's keynote on negative stiffness. The researcher from the University of Cambridge, UK, affirmed that pre-stressing a mechanism will change its stiffness, allowing, for instance, a zero-stiffness compliant mechanism. He argued that typically in structural mechanics the aim is to increase structural stiffness by pre-stressing, but that the reverse is also possible and indeed desirable for compliant mechanisms. This "manifesto", as he called it, was demonstrated in several mechanisms presented at the symposium.

One example was given in the interactive presentation by Lodewijk Kluit, from The Hague University, the Netherlands, in which a negative-stiffness mechanism was designed for use in a body-powered hand prosthesis, such that the stiffness due to the cosmetic covering experienced by the user can be reduced. This is essential to ensure that no excessive operating effort is required from the user, a common reason for the abandonment of the prosthesis; see Figure 3. Another application of a zero-stiffness mechanism was provided by Jan Vaandrager, from the University of Twente. Here, a compliant gripping mechanism was statically balanced for a large range of motion. The force needed to deflect a gripper finger was reduced to 5% of its initial value, as a result of the addition of a pre-stressed structure to the mechanism; see Figure 4.

Additionally, innovative design methods were discussed with the keynote of Prof. Ole Sigmund, from the Technical University of Denmark. As one of the pioneers of topology optimisation, he presented a method for robust design of compliant mechanisms. The method is based on the distribution of material density in a design space by an algorithm, subject to boundary conditions and an objective function. While the method is essentially the same, Sigmund showed that it can be applied to a remarkable variety of areas, including acoustics, photonics, fluids, antennas, as well as multiphysics problems such as micro-thermo-electric actuators.

This method was further discussed in Boyan Lazarov's interactive presentation, with examples of application on the design of MEMS-scale mechanisms. The optimisation procedure avoids lumped compliance throughout the mechanism and provides an output that is robust to fabrication uncertainties and geometric manufacturing errors, such as over- or under-etching. An example of a mechanism designed with this topology optimisation method is shown in Figure 5.

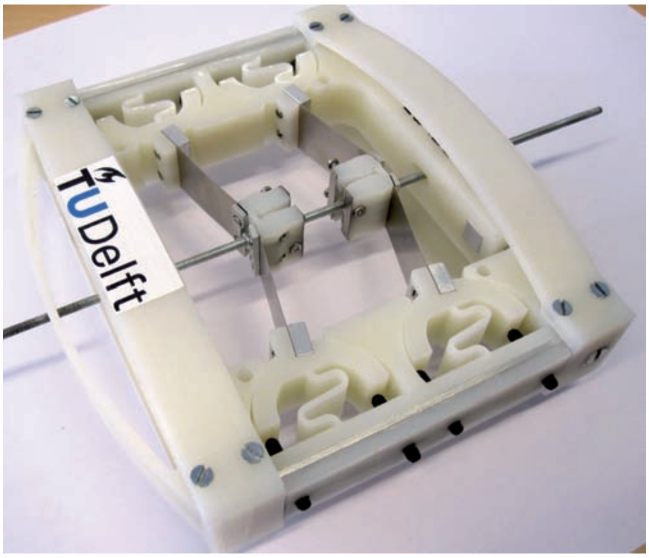



Figure 3. Adjustable negative-stiffness mechanism to cancel out the cosmetic covering stiffness in body-powered hand prostheses. Negative stiffness occurs after snap-through and is adjustable by the compliant structures along the sides.

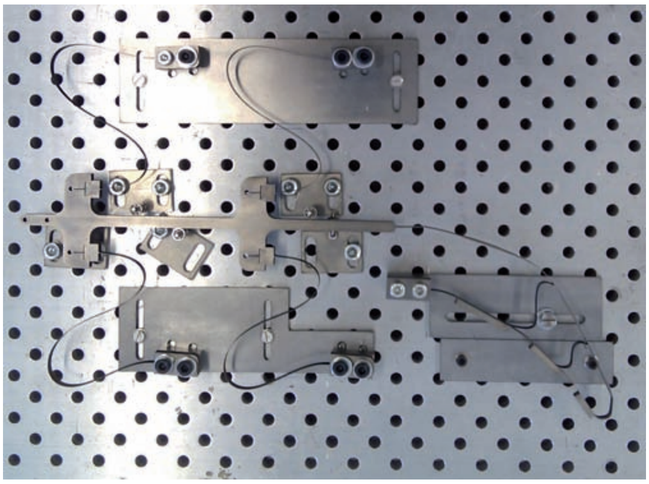


Figure 4. Compliant finger (right part) and negative-stiffness mechanism consisting of four prestressed S-shaped segments, resulting in a near-zero-stiffness behaviour.

Figure 5. Compliant mechanism designed to be robust to manufacturing uncertainties. The over-etched, the nominal design and the under-etched are shown.


Figure 6. Plenary lecture by Herman Soemers in the podium presentation room.

Practical design issues and industrial applications were brought up in the keynote of Herman Soemers from Philips Innovation Services and (until 1 April 2011) University of Twente, especially on the subject of precision engineering; see Figure 6. Besides presenting a series of application examples from his experience both in Philips and at the University of Twente, Soemers reinforced the importance of correctly tuning the resonance frequencies, separating the fundamental, the parasitic and the internal modes.

Future research directions were presented in the keynote by Prof. Larry Howell, who is heading the Compliant Mechanisms Research group at Brigham Young University, Utah, USA, supporting the idea that compliant mechanism design is a fast growing field of knowledge and that there are three main application areas that can benefit exceptionally from their use. The first of them is technology made to be launched to space, an area driven by a need for very light and highly reliable solutions, with no lubrication, high precision and long lifetime. Next, the nanometer-scale application area was brought up. At this scale, mechanical stiffness is less predominant, as compared to thermal fluctuations, chemical potentials or electromagnetic effects. Thus, the use of mechanisms that can deform without losing their effectiveness can allow a great expansion of this knowledge frontier. Howell's last view on future application areas was concerned with the development of "disruptive solutions", innovative designs for classical equipments, lowering the costs and making them available for a wider market, including underdeveloped countries.

Finally, the closing plenary was presented by Prof. G. K. Ananthasuresh, who suggested an integrative view on compliant mechanisms, rigid-body linkages and structures. He presented a compliant mechanism design software which supports the development of feasible designs. In addition, Ananthasuresh invited everyone to try it and include their examples in the database. Finally, he showed how a design paradigm of putting back the material at one end that was taken away at the other end in a topology optimisation algorithm produced artistic, Escher-like patterns, that turned out to have practical use in MEMS where no space on the wafer should be wasted.

The interaction of researchers with different perspectives and approaches on the same problem was an enriching experience for all present. Students and researchers, directly involved in the design of compliant mechanisms, returned home inspired and with new ideas in their minds.

**Acknowledgement**

The input and paper review by the symposium organisers Juan A. Gallego, Nima Tolou and Prof. Just Herder is gratefully acknowledged. The symposium was a result from the Dutch VIDI Innovational Research Incentives Scheme grant for the project "Statically balanced compliant mechanisms", NWO-STW 7583. The works presented in the meeting will be published in the open-access journal Mechanical Sciences as a special issue on Future Directions in Compliant Mechanisms. In addition, the symposium website hosts videos of the conference keynotes.

compliantmechanisms.3me.tudelft.nl
www.mech-sci.net

# Special innovations in geometric measuring technology

**New developments and concepts, such as non-contact measurement and virtual measuring machines, are turning measuring technology into an exciting field. For that very reason, Mikrocentrum is organising a "Geometric Measuring Technology in Precision" theme day at the Nederlands Meetinstituut (NMi) in Delft, the Netherlands, on Tuesday, 11 October 2011.**

Non-contact measurement is booming because of the advantages it offers in terms of measuring speed and the fact that the workpiece does not have to be physically handled or affected. Laser scanners, for example, are being used to measure complex 3D shapes and workpieces. Another development is the performance of non-destructive measurements using tomographic techniques. This non-contact method can determine dimensions that conventional gauging systems simply cannot reach.

## Virtual measuring machine

For reducible measuring results, as required under ISO 17025, it is important to be able to substantiate measurement uncertainty. The conventional method, which outlines uncertainty in the measuring process in an analytical way, generally provides satisfactory results.

However, the increasing complexity of measuring machines means that this analytical method is becoming less and less practical and sometimes even impossible. In cases like these, a virtual measuring machine can provide a solution. Using a virtual measuring machine, the uncertainty of specific measuring tasks can be determined via Monte Carlo calculations based on the behaviour of the machine and the origins of uncertainty in the measuring process.

## The right construction principles

Precision measuring machines require a sound design that is based on the right construction principles to make the system's behaviour predictable. The importance of applying these construction principles will be illustrated during the theme day using the development of a new precision translation platform as an example.

## Target groups

- Engineers and other qualified technicians working in development, materials research, engineering, production and assembly, work preparation, quality services and purchasing.
- Managers working in or with production, assembly, quality services, measuring technicians or surveyors.
- Entrepreneurs who want to increase/improve quality.
- Business consultants, business training experts and senior secondary vocational and higher professional education teachers.

www.mikrocentrum.nl/evenementen

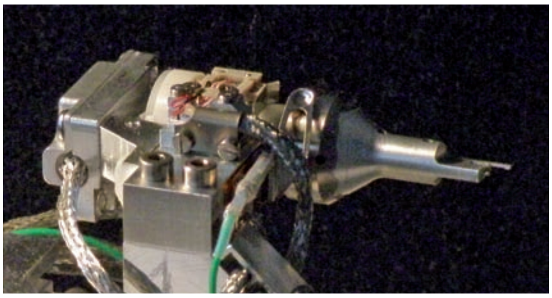
### 2011 Precision Fair

This year, the Precision Fair will be held on 30 November and 1 December, once again in the NH Conference Centre Koningshof in Veldhoven, near Eindhoven, the Netherlands. The eleventh edition of this fair will include over 200 exhibitors, a highly relevant lecture programme and the Technology Hotspot, featuring some twenty knowledge institutes from the Netherlands, Germany and Belgium.


www.precisiebeurs.nl

# Even slower movement, even more accurate

***Whether dealing with transporting solar cells in the making through a production line, or the manipulation of miniscule slides in an electron microscope, utmost accuracy in managing the movement (and the stationary status) is crucial. To obtain even better control over the motion control, the Point-One project "Positioning and image formation at micro and nano level" was started. Towards the end of autumn last year, the project, which covered the domain of the micrometers and nanometers, was successfully completed. The high-tech linear motor now holds almost no more secrets for Bosch Rexroth and the first piezo motor applications have already found their way to customers.***



Bosch Rexroth in Eindhoven, the Netherlands, develops drive and motion control technology for the semiconductor and the solar cell markets. To obtain even better control over the motion control, in 2006 the company took the first step towards the project "Positioning and image formation at micro and nano level", under the flag of the Point-One innovation programme; the subsidy was provided by SenterNovem (now part of NL Agency). Based at Eindhoven University of Technology (TU/e), the groups of Professor Steinbuch (Control Systems Technology) and Professor Lomonova (Electro-mechanics and Power Electronics) acted as knowledge partners; manufacturer of electron microscopes, FEI Company, was the application partner and SME company, Technolution, the technology partner.

**Editor's note**

This article was based on a Point-One press release.
www.point-one.nl

## Micrometers

For the transport and the positioning of silicon wafers in solar cell production, micrometer accuracy is required. That production takes place in a vacuum and that must not be disrupted on account of (potentially leaking) lead-throughs to the outside world for, for example, the drive. Bosch Rexroth developed the Linear Motion System (LMS) for this, which is based on linear motors. The launching customer was the company's neighbour in Eindhoven, OTB, manufacturer of solar production lines. Unlike the standard design of a linear motor, in the LMS the coils along with the electronics and connecting wires are situated on the (stationary) outside world and permanent magnets move as product carriers in the vacuum.

The study into the linear motor mainly focussed on the functional modelling for better control of the physics behind this technology. This involved, amongst others, the cogging phenomenon, the jerky movement of the permanent magnet across the magnetic field of the (distributed) coils. The insights gained were translated

# when stationary

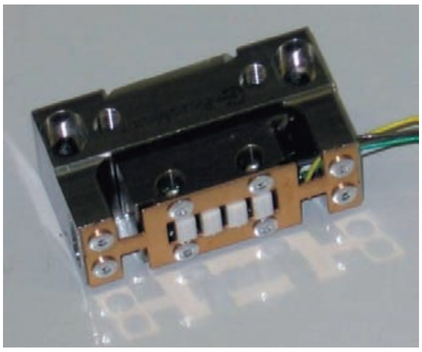
into advanced control algorithms to achieve flowing, well-controlled movements. Meanwhile this has already resulted in other applications, including one for the American company Intevac, manufacturer of equipment for hard disk production. During magnetic sputtering of the hard disks, it is important that they remain totally stationary, down to the micrometer.

## Nanometers

The production and inspection (with electron microscopes) of semiconductor components has now entered the nanometer domain. Not only must the positioning take place accurately down to the nanometer, it also has to be possible to perform both very fast and extremely slow (down to 10 nm/s, or less than 1 mm/day) movements with the greatest degree of accuracy. Even the minutest disturbance is already too much. Smart control engineering can 'control away' disturbances and that is right up the street of piezo technology; piezo material is able to expand or contract in an extremely controlled manner when a voltage is applied. However, piezo motors have to be able to become even faster, even slower and even more accurate. To that end, during the project research was performed into new piezo motors, amplifier technology and control algorithms.

An initial nano subproject involved the development of an extremely accurate piezo amplifier for a conventional piezo stack. A use has already been found in the Yieldstar, a metrology tool by lithography machine builder ASML. In that tool, using light, the quality of lithography on wafers is investigated; piezo stacks guide lenses in the optical lens system.

The second nano subproject involved a piezo motor that is equipped with four styli (or 'legs'), which make a repetitive movement and, in turns, push against a stage, which is then moved forward. This drive principle is suitable for extremely accurate and slow movements of, for example, samples in an electron microscope of FEI. When under load, the styli were found to quickly break off as a result of material problems. An improvement of the piezo motor design was needed. In addition, in close collaboration with the TU/e group of Professor Steinbuch, smart control algorithms were worked out in order to optimise the drive.

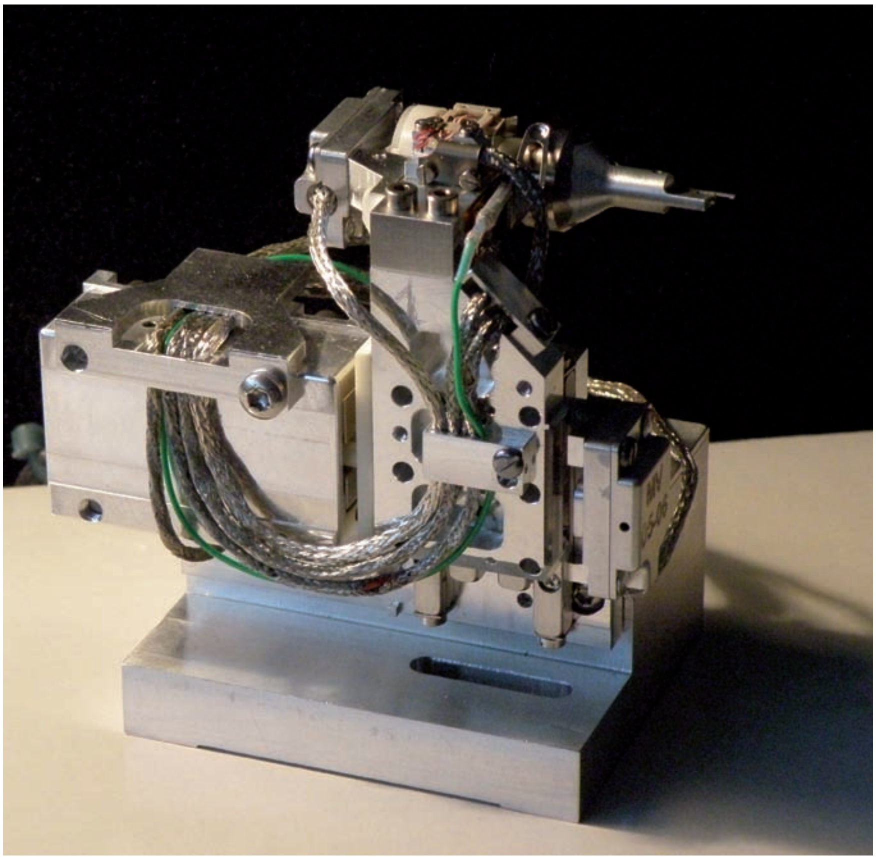


A piezo 'walking leg' motor.

## Worldwide effect

In addition to specific applications for customers such as ASML and FEI, the project also resulted in a generic spin-off. A lot of energy was put into the further development of 'distributed control'. Because controls increasingly have to be faster (operate at a higher control frequency) and really do have to respond in real time to, for example, signals from sensors. To that end, intelligence, in the form of application software, of the central control PC has to move to the decentralised motion controllers. Because those are equipped with more limited processors, it required quite a bit of fitting and measuring. In addition, the functionality of motion control platform NYCe 4000 of Bosch Rexroth was expanded. Now many different drives, from piezo motor to high output drive, can be driven from one motion controller.

The results of the project have a worldwide effect, states Wilco Pancras, technology development manager at Bosch Rexroth. "Together with the partners and customers such as ASML and Intevac, we have gained a lot of experience and developed new applications, because of which we are able to perform at a higher level. Last year, an American company called for tenders for the control of a certain wafer handler. In competition with other parties, we secured the contract. What particularly motivated us in that process was that the customers' senior engineers set to work using our technology and



An example of motion control for one of FEI Company's devices: a so-called flip stage, mounted on top of a normal stage, with two axes, Z and Rx. For subsequent manoeuvring under the ion beam in such a way that the sample's plane is parallel to the beam, a sample can be attached to the end of Rx. Now, by removing material from the top and the bottom sides, the sample can be made thinner by a few tens of nanometers.

were surprised about everything they were able to do with it and how, because of that, they were able to make significant advances in the performance of their wafer handler."

## High-speed control systems

As an SME company, Technolution in Gouda, the Netherlands, was the technology partner of Bosch Rexroth in the project. The company develops electronics and software solutions for technical information systems and embedded systems. In this project, the emphasis was on the hardware for the NYCe 4000 motion control platform of Bosch Rexroth. Both parties had already been working jointly on this for ten years, says the project manager at Technolution, René Stallen: "We invest in the necessary knowledge and, from its view of the market, Bosch Rexroth declares where we can apply that knowledge for innovation." In the project in question, for Technolution the challenges mainly lay in the extremely high accuracies of the piezo motion control system. That meant that, in the design, significant attention had to be paid to the noise levels in the system. Beforehand, the requirements were carefully examined, simulations were performed and the correct components selected. Another item for consideration was improvement of the performance of the control systems under a standard operating system (OS), so without using a dedicated OS. Technolution is able to generally use the knowledge that it accumulated in this way for high-speed control systems. "The need for high control frequencies, up to above 100 kHz, pertains to all kinds of high-tech systems."

## Sample manipulation

An example of those high-tech systems are the aforementioned electron microscopes that FEI Company develops and produces. The Eindhoven branch, which acted as application partner during the project, accommodates the 'centre of excellence for sample manipulation', explains Director of Research and Technology Frank de Jong. "In our so-called dual-beam devices, extremely small samples are produced, which are taken from a material as a sort of biopsy, with dimensions of five by five micrometers and a thickness of just 100 nanometers. To be able to properly manipulate such vulnerable samples, substages were developed in this project. These will soon be on the market in our devices. Through the collaboration with Bosch Rexroth and TU/e, we were able to maintain the competences for the required motion and develop new competences. Because, although we have been working on piezo motors for some time, the control of those motors remains a difficult task. We mainly work on the mechanical design ourselves, but if you want to properly integrate the sample movements in the entire design, you have to combine motion control, electronics and software. In the project, in terms of that, the collaboration was extremely good".

De Jong acknowledges that the project has not yet delivered an entirely new stage, but that is because of the market demand. "The project has resulted in a lot of knowledge and technological options for us. It is now down to us to determine the rate at which that will lead to new products."

## Innovation power

As far as De Jong is concerned, there will be a follow-up project because FEI has not yet learned everything there is to know about motion control. "But under which subsidy programme?" Pancras already has a file of new ideas ready, for, amongst others, further development of the 'walking leg motor' and the design of more complex controls (Multi-Input, Multi-Output), but he shares the concerns of De Jong about the "uncertain subsidy land". Because subsidies such as those received through Point-One are certainly worthwhile. "Without that money we would have done the same things, but now we were able to take faster steps and we were able to seek the help of TU/e at a level that would otherwise not have been possible. It is good that young researchers work on resolving industrial problems, thereby generating relevant knowledge. These types of industrial innovation subsidies bring the various parties together, thereby creating a greater innovation power."

**Information**

www.boschrexroth.com
www.fei.com
www.technolution.nl

# Hembrug goes into large grinding optics

**Hembrug Machine Tools, manufacturer of ultra-precision finish hard turning machines, and a new spin-out company from Cranfield University, Loxham Precision, have made an exclusive licence agreement which will see Hembrug build and bring BoX® ultra-precision freeform optics grinding machines to the market. The machines will be branded under the Hembrug name. Through the agreement Loxham Precision (Cranfield, UK) will provide Hembrug (Haarlem, the Netherlands) freeform optics tool-path generation software and necessary optical grinding expertise.**

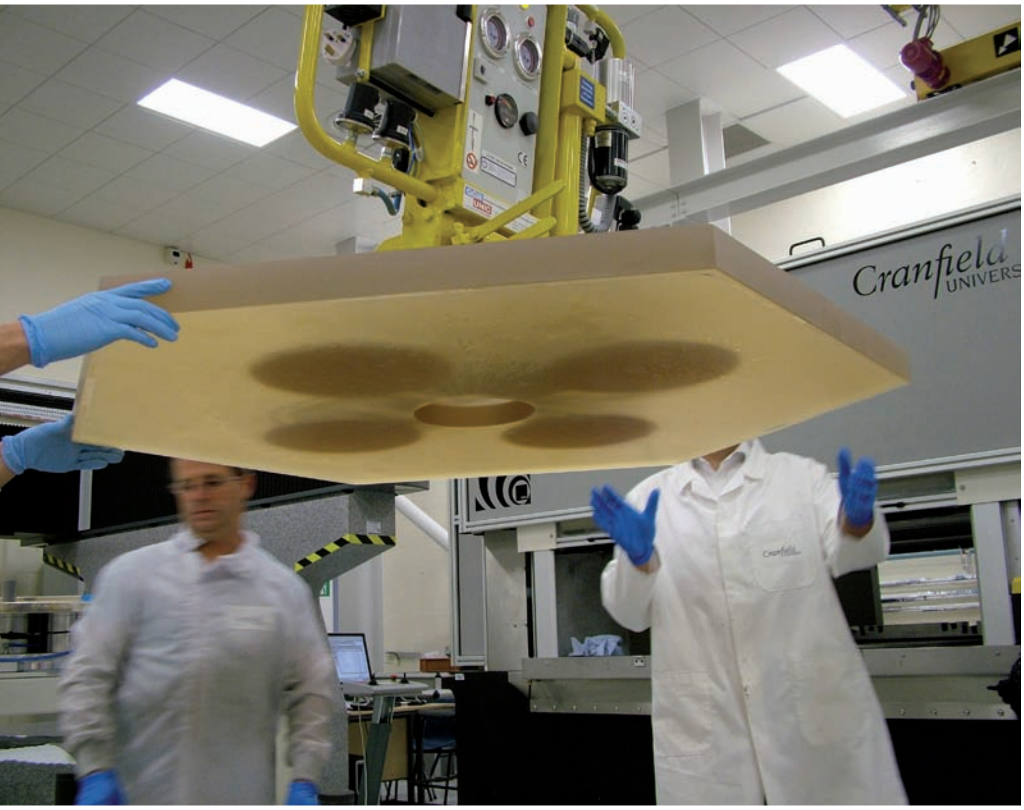
The BoX® (Big OptiX) machine, according to a press release, is a unique machine, specifically designed for grinding large optics in the highest accuracy range, but also in an unrivaled productive way. The machine is fully oil-hydrostatic in all rotary and linear axes including the grinding spindle. The linear axes employ the latest generation linear motors. Hembrug already uses hydrostatics for all its machines and will use standard components where possible for the BoX®. The design is focused and uncompromised towards maximising the stiffness at the grinding wheel.

Material removal rates of up to 200 mm$^3$/sec are therefore possible, so the grinding time of a 1.5m mirror segment can be shortened from hundreds of hours down to 20 hours. High precision, stiffness and damping, brought by the hydrostatic elements, ensure levels of induced subsurface damage (SSD) can be limited to 3-5 µm. Low SSD has huge consequences for the subsequent step in the process chain for making larger optics, the polishing process. The polishing time can be shortened with a factor of ten. The BoX® machine therefore brings a solution to shorten the whole process chain of large optics fabrication and enables freeform optics generation to be achieved with unprecedented accuracy levels.


The BoX® ultra-precision freeform optics grinding machine.

Large optics can be found in the latest generation extremely large telescopes (ELTs) and high-power laser systems. For example, before 2018 a demand of almost 1,000 1.5m mirror segments has to be fulfilled to produce the ESO E-ELT ground-based telescope. The market for grinding large optics is a niche but growing market, with an annual need of several machines a year. The first machines will be ready for shipment at the end of 2012.

www.hembrug.com
www.cranfield.ac.uk




A big optic mirror segment, ready for grinding by the BoX(R) machine.

# Europe's most accurate optical metrology bench

**Recently, the possibly most accurate optical metrology bench in Europe, according to Q-Sys, was built and delivered by Q-Sys to the Alba synchrotron near Barcelona, Spain. It represents the third iteration of this design and comprises a split axes 1500x300 mm travel XY motion platform with precision lapped granite guideways, air bearings and linear motors.**

Now installed in a climate-controlled enclosure, the system is used to measure the surface profiles of the large focussing mirrors used in the synchrotron. With a mirror assembly of up to 150 kg mounted on the lower granite carriage, a laser autocollimator beam is directed down via a pentaprism on the upper carriage and scanned along the mirror surface. Because of the comparatively long beam path and the accuracy required, the angular errors of the motion platform need to be extremely small and very repeatable. The system exceeds, so Q-Sys claims, all expectations and has measured a slope error in a nominally flat 300mm mirror of just 55 nanoradians with a noise level better than 15 nanoradians.

www.q-sys.eu

# Capacitance calibration standard for AFM

**This summer, Agilent Technologies introduced the first commercially available capacitance calibration standard for an atomic force microscope (AFM). Calibration specifications were issued for capacitance measurements that allow quantitative assessment of material and device properties via the Scanning Microwave Microscopy Mode. Researchers from Agilent collaborated with the National Institute of Standards and Technology (NIST Boulder Laboratories) to establish the new standard.**

According to Agilent, its SMM Mode is the only AFM-based electrical characterisation technique that gives researchers true calibrated capacitance. The method utilizes an Agilent microwave vector network analyzer in concert with an AFM to measure properties associated with small variations in the electromagnetic interactions of a sample's different components with the incident microwave signal, statically or dynamically.

www.agilent.com

## 28-29 September 2011, Veldhoven (NL)
## High-Tech Product Lines

Event where software practitioners learn to understand how to benefit from emerging approaches, technologies and tools in the field of software product lines.

www.bits-chips.nl/events/hpl

## 5 October 2011, Eindhoven (NL)
## Packaging and Integration of MEMS

Exploring the industrial need for knowledge exchange in a technology cluster regarding 'Packaging and Integration of MEMS'.

jan_eite.bullema@tno.nl

## 12 October 2011, Bussum (NL)
## 10th National Cleanroom Day

Event for cleanroom technology users and suppliers in the fields of micro/nano electronics, healthcare, pharma and food, organised by the Dutch Contamination Control Society.

www.vccn.nl

## 15-16 November 2011, Ede (NL)
## Netherlands MicroNanoConference '11

An overview of the latest developments in micro- and nanotechnology, both from the academic and industrial point of view.

www.micronanoconference.nl

## 18 November 2011, Eindhoven (NL)
## Bits&Chips 2011 Embedded Systemen

Conference on embedded systems and software; keynote speaker will be the ASML CEO, Eric Meurice.

www.embedded-systemen.nl

## 30 November - 1 December 2011, Veldhoven (NL)
## Precision Fair 2011

Eleventh edition of the Benelux premier trade fair on precision engineering. Some 200 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 Precision Fair is organised by Mikrocentrum, with the support of DSPE, NL Agency and media partner Mikroniek.

Precision Fair 2011

www.precisiebeurs.nl

## 25-26 January 2012, Veldhoven (NL)
## RapidPro 2012

The annual event for the total Additive Manufacturing, Rapid Prototyping and Rapid Tooling chain.

www.rapidpro.nl

# Introducing DSPE board members: Henk van Zeijl

My name is Henk van Zeijl (52). I studied in the Netherlands at the HTS Rijswijk institute of technology, where I received a B.Eng. in Physics in 1981. In that same year I joined the Interuniversity Reactor Institute in Delft to work in the field of neutron diffraction and instrumental neutron activation analysis. In 1986 I moved to the Delft Institute of Microelectronics and Submicron Technology (DIMES). From 1989 until 1998 I was responsible for photolithographic processes in the DIMES IC process research sector. In 2005 I was awarded a Ph.D. from Delft University of Technology for my research on bipolar transistors.

I have developed several technology courses, including a full-week's training programme for engineers from relevant fields in the industry and academia. These courses have been run over forty times and are also taught at universities in China (Beijing, Shanghai and Chengdu). I have been working as a lecturer at Delft University of Technology since 2007. In addition to my work in education, I have collaborated on various research projects concerning photolithography and Micro Electro-Mechanical Systems (MEMS). I am currently working as a senior researcher at DIMES, where I am involved in several research projects related to MEMS, 3D integration and Solid State Lighting integration. I have (co-)written more than 60 technical papers.

Although I have a physics background, I have developed a strong affinity with mechanics in general and micro-mechanics in particular because of my hobbies (vintage motorcycles, car maintenance, etc.) and work (MEMS). In my opinion, the combination of IC production technologies and miniaturised mechanics should be made available to SMEs. This will create new opportunities for precision engineering in the Netherlands. As a DSPE board member, I aspire to promote this development and to encourage industrial activity in this area. In the board, I will of course also strive to be a worthy representative of Delft.

www.dimes.tudelft.nl

### Call for Ir. A. Davidson Award nominations

Every two years, DSPE presents the Ir. A. Davidson Award, aimed at encouraging young talent. This prize is intended for a young precision engineer who has worked for several years for a company or institute and has delivered demonstrable performances that are recognised both internally and externally. The award is named after A. Davidson, the authority in the field of high-precision mechanical engineering at Philips in the 1950s and 60s.

The fourth prize-giving ceremony for this award will take place at the 2011 Precision Fair, which is being held on 30 November and 1 December in Veldhoven, the Netherlands. The DSPE board now accepts nominations for the award.

info@dspe.nl

### Mikroniek available online

Copies that are more than one year old can be downloaded as PDFs from the Mikroniek archive on the DSPE website. More recent copies are for members only and will be distributed as hard copy. For subscription information, please email info@dspe.nl.

www.dspe.nl/mikroniek/archive

# Summer school report

**_Following the success of the 2008, 2009 and 2010 Opto-mechatronics Summer schools, DSPE and TNO organised a fourth one from Monday, 27 June to Friday, 1 July 2011 in Eindhoven, the Netherlands. Once again, this summer school was the place to be for anyone working in the field of precision engineering and wanting to learn and experience from experts how to design opto-mechanical instruments that are actively controlled, operating in the non-perfect environment. One of the participants, ASML employee Lisanne Bechthum-Ravensbergen, wrote the following report._**

Summer school Opto-Mechatronics
Precision Technology

“This year’s summer school started with the promise of a certificate of participation, similar to an MBA certificate. The ‘classes’ started on Monday with system engineering. Friso Klinkhamer, a former TNO employee, explained how to clarify specifications, on the basis of which a number of conceptual designs can be made. An overview of all designs is drawn up and a preferred concept chosen based on discriminating specifications. When the problem is a substantial one, it should be divided up into smaller issues, each with their own specifications, which can then be solved by teams of engineers. Each submodule should be verified and, once assembled, the entire module should be verified to check whether the requirements have been met. To get a good idea of what things are like in a real project, we applied the theory to the ESO Very Large Telescope (VLT) delay line. ESO’s Frederic Derie provided us a glimpse of their new telescope, the E-ELT (European Extremely Large Telescope).

On Tuesday, Stefan Bäumer from Philips taught us how to design an optical system. Some basic optics were discussed first, i.e. what is a positive lens and what is a negative one, how can the focal length be calculated, what is an NA, what are aberrations and how can the related problems be solved, and how do you check the manufactured lens? In the evening, ASML’s Frank de Lange presented an example of system engineering at his company. He showed us how to work on projects that are too big to be tackled by one person. In order to be able to do the exercises on Wednesday, a document with a Matlab crash course was handed out. We were then able to practise on the VLT

Social summer school activities included a “K’nex party”.

The 2011 Opto-mechatronics Summer school participants.

delay line, examining which different optical elements can be used, as well as the advantages and disadvantages.
So what do you normally do with Matlab in the field of opto-mechatronics? Control engineering of course. Peter Nuij from Eindhoven University of Technology gave us the theory, after which we could practise with Matlab to see if we were able to design a controller with which to make an unstable system stable. The reality was revealed by TNO's Niek Doelman, who told us about the control of an optical delay line.

To relax a bit, each group had to design a K'nex structure that would be able to stay in the air for as long as possible and land in one piece on its way down from the third floor to the ground floor. Unfortunately, our parachute with landing gear system turned upside down during its flight and crashed on the floor, breaking into pieces.

Thursday was opto-mechanical day. TNO's Jan Nijenhuis gave us tips on how to mount optical components and showed us some examples of aberrations induced by incorrect mounting. The alignment of optical components with respect to each other is critical, as this also has an impact on the opto-mechanical design. To maintain the alignment within the specification in the future as well, it is wise to make the mounting insensitive to temperature gradients and temperature fluctuations. Fred Kamphues from TNO showed us how this was handled in the VLT delay line and included some really nice pictures of the telescope in Paranal (Chile).

On the last day, Prof. Rob Munnig Schmidt from Delft University of Technology and Adrian Rankers from Armunus brought everything together by looking at how to design a system from a performance objective, what dynamics are introduced by the environment, which sensor and actuator to choose and which measurement system, how to provide damping, etc.

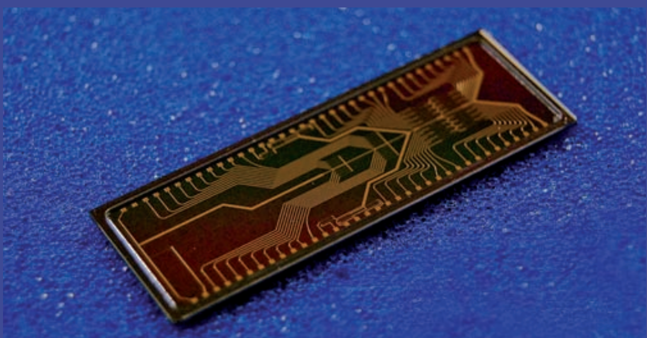
At the end of the week, I felt like I'd been overloaded with information, but maybe I'm just not used to going to school anymore. I liked the friendly atmosphere and the ease with which you could meet new people. The meals were delicious as well. Overall, we had a lot of fun and learned a great deal from excellent teachers brought together by TNO and DSPE."

www.summer-school.nl

# XiO Photonics - Making photonics simple

***XiO Photonics is a young company (2008) with a strong competence in integrated optics or 'light on a chip'. XiO Photonics primarily focuses on the design and assembly of modules that incorporate the optical chips for products in visible light applications. The Integrated Laser-Beam Combiner is XiO Photonics' first product that offers the advantages of integrating optics on a chip for visible light applications.***

XiO Photonics is located in Enschede, the Netherlands, in close vicinity of foundries, research institutes and universities both in the Netherlands as well as in Germany, which allows the company to be state of the art in the field of integrated optics. XiO Photonics strives to be an important international supplier of integrated optical modules ('light on a chip') for laser technology in visible light applications. New photonic applications are enabled by removing the barriers imposed by the complexity and the intensive maintenance required of existing technology. Using XiO Photonics products makes laser photonics more simple and robust. Customer benefits include more compact, simpler and more efficient systems.



*Example of an integrated optical chip.*

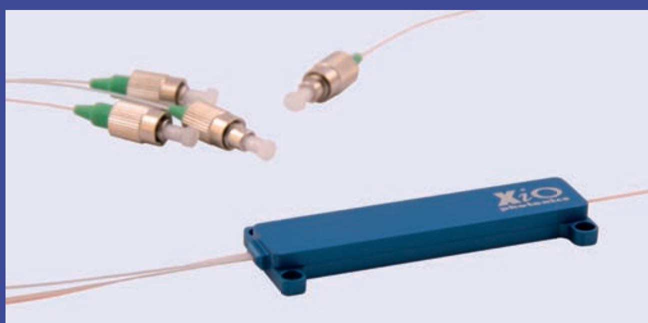
## Technology

During the last decade, all the major companies that fabricate lasers have developed compact and robust solid-state lasers, to replace the large and complex gas laser systems. New applications became possible because of the lower prices and the increased ease of use of these new solid-state lasers. The latest generation of solid-state lasers will have a fiber-optic output that simplifies the means of light transportation.

XiO Photonics contributes to this trend of miniaturisation and integration, as it deals with one of the problems associated with lasers: combining different colours of light in a simple and robust manner. XiO Photonics products are based on compact optical chips that integrate a number of complex functions in a single device. The technology is perfectly suited for exploiting the interesting domain of visible light applications. XiO Photonics has exclusive access to proprietary optical chip technology that enables the use of visible light. Based on integrated optical technology a filtering technology was developed that efficiently combines several laser wavelengths.

## Integrated Laser-Beam Combiner

The first product of XiO Photonics is the Integrated Laser-Beam Combiner (ILBC), which combines up to eight visible wavelengths from fiber-pigtailed lasers into one single mode and polarisation maintaining fiber. The main applications for this product include confocal microscopy, flow cytometry and food sorting; all these applications require different visible laser colours to be combined, while the current solutions do not meet the requirements regarding compactness, robustness or polarisation behaviour. The ILBC opens up new markets for these applications, as it supports a more compact and highly stable device.




*A 3-channel ILBC, for combining red, green and blue light.*

**Information**

www.xiophotonics.com

# Mikroniek guide

## Bearing and Linear Technology

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Schaeffler Group - LuK, INA and FAG - is a world wide leading company in developing, manufacturing and supplying of rolling bearings, linear systems, direct drives and maintenance products. Applications: automotive, industrial and aerospace.

## Development

TNO innovation for life

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

member DSPE

## Education

LiS Leidse instrumentmakers School

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The LiS is founded in 1901 by the famous scientist prof. Kamerlingh Onnes. Nowadays the LiS is a modern school for vocational training on level 4 MBO-BOL. The school encourages establishing projects in close cooperation with contractors and scientific institutes, allowing for high level “real life” work.

member DSPE

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opleiden • ontmoeten • ondernemen

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THK The Mark of Linear Motion

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**E** info@thk.nl
**W** www.thk.nl

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Belgium
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**E** info@argon-ms.be
**W** www.argon-ms.be

- Dimensional Quality Control
- Process Maintenance
- 3D Scanning / Reverse Engineering

3D measurement services range from ad-hoc interventions to turn-key metrology projects

Carl Zeiss B.V.
Industriële Meettechniek
Trapezium 300
3364 DL Sliedrecht
**T** +31 (0)184 433 551
**F** +31 (0)184 433 500
**E** m.trupia@zeiss.nl
**W** http://www.zeiss.nl

Carl Zeiss Industrial Metrology is the world’s leader in CNC coordinate measuring machines and complete solutions for multidimensional metrology in the metrology lab and production environment. We also provide contract programming and contract measuring in our newly founded Measuring House near Eindhoven (NL).

# Mikroniek guide

## Mechatronics Development

centre for concepts in mechatronics

CCM Centre for Concepts in Mechatronics
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**F** +31 (0)40 2635555
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CCM translates technology into technique.
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**F** +31 (0)40 2302770
**E** mechatronics@mecal.eu
**W** www.mecal.eu

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## Metal Precision Parts

ETCHFORM metal precision parts

Etchform BV
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**E** info@etchform.com
**W** www.etchform.com

Etchform is a production and service company for etched and electroformed metal precision parts.

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## Micro Drive Systems

MINIMOTOR Benelux
Miniature Drive Systems
FAULHABER

Minimotor Benelux

Belgium
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B-2200 Herentals
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**F** +32 (0)14-21 64 95
**E** info@minimotor.be

The Netherlands
Postbus 49
NL-1540 Koog a/d Zaan
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Faulhaber is a leading manufacturer of miniature drive systems based on ironless micromotors with the highest power-to-volume ratio.

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## Micromachining

REITH LASER

Reith Laser bv
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6604 LK Wijchen
The Netherlands
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**F** +31 (0)24 3787586
**E** info@reithlaser.nl
**W** www.reithlaser.nl

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Aldermaston
Berkshire
RG7 8NN England
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**E** sales@aerotech.co.uk
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ALT

Applied Laser Technology
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IBS Precision Engineering

IBS Precision Engineering
Esp 201
5633 AD Eindhoven
**T** +31 (0)40 2901270
**F** +31 (0)40 2901279
**E** info@ibspe.com
**W** www.ibspe.com

IBS Precision Engineering is an innovator in high-grade precision engineering and involved in special machines, machine tool calibration & inspection, noncontact precision sensors, air bearings and laser interferometer systems.

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MARTEK

MARTEK BVBA
René Comhairelaan 82
1082 Brussel
Belgium
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**F** +32 2 4670049
**E** info@martek.be
**I** www.martek.be

MARTEK is the BeNeLux specialist importer company for precision sensors, linear and angular encoders, inspection instrumentation, digital readouts and probing systems for machine tools.

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Newport Spectra-Physics BV, a subsidiary of Newport Corp., is a worldwide leader in nano and micropositioning technologies.

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Reliance Precision Mechatronics LLP
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ROTERO ELECTRICAL MOTION & CONTROL

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Postbus 126
3440 AC Woerden
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molenaar optics

Molenaar Optics
Gerolaan 63A
3707 SH Zeist
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**F** +31 (0)30 6961348
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## Piezo Systems

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HEINMADE supplier piezo ceramic solutions

Heinmade B.V.
High Tech Campus 9
5656 AE Eindhoven
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**F** +31 (0)40 7440033
**E** info@heinmade.com
**W** www.heinmade.com

HEINMADE develops and supplies piezo system solutions for positioning and vibration damping. HEINMADE cooperates with and is distributor of Nanomotion, Noliac and Piezomechanik.

## Technical Ceramics

ceratec Technical Ceramics BV

Ceratec Technical Ceramics BV
Poppenbouwing 35
4191 NZ Geldermalsen
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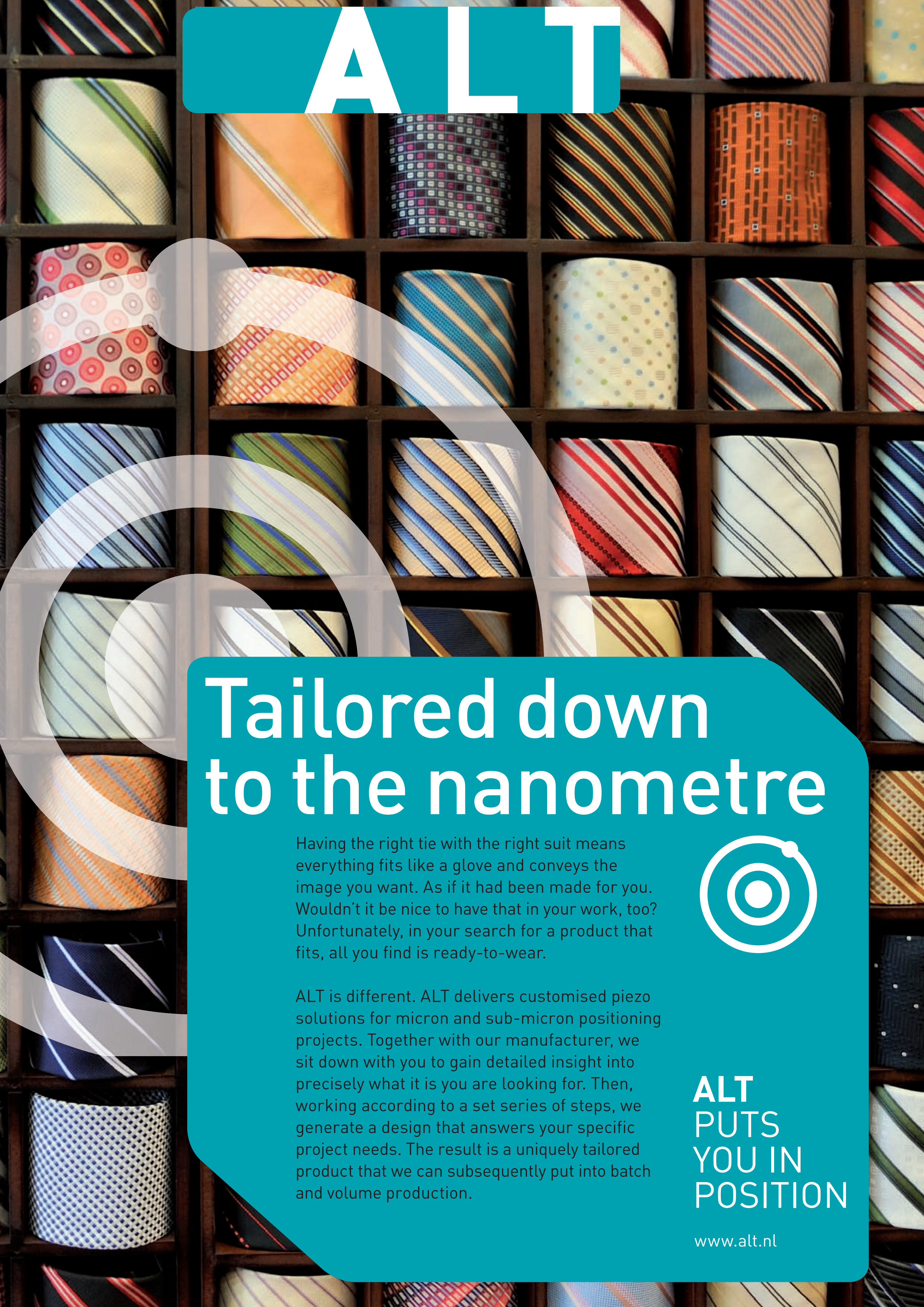
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