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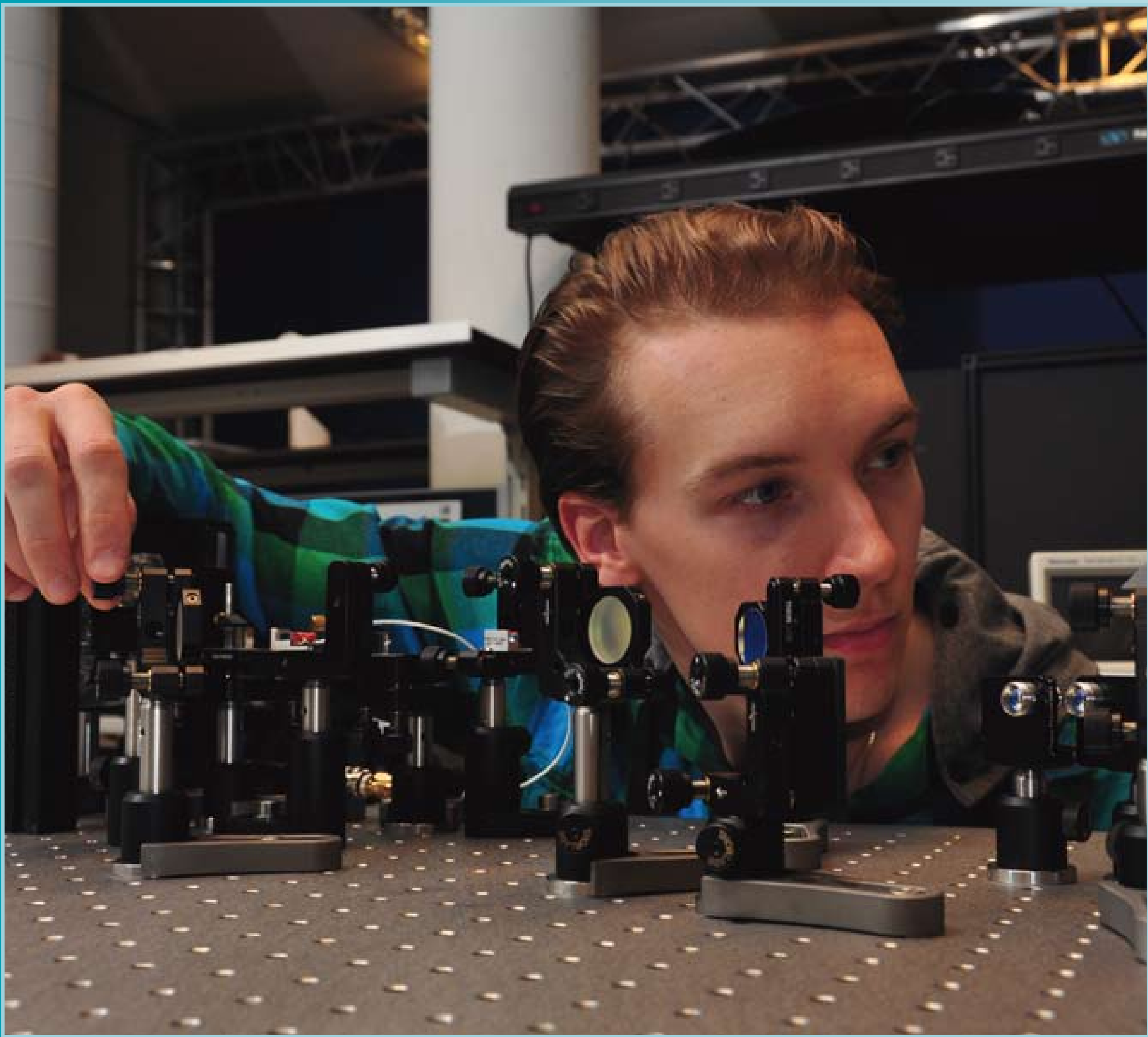

New heterodyne interferometer concept • Design of 6-DoF magnetically levitated stage
Exploring the Additive Manufacturing design potential
Laser process development • Micro-tools for micro-milling and -grinding
High Tech Systems challenges • Graphene – a promising engineering material?

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Mikroniek - 2012

In this issue

4 **Editorial**
Bert-Jan Woertman (High Tech Campus Eindhoven) on the part of campus development that you can't copy.

5 **Sub-nanometer accurate fiber-fed heterodyne interferometer**
A Delft University of Technology design for position measurements with resolutions and accuracies in the order of sub-nanometers over a decimeter range.

12 **Micro-positioning**
The design of a 6-DoF magnetically levitated stage for haptic micro-manipulation.

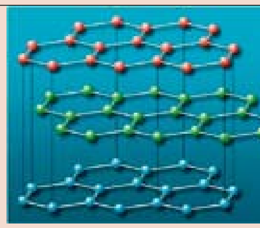
18 **Exploring the Additive Manufacturing design potential**
Collaboration of LayerWise and TNO aimed at reducing a metal spring's internal stress and weight.

22 **Laser process development**
Philips introducing robust mass production processes with micron accuracy.

26 **Micro-tools for micro-milling and -grinding**
From the Institute of Manufacturing Technology and Production Systems, University of Kaiserslautern, Germany.

30 **Getting High Tech Systems in shape and fit for the future**
On tough roadmap challenges and required innovations.

37 **Mikrocentrum**
Including: Vision & Robotics 2012 featuring second RoboNED Conference.



38 **Graphene**
A promising engineering material?

42 **Upcoming events**
Including: euspen 12th International Conference and Exhibition.

44 **DSPE**
Including: Summer school, and DSPE Conference.

46 **News**
Including: Techni-Show Innovation Awards.

50 **CPE course calendar**
Overview of Certified Precision Engineer courses.

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+31 (0)40 – 296 99 15 / 26 (tel/fax)
info@dspe.nl, www.dspe.nl

Editor
Hans van Eerden, hans.vaneerden@dspe.nl

Advertising canvasser
Sales & Services
PO Box 2317, 1620 EH Hoorn (NL)
+31 (0)229 – 211 211, gerrit@salesandservices.nl

Design and realisation
Twin Media bv
PO Box 317, 4100 AH Culemborg (NL)
+31 (0)345 – 470 500, info@twinmediabv.nl

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The cover photo (experimental set-up for heterodyne laser interferometer) is courtesy of Oscar van de Ven, Delft University of Technology.

editorial

The part you can't copy...

Recently I met Sjoerd Romme, Professor of Entrepreneurship & Innovation at Eindhoven University of Technology, during a network meeting at High Tech Campus Eindhoven. He has researched the success factors behind (R&D) campus development. "The value proposition of a campus partly depends on the facilities present, but to a far greater degree on the community populating the campus. This is the part you can't copy; it is what distinguishes a campus from others." Or to put it another way, every region, every city can build campuses with perfect infrastructure, useful facilities and beautiful offices, the so-called 'hard' aspects. However, the 'soft' aspects are as – or perhaps even more – important.

In today's economy, successful innovation is not something companies can accomplish (repeatedly) on their own. The sure-fire route to success is open innovation. You have to work from your core and cooperate with others to speed up and improve innovation, and share costs. It's about smart connections and sharing knowledge. Networking is key, meeting each other in real life. According to an MIT study, 80% of breakthrough innovations in products and services did not occur during formal sessions or planned brainstorms. Innovation was merely the result of informal/ chance encounters between dedicated professionals, i.e. of informal get-togethers and 'chaos' rather than of organised processes.
A perfect example of informal conversations and organised 'chaos' that leads to innovation and business development is the international phenomenon Startup Weekend. In just 54 hours (!), developers, designers, marketers, product managers and entrepreneurs come together to share ideas, form teams, build products and launch start-ups. I was part of the Eindhoven edition last year, an event that gave me by far the most energy and inspiration.

In a nutshell, Startup Weekend achieves the same effect as what we are doing here at the Campus. It creates a one-weekend open innovation ecosystem where interaction is stimulated, and knowledge, experience and facilities are shared with the goal to accelerate innovation and business development. And of course, you need a pleasant location, Wi-Fi, food and drinks. But without the social networking, the mixing of people of diverse talents, the sparks of inspiration flying around, the ideas popping up … there won't be any results. This is the real foundation for breakthrough innovation. The part you can't copy…!
By the way, the next edition of Startup Weekend Eindhoven is planned for June. Check www.eindhoven.startupweekend.org

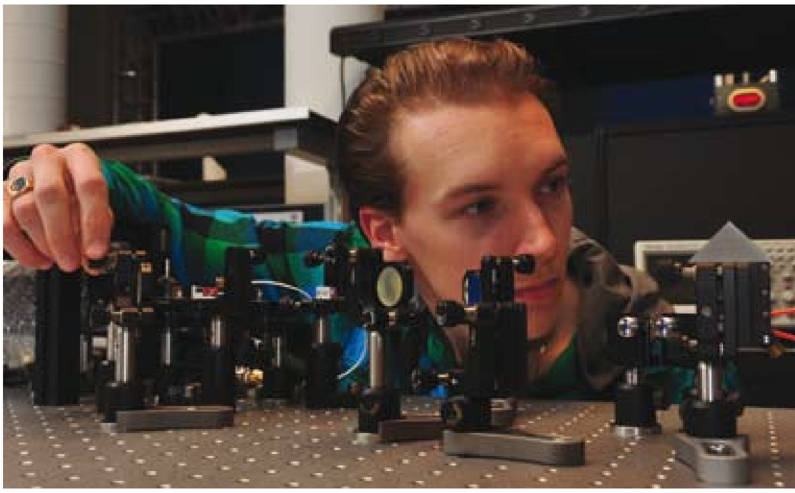
Bert-Jan Woertman
Marketing & Communications Director, High Tech Campus Eindhoven

Sub-nanometer accurate fiber-fed heterodyne interferometer

IC production processes are among the most demanding ones when it comes to high-precision positioning. For most systems performing long-range measurements, sub-micrometer resolutions and displacement accuracies over long strokes are common. Now the semiconductor industry pushes its demands to the extreme with the advent of Extreme Ultraviolet Lithography (EUV). Accelerations and velocities are high in these systems (120 m/s² for the reticle and 30 m/s² for the wafer stage), whereas the required position measurements have to be performed with resolutions and accuracies in the order of sub-nanometers over a measurement range of a few decimeters. Delft University of Technology (TU Delft) has introduced a new heterodyne interferometer concept using spatially separated optical input beams to address this challenge.

• *Arjan Meskers* •

The very first layers on a wafer contain the smallest details and require the highest positioning accuracy. EUV-machines, as developed by lithography market leader ASML, are able to pattern details of 13 nm (see Figures 1 and 2) and require the overlay error to be less than 5 nm (see Figure 2) for obtaining high yield. Current ASML Twinscan machines operate with the wafer in a controlled aerial environment where encoders are applied for the positioning of the wafer. The EUV-machines operate internally at vacuum, where laser interferometers can outperform these optical encoder systems when it comes to resolution and accuracy at high target accelerations and velocities.



The author with part of the set-up as described in this article.

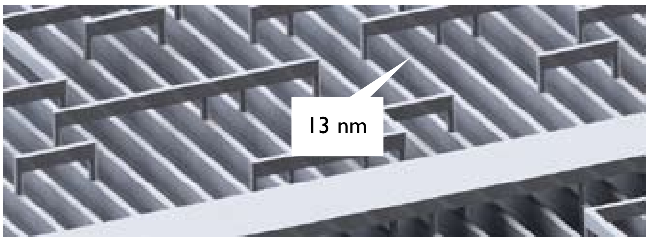


Figure 1. The smallest details of future chips will measure in the order of 13 nm. The overlay error needs to be less than 5 nm (!) to obtain sufficient yield.

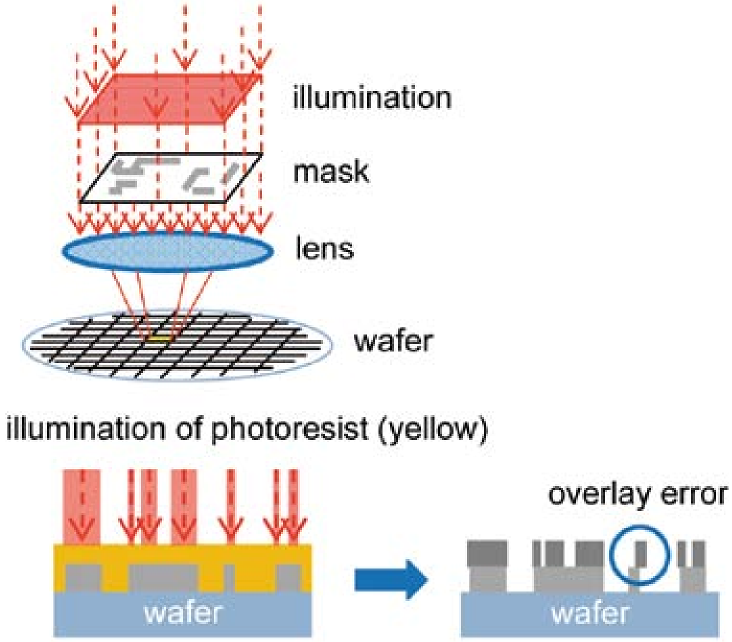


Figure 2. Schematic of a photolithography process, showing a positional-overlay error: the overlap between the first structural layers on the wafers containing the smallest details.

Commercial heterodyne interferometer systems use heterodyne coaxial output beams that are subject to polarisation leakage (i.e. frequency mixing), which eventually leads to periodic nonlinearities [1] [2]. These periodic nonlinearities negatively affect the measurement accuracy. The magnitude of this error can be in the order of several nanometers, depending on system architecture [3]. The TU Delft has introduced a new heterodyne interferometer concept using spatially separated optical input beams to prevent periodic nonlinearities [4, 5] (see Figure 3). This periodic error can be prevented by working with two spatially separated input beams containing the source frequencies instead of a coaxial heterodyne beam. These beams are kept separated until detection [1], enabling the

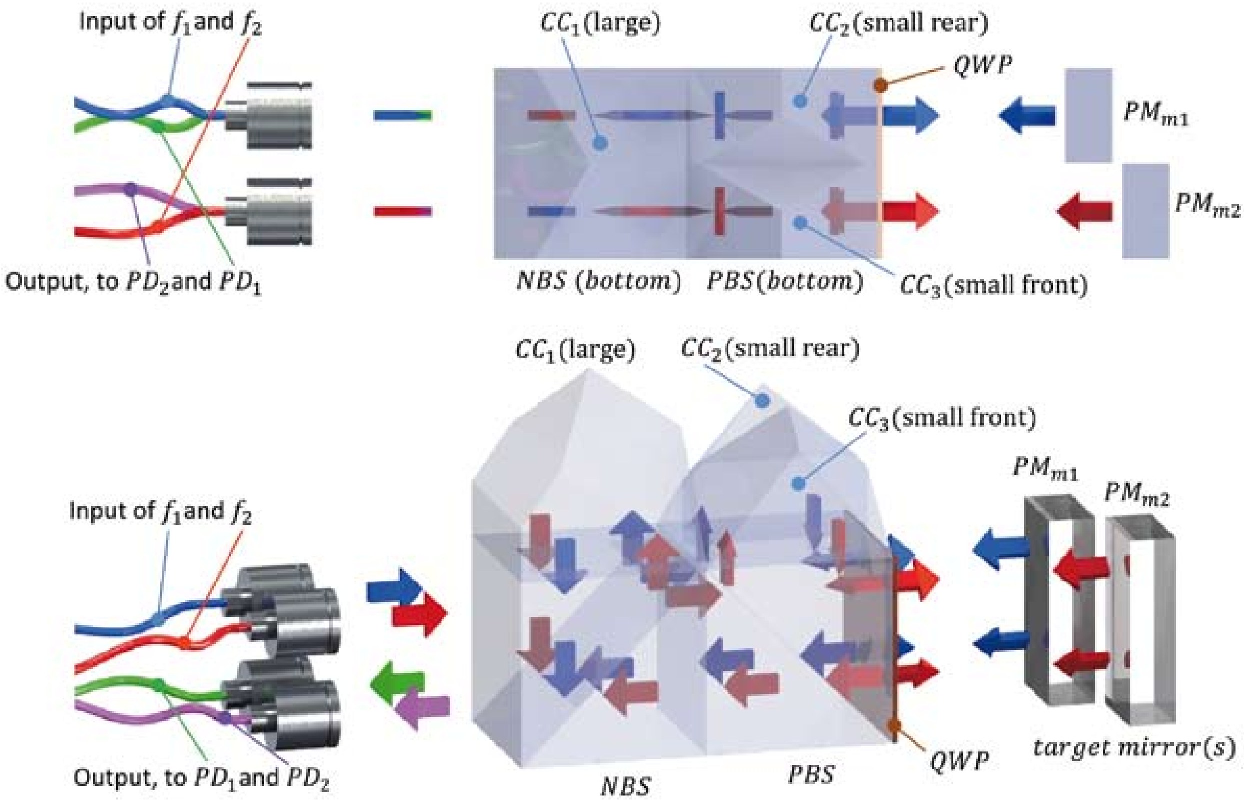


Figure. 3 The optical pathways of the individual rays of the TU Delft interferometer are shown in top and side view (below). The arrows indicate the direction of travel and the polarisation orientation. The source frequencies f_1 and f_2 are here delivered by means of two polarisation maintaining Single Mode optical fibers (SM-fibers) (red and blue), while detection takes place by means of two Multi Mode step index optical fibers (MM-fibers) (purple and green).

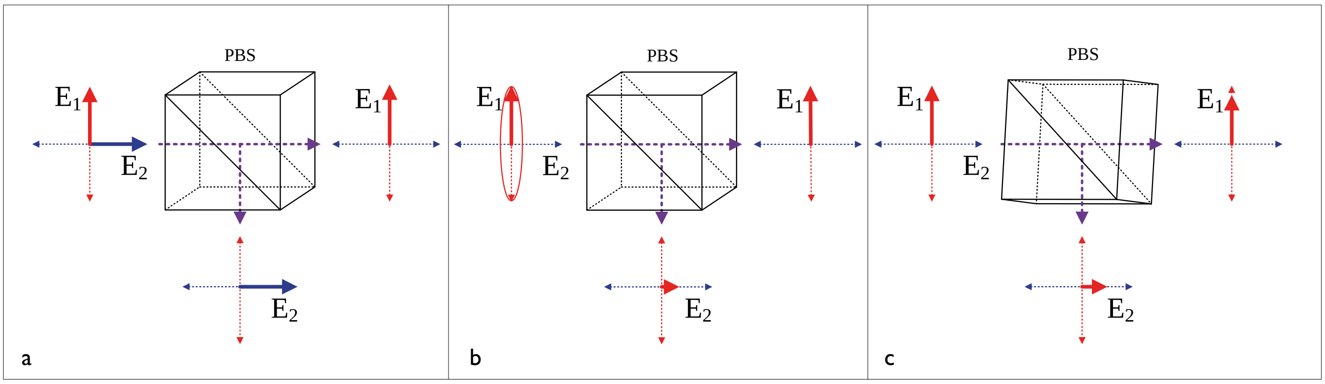


Figure. 4. Showing how polarisation leakage leads to frequency mixing.
(a) A coaxial heterodyne light beam contains two orthogonally polarised frequencies of light. In case of ideal alignment, the vertical orientation (red) is transmitted by the *PBS* while the horizontal orientation (blue) is reflected.
(b) A single-frequency elliptically polarised beam propagating through a *PBS*. Due to the nonlinear polarisation state, this frequency is both reflected as well as transmitted.
(c) The same, with an ideal linearised polarisation state and a rotationally misaligned polarised beam splitter. This frequency leakage takes place for both frequencies and will result in unwanted interference signals within the system.

elimination of periodic nonlinearities down to the noise floor < 50 pm. This concept of optical separation of measurement beams is known from complex astronomy applications.

The TU Delft interferometer

The interferometer discussed in this article is a displacement measurement tool that uses interference of laser light to measure relative displacement. In this article a heterodyne measurement system measuring one translational degree of freedom (DoF) is assumed. Later on the difficulties with measuring rotational DoFs will be discussed.

The interferometer concept is shown in Figure 3; it has two vertically oriented linearly polarised input frequencies, f_1 (blue) and f_2 (red). The two light beams containing these frequencies can be delivered free-space (guided by mirrors through the air) or by optical fibers, as shown in the figure. After entering, the light is split by a Neutral Beam Splitter (*NBS*). The first 50% propagates to Cube Corner reflector 1 (CC_1) and is reflected via the *NBS* towards two fiber-coupled Photo Detectors (PD_1 and PD_2) located at the phase measurement board (Agilent N1225A). These two beams act as the reference beams. The transport to the *PD*s is less critical and therefore takes place using two step index Multi Mode fibers (MM-fibers) (green and purple). The other 50% is transmitted through the *NBS* and propagates through a Polarised Beam Splitter (*PBS*) and a Quarter Wave Plate (*QWP*) towards the target mirrors. The beam containing f_1 is reflected off plane mirror PM_{m1}, while the beam containing f_2 is reflected off plane mirror PM_{m2}. Travelling back, both beams will pass the *QWP* for a second time and are now reflected by the *PBS* due to their polarisation orientation. After reflection by CC_2 and CC_3, the light again reflects off the *PBS*, through the *QWP* and forth and back PM_{m1} and PM_{m2}. The beams will then finally recombine with the reference beams and propagate to the *PD*s through the MM-fibers.

The target mirrors can be configured in two ways. In the first configuration PM_{m1} is fixated to the *QWP*, thereby functioning as a thermal reference. This reference compensates for path length changes due to thermal expansion, while in the second configuration both beams measure the same *PM*. The advantage of this second configuration compared to the first one, is that the optical sensitivity will be doubled, as shown later on.

Preventing periodic nonlinearities

Interferometers operating in open-air environments can suffer from measurement errors/uncertainties in the order of micrometers or more, depending on measurement range (the larger the displacement, the bigger the uncertainty). In these systems the most dominant error source is the time-varying refractive index of the air through which the light propagates. When operating in vacuum this refractive index error is eliminated, but then new error sources that were previously neglectable will arise. One of these errors is the ‘periodic nonlinearity’. Periodic nonlinearities originate from a phenomenon called polarisation leakage.

This polarisation leakage causes frequency mixing and that phenomenon eventually causes the periodic nonlinearities to appear in a heterodyne interferometer system. Polarisation leakage can be caused in a number of ways [5] [6], such as: non-orthogonal and elliptically polarised laser beams, rotational misalignment between laser beam and polarised optics (Figure 4), and a difference in transmission coefficients of polarised beam splitting components. Figures 4b and 4c show how a ‘vertically’ polarised light beam propagating through a *PBS* is present in the reflected

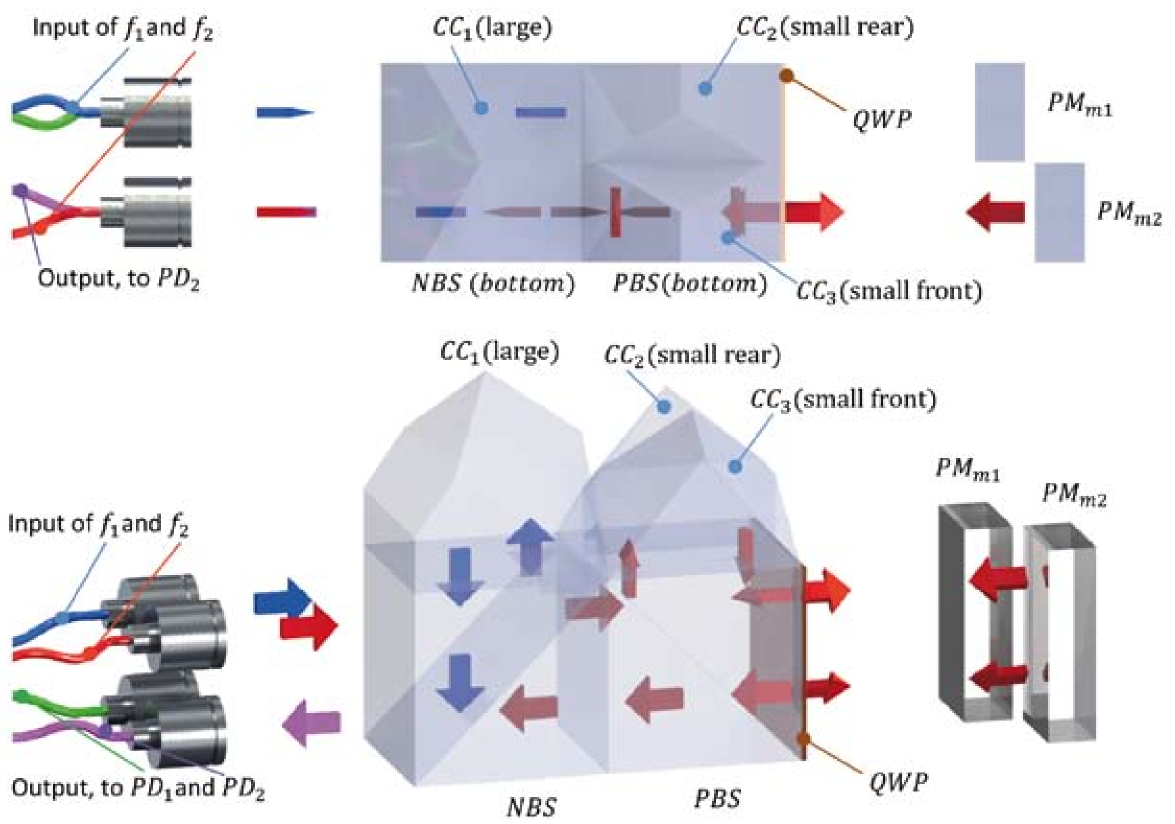


Figure 5. The 3D model in top and side view (below) shows the TU Delft interferometer principle with only one of the two outputs. The two source frequencies (red and blue) are launched into the interferometer through fixed-focus lenses. One of the source frequencies functions as a reference (blue), while the other one measures target displacement. These two beams are then recombined (purple) creating an interference signal and are then transported through a Multi Mode step index optical fiber (MM-fiber) to the detector.

as well as the transmitted beam. When using a coaxial heterodyne beam containing two linearly polarised frequencies with $f_1 \neq f_2$ and orthogonally oriented, the same happens with the 'horizontally' polarised beam.

Taking into account that light interferes when polarisation states match, it can be seen that f_1 interferes with f_2, leading to unwanted extra interference signals in the system. When a system operates with coaxial heterodyne beams, an error like this cannot be prevented but only minimised.

If no coaxial heterodyne beams are used, prevention of this error can be accomplished by making sure that the two source frequencies f_1 and f_2 have spatially separated optical pathways throughout the interferometer. This prevents overlap of the beams and eliminates premature mixing of frequencies before detection occurs [1] [2]. This is the main reason the TU Delft interferometer concept uses spatially separated optical pathways.

Cancelling fiber-induced phase shifts

The interferometer concept presents an additional advantage besides preventing periodic nonlinear errors. The configuration and means of signal detection cancel any phase addition to the two source frequencies (f_1, f_2) that arises during transport towards the interferometer.

When the light propagates through two separate air paths or optical fibers, a change in phase arises due to refractive index differences between the separate optical pathways. Influences include vibrations in air/fiber, changes in air/fiber temperature, turbulent air flow, air pressure, fiber-clamping, -stretch, -bending, -torsion, etc. All these external influences act on the refractive indices of the media encountered during beam propagation. The local changes in refractive index affect the propagation velocity of light according to Snell's law:

$$v_1 n_1 = v_2 n_2 = c \qquad (1)$$

Where c, $v_{1,2}$ [m/s] and $n_{1,2}$ are respectively the propagation velocity of the light in vacuum, the propagation velocities of the light in the two media and the refractive indices of the two media.

Thus, due to non-common optical pathways of the source light containing f_1 and f_2, phase changes during transport will arise. These phase changes will eventually be seen as a virtual target displacement and thus negatively influence measurement accuracy. How can this be solved?

Detection of the two interference signal takes place by two photodetectors (PD_1 and PD_2) and both receive f_1 and f_2 (see Figures 3 and 5). Between the two detectors a differential measurement is performed (i.e. one output is subtracted from the other, leaving the difference between the two). This will eventually result in the cancellation of the fiber- or air-path induced phase changes as will be demonstrated.
Taking a look at the complete system as shown in Figure 3, it can be seen that the green fiber towards PD_1 uses frequency f_2 (red) as a reference and f_1 (blue) for measuring. While the purple fiber (see also Figure 5) leading to PD_2 uses f_1 (blue) as a reference and f_2 (red) for measuring. This can be written as in:

$$I_{PD1} = f_2\,(reference) \cdot f_1\,(measurement) \qquad (2)$$

$$I_{PD2} = f_1\,(reference) \cdot f_2\,(measurement) \qquad (3)$$

The two interference signals I_{PD1} and I_{PD2} take the form of:

$$I_{PD1} = \cos(2\pi f_2 t + \theta_2) \cdot \cos(2\pi f_1 t + \theta_1 + \theta_{m1}) \qquad (4)$$

$$I_{PD2} = \cos(2\pi f_1 t + \theta_1) \cdot \cos(2\pi f_2 t + \theta_2 + \theta_{m2}) \qquad (5)$$

where $f_{1,2}$ are the two optical source frequencies [Hz], $\theta_{1,2}$ are the phases of the two input beams (due to the refractive index differences during transport, with $\theta_1 \neq \theta_2$), and θ_{m1} and θ_{m2} are the measured phase shifts due to mirror displacement of PM_{m1} and PM_{m2}, respectively.

Equations (4) and (5) can be rewritten into (6) and (7), ignoring the terms containing $(f_1 + f_2)$, since this signal frequency is too high to detect and will only be seen as a DC component. The resulting interference signals become:

$$I_{PD1} = \tfrac{1}{2} \cos[2\pi(f_1 - f_2)t + \theta_1 - \theta_2 + \theta_{m2}] \qquad (6)$$

$$I_{PD2} = \tfrac{1}{2} \cos[2\pi(f_1 - f_2)t + \theta_1 - \theta_2 - \theta_{m1}] \qquad (7)$$

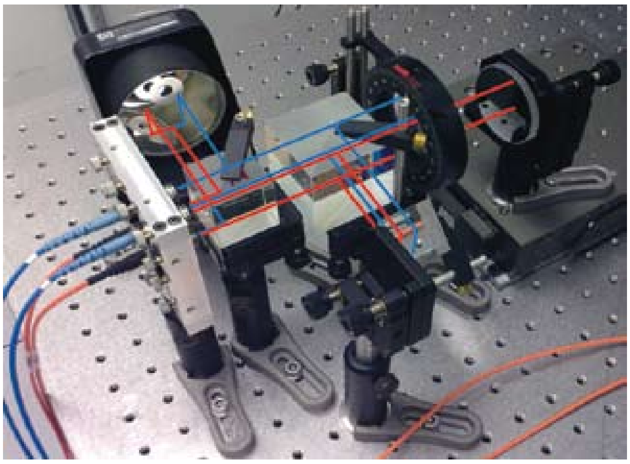


Figure 6. Fiber-coupled setup, using two single-mode polarisation maintaining fibers (blue) for source frequency delivery and two MM-fibers for detection (orange). The set-up depicted uses PM_{m1} as a reference mirror, PMm^2 as a target mirror and a right-angle prism is applied instead of CC_2 and CC_3.

Assuming $|f_1 - f_2| = f_s$, which is the split frequency, and unifying the amplitudes, Equations (6) and (7) can be rewritten as:

$$I_{PD1} = \cos[2\pi f_s t + \theta_1 - \theta_2 + \theta_{m2}] \qquad (8)$$

$$I_{PD2} = \cos[2\pi f_s t + \theta_1 - \theta_2 - \theta_{m1}] \qquad (9)$$

Performing a differential measurement between the two photodetectors yields:

$$I_{diff} = \cos[2\pi f_s t + \theta_1 - \theta_2 + \theta_{m2}] - \cos[2\pi f_s t + \theta_1 - \theta_2 - \theta_{m1}] \qquad (10)$$

And when the target mirror configuration is taken into account (either a shared target, i.e. one plane mirror, or two plane mirrors of which one is a reference), the target displacement can be extracted. Note that when one of the two mirrors is used as a reference mirror, as shown in Figures 3, 5 and 6, measurement takes place at only half the resolution (i.e. $\theta_{m2} + 0$). Measuring the same target mirror with both beams, doubles the resolution (i.e. $\theta_{m2} + \theta_{m1}$).

The eventual target displacement can be calculated using:

$$\Delta\theta_{m1,2} = (2\pi N n_i \Delta x_{1,2})/\lambda \qquad (11)$$

Where N is the interferometer fold constant (four in the shown configuration), n_i are the encountered refractive indices, λ is the wavelength, and $\Delta x_{1,2}$ is the displacement of the measurement mirror(s).

The fact that this design creates its own optical phase reference within the interferometer itself, makes it a robust

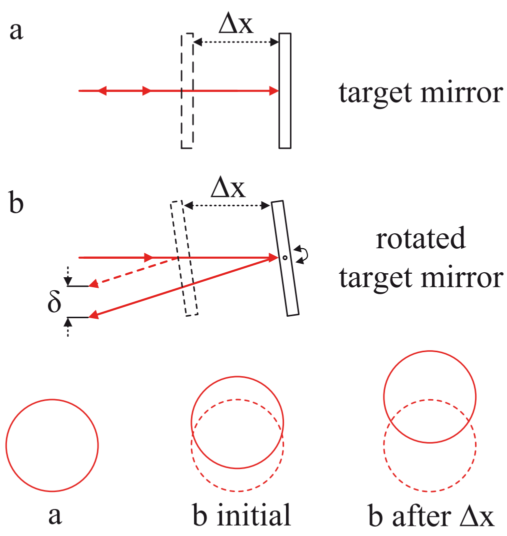


Figure 7. Sketch illustrating 'beam shear'.
(a) A single-DoF system where no beam shear will be present, when it is correctly aligned (*Δx* is the target displacement).
(b) A plane mirror target rotation causes beam shear *δ*, the magnitude depending on both target rotation and translation, *Δx*.

one. Because as long as the source frequencies have sufficient coherence and single-mode behaviour, it does not matter what happens with these source frequencies before they reach the interferometer. Even when the added phase results in a large difference between the two source frequencies, as is the case when using optical fibers [7] (see Figure 6), this will not affect the measurement accuracy.

Target angle measurement

Till so far the TU Delft interferometer design is a periodic-error-free interferometer capable of measuring with sub-nm accuracy and it can operate with fiber-delivered source frequencies [8]. During experiments with this concept design, only a single-DoF system was used. When this system is well aligned (see Figure 7a), the

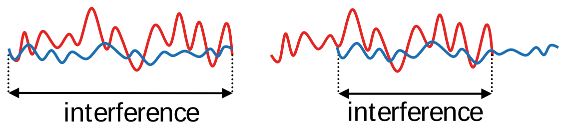


Figure 8. An AC interference signal will be generated at the overlap between the reference beam wavefront (blue) and the measurement beam wavefront (red). The reference wavefront is less deformed than the measurement wavefront. The integration area of the interference surface changes due to beam shear, resulting in a different phase to be measured.

amount of beam overlap between the reference and the measurement signal does not change, the measurements do not suffer from 'beam shear' or 'walk-off' (see Figures 7b and 7c). These two terms are related to the transverse motion of the measurement beam at the location of the detection surface. When beam overlap is constant during measurement, the wavefront deformations are no problem, since the integration area of the interference signal stays unaltered (see Figure 8).
Wavefront deformations arise during propagation through media that have a non-homogenous refractive index. At the ideal exit from a light source such as a helium-neon (HeNe) laser tube, all photons are in phase with each other. The wavefront that the photons make up together will be 'flat'. As the photons propagate, they travel through gaseous (air, helium, low vacuum, etc.) and solid media (glass, crystals, etc.), and they reflect.

The light encounters local changes in refractive index in the plane orthogonal to the direction of propagation. These local changes result in local differences in propagation velocities over the cross section of the beam. This phenomenon results in not all photons arriving simultaneously anymore. In other words, the wavefront is 'deformed' compared to the start (see Figure 9).

These deformations are not problematic when measuring in one direction only (i.e. Figure 7a). But when the system

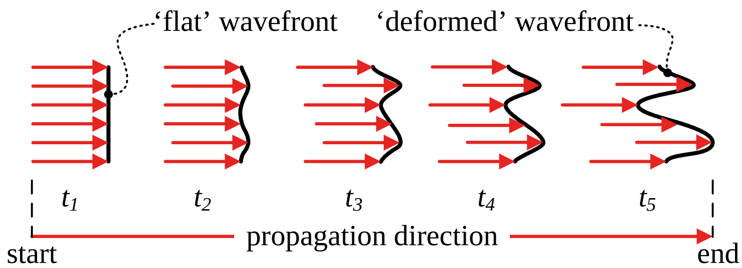


Figure 9. The wavefront starts 'flat' when exiting the laser tube. During propagation through several media, local refractive index changes cause parts of the beam to travel locally faster or slower than the rest of the beam. Introduction of these phase differences causes the wavefront to 'deform'.

encounters beam shear during the measurement, a change in integration surface will occur and a different phase will be measured (see Figure 8). Pure rotation of the mirror in Figure 7b will thus be seen as target displacement, while in fact there is none.

To conclude

All commercial interferometric systems have wavefront deformations present when delivered and fed into the interferometer optics. This decreases measurement accuracy when the reference signal is not generated prior at the interferometer where the interference takes place. In the design described here the beams are delivered through single-mode optical fibers that by definition have a flat wavefront as output. The reference in the system is generated at the interferometer itself, using the output of the single-mode fibers. This makes the design very robust, since there is less space for wavefront deformations to occur. And the means of detection using two photo-detectors eliminates the phase disturbances caused by the optical single-mode fiber transport.
The wavefront deformations and their sources and level of impact on measurement accuracy are currently being researched.

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Author's note

Arjan Meskers is working as a Ph.D. researcher at Delft University of Technology (TU Delft), the Netherlands, in the Mechatronic System Design group headed by professor Rob Munnig Schmidt and under the daily supervision of associate professor Jo Spronck. He received both his M.Sc. in Biomedical Engineering and M.Sc. in Mechanical Engineering from the TU Delft. He is now focusing on the overall measurement system design related to the TU Delft interferometer concept and on the impact of wavefront deformations on the measurement accuracy that arise especially during target rotations.

a.j.h.meskers@tudelft.nl
www.pme.tudelft.nl

A 6-DoF magnetically for haptic

Current trends in the electronic and mechanical industry include ongoing miniaturisation, increasing complexity and functionality, and the introduction of MEMS devices (Micro Electro Mechanical Systems). This requires the further development of micro-manipulation and micro-assembly technology. A recent innovation in this area is the application of haptic feedback. This article describes the design of a 6-DoF magnetically levitated micro-positioning stage for haptic micro-manipulation.

• ***Alexander Mulder*** •

The haptic micro-manipulation scheme is a compromise between fully automated and manual operations. This allows a human operator to work with the sub-micrometer precision of automated equipment, while retaining task flexibility. The intent of the haptic micro-manipulation research project at Delft University of Technology (TU Delft) is to develop an affordable haptic micro-manipulation system, targeted towards varied assembly tasks, in small production series and for prototyping purposes.

Several components make up a haptic micro-manipulation system: a master robot, a slave robot, a computer control system, force sensors, and a visualisation system. The operator has no direct contact with the parts to be assembled, but rather commands the slave robot to perform the manipulation task, see Figure 1. The operator commands are issued via the master robot. Visual feedback is provided to the operator through cameras and a screen, together with force feedback through sensors in the slave robot and actuators in the master robot.

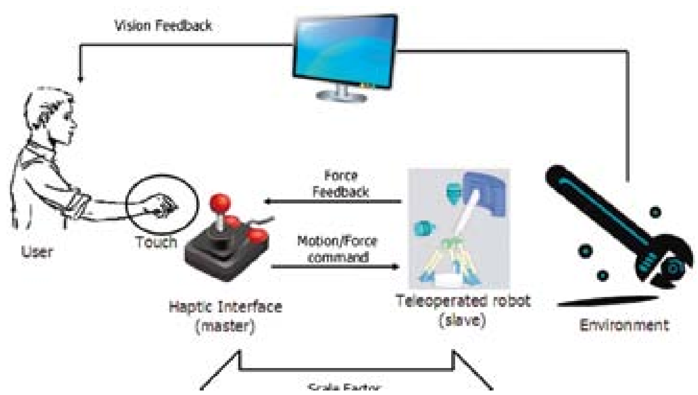


Figure 1. Haptic control scheme for micro-manipulation tasks.

levitated stage micro-manipulation

The operator commands can be scaled down, so more accurate positioning can be achieved. Depending on the application, the scale factor can be varied. This approach yields a flexible system for a variety of tasks. The haptic force feedback provides additional information to the operator, which improves performance (e.g. assembly time, precision).

Slave robot layout

In this specific case, the manipulation tasks concern parts that have a 2.5-dimensional geometry as a result of the planar manufacturing techniques used to fabricate them. A typical assembly operation on a 2.5D part requires two in-plane translation degrees of freedom (DoFs) to move the part to its proper location, and an out-of-plane translation DoF to stack parts or to insert parts into holes. An in-plane rotational DoF is needed to align parts to each other. Finally, a gripping DoF is needed to handle the parts.

The largest component dimensions are in the order of a millimeter, and assembly tolerances generally lie between 2 μm and 200 nm. The overall motion range of the slave robot should be about 20 x 20 x 20 mm^3. Two additional degrees of freedom with a small motion range are needed to correct out-of-plane tilting misalignments of the parts. In the current research at the TU Delft, the slave robot consists of two positioning stages, a coarse and a fine stage. This subdivision was chosen to accomodate the different requirements for coarse (transport, pre-alignment) and fine (mounting, assembly) manipulation tasks. The design and testing of the fine stage is the scope of the current work.

The coarse stage is implemented as a stiff 4-DoF stepper motor stage. However, it is desirable to have some compliance in a haptic slave robot, so it can be used in a so-called ‘hard master, soft slave’ set-up [1]. A compliant slave robot also offers protection against damage to parts due to e.g. collision. This compliance will be implemented in the fine stage. The slave robot gripper or other end-effector is equipped with a 6-DoF MEMS force sensor to provide the haptic feedback.

Requirements and design considerations

Using magnetic levitation technology for the fine stage allows a variable, low-stiffness stage in six DoFs. The stage is also contact-free, eliminating friction and stick-slip from assembly operations. Existing 6-DoF maglev stages have been developed by, for example, Kim et al. [2] [3]. The physical size of these stages however is too large for the current application. This is a result of the relatively large payloads for which they have been designed (several kilograms). The goal of the current work was to design a miniaturised version of such a stage.

In view of the current application, the stage should be affordable and usable for a variety of assembly and manipulation tasks. The stage can be more affordable and simple in design if certain requirements can be kept low, in accordance with the limited capabilities of a human operator. Most notably, the operator commands will have limited bandwidth (< 5 Hz, [4]) and absolute accuracy is not needed, since the operator will correct for mistakes during operation. Further requirements are listed in Table 1.

Table 1. Main design requirements of the fine stage.

Requirement	Design value
Range, translation	200 x 200 x 200 μm^3
Resolution, translation	40-100 nm
Range, rotation	±1° x 1° x 1°
Resolution, rotation	≤ 0.002°
Number of DoFs	6
Velocity, translation	> 1 mm/s
Acceleration, translation	> 5 mm/s^2
Perturbation rejection, floor vibrations	> 40 dB @ 10 Hz
Closed-loop bandwidth	100 Hz
Interaction force range	10 mN
Force resolution	< 100 μN
Stage payload	1 g

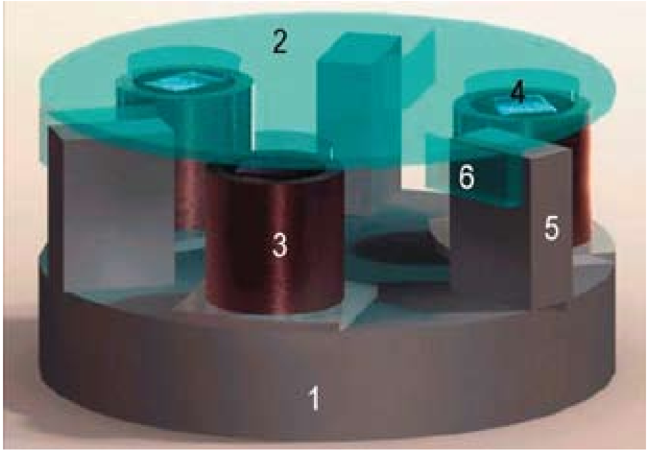


Figure 2. Concept sketch of the 6-DoF magnetically levitated micro-slave stage.
1. Base structure
2. Floating disk
3. Actuator coils
4. Actuator magnets
5. Sensor holders with sensors
6. Sensor targets

Perhaps the most important requirement during operations involving contact between parts is force resolution. This resolution needs to be fine enough that small force increments will not lead directly to damage to parts, but rather will provide the operator with haptic information about the assembly operation. To achieve this, the use of low-force, contact-free actuators is advantageous.

Fine-stage concept

The concept for the fine stage based on magnetic levitation is shown in Figure 2. The stage consists of a magnetically levitated disk with three actuators. Each actuator can provide an electromagnetic force in two independent directions, so that all six degrees of freedom are actuated. On the levitated disk, targets are provided for six position sensors. These sensors are optical reflective sensors.

In this concept, there is no mechanical contact between the disk and the base structure when the stage is in operation. Another advantage of this configuration is that there are no components above the disk; its surface is entirely free. This allows access to the assembly area from any direction with any tool type, and makes the device much more flexible regarding possible applications.

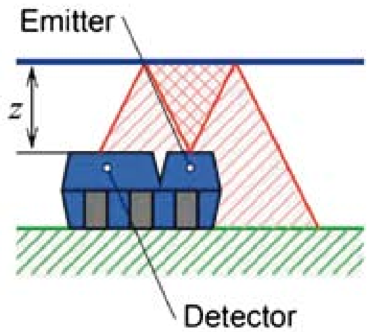


Figure 3. Sensing principle of the reflective position sensor.

Sensors

The sensors measure linear displacements, in six independent directions. These are three vertical displacements and three horizontal displacements. Each sensor should have a range of at least 200 µm, with a sensor noise of around 20 nm (6σ). The sensing principle should of course be contact-free. Based on these requirements and low-cost and small-size considerations, SMD-based optical reflective sensors were chosen.

In such a sensor, light is emitted by an infrared LED and reflected by a target at some distance z above the sensor (see Figure 3). A phototransistor receives the reflected light. When z is zero, no light is reflected and the transistor is cut off. This also happens when z is very large. A conduction maximum lies somewhere around z = 500 µm, and there are two measurement ranges with a different slope (see Figure 4). The linear part of the “near” range is approximately 200 µm long and is used in this stage. Sensor read-out electronics have been designed for low noise and optimum linearity. With these, the reflective sensor achieves 14-28 nm (6σ) position noise over a 210 µm range. Sensor bandwidth is 1 kHz (ten times the system bandwidth), while nonlinearity is better than 2.5% relative to full scale.

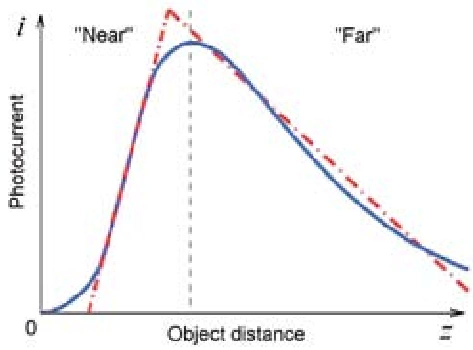


Figure 4. Near and far measurement ranges of the reflective sensor.

Author's note

Alexander Mulder obtained his M.Sc. degree in Mechanical Engineering at the Precision & Microsystems Engineering department of Delft University of Technology (TU Delft), Delft, the Netherlands. He was awarded the 2011 Wim van der Hoek Constructors Award for his M.Sc. thesis on the design of a 6-DoF maglev stage, and is currently working as a mechatronics engineer in the solar energy industry.

Figure 5. Schematic overview of the Lorentz actuator concept.
1. Base structure
2. Square coil
3. Cylindrical coil
4. Permanent magnet

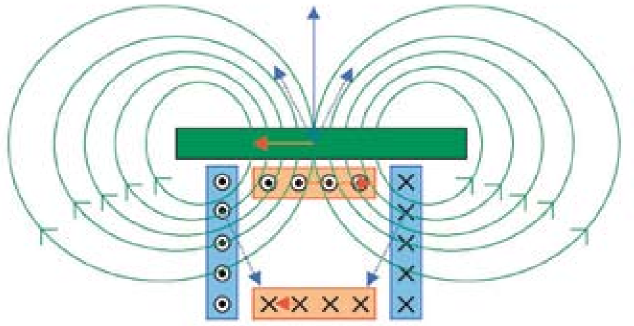


Figure 6. Schematic cross-section of the dual Lorentz actuator. The permanent magnet and its field lines are shown schematically in green. The vertical (cylindrical) coil and its associated force components are shown in blue, the horizontal (square) coil and its force components in red.

Actuators

The actuators designed for this stage are novel 2-force Lorentz actuators. Six independent forces are provided by three of these actuators. The actuator geometry is shown in Figure 5. It consists of a square coil and a cylindrical coil. The actuator magnet, attached to the floating disk, is a cylindrical NdFeB permanent magnet, which is kept floating 500 µm above the coils.

The horizontal Lorentz force is generated by the current flowing in the top section of the square coil (see Figure 6). The Lorentz forces acting on the vertical sections of the square coil cancel out when the magnet is centred. The Lorentz force acting on the lower section of this coil counteracts that of the upper section, but is much smaller. Therefore, there is a net horizontal Lorentz force on the square coil, and an opposite reaction force on the magnet.

The vertical force is generated by the current flowing in the cylindrical coil. The resulting reaction force contributions are directed upwards and inwards, adding up to a net vertical force. When the magnet is centred above the coil, horizontal force contributions cancel out due to the axial symmetry.

Extensive FEM modelling (Finite Element Method) was done to characterise this actuator, and to determine the optimum dimensions. This showed that the available peak vertical force is theoretically about 160 mN, and the horizontal force about 20 mN, for an actuator that is about 10 x 10 x 13 mm^3 in size. FEM modelling and practical experiments further showed that this actuator has a position-dependent force characteristic (in all directions) due to the non-homogeneous field of the permanent magnet and coils. Additionally, the actuator exhibits non-negligible crosstalk between the horizontal and vertical coils, which leads to parasitic forces. However, it was found that these effects are manageable by the system controller over the stage displacement range of 200 µm. Together with custom-designed amplifiers, the actuators achieve a force resolution (noise-limited) of 100 µN vertically, 13 µN horizontally.

Control and modelling

An electromechanical model was made of the complete system. This model includes the mechanical properties of the stage, the electrical and force characteristics of the actuators, a model of the sensors and external disturbance forces (i.e. floor vibrations and assembly interaction forces). Since the system is inherently open-loop unstable, a controller is also included in the model (see Figure 7).

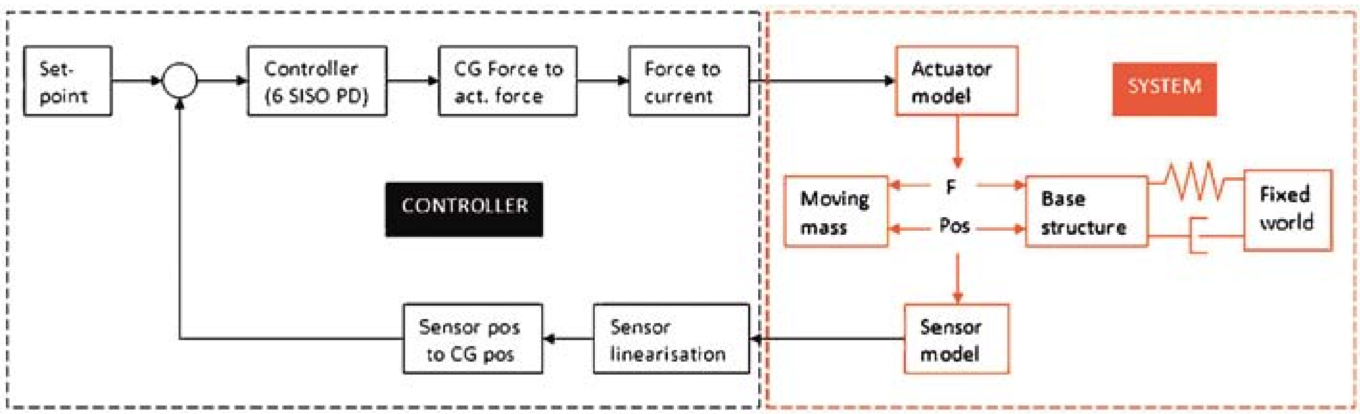
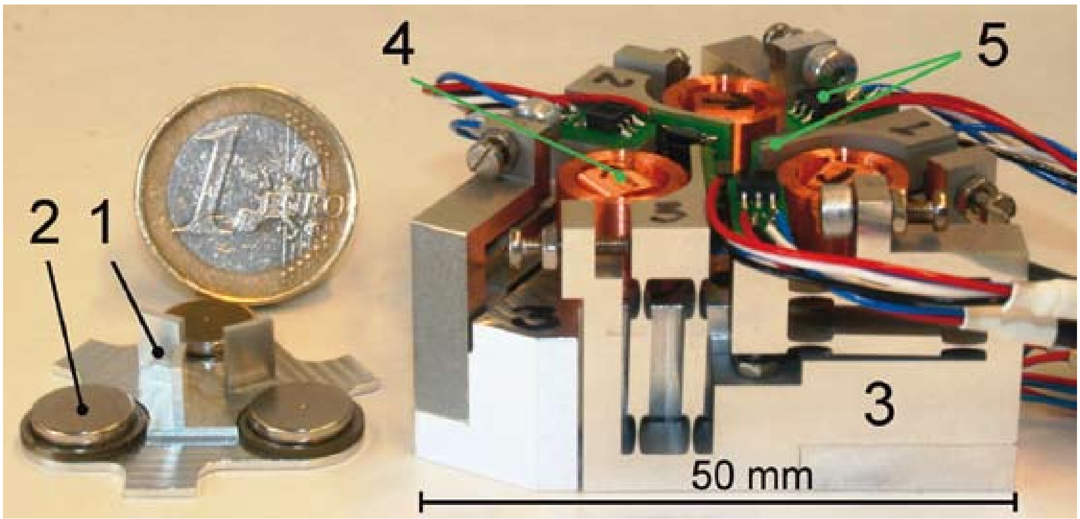


Figure 7. Simplified model of the micro-slave stage.



1. Permanent magnet
2. Moving part
3. Sensor alignment mechanism
4. Actuator coils
5. Optical sensors

Figure 8. The completed maglev stage.

Although the system is a 6-DoF MIMO system (Multiple Input, Multiple Output) with considerable crosstalk, the controller is implemented as six independent SISO PD controllers (Single Input, Single Output). This approach was taken for simplicity and has been proven sufficient in similar set-ups [2] [3]. There is no integrator present in the controller since this may cause high actuator forces, leading to damage to parts and tools. The controller operates in centre-of-gravity coordinates of the moving mass, so transformation matrices are needed for sensor and actuator coordinates.
Using the model, the controller gains have been tuned and sensitivity to noise in sensors, actuators and external vibrations has been determined. This showed that the biggest position error is due to external vibrations, and that the achievable perturbation rejection is 10 dB smaller than the requirement, due to actuator saturation. The stage must therefore be used in conjunction with a vibration isolation table.

Another aspect that was investigated with the model is sensitivity to assembly tolerances. The coordinate transformation matrices assume perfect alignment of sensors and actuators, and any deviation will cause steady-state position errors. Misalignment of the magnets relative to the actuator coils will cause extra parasitic forces and gain errors, due to the position-dependent actuator characteristics.

Using a Monte Carlo inspired method, normally distributed random misalignments were added to all sensor and actuator positions, as well as to the relative positions of the magnets with respect to the coils. This showed that assembly tolerances in the order of 200 µm / 2° (representative for the actual device) cause static position errors of about 2.5 µm / 0.012°, and system stability is retained even in the worst cases. These errors can be compensated for by system identification and adjustment of the transformation matrices. It was also shown that the relative misalignment between coils and magnets gives the largest contribution to the position error. Minimising these misalignments is therefore the most effective way to reduce the position error. This was realised in the practical stage by designing an alignment tool, used during the stage-assembly procedure.

Practical results

The stage concept has been developed into a detailed mechanical design (see Figure 8), which was then built and tested. Since the sensor measurement range is no greater than the movement range of the stage, these should overlap to within a few µm. Because of component and assembly tolerances an alignment mechanism is needed. An elastic-hinge-based parallel guide has been designed for this purpose.

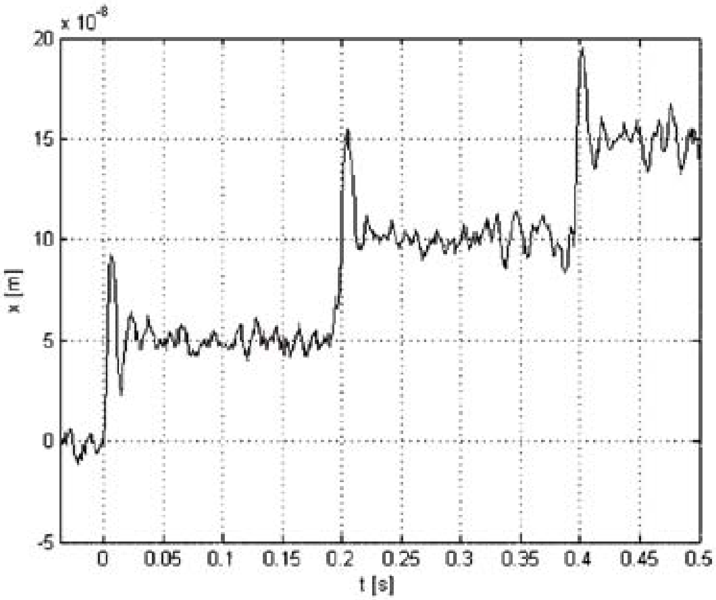


Figure 9. Measured system step response to 50 nm steps.

The moving part of the micro-slave stage contains the actuator magnets and the optical sensor targets. It should combine low mass with high stiffness. Its eigenfrequencies should lie far above the overall system bandwidth, to avoid interference with the control loop performance. Using FEM eigenmode analysis, a moving part could be designed with an 8 g mass and lowest eigenfrequency of 7 kHz.

The completed stage has been tested to determine its movement ranges, noise levels and other characteristics. The results are summarised in Table 2. Most design requirements have been achieved. However, the out-of-plane rotation range is only half the requirement, due to the limited sensor range and the distance of the sensors from the moving part CG. Bandwidth and perturbation rejection are lower than the requirement due to actuator saturation.

However, the system performs satisfactorily in practise. Figure 9 shows measured step responses for 50 nm steps, with peak-peak noise around 25 nm in this case. At the moment of writing, the stage is being integrated with a coarse stage, force sensor and other components to build the entire haptic slave robot.

Table 2. Achieved system specifications.

Specification	Achieved value
Range, translation	210 x 210 x 210 μm^3
Translation noise level	40 nm (6σ), with vibration isolation table
Range, rotation	±1.2°, vertical axis ±0.5°, horizontal axis
Rotation noise level	0.0002° (6σ), vertical axis 0.0004° (6σ), horizontal axis
Force range	> 10 mN
Payload	> 3 g
Controller bandwidth	50 Hz
Perturbation rejection	30 dB @ 10 Hz

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Reducing a metal stress

As part of a scientific instrument development project, TNO developed an actuator for high-accuracy positioning. Critical components in this actuator assembly were metal springs designed by TNO. To demonstrate Additive Manufacturing (AM) possibilities, TNO designed a dedicated AM version of the spring that was prototyped by LayerWise. AM allowed the original thick coil to be replaced with multiple thin hollow coils, drastically reducing internal material stresses and overall weight. By mastering the technology of building parts layer by layer, LayerWise stretches the limits of traditional metalworking in favour of functional designs offering peak performance.

• Rob Snoeijs •

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"We contracted LayerWise to investigate AM technology capabilities with regards to optimising the performance and weight of metal actuator springs", says John van der Werff, Mechanical Designer for TNO's Rapid Manufacturing department in Eindhoven, the Netherlands. "We met their specialists at one of the TNO-hosted rapid manufacturing workshops. Since then, LayerWise has successfully completed several titanium component AM projects for TNO."

Investigating AM technologies

Van der Werff explains that the original high-tensile steel spring prototype is precision-machined. "Although the spring stiffness is sufficient for its specific purpose in the actuator assembly, the spring's internal stresses rose as high as 1,200 MPa. TNO engineers collaborated with LayerWise to re-think the spring design with AM in mind, and explored what weight and performance gains were within reach."

Author's note

Rob Snoeijs studied Engineering in Leuven and Mechelen, Belgium. He held several R&D, marketing and services positions in technology firms in the USA, Belgium and the Netherlands, and now is a technology writer for LayerWise. He focuses on sharing insight into challenging metal additive manufacturing (AM) projects realised by LayerWise. This Belgian company is a technology innovator and technology user that stretches the limits of metal part performance and manufacturing economics.

spring's internal and weight

The spring is produced directly from its STL design files using a powerful yet high-precision laser beam. The laser pinpoints metal powder particles to selectively build up a 20 to 40 micron horizontal layer. As the layers are built successively, AM hardly faces any restrictions in realising the most complex shapes, which often cannot be produced any other way.

Titanium

"The first step in dealing with the spring's peak internal stresses is the use of titanium", marks Van der Werff. "It's a stiff, lightweight material that offers a low E-modulus and is available in multiple grades." The engineers selected TiAl6V4, which reliably withstands 300 MPa. This value is not good enough when considering the original spring design, but TNO and LayerWise redesigned the spring geometry to keep stresses below this threshold value; see Figure 1.

Figure 1. The original precision-machined steel spring (left) next to AM-produced titanium prototypes with parallel coils.

Unlimited design freedom

Van der Werff explains that the design freedom associated with AM allowed TNO to opt for a spring coil design that's half as thick. "Building a coil with a cross section half the size, reduced internal stresses 50% when considering equal spring compression. We found out that a hollow coil with a triangular instead of rectangular cross section distributes the stresses more evenly over the entire coil surface. Altogether, the new spring concept faces stress levels that are four times lower compared to the original design." See Figure 2.

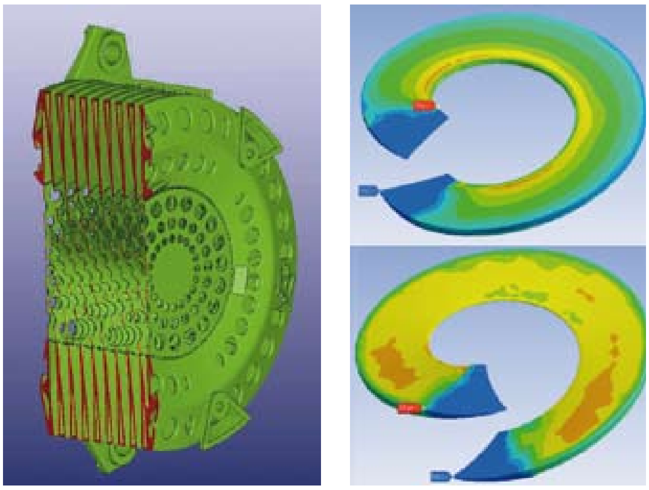


Figure 2. Thin hollow spring coils with a triangular cross section reduce stresses and distribute these more evenly.

"To compensate for the spring's reduced stiffness, we implemented a design comprising of eight identical parallel spring coils. This had no impact on production cost, because AM produces the entire spring, including all spring coils, as a single part in one production step. The titanium spring part incorporating perforated top and bottom disks with eight thin hollow spring coils in between enabled us to cut spring weight by 70%. Such impressive results underline AM's superior lightweight design capabilities."

Post-processing

Custom center support was added to the AM design to avoid support attachments on critical part surfaces or hard-to-reach part locations. Special side-support structures, which easily can be removed afterwards, were added to keep the coils locked in position during post-processing; see Figure 3. Furthermore, the design incorporates three tiny angled surfaces that center the spring during post-processing of the mounting surfaces; see Figure 4.

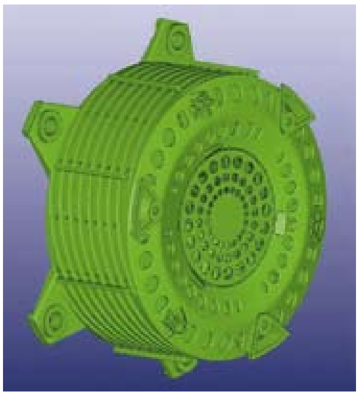


Figure 3. AM provides center and side supports to ensure linear spring compression and decompression.

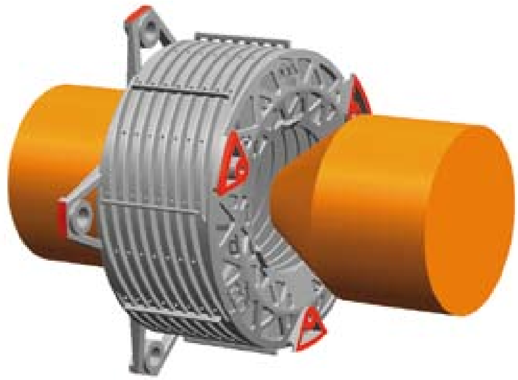


Figure 4. The red-marked surfaces require post-processing; the three tiny angled surfaces center the spring during this procedure.

To conclude

Throughout the spring project, TNO and LayerWise collaborated intensively. Through positive interaction, multiple prototypes have been built and the production process was tuned to achieve the best results. "AM proved to be suitable for functional prototyping in the design and test phases", concludes Van der Werff. "Although no real cost reduction could be realised in this case, AM's design freedom resulted in major weight savings. By changing design and production rules, AM stretches design limitations in favour of extreme part optimisation. Material properties of AM products is one aspect that needs further investigation; in particular fatigue on high-stress AM parts is uncharted territory."

Mass with micron

Various trends that have helped move the reliability and accuracy of process technology forward can be identified in the evolution of production processes during the last decades. This article shows how Philips is introducing robust production processes that guarantee the user the required output quality. The emphasis here is on laser applications, seeing as they offer many manufacturers unprecedented possibilities. By developing and applying lasers, Philips has repeatedly been able to create a competitive edge.

• *Jurgen Adriaensen* •

Lasers are still regarded as expensive, dangerous and complex. This stigma deserves to be removed because experience has shown that a well-thought-out process and a robust production platform guarantee high output, low maintenance costs and reliable quality. The price of lasers is continuing to drop, and a great many solutions are being standardised, thus markedly lowering the entrance threshold. The only threshold that still has to be negotiated, day in day out, is the fact that these processes cannot be devised at a desk but that you have to go to a lab to see whether lasers might be a solution for the problem posed. Various steps have to be taken to develop a laser process, and the risks also have to be catalogued. These steps are listed and further elaborated below.

Boundary criteria

Various boundary criteria have to be met to be able to make a product using lasers. These include choice of material, tolerances, possible contaminations, demands made on the end product, machine speeds, etc. These criteria differ greatly from one project to the next. A number of solution strategies can be formulated on the basis of these criteria.

Process variation

Each process is subject to dispersion, which for laser processes can come from various angles.

1) Material
   a. Dimensions
   b. Finishing quality
   c. Surface condition
   d. Possible thermal after-treatments of the material
   e. Contamination on the surface
   f. Contamination in the bulk

2) Machine
   a. Positioning accuracy
   b. Vibrations
   c. Forces during welding
   d. Tool wear
   e. Contamination
   f. Stability
   g. Protective gas management

production accuracy

3) Laser variations
   a. Power stability
   b. Pointing stability
   c. Beam profile

4) Environment
   a. Vibrations
   b. Draught/disturbance (protective gas conditions)
   c. Ambient gas
   d. Temperature variation

Process development

The largest risks in the above list have to be recognised and systematically examined at the start of process development. By intentionally introducing process variations, the process window can be defined with great accuracy. Where controlled introduction of variations is not possible, measuring systems are an option for recording the dispersion of each product, after which the process window can still be defined by grouping and analysing products. This process window is a graphic representation of the physical dimensions within which the quality of the product can be guaranteed.

Machine specification

Starting from this process window, the requirements and wishes the machine is to meet can be formulated in order to guarantee that all products made have the same desired quality. It is very important here to recognise the possibilities and limitations of the various process technological, mechatronic and optical systems. The fact is that there is no guarantee that aspects that meet specifications at the start (or according to the catalogue) will continue to do so once they have to produce round the clock. That is why they are first placed on a test bench for a longer period and observed continuously.

Laser and vision hand in hand

In the last decade, the increasing need to fall back on vision systems in order to meet the set product requirements has become evident. Indeed, production cannot do without it, especially as tolerances become tighter, products smaller and processes more critical. Different levels of interaction between laser and vision can be identified, however, as the pyramid below shows.

Once the first laser systems are introduced on the shop floor, they will be used extensively in other applications.

Level 1. Good/bad selection

The control of the product parameters forms the basis: check that the critical aspects of the product meet the requirements. Based on these measurements, the product will be either approved or rejected. After a number of rejects, the machine will be stopped and the operator has to take action. The measurements are represented on control cards thus enabling a rapid problem analysis, for which the operator's interpretation is still needed.

Author's note

Jurgen Adriaensen is a specialist in process development for laser applications at Philips Innovation Services and in that capacity he manages the laser labs of production mechanisation in Turnhout, Belgium.

jurgen.adriaensen@philips.com
www.innovationservices.philips.com

Level 2. Vision correction
The machine can also be guided using vision measurements. As a result, the measuring time may well enter the machine's cycle time and the machine will slow down as the measuring time increases. To minimise this effect, the measuring algorithms are made as fast as possible and, if necessary, several systems are positioned in parallel. Despite tool wear or varying dimensions or positioning of input materials, a reliable quality can still be guaranteed using this technology.

Level 3. Trend analysis
At a higher level are the systems that analyse trends in the key product parameters and make corresponding adjustments. Again, the knowledge of the process window is essential. This shows which parameters may be adjusted, on the basis of the measurement data. This technology is especially good at overcoming slow process variations, e.g. laser power variation, thermal drift of laser scanners and fluctuations from within the laser system.

Level 4. In-process correction
The critical parameters can be adjusted by following the process via image, sound or spectral analysis during the process. Processing data and guiding the laser will be directly linked to each other.

Practical cases

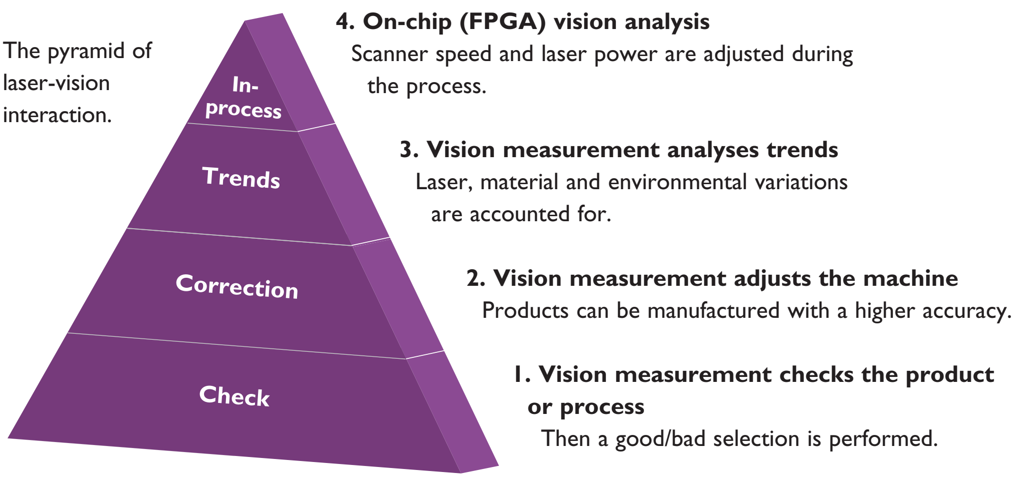
The cases below demonstrate how vision enables a reliable manufacture of products.

Case 1: Sealing off glass tubes with a high level of control over a longer period of time (vision integration level 3)

Input materials	• Glass tubes with a diameter of less than 0.8 millimeters
Objective:	• Controlled sealing off of glass tubes
Functional specifications	• Minimal thermal load • Gas-sealed also in operation • Reliable melt quality irrespective of material or laser variation

The mechanical positioning of the products is feasible, seeing as the laser spot is fairly large in relation to the product to be worked. The limitation with regard to positioning comes from the laser source. Seeing as glass is involved, a CO_2 laser system is needed to heat the material. Unfortunately, this type of laser has two significant disadvantages: on the one hand, the variation of the power in time, and, on the other, the variation in the position of the laser spot. These parameters can by no means be measured with an accuracy that guarantees a reliable process, which is why the following conclusions formed the starting point for construction of the machine:

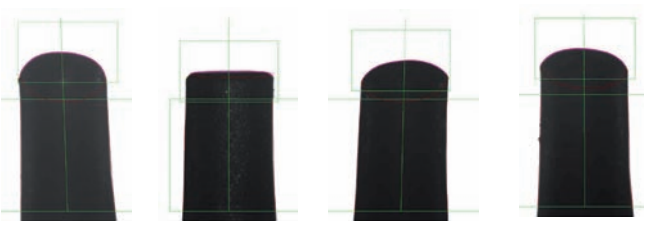
1) The laser source and optics are the major source of variation. These have to be properly selected and tested.
2) The design of the machine should take account of the fact that the stability of the spot position is highly critical. This becomes evident in minimal beam distances and very sturdy constructions.
3) A product characteristic is measured to guarantee the



The pyramid of laser-vision interaction.

combined effect of the process, making a reliable adjustment to the process possible.
4) The control curve of the process has to be made insensitive to incidents, measuring errors and process drift.

In this case, it is the combination of the volume and the slope of the melt that indicates whether the process is going well or drifting. It can also be concluded from this how much compensation is needed and in which direction.



a b c d

Measurement method: the volume of the ellipse is a function of the laser power; the slope of the ellipse represents the laser beam positioning error.
(a) Power ok.
(b) Power too low.
(c) Laser spot too far to the left.
(d) Laser spot too far to the right.

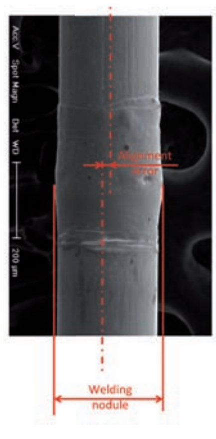
Case 2: Welding thin wires (vision integration level 2)

Input materials	• 300 µm and 280 µm wire of various materials
Welded joint	• Axial with an upsetting movement during welding
Functional specifications	• Welded joint as strong as possible • Maximum tangential alignment error 15 µm • Maximum external diameter welding nodule: 320 µm • 100% control of all functional specifications

Considering the requirements and taking the dispersion of the input material into account, the tolerance analysis will prove that a purely mechanical positioning of the components with that accuracy and in a robust manner is impossible. The process review also shows that the upsetting path during welding, the laser power and the spot position of the laser are the key parameters affecting the imposed functional specifications.

In order to make this machine, the following choices have therefore been made to minimise the variations:
1) Purely mechanical positioning is no longer possible at these levels of accuracy. Tool wear is also believed to have a rapid effect and introduce errors. The positioning of each product will have to be actively adjusted by measuring. A 'rough' positioning is followed by measuring the correction that has to be made in three directions, so as to finally be able to position the products with the greatest accuracy.
2) Positioning the laser is so critical that scanner optics cannot be used. Fixed optics are preferred.
3) To stabilise laser power, it is adjusted during the laser pulse in order to retain a stable quantity of energy, also over a longer period of time.
4) After making the weld, the finished joint is measured at various angles. If one of the measurements is not satisfactory, the product is rejected. This procedure guarantees 100% good products.

a b c



d

Welding a thin wire.
(a) Rough positioning.
(b) Positioning after correction.
(c) Welded product.
(d) Stereo electron microscope image of the weld.

Conclusion

Laser technology remains a strong driving force behind the automation of production processes. Once the first laser systems are introduced on the shop floor, they will be used extensively in other applications. Highly robust, self-correcting production processes can be created by a further entwining of laser and vision technology. It goes without saying that each time it is essential to consider what level of vision integration is really needed to meet customer demands.

Micro-tools for

Milling and grinding are cutting technologies that are almost as old as the craft of refining and forming metals itself. Traditionally, the appropriate tools were huge and heavy: milling cutters and grinding wheels. It's almost unimaginable that today such tools may have diameters of no more than ten micrometers! The Institute of Manufacturing Technology and Production Systems (FBK) of the University of Kaiserslautern, Germany, has succeeded not only in making those micro-tools, they also designed and manufactured machines that make and apply them.

• *Frans Zuurveen* •

One application area for micro-milling and -grinding tools (see the SEM pictures in Figure 1 and the appropriate machines in Figure 2) is the manufacturing of moulds for micro-optical workpieces made of plastics and glass. Such moulds have to be heat- and wear-resistant and are therefore made of such materials as hard metal, tungsten carbide and ceramics, which are difficult to machine. Another important application area is the manufacturing and structuring of micro-medical parts, e.g. implants. Such parts are very often made of titanium, a material that is very difficult to cut and that is used mainly because it is easily accepted by human tissue and bone.

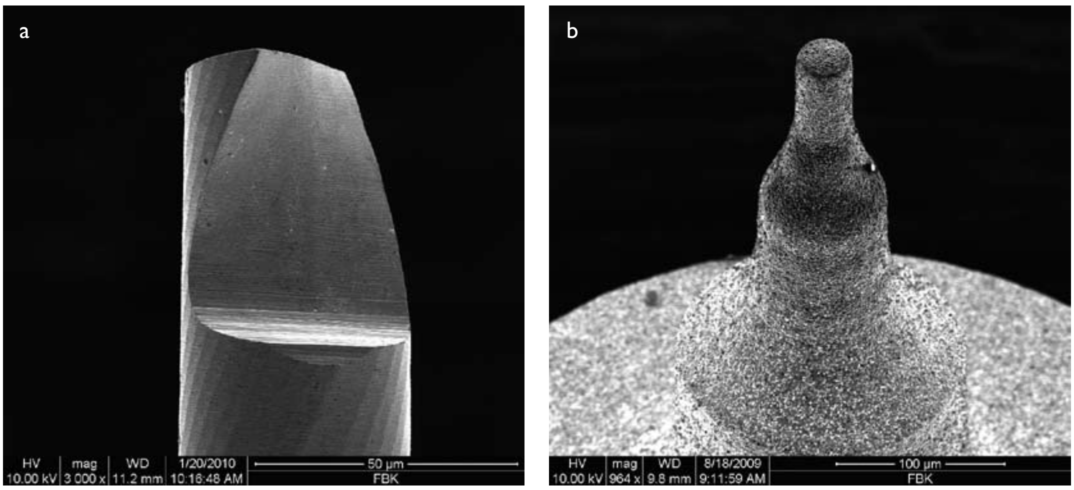


Figure 1. SEM pictures of micro-tools made by experts from the University of Kaiserslautern.
(a) Micro end mill.
(b) Micro pencil grinding tool.

micro-milling and -grinding

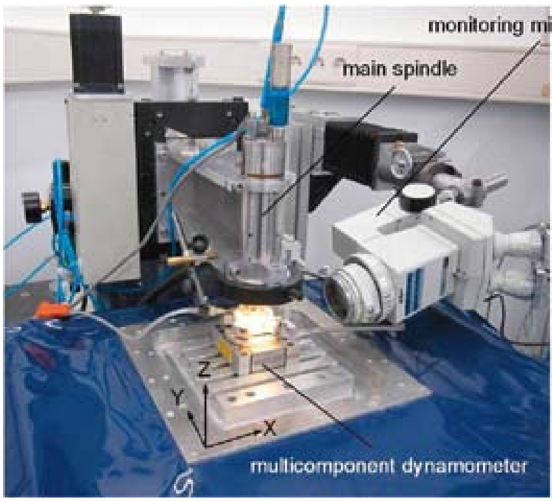


Figure 2. A precision grinding and milling machine applying the tools of Figure 1. Working area 100 x 100 x 100 mm^3, positioning resolution < 0.1 µm.

Micro end mill

The specialists of FBK also developed a machine for the manufacturing of micro-mills, wich roughly resembles the machine shown in Figure 2. A common property of the FBK precision machines is the resolution of 0.1 µm of air-guided slides driven by stepping motors, thanks to precision measuring scales from Heidenhain and base frames of very stable granite.

The preferred material for a micro end mill is tungsten carbide. This extremely hard material can be machined only with diamond grinding wheels. The making of a micro-mill starts with a solid tungsten carbide shank with a diameter of 3.175 mm clamped in a monolithic hydraulic expansion device (see Figure 3). This clamping device is connected to a precision spindle rotating in air bearings.

In just ten minutes, this machine produces a micro-milling tool with an extremely small diameter, high aspect ratios and a long cutting life. To keep the cutting edge as sharp as possible – radius below 0.2 µm – a coating is not used. The end mill has only one cutting edge with a positive wedge angle and a clearance angle of 6 degrees.

Micro pencil grinding tool

Making a micro-milling tool is a masterpiece of precision engineering, but the manufacturing of a pencil grinding tool is even more complicated because of the combination of three processes in one machine: grinding, electrolytic

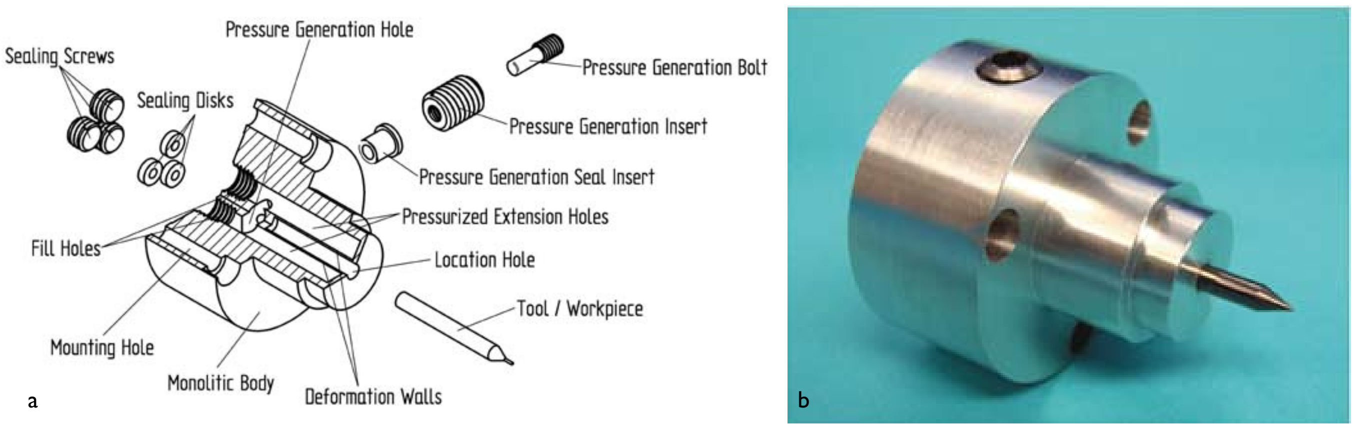


Figure 3. A monolithic hydraulic expansion device for clamping a tungsten carbide shank that is to be ground into a micro end mill. The device symmetrically compresses the shank to realise a rotational accuracy better than 0.2 µm.
(a) Exploded view.
(b) Realisation.

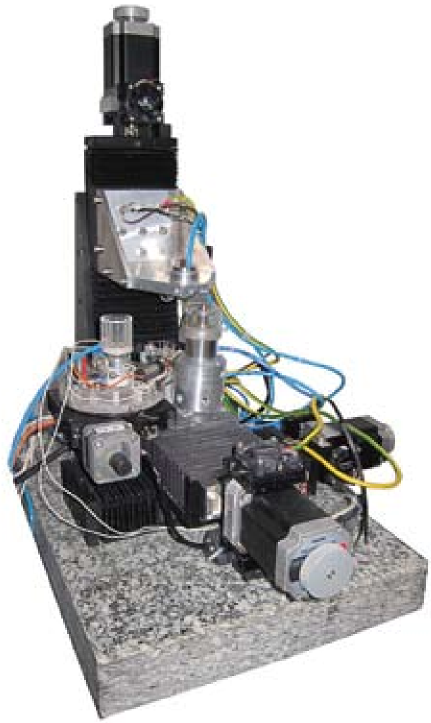


Figure 4. A machine developed by FBK for making micro-grinding tools. It combines three processes: grinding, coating and EDM.

coating and electrical discharge machining (EDM). Figure 4 shows the – again self-developed – machine for making micro-grinding tools.

The manufacturing process starts with a fine-grained tungsten carbide blank, clamped in the device of Figure 3. This clamping mechanism is part of a micro high-speed, air-bearing spindle with an incredibly high rotation speed of 7.5 kHz, 450,000 min^{-1}. A second rotating spindle with 120,000 min^{-1} can be equipped with segmented miniature grinding wheels for pre- and fine-grinding the blank for making a micro-shank according to Figure 1b.

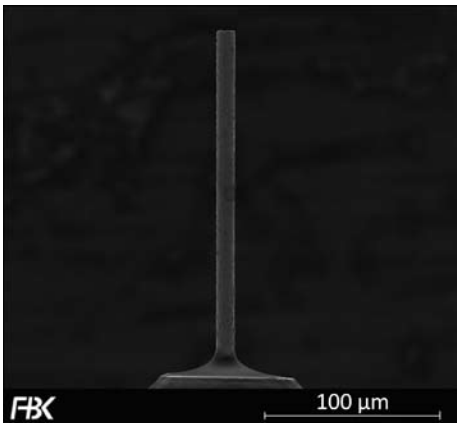


Figure 5. A shank with a diameter of 10 µm and a length of 200 µm to be used as a micro-EDM tool to make a centric hole in a micro pencil grinding tool (Figure 1b).

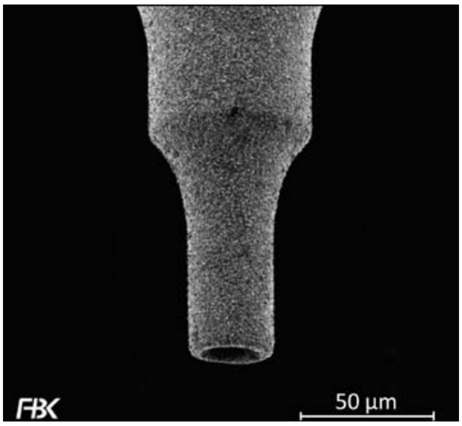


Figure 6. A micro pencil tool with a centric hole, aimed at avoiding low cutting speeds in the centre.

The same process is used to grind a shank with a diameter of no more than 10 µm and a length of 200 µm, see Figure 5. This tool is applied as a micro-EDM device in the machine of Figure 4 to make a centric hole in a micro pencil grinding tool (Figure 1b). The aim is to avoid low, nearly zero, cutting speeds in the centre of a pencil grinding tool.

Figure 6 shows a micro pencil tool after a centric hole has been made. Abrasive material for the real grinding process still has to be adhered to this tool. This material should be diamond or CBN (cubic boron nitride) in the form of small grains. In the same machine (Figure 4), the micro-grinding tool is electroplated with nickel. Diamond or CBN grains are suspended in the nickel electrolyte, resulting in a thin homogeneous nickel layer with abrasive grains embedded in it.

Applying micro-tools

As we have already said, the machine in Figure 2 was specially designed to cut workpieces with the micro-tools described above. Micro-milling tools are used to manufacture and finish medical implants, mostly made of

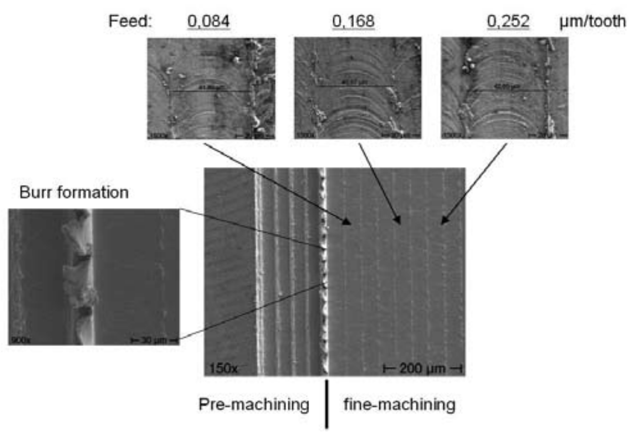


Figure 7. Grooves milled with micro end mills with different feeds in titanium alloy Ti-6Al-7Nb to improve biocompatibility.

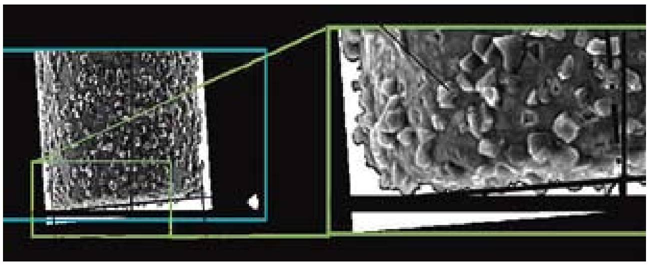


Figure 8. Grinding a groove with a micro pencil tool inclined to an angle ρ = arctan 2 X_{max}/d, with X_{max} the maximum grain size in the tool and d its diameter.

titanium alloys, because of the high strength, low weight, corrosion resistance and biocompatibility of these alloys.

Micro-milling titanium alloy surfaces results in a better adherence to human tissue. In tests, tiny grooves were milled in titanium alloy Ti-6Al-7Nb with micro end mills with a shank diameter down to 48 µm. The surfaces in the bottom of the grooves and the sidewalls have been studied, see Figure 7. The cutting speed was 9.05 m/s at a rotational speed of 60,000 m^{-1}, a feed of 0.1 to 0.25 µm per tooth and an axial depth of cut of about 2 µm.

Diamond tools are not suitable for grinding hardened steel because of their high chemical wear, which is why CBN grains in nickel-coated grinding tools have to be applied. The surface structure of micro-ground grooves was investigated to optimise the process geometry of micro pencil grinding tools. Grooves were ground in hard metal DK 460 with 90% tungsten carbide with a 30 µm pencil tool according to Figure 1b. With 1 to 3 µm diamond grains, relatively rough grinding marks were observed in the middle of the groove bottom. They were presumed to be due to the low cutting speed in the centre of the pencil tool, referred to above. Tests were therefore performed with a slightly inclined tool, according to Figure 8, which showed an improvement of the surface structure of the micro-ground groove bottom, see Figure 9. However, an inclined pencil grinding tool causes a geometrically defined flatness deviation of the groove bottom. That is why tools such as in Figure 6 with embedded abrasive grains are preferred for the precision micro-machining of workpieces such as miniature moulds, and are known as optimised micro pencil grinding tools.

To conclude

It is astonishing how precision-specialised scientists took up the challenge to create grinding and milling tools that are more than ten times thinner than a human hair. What's more, they developed machines to manufacture and apply them. Not to mention the efforts undertaken to optimise the appropriate cutting processes.
Now the precision engineering world has to convert the successes of this laboratory research of the University of Kaiserslautern into commercial practice. Who will recognise and accept this challenge?

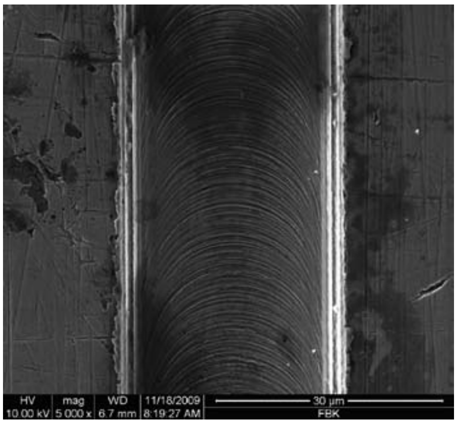


Figure 9. Bottom surface structure of a groove ground with an inclined pencil tool according to Figure 8.

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Author's note

Frans Zuurveen is a freelance text writer who lives in Vlissingen, the Netherlands. This article was based on a lecture by Dipl.-Ing. Marina Carrella held during the Micro and Precision Manufacturing seminar in November 2011 in Aachen, Germany, as well as on publications by other specialists at the Institute of Manufacturing Technology and Production Systems (FBK), University of Kaiserslautern [1].

www.fbk-kl.de

Getting high-tech and fit for the

The high-tech systems industry is a major asset for the Dutch economy and has established a unique ecosystem of knowledge, suppliers and OEMs. The combination of precision engineering, mechatronics and high-tech manufacturing has been very successful and has showcased the expertise of system thinkers and builders in a collaborative community. These were clearly deciding factors for the Intelligent Community Forum think tank when it awarded the Brainport

Eindhoven region the title of 'Smartest Region of the World 2011'. When looking at the future of high-tech systems, the tough roadmap challenges ahead raise the question of how this strength can be maintained and what innovations are required to ensure a healthy future.

• *Gregor van Baars* •

Although many high-tech systems are quite different on the application side of things (e.g. semiconductor lithography is a completely different process than wide-format printing or electron microscopy), there are strikingly similar challenges when developing equipment. In almost any high-tech systems roadmap, there is a continuous and primary need for:
- improved accuracy,
- increased productivity, and
- larger substrate capability.

There is also an obvious need to reduce costs and complexity, achieve right-first-time designs, improve robustness and reliability, and shorten the time to market.

The competence base of precision engineering and mechatronics has been continuously developing over the last few decades, and has so far delivered effective high-tech equipment solutions. Lately, however, it has become clear that each incremental step forward being taken requires more and more effort at a faster and faster rate, indicating that the end of the road may well be in sight. This is the impetus for an open call for new architectures and technologies, in order to be ready by the time there is a real need for new solutions. This article aims to share elements of a preliminary vision on future solutions, and to trigger a collective thinking among those living in the high-tech ecosystem. It is as an open invitation to join, discuss, debate or contribute in any other way.

systems in shape future

Critical to successful innovation, this is a matter of joining forces across two key areas spanning our ecosystem:

- *The total spectrum of competences* necessary to build the next generation of high-tech systems. It is immediately clear that no party has all of the competences and technologies in house. The potential failure to integrate single disciplines into integral system solutions poses the biggest threat to the healthy and prosperous future of all players.
- *The innovation chain* from academia through industrial innovation to realisation in the supply and integration chain, or, similarly, from idea to volume. A collective effort from all of the links in the chain is required to translate ideas into business with which the food chain of high-tech systems industries will secure its survival.

To put this into perspective, the top economic sector High Tech Systems and Materials (HTSM) has produced roadmaps, including one on mechatronics/manufacturing. The innovation contracts recently signed with the Dutch government have provided an excellent opportunity for this innovation to take shape for everyone's benefit. Furthermore, activities related to the development of semiconductor manufacturing equipment for 450mm wafers are on the up. For wafer stages, as developed by ASML in the nanometer accuracy range, it is immediately clear that scaling up dimensions in parallel with the desired improved positioning accuracy will be no mean feat. Supposing the current competence base will not be able to provide proper wafer stage designs, any progress in equipment accuracy will come to a halt and an important factor fails to obey Moore's law, blocking the path to the next semiconductor manufacturing node. This would undoubtedly cause shockwaves across the semiconductor industry, with a significant impact in many respects.

High-tech system fundamentals

To find a direction for innovation, the main drivers for high-tech systems – accuracy, productivity and substrate size – need to be translated into technical insight, followed by the identification and analysis of foreseeable bottlenecks in view of future equipment roadmap needs.

The starting point in the development of high-precision systems has been to imitate rigid-body behaviour as much as possible. Since no construction will have infinite stiffness, the system will exhibit dynamic behaviour at higher frequencies. Typically, the combination of high stiffness and low weight helps to push this dynamic towards higher frequencies. The first appearance of dynamic system behaviour at high frequencies allows for high-bandwidth servo control, which leads to a strong suppression of disturbances and, therefore, high motion accuracy along the desired motion trajectories.
High productivity requires rapid motion and, thus, high acceleration. To get a mass to accelerate, a large force is needed and, therefore, strong actuators. Since actuators typically have a moving part that adds to the mass to be accelerated, it is also beneficial in the context of high productivity to strive for low mass designs to begin with.
In addition, there is the trend of increasing substrate dimensions to consider. In the conventional line of development, this immediately leads to larger substrate carriers that will obviously be heavier and, therefore, conflict with the desire to keep mass down from an accuracy and acceleration perspective.

If developing existing architectures and technologies further (plan A) does not provide effective solutions for the stretched requirements, a plan B is required. The following sections will outline some views on elements of a possible plan B.

Author's note

Gregor van Baars is a senior system engineer/project manager at the applied scientific research organisation TNO. As TNO's liaison, he was involved in drafting the mechatronics/manufacturing roadmap within the framework of the High Tech Systems and Materials (HTSM) top economic sector.

gregor.vanbaars@tno.nl
www.tno.nl
www.htsm.nl

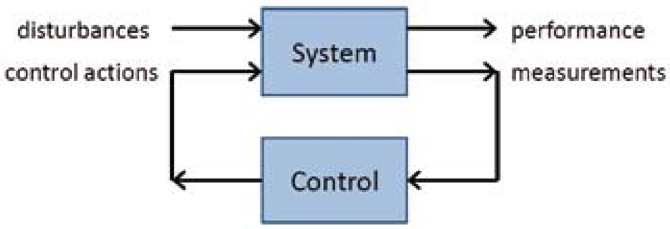


Figure 1. A typical motion system servo control loop.

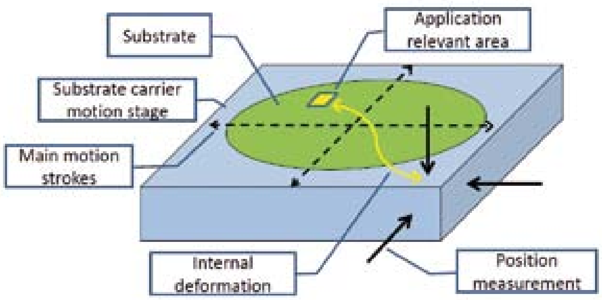


Figure 2. Schematic of a motion stage.

Alternative solutions

To pinpoint the bottleneck issues and really trigger creativity and vision to the fullest, the case will be exaggerated to some extent. To illustrate the discussion, see Figures 1 and 2.

New design approaches are facing the following three major challenges:
- Learning to deal with deformations;
- Only demanding precision at the application-relevant area; and
- Keeping out of the mass avalanche.

These challenges will be addressed individually, although combinations may very well be possible and eventually amplify the associated benefits.

Learning to deal with deformations
Attempts to completely avoid deformations as the main architectural starting point will inevitably lead to heavy designs and all kinds of collateral technical complications. Finding clever ways to accept deformations at a system architectural level will open up new high-tech system solutions. This instantly extends the mechatronic challenges to controlling motion *and shape* (hence the title of this article).

A current approach to tackle this has been suggested under the name 'Beyond Rigid Body'. Basically, this approach takes its cue from the well-known design principles and architectures for high-precision systems and adds mechatronic technologies to deal with the non-rigid body shape and deformation issues. This approach has already been addressed by various players in the ecosystem, and research has been progressing rapidly over the last few years, e.g. as part of the Xtreme Motion innovation project.

Enabling technologies and competences:
- *Over-actuation:* applying more actuators than strictly necessary to control the rigid-body degrees of freedom. With the proper control strategy, this facilitates, for example, the suppression of internal deformations associated with dynamic mode shapes.
- *Advanced thermal management:* a more dynamic and spatial consideration of thermal processes compared to the conventional approach of having constant and uniform temperature across the performance-critical parts within very tight boundaries.
- *Internal deformation measurement:* the metrology of system shape with internal sensors that, in combination with the servo positioning signals, will outline the position at the performance area of interest.
- *Inferential control:* modern model-based control methods that can enforce positioning performance at the area of interest, using servo positioning measurement information obtained from other system locations. This obviously requires a good model description of the dynamics between control actions and the performance point of interest.

Impressive progress has been made with these knowledge-intensive topics and some have already proven practically viable with experimental test rigs. When deformations are incorporated into mechatronic architectures and supported by technologies and competences to design and predict performance, a new solution space is established, which is no longer restricted to the dilemma of stiffness, mass and acceleration forces outlined above.

Precision at application-relevant area
With substrate dimensions increasing, we are being forced to think about metrology as well. In conjunction with inter-

nal deformations, the question that could be asked is to what extent positioning metrology is still connected to the real performance. It is obvious that obtaining position information close to the area of performance interest is preferable. In practice though, this is limited by application constraints and the restricted volume available for sensors. Another question is whether the area demanding high precision can still be considered to be in proportion to the actual area where the application requires accuracy (see Figure 2). In most current high-precision systems, the substrate is placed on a carrier stage that is moved around. The position of the carrier is controlled based on position measurement signals obtained at the outer geometry of the carrier, while the application-critical precision is required at a small area on the substrate. Through repetition or continuous scanning, the whole substrate is covered.

For instance, in wafer lithography, the position of a full 300mm wafer (comparable in size to a vinyl record LP) is controlled, whereas only the area of an exposure die (comparable to a post stamp) is relevant. The transition to 450mm wafers (the size of sewer lids) will make the argument even stronger. For example, the typical outer dimensions of a wafer chuck for 450mm wafers will probably be at least 0.5m x 0.5m, which is a 0.25m^2 surface. The exposure die size is at least a factor ten smaller in length and width, so, in area, much less than 1% of the substrate area. So, achieving higher accuracy over bigger systems is becoming increasingly overdone and counter-intuitive. At least, it is an issue to consider at the equipment architecture level. Similar examples can be found in wide-format printing and flat-panel display production.

Enabling technologies and competences:
- *Collocated metrology concepts:* The starting point will be to search for accurate local sensors as close as possible to the process with no interference. Typically, small form factors are needed in view of space limitations. Having position metrology closely around or at the application relevant area is very attractive since it concentrates efforts exclusively around the real area of relevance and relaxes architectural requirements in the mechatronic design of the carrier stage. Basically, the deformations in the substrate carrier outside the application area of actual interest are less relevant. This decouples the substrate size from the accuracy considerations, and for example stringent temperature uniformity and stability across a sizeable carrier are no longer necessary.

Keeping out of the mass avalanche

The drive to keep system moving mass down is generally accepted and understood. The field of stiff, light and stable high-tech base materials has been explored over the last few years and this has encouraged developments in the area of technical ceramics, for example. Although this progress has proven very valuable, requirements at the architectural level are significantly higher. The avalanche effect in system design implies that the initial mass at the precision critical moving part will determine the mass of the rest of the system and introduce associated problems, such as high reaction forces as a consequence of high accelerations of the initial moving mass, significant dissipation and, thus, threats to thermal performance, more hoses and cables, power consumption, etc.

One interesting development, already industrially applied in aerospace and automotive applications, concerns the structural topology optimisation approaches to the combined stiff and light-weight design requirements. Until recently, the resulting designs appeared almost impossible to manufacture, at least not without significant Design-for-Manufacturing (DfM) input, thereby eroding optimality. The rapid rise of additive manufacturing technologies over the last few years is a very encouraging trend in this context. Given the nature of the manufacturing process, it might be possible in the near future to manufacture high-tech products (e.g. various relevant metals, ceramics) almost straight from the optimal design file, practically without any DfM input. This will be discussed further in following paragraphs.

Enabling technologies and competences:
- *Structural topology optimisation:* a model-based design method to find optimal design solutions within a specified design volume, under given loading conditions, obeying performance requirements (e.g. limited deformation and minimal weight) and, if any, design constraints. Multi-criteria optimal solutions for light-weight, dynamics, thermal and flow performance, etc. are relevant for high-tech systems design.

- *Additive manufacturing:* a large number of manufacturing processes that, as opposed to conventional machining like milling, drilling, etc. where material is removed, create products by incrementally adding material, driven from a 3D design file. This technology is developing rapidly in many industrial fields and has huge potential because of the almost unlimited design freedom and the inherent fact that manufacturing cost does not depend on design complexity or series size.

Mechatronics and manufacturing

The above ideas on alternative solutions will probably not be achieved by taking incremental steps. The challenge is to look for breakthroughs and to establish new combinations of technologies that provide more leeway for high-tech equipment design. For instance, a weight reduction of typically 10% is very welcome, but it is insights that result in improvements of a factor two that are really interesting, because of the benefits they can bring throughout the system. The biggest potential is in the combination of novel manufacturing technologies and mechatronics competences (see Figure 3).

More specifically, additive manufacturing (AM) brings a few benefits to the table that, when combined, may open up new focus areas of potential breakthrough:

- *Freeform*
  Unlike conventional machining technologies such as milling and drilling, the majority of AM processes are almost completely freeform and not subject to DfM constraints. Imagine that during the design phase you had

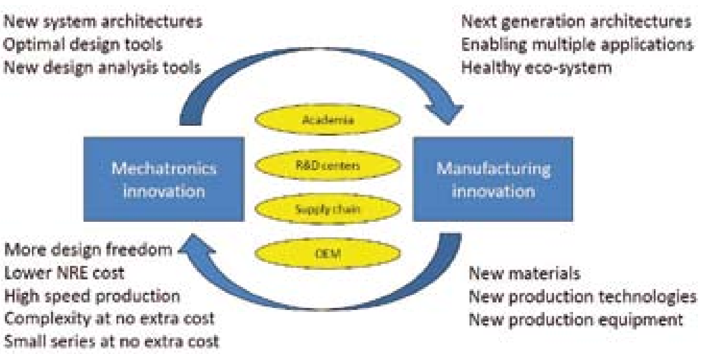


Figure 3. The interaction between mechatronics and manufacturing innovation.

Figure 4. A manifold, produced in one piece, using the limited space optimally, yet showing smooth corners.

every freedom to achieve performance and you did not have to make any compromises; there could be countless benefits. A simple example is given in Figure 4.

- *Integrated*
  The inherent production processes of AM open up the possibility of manufacturing parts in one piece that would require a list of parts obtained by traditional manufacturing (see example in Figure 5).
  The advantages of fewer parts, fewer assembly steps, fewer connections, fewer adjustments, etc. are obvious and benefit the entire innovation chain, even beyond the primary performance critical aspects. For example, reliability, logistics, spare parts, assembly and tooling costs are also very important in equipment development.

- *Lightweight*
  In the automotive and aircraft and aerospace industries, design optimisation tools have already been adopted and weight reductions by a factor of two or three are typical. Driven by the rapid AM advances, these kinds of benefits may also become available to high-tech systems. Lightweight, but stiff construction designs typically show skeleton-like or open structure solutions, as illustrated in Figure 6.
  By fully exploiting the combination of topology optimisation and AM, a huge difference can be made compared to more conventional methods of design and

Figure 5. A cardan hinge with integrated intelligent leaf springs, manufactured in one piece.

manufacturing. This will benefit system performance as well as energy consumption, as less mass has to be accelerated. This is a strong selling point for some high-precision equipment markets, e.g. pick & place in board assembly.

- *Material properties à la carte*
  When considering the essence of AM, it is not only the freeform benefits that can be identified, but also the opportunities related to material properties. A completely new design space opens up, with two new options:
  - *Multi-material*: Combining different materials during the AM process is already possible to some extent. The quest for more high-tech relevant AM materials and processes will increase the curiosity to find optimal combinations of materials. Think of gradients, local alloys, low-quality material inside and a high-quality shell, etc.
  - *Tailored mechanical properties*: The AM process also opens up the possibility of tailoring mechanical properties such as density, stiffness, damping, directionality, etc. To some extent, these are becoming design choices that are not accessible for monolithic parts, which, given the nature of their base material, were traditionally governed by isotropy and homogeneity.
    Although there may be an intuitive sense that this design freedom offers huge potential for high-tech systems, it is still difficult to grasp. It will probably take a considerable change in mindset and a collective effort to exploit this as much as possible.

Underlying key competences and technologies

It is clear from the above considerations that a lot of potential will depend on the industrial translation and application of the underlying competences and technologies, as illustrated in Figure 7:
- mechatronics architecture and technologies,
- structural topology optimisation,
- additive manufacturing.

What connects these three pillars for high-tech systems innovation is that the freeform nature of AM provides a new design freedom essential to reach breakthrough architectures. To exploit this design freedom as much as possible requires design optimisations aimed at simultaneously satisfying multi-criteria system specifications. Further still, the key competences and technologies that will most likely make the biggest difference are:
- multi-physics modelling,
- materials sciences,
- manufacturing process control,
- multi-criteria, constrained optimisation and efficient algorithms.

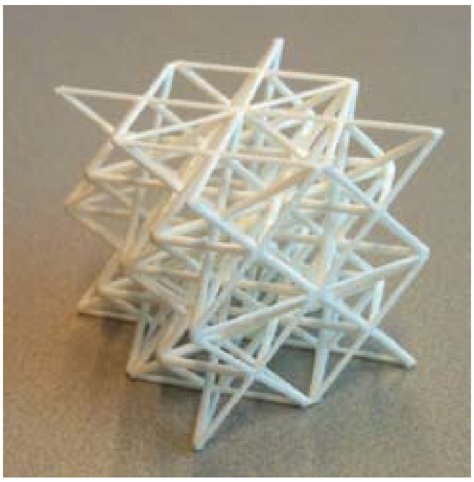


Figure 6. This sample has considerable stiffness and an extremely low weight. The structure was deliberately designed to have different stiffnesses in the three cube directions.

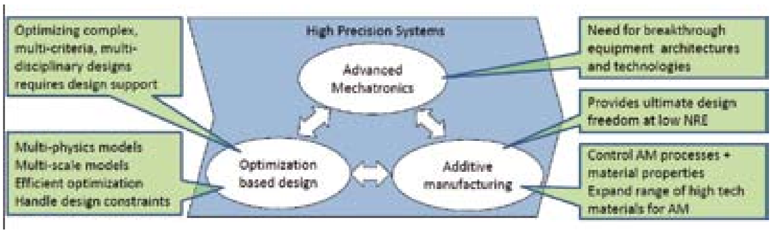


Figure 7. A mechatronics and manufacturing vision on future high-tech equipment

One should bear in mind, however, that these are firmly developed and not at all new competence or technology areas, as they are some of the things that have provided the basis for high-tech systems successes over the last few decades.
It is generally accepted that realistic prediction of system behaviour during the design phase hinges on the availability of reliable models, i.e. predictive modelling. On the other hand, fulfilling the promise of a design and turning it into real hardware depends on the quality and process control during manufacturing and on the knowledge of materials associated with that. For future innovations, depending on good models and materials sciences / manufacturing process control will become even more important.

When these competences are aligned with the high-tech vision as outlined above, breakthroughs may be possible and future progress through novel architectures and designs will be secured. The fact that this involves all of the parties and all of the steps in the innovation process bodes well for a healthy future for the entire ecosystem, provided that innovation starts now and is based on a collaborative effort.

Closing remarks

One could argue that the author has taken too optimistic or too pessimistic a view in many ways. For example, it is not that simple to achieve new technologies or even breakthrough system solutions; and it may be naive to envision all of the parties collaborating harmoniously for the collective benefit of the ecosystem. Some will argue that the existing competences, technologies and architectures will be sufficient to realise systems for the long term.

This is understood and there is no claim that the ideas presented here are the truth or conclusive in any way. They are intended solely to trigger collective thinking and invite debate, further development, fine-tuning visions, etc. It is the author's belief that something seriously needs to be done, possibly in the direction of innovation outlined, so feedback would be more than welcome.

References

- HTSM top sector roadmaps: www.htsm.nl
- XTreme Motion subsidy programme: www.rijksoverheid.nl/documenten-en-publicaties/brochures/2008/07/01/nieuwe-generatie-chip-machine-voor-gezonde-industrie.html
- Additive manufacturing: a simple internet search will provide lots of introductory sites; see also www.tno.nl
- Structural topology optimisation: a simple internet search will provide lots of introductory sites.

Vision & Robotics 2012 featuring second RoboNED Conference

On 5 and 6 June 2012, RoboNED will be holding its second conference, this year in collaboration with the Vision & Robotics trade fair. RoboNED will be presenting its strategic agenda during the conference.

Chris Buijink, Secretary-General of the Dutch Ministry of Economic Affairs, Agriculture and Innovation, will receive the strategic agenda and respond to it during his speech. RoboNED will arrange two theme plazas at the Vision & Robotics trade fair, allowing knowledge institutes and companies to show what they can offer, supporting this with live demos. RoboNED will be organising one of the three parallel sessions as part of the lecture programme on both days. Presentations will focus on robotic technology and its application areas.
Henrik Christensen, a full professor at the Georgia Institute of Technology (USA), has been invited as a plenary keynote speaker. He will talk about his experience as the founding chairman of the European Robotics Research Network (EURON) and the chairman of the US Robotics Roadmap Committee.

www.vision-robotics.nl
www.roboned.nl

500th participant in the High Tech Platform

Mikrocentrum recently welcomed the 500th participant in the High Tech Platform. This platform brings companies together at meet & match sessions, for theme days, at trade fairs and in working groups such as High Tech Specialists or the recently set up Vision & Robotics Solutions.
Mikrocentrum encourages participation in these activities, which are also open to other companies, by providing participants in the High Tech Platform with discounts and giving them priority. HTP-participants are presented in the High Tech Business Directory, whose 6,500 print run is distributed every year among the industry's decision-makers and buyers. This directory has been online since 2006 and it gets 5,000 visits a week.

www.mikrocentrum.nl/high-tech-platform

Precision Fair expanding on existing site

The annual Precision Fair at the NH Conference Centre Koningshof in Veldhoven, the Netherlands, attracts a great deal of attention from visitors and exhibitors alike, and it was in fact fully booked with exhibitors in recent years. Organiser Mikrocentrum therefore decided to look at alternative sites or explore the possibility of expanding at the existing site. Based on feedback from the exhibitors and visitors, there is a strong preference to stay at the existing site because of all the facilities available and the idea that 'Veldhoven' has become synonymous with the Precision Fair.
Expanding at the current site could be achieved thanks to the combined effort of Koningshof and Mikrocentrum. Koningshof is investing in modifications to the infrastructure and Mikrocentrum is investing in a new, semi-permanent hall that will provide space for approximately forty further exhibitors. Preference for these additional stands will be given to companies from the Netherlands or Belgium that have already shown interest, and then to international companies.

www.precisiebeurs.nl

Strongest,

Graphene is the strongest, stiffest and thinnest material ever made by man. It consists of a monolayer of carbon atoms packed in a honeycomb crystal lattice. Andre Geim and Kostya Novoselov were awarded the 2010 Nobel Prize for Physics for making a small quantity of graphene by simply peeling it from graphite with adhesive tape. Today, more sophisticated methods have been developed to produce sheets of graphene. So it's high time to consider the possible applications of this promising material in precision engineering.

• *Frans Zuurveen* •

Graphene as such is a well-known material, seeing as graphite consists of layers of graphene, only held together by – weak – Van der Waals forces, see Figure 1. The easy mutual moving of these layers makes graphite a useful lubricating agent. On a magnified scale, graphene looks like chicken wire composed of individual C atoms connected by their bonds, with six atoms arranged in one hexagon, see Figure 2. The carbon-carbon bond length amounts to 0.142 nm with an interplanar spacing of graphene sheets in graphite of only 0.335 nm.

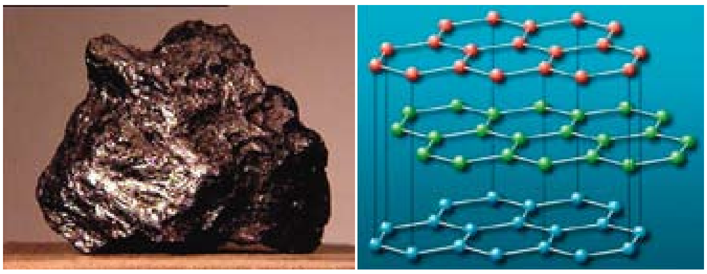


Figure 1. Graphite.
(a) A sample.
(b) The layers of graphene in graphite.

Figure 2. Schematic drawing of the 2D carbon grid of graphene.

It has only recently been possible to make and study isolated graphene, which has such remarkable properties as high optical transparency, semi-metal semiconductivity, large electrical conductivity thanks to its special band structure, and high thermal conductivity. A popular way of understanding the high electrical conductivity is to remember that every C atom has three neighbouring C atoms, whereas every atom has four electrons for covalent bindings with its neighbours. This way, every atom

stiffest, thinnest

delivers one extra free electron that contributes to the electrical conductivity.

Future electronic applications are expected in quantum-effect computers (molecular electronics), high-capacity electric batteries, solar cells, etc. These applications are beyond the scope of Mikroniek, and therefore not dealt with further. Originally, two-dimensional one-atom layers were thought to be thermodynamically instable: they were supposed to scroll or curl up. But the marvel of making real graphene sheets gave birth to a family of promising new one-molecule thick 2D materials: boron nitride (BN), niobium selenide ($NbSe_2$), superconducting $Bi_2Sr_2CaCu_2O_x$ and molybdenum disulfide (MoS_2).

Mechanical properties

Physicists of the Kavli Institute of Nanoscience at Delft University of Technology have measured the mechanical properties of few-layer graphene suspended over circular holes [1]. Samples were made from doped silicon wafers with 285nm silicon oxide on top, in which circular holes were etched with HF using resist masks. Graphene was produced with adhesive tape from graphite grains, after which the tape was pressed onto the substrate at the location of the holes.
The mechanical properties of the graphene sheets on the holes could be measured by pressing the tungsten tip of an atomic-force microscope (AFM) against the membrane formed by the sheets. Thanks to the vertical displacement measurement system of the AFM and the knowledge of the spring constant of the AFM tip, reciprocal-force against distance curves could be recorded, see Figure 3. The curves show that even the unsuspended part of the flake shows some compliance of flake and substrate.

Author's note

Frans Zuurveen is a freelance text writer who lives in Vlissingen, the Netherlands. This article is based in part on a lecture by Prof. Lieven Vandersypen of Delft University of Technology, the Netherlands, given at a meeting of the Natuurkundig Gezelschap Middelburg (Society of Natural Sciences Middelburg) in November 2011.

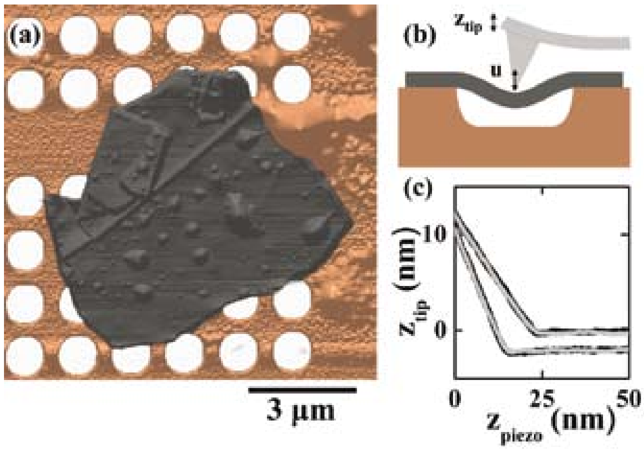


Figure 3. Measuring the mechanical properties of graphene sheets.
(a) AFM image of a suspended flake of graphene on circular holes etched in SiO_2.
(b) Measuring reciprocal-force-distance curves with the AFM tip.
(c) Measuring results; z_{piezo} is the real displacement, z_{tip} is inversely proportional to the force exerted by the tip and proportional to the compliance of the supported flake. The bottom curve corresponds with an unsuspended part of the flake, the upper one with the flake at the centre of one hole [2].

The measurements enabled the calculation of the eigenfrequency of the suspended multilayer graphene membranes. For holes with an 84nm radius, the eigenfrequency showed to be over 10 GHz. Such high frequencies make these nanodrums ideally suitable for application in nanomechanical devices.
Measurements by other institutes showed values for the Young's modulus of 0.5 TPa, which is about 2.5 times the Young's modulus of steel. With a tensile strength of about 130 GPa, graphene is about 100 times stronger than steel. The effective thickness – a nearly unimaginable and immeasurable property – amounts to about 0.02 nm, which makes graphene the thinnest material on earth.

Graphene in large quantities

Will graphene in the near future be available as some kind of wide tape on rolls? That looks to be a rather real prospect thanks to the roll-to-roll production of 30-inch graphene films, see Figure 4, by a team of Korean scientists [2]. They used large flexible copper foil as a

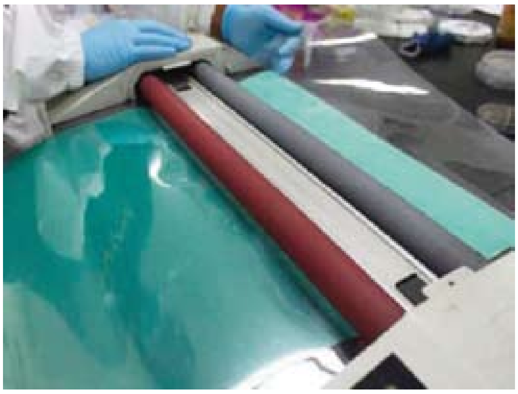


Figure 4. Graphene on a substrate of polymer film [1].

substrate for Chemical Vapour Deposited (CVD) graphene. For the CVD process, a gas mixture of hydrogen (H_2) and methane (CH_4) was applied, resulting in a carbon monolayer. The chemical reaction took place in a quartz tube at a temperature of about 1,000 °C.

After the CVD deposition, the graphene film is transferred to a PET polymer substrate (polyethylene terephthalate) by means of a thermal release procedure (90 to 120 °C) by applying soft pressure between two rollers. After that, patterns can be etched in the graphene film by using a screen printing process with silver paste. Finally, the graphene pattern is transferred to the final product substrate.
The process schematically described above aims to replace layers of indium tin oxide (ITO) in solar cells, touch sensors and LCD flat panel displays, see Figure 5. Such patterned ITO layers serve to electrically control the opacity of pixels without absorbing too much locally transmitted light. Therefore, the layer has to have an extremely low ohmic resistance together with a very high transparency. Graphene's far superior optical and electrical properties make it a highly valuable substitute for ITO.

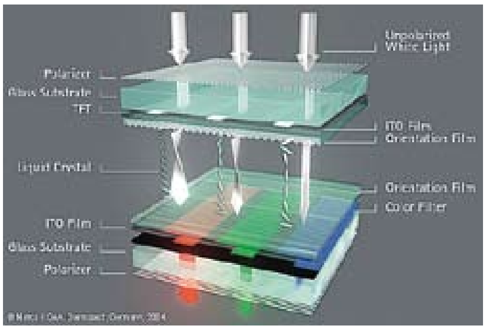


Figure 5. Application of indium tin oxide or graphene (better) to control the opacity of pixels in LCD displays.

Possible applications

We already mentioned some of the electronic applications of graphene. For example, IBM researchers demonstrated a radio-frequency graphene transistor with the highest cut-off

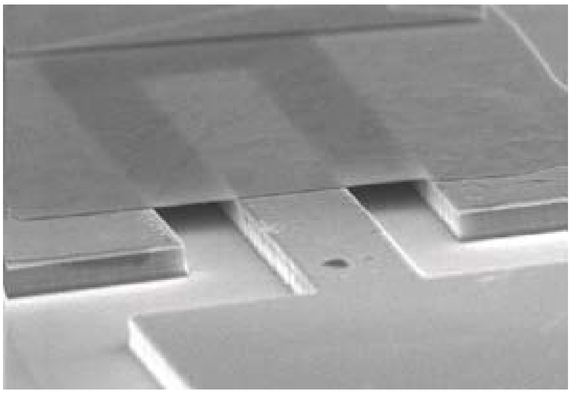


Figure 6. A graphene resonator, 700 nm in width, made at the Kavli Institute of Nanoscience at Delft University of Technology.

frequency achieved so far for any graphene device, and also – at 100 GHz – much faster than silicon transistors. Graphene sheets are also promising components in LCDs, integrated circuits and batteries, and they can also be used as an excellent substrate for flexible electronics and solar cells.

But the readers of Mikroniek are more interested in real mechanical applications, of course. The high strength and stiffness of graphene are the properties that make it an ideal material for membranes, e.g. in miniature pressure sensors. Creative minds may invent applications in, for example, light-weight small – or large? – balloons, a not unrealistic application because of the high gas tightness of graphene, even for helium.

Sandwich materials may also turn out to be a very promising application area for graphene. The use of glass and carbon fibres in composite materials is well-known. Graphene would be a much better alternative as it is stronger and stiffer than a carbon fibre network. An additional advantage is graphene's isotropy, apart from the extra stiff directions due to its hexagonal structure.
Real nano-electromechanical application areas for graphene are electromechanical resonators, see Figure 6. Various articles have shown that wafer-scale production of low-mass, high-frequency and highly tuneable nanomechanical membrane resonators opens the way to applications in various areas, from sensing to signal processing. Such resonators may be integrated with MEMS and NEMS structures (Micro and Nano Electro Mechanical Systems, respectively).

To conclude

For precision engineers, thinking in terms of materials that are only one atom thick is quite unusual and strange. IC engineers may be more familiar with thinking in terms of such extremely small dimensions. Be that as it may, graphene will provide applications in areas in which dimensions are getting smaller and smaller, namely micro-

a

b

Figure 7. Potential for graphene?
(a) An Airbus A380 taking off. (Photo courtesy of Airbus)
(b) A GLARE fuselage panel made by Fokker Aerostructures.
(Photo courtesy of Fokker Aerostructures)

and nano-electronics. On the other hand, graphene's extreme strength and stiffness open perspectives for extremely large applications. Today, the Airbus A380 proudly flies thanks to GLARE (GLAss REinforced aluminium) from Fokker Aerostructures; see Figure 7b. Why not take aluminium reinforced with an even stronger material, graphene?

Literature

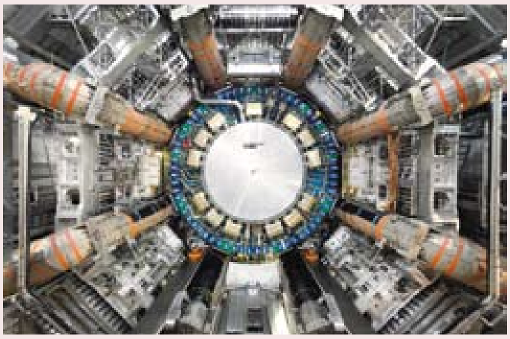
[1] M. Poot and H.S.J. van der Zant, "Nanomechanical properties of few-layer graphene membranes", *Appl. Phys. Lett.* 92, 063111, 2008.

[2] S. Bae et al., "Roll-to-roll production of 30-inch graphene films for transparent electrodes", *Nature Nanotechnology* 5, 574-578, 2010.

2-3 May 2012, Thoiry (FR)
Precision Engineering at CERN: Future Challenges & Opportunities

Another euspen event addressing 'Manufacturing Technologies to Support Large Science Projects', matching industry and science, and identifying potential suppliers, for the electron-positron compact lienar collider programme (CLIC). Part of the two-day programme is a CERN tour, including a visit of the ATLAS Visitor Centre.

www.cern2012.euspen.eu



ATLAS is one of the experiments at the Large Hadron Collider at CERN. (Photo: Claudia Marcelloni, courtesy of CERN)

9 May 2012, Den Bosch (NL)
Model-Driven Development Day 2012

Conference and exhibition, organised by Techwatch Events, on model-driven development, focusing on high-end engineering with high-level tooling, including finite elements, multi-body dynamics, multi-physics development methods and simulation.

www.hightech-events.nl/mdday

9-10 May 2012, Brussels (BE)
DRIVES & CONTROL 2012

Trade show for transmissions, motion control & robotics, organised by easyfairs, co-located with SENSOR & VISION 2012, and AUTOMATION & ENGINEERING 2012.

www.easyfairs.com

10 May 2012, Eindhoven (NL)
DSPE Precision in Business day: VDL ETG Research

Organised by DSPE, hosted by VDL ETG Research at the High Tech Campus Eindhoven. Theme: From submicron manufacturability to concurrent prototyping. Registration before 3 May 2012.

info@dspe.nl

23 May 2012, Nijmegen (NL)
VCCN Cleanroom Symposium and 15th Contamination Control

Symposium and trade fair organised by the Dutch Contamination Control Association (VCCN).

www.vccn.nl

4-7 June 2012, Stockholm (SE)
euspen 12th International Conference and Exhibition

Conference topics will include:
- Precision Engineering of Plastic based Electronics and Optronics
- Scandinavian Precision Engineering and Nanotechnology
- Nano & Micro Metrology
- Ultra Precision Machines & Control
- High Precision Mechatronics
- Ultra Precision Manufacturing & Assembly Processes
- Important/Novel Advances in Precision Engineering & Nano Technologies

www.stockholm2012.euspen.eu

5-6 June 2012, Veldhoven (NL)
Vision & Robotics 2012 / RoboNED Conference

Knowledge and business network event, organised by Mikrocentrum, on robotics and automation solutions. The focus is on innovations and solutions for vision systems, robotics, motion control, sensors and machine automation. Featuring the second RoboNED Conference. See also page 37.

www.vision-robotics.nl

25-29 June 2012, Eindhoven (NL)
International Summer school Opto-Mechatronics 2012

Organised by DSPE and The High Tech Institute. See also page 44.

Summer school Opto-Mechatronics

Precision Technology

www.summer-school.nl

4-5 September 2012, Deurne (NL)
DSPE Conference

DSPE and Brainport Industries organise this first conference on precision mechatronics. The target group includes technologists, designers and architects in precision mechatronics, who (through their respective organisations) are connected to DSPE, Brainport Industries, the mechatronics contact groups MCG/MSKE or selected companies or educational institutes. See also page 45.

www.dspe-conference.nl

25-28 September 2012, Besançon (FR)
Micronora 2012

The biennial microtechnology and precision trade fair features multiple activities – from assembly, engineering and machining to metrology and nanotechnology – for markets with high technological value, including aerospace, (bio)medical, microelectronics and telecommunications. The event includes conferences and a European technology brokerage event on micro- and nanotechnology. Micronora 2010 attracted over 14,000 visitors and 565 direct exhibitors (200 from abroad), with a further 300 firms or brands represented.

www.micronora.com

Overview of the Micronora 2010 social event in a very nice art-deco restaurant in the old town of Besançon. (Photo courtesy of ARIST)

Summer school Opto-mechatronics 2012

Following the success of the 2008 to 2011 editions, DSPE and The High Tech Institute organise the Summer school Opto-Mechatronics 2012, from 25 to 29 June in Eindhoven, the Netherlands. Once again, it is the place to be for anyone working in the field of precision engineering and wanting to learn and experience from experts how to design actively controlled opto-mechanical instruments.

The Summer school Opto-Mechatronics 2012 comprises five days of intensive course, taught by excellent Dutch professors and scientists in the field of precision engineering, who work at TU Delft, TU Eindhoven, ASML, Philips, TNO, ESO and The High Tech Institute, combined with hands-on training. Participants will come from universities and high-tech large companies and SMEs. The programme includes social events and venue is TNO at the university campus in Eindhoven.

Programme

Monday 25 June: Systems Engineering
Opto-mechanical instruments are always co-existing with other equipment. So, before starting their design, the essence of the systems engineering has to be considered. What is critical and what are the margins? How to approach such a project and how to gain insight in the background of the requirements?

Tuesday 26 June: Optical Design
The case starts with an introduction to the optical design and its use in optical aperture synthesis applications. Next, in teams, several delay line designs will be compared, in order to select the best design with respect to the optical requirements. Also, an effective optical design has to be found for measurement of the optical path differences. Zemax will be used to analyse the optics in the delay line. Further work pertains to wave-front analysis and pupil imaging while moving the delay line, and assessment of alignment accuracy.

Wednesday 27 June: Control Design
Based on the functional requirements of the optical delay line, the challenges for control will be discussed. These include actuation for a high dynamic range, servo behaviour, vibration rejection, sensor noise, closed-loop stability and others. An introduction of suitable control design methods is presented to achieve nanometer positioning accuracy.

Thursday 28 June: Opto-Mechanical Design
The trade-off made for a linear guiding of 66 m, with sub-mm accuracy, will be presented. The students are requested to design and assess, in a team effort, the performance. Emphasis will be put on the interactions with the other key technologies needed (optics, control and electronics) and on the mechanical design itself.

Friday 29 June: Mechatronics
Designing an actively controlled delay line that is stable enough to perform interferometry over large distances, is far from trivial. Some still missing elements will be presented that are necessary to realise high performance active positioning and control systems for optics. Following an overview on electromagnetic and piezoelectric actuators, optical position measurement systems and capacitive sensors, attention will be given to the performance determining mechanical system dynamics and vibration isolation. The new field of adaptive optics will also shortly be touched upon.

Information and registration:
www.summer-school.nl

Papers, posters and demos at the first DSPE conference

To promote sharing the expertise and experience available in the field of precision and control technology, DSPE and Brainport Industries have taken on a new challenge; they are organising the first DSPE conference on precision mechatronics. The conference will be held at the inspiring conference location of Willibrordhaeghe in Deurne, the Netherlands, on 4-5 September 2012. The target group includes technologists, designers and architects in precision mechatronics, who, through their respective organisations, are connected to DSPE, Brainport Industries, the mechatronics contact groups MCG and MSKE, or selected companies and research/educational institutes.

In addition to demos and paper and poster presentations, the conference will provide the ideal setting for networking, technical discussion and sharing the enthusiasm of working in this challenging field. The theme this year is 'Systems Thinking', which is vital at a system level, but also at a detail level. System performance is determined by the optimal balance between system architecture and mission-critical details. The overall system architecture often determines whether a component is mission-critical or not. However, it also requires systems thinking to work out the optimal solution at a detail level. And, last but not least, it is only using systems thinking that you can question and challenge the requirements imposed on a component, thereby avoiding 'over-specification' and high costs.

Areas of interest of the papers, posters and demonstrations for which abstracts have been submitted include, but are not limited to, innovative solutions at a system and detail level, creating value, systems architecture, 450mm challenges, nanometer stability, platforms, thermo-mechanical effects, new materials, design principles, electro-mechanics, power electronics, actuators, sensors, control systems, modelling, instrumentation and measurement, software and hardware implementation, manufacturing, and testing.

info@dspe-conference.nl
www.dspe-conference.nl
www.brainportindustries.com

Timetable

- 1 May: notification of acceptance of abstracts and provisional programme ready.
- 15 May: end of early registration bonus (free copy of "The Design of High Performance Mechatronics" by Robert Munnig Schmidt, Georg Schitter and Jan van Eijk – see the review in the previous issue of Mikroniek).
- 1 August: deadline for submitting final papers/extended abstracts.
- 4-5 September: the first DSPE conference on precision mechatronics.

Brainport Industries

DSPE

The DSPE Conference is organised by DSPE and Brainport Industries, the association of leading tier-one, tier-two and tier-three high-tech suppliers in the Eindhoven region.

Techni-Show Innovation Awards

At the Techni-Show 2012 in the Jaarbeurs in Utrecht, the Netherlands, in March, GF AgieCharmilles and Renishaw were honoured with Innovation Awards for their innovative development activities.

AgieCharmilles was awarded a platinum medal for its Mikron HSM 400 LP machining centre for ultra-precision high-speed milling (F. Zuurveen, “Milling in steps of a micrometer”, *Mikroniek*, Vol. 50 (6), pp. 26-28, 2010). Figure 1 shows the high-precision milling of a pump impeller; this precision is possible because the slides can perform steps as small as 0.1 µm. The StepTec tool spindle with ceramic elements rolling in steel races is another precision aspect of this machining centre with a work space of 500 mm x 450 mm x 360 mm. Heidenhain optical scales also contribute to the precision of the slide position measuring system.

Renishaw was awarded a gold medal for the Equator 300 gauging system with kinematic parallel structure and user-friendly software. The Renishaw Equator gauging system has a rather unusual ‘legs-and-arms’ appearance. Its patented light-weight and cost-effective kinematical design with parallel rod mechanisms instead of the usual Cartesian construction of orthogonal X, Y and Z slides makes it different to traditional measuring machines. Three parallelogram structures (see Figure 2) ensure the parallel displacement of a platform with a measuring stylus connected below. Three struts connect the measuring platform with an upper plateau, firmly resting on the machine base by means of heavy columns. These struts serve to perform the real measurements.

Figure 1. High-speed precision milling of an impeller with a GF AgieCharmilles Mikron HSM 400 LP machining centre.

Each parallelogram structure consists of two parallel rods that are mounted opposite each strut. The rods connect the platform with a hinged box-like object, which Renishaw insiders call a ‘barn house’ (in Figure 2, the orange cap of one of these can be seen). A hinge connects each ‘barn house’ to the upper plateau. Three combinations of two parallel rods and one ‘barn house’ each take care of the continuous parallel positioning of the measuring platform with respect to the plateau. Parallel rods and struts together define six degrees of freedom. Needless to say, all these hinges and pivot points should work absolutely perfectly. This challenge has been met by integrating pre-tensioning into the design of this complicated kinematical mechanism. A stylus rack for the ‘automatic’, i.e. software-controlled, interchanging of measuring tools from the well-known Renishaw stylus programme has also been integrated.

Traditional orthogonal measuring systems originate from the need to provide direct three-dimensional X, Y, Z measuring results. But today’s fast computers and sophisticated mathematical algorithms allow such measuring results to be calculated from data acquired from position measurements in other directions. This non-orthogonal measuring data is provided by Renishaw measuring scales mounted in the struts mentioned before. The three measuring struts are mounted onto pivots on the measuring platform and shift through three Hooke’s joints on the top plateau. Measuring encoders and linear driving motors are integrated into each Hooke’s joint.

The strut position measurements conform to Abbe’s law: measurement trajectory and scale are in line. The mounting of hinges, pivots and Hooke’s joints implies that all kinematic elements remain in pure tension and compression, without any bending effects that might cause inaccuracies. The strut ends are fitted with ergonomic knobs for stylus positioning by hand, aimed at manually defining a workpiece measuring loop.

The comparison method is the usual way of working with the Equator system, i.e. mastering and measuring. Firstly, a master component of known dimensions is used to ‘zero’ the system. After that, subsequent measurements compare finished or unfinished workpieces with this master part, using Renishaw touch and scanning styli from the stylus change rack. User-friendly Modus Equator programming software allows a measurement cycle to be defined.
If necessary, Equator can be used for multiple parts, switching between them in a very short space of time. Workshop Equator measurements can also be correlated with calibration data from a separate measuring machine in the measuring room. The software then automatically defines

and applies some kind of measuring envelope, consisting of compensation values according to differences between nominal CAD dimensions and real measured values. Careful and cumbersome alignment procedures are unnecessary, because the software 'recognises' a workpiece when the positioning deviation is within 1 mm.
For its Equator 300 system, Renishaw specifies a half-spherical working volume with a diameter of 300 mm and a height of 150 mm. For comparing objects, Renishaw guarantees an uncertainty of ± 2 µm. The resolution of the scales in the struts amounts to a mere 0.2 µm. At a scanning rate of 1,000 points per second, the maximum scanning speed is no less than 100 mm/s.

www.gfac.com, www.renishaw.com

(by Frans Zuurveen, freelance text writer)

Figure 2. Equator gauging a medical component.

A 'talented' 5-finger hand

There are great expectations of the capabilities of service robots used in domestic settings: they should intuitively adapt to humans, communicate in the usual human way and even master complex gripping operations. With its Anthropomorphic Gripper Hand, Schunk, a competence leader for clamping technology and gripping systems, is advancing the development of humanoid service robots. The design study, which was introduced at the International Expert Days on Service Robotics 2012, is available as a right and a left 'hand'.

The robot hand resembles its human counterpart in size, shape, appearance and mobility. Nine drives allow the 5-finger hand to perform various gripping operations. It has been found that many human gestures can be replicated, thereby simplifying visual communication between a human and a service robot, which in turn increases the acceptance of using them in the domestic setting. By using tactile sensors in the fingers, the gripper hand has the requisite sensitivity and can, therefore, handle every gripping and manipulation task, even in unstructured and unpredictable situations. Elastic gripping surfaces ensure that the gripped objects can be held reliably. The gripper hand can be connected to lightweight arms, such as the LWA by Schunk, via defined interfaces. Christopher Parlitz, Manager for Service Robotics at Schunk: "The 5-finger hand offers new approaches to research in the field of service robotics in the immediate environment of humans. Studies on human-robot communication show that due to the gesticulating hand, new strategies can now be explored, since the hand allows a realistic form of non-verbal communication."

Schunk's 5-finger hand enables service robots to perform complex gripping tasks and communication by means of gestures.

www.schunk.com

High Tech Systems requirements management

To help organisations in the High Tech Systems market to properly specify high-quality requirements, Usoft, an independent Dutch software vendor, is introducing its proven requirements management solution, URequire Studio. This solution enables consistent and complete specification and management of requirements. Existing requirements can easily be re-used and language barriers between marketing or product management and R&D are broken down.
URequire Studio is a web-based software application that enables users to specify business requirements and processes easily in natural language. This results in a complete set of consistent and traceable requirements that are unambiguously usable by both Business and R&D. In addition, URequire Studio facilitates the generation of functional documentation, and recorded requirements are available for re-use in future projects.

www.usoft.com

Mikrocentrum expands vision and robotics activities

Mikrocentrum recently launched a new working group on the High Tech Platform. Under the name Vision & Robotics Solutions, fifty or so companies will be dedicating themselves to creating a better foothold for vision, robotics, related industrial automation and system integration both in the Netherlands and Belgium. Vision and robotics are hot in the Brainport Eindhoven region. For example, in late 2011, there were various get-togethers with experts from vision as well as robotics, plus Eindhoven University of Technology launched the Robotic Open Platform, aimed at accelerating the exchange of practical knowledge on robotics.

With its new Vision & Robotics Solutions working group, Mikrocentrum is combining and enhancing various activities in the field. It shares common ground with the renowned trade fair Vision & Robotics, but it is its own entity. Mikrocentrum's Els van de Ven explains: "At Mikrocentrum, we make our own contribution to knowledge development in the field of vision and robotics and related areas, by way of a trade fair plus conference, theme days and training courses. Now, however, we've gone a step further. In addition to promoting the technology, the new working group will bolster the sector by formulating joint objectives and combining strengths when developing innovative and relevant solutions."

www.mikrocentrum.nl

Next generation optical chips

In addition to the close collaboration with German company Raith on research into improving the method of preparation and the limits of electron beam lithography, TNO has now also laid the foundation for a scientific collaboration in that same field with Stanford University. At Raith's invitation, TNO researcher Ruud Schmits gave a lecture at the Advanced Nano Lithography Workshop at Stanford University in California, USA, on 15 February, which paved the way for collaboration with Stanford University.

Schmits showed how perfect optical structures only millimeters in size could be made using Raith electron beam lithography at the TNO Van Leeuwenhoek Laboratory in Delft, the Netherlands. Usually, stitching errors occur with e-beam lithography because the image fields of the e-beam equipment do not join up exactly during the production process. Raith developed a software tool, with a stationary electron beam and a table with a silicon workpiece on it that moves at a high speed and with nanometer precision: there is significant interest in this because the loss of light in optical structures with stitching errors is unacceptable given the unwanted reflections by the irregularities in the walls of the optical guides. The new writing method rectifies that issue.

Stanford is interested in TNO's research because the research institute in Delft has already been working with this new application of the technology for a few years, which allows relatively large structures to be built onto silicon chips with a very high placement precision of only a few nanometers. Furthermore, close collaboration with Stanford University will allow TNO to learn about and apply other specialist aspects of nanomanufacturing. TNO is using the research to develop applications for the next generation of optical chips that can be used in medical and other instruments, e.g. to measure the flow, temperature and pressure in the bloodstream or even the heart. One of the advantages is that these optical instruments utilise light, which means that 'disruptive' electrical signals that may negatively impact the human body (even during measurements) are now a thing of the past.

www.tno.nl

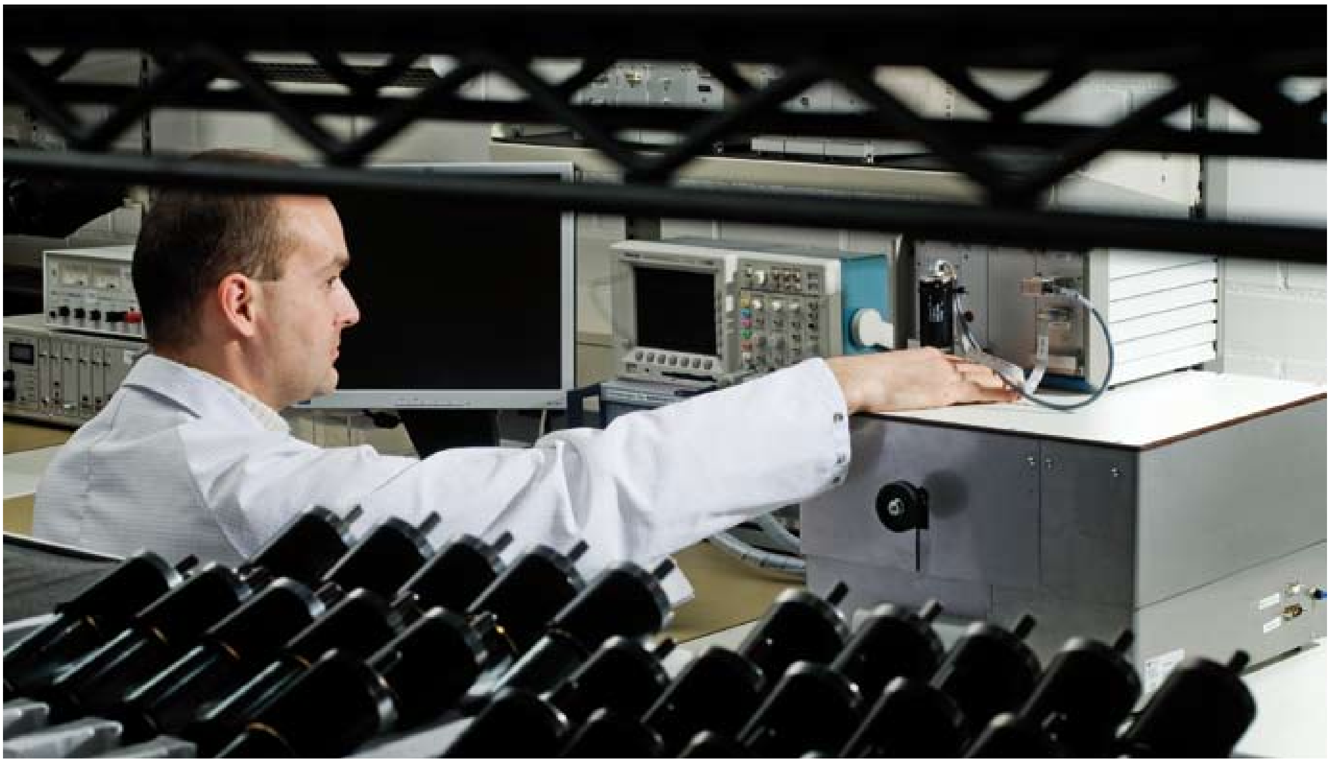
Maxon, 100 years of high-tech

Maxon motor benelux, founded in 1912 as Technisch Bureau Sanders Birnie, celebrates its 100th anniversary this year. In the history of the company, the central theme has always been 'high-tech' and for the last few decades the accent has been on precision drive systems. This has produced continued growth for maxon motor benelux – 2011 was the best year ever – and the company now has 27 employees.

In the last few years, maxon motor benelux has been moving further up in the high-tech manufacturing chain, according to Director Gerwin Geukes. The company has moved, in many cases, from being a component supplier to being a partner in complex development projects. In this way, maxon motor is able to offer its customers – the first-tier suppliers or system suppliers and sometimes also the producers of finished products – more added value. In addition to reliable and robust products, maxon motor delivers knowledge of precision drive technology, can take responsibility for parts project management and handles the necessary assembly, certification and packaging of the drive systems.

Maxon motor is a leading world-wide supplier of precision drives and systems of up to 500W output. Maxon motor ag, with its head office in Switzerland and production units in Switzerland, Germany and Hungary, has more than 2,000 employees and sales offices in forty countries including Belgium and the Netherlands. With its drive solutions, maxon motor serves markets such as the semiconductor industry, medical technology, laboratory and measurement technology, robotics, machine construction, industrial automation, the automobile industry and the air and space industry. The drives are characterised by their high power density, which makes lightweight applications possible, such as an insulin pump that a diabetes patient can carry on his or her belt.
Maxon motor benelux, with offices in Belgium (Mechelen) and the Netherlands (Enschede and High Tech Campus Eindhoven), delivers the complete, modular maxon assortment: from dynamic and powerful DC motors and special transmissions to intelligent compact drives and ceramic and metal injection moulding components. In addition, maxon motor benelux can provide the assembly and testing of customer-specific high-quality drive systems. Thanks to the modular makeup of the range, customers can be offered 'plug & play' solutions.

www.maxonmotor.nl



Maxon motor benelux offers clients added value, for example the testing of precision drive systems.

Course	CPE points	Provider	Starting date (location, if not Eindhoven)
Basic			
Mechatronic System Design (parts 1 + 2)	10	HTI	11 June 2012 (part 1) 5 November 2012 (part 2)
Construction Principles	3	MC	30 October 2012 (Utrecht)
System Architecting	5	HTI	4 June 2012
Design Principles Basic	5	HTI	23 May 2012
Motion Control Tuning	6	HTI	30 May 2012
Deepening			
Metrology & Calibration of Mechatronic Systems	2	HTI	to be planned
Actuators for Mechatronic Systems	3	HTI	8 October 2012
Thermal Effects in Mechatronic Systems	2	HTI	to be planned
Summer school Optomechatronics	5	DSPE	25 June 2012
Dynamics & Modelling	3	HTI	3 December 2012
Specific			
Applied Optics	6.5 6.5	MC HTI	to be planned 30 October 2012
Machine Vision for Mechatronic Systems	2	HTI	27 September 2012
Electronics for Non-Electronic Engineers	10	HTI	8 January 2013
Modern Optics for Optical Designers	10	HTI	to be planned
Tribology	4	MC	30 October 2012 (Utrecht) 27 November 2012
Introduction in Ultra High & Ultra Clean Vacuum	4	HTI	29 October 2012
Experimental Techniques in Mechatronic Systems	3	HTI	to be planned
Design for Ultra High & Ultra Clean Vacuum	4	HTI	to be planned
Advanced Motion Control	5	HTI	8 October 2012

DSPE Certification Program

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

www.dsperegistration.nl/list-of-certified-courses

Course providers

- The High Tech Institute (HTI)
  www.hightechinstitute.nl
- Mikrocentrum (MC)
  www.mikrocentrum.nl
- Dutch Society for Precision Engineering (DSPE)
  www.dspe.nl

Mikroniek guide

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  www.heidenhain.nl
- Mikroniek Guide — 51-53
- Minimotor Benelux — 17, 29
  www.faulhaber.com
- Schaeffler Nederland BV — 55
  www.schaeffler.nl
- Renishaw Benelux BV — 41
  www.renishaw.com