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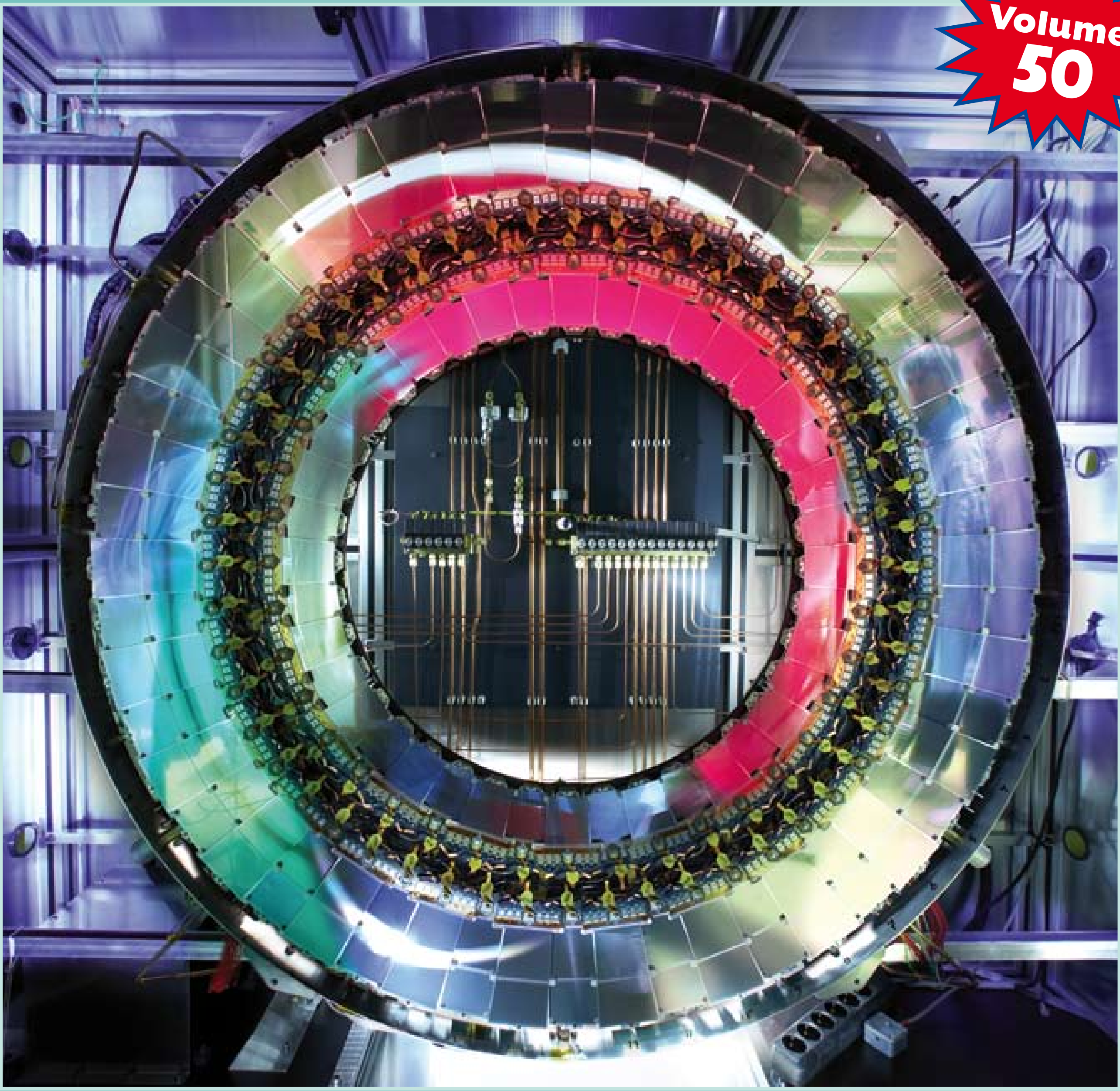

## Special Issue Opto-Mechatronics

An open 300mm Cassegrain telescope • Smart mounts • Analytical Software Design
A semi-transparent mirror in component placement • Trumpf Technology Day
DIMES symposium report • Cornea Topographer • The smart mix of MEMPHIS
Gravitational wave detection in space • TValley 2010: "More than mechatronics"

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# In this issue




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The cover photo (the ATLAS SemiConductor Tracker) is courtesy Peter Ginter/Nikhef.

editorial

# Taiwanese precision engineering

While on a business trip to Taiwan, DSPE president Hans Krikhaar visited me at the National Taiwan University (NTU), Department of Mechanical Engineering. Since 1945, NTU has been the most prestigious university in Taiwan, with currently some 33,300 students and nearly 2,000 full-time faculty members. The Mechanical Engineering department has research laboratories for Design and Mechanics, Manufacturing, Thermal and Fluidic Mechanics, Controls and Materials.

There have been relations between the Netherlands and Taiwan since 1624, when the island was still called Formosa with Tainan as the capital. The relationship in the field of precision engineering started when Philips decided to invest in Taiwan, starting from 1966. Philips explored activities for Lighting, Components, Displays and Semiconductors. Through these activities, Philips stimulated the development of precision engineering skills in Taiwan, which are present all over the country. In 1987, the first semiconductor foundry was set up at TSMC, which was unique in the world. Philips was a major shareholder of the company. Today, many chips are produced in foundries, with more and more OEMs being fabless. TSMC is by far the largest foundry in the world.

In my opinion, Taiwan has acquired a leading position in precision engineering due to Philips's major investments in manufacturing engineering. This singular situation should be developed further, seeing as it is a unique selling point for the Taiwanese industry. Understanding the outstanding role of the Netherlands in precision engineering, I am interested in further exploring collaborative opportunities. To start with, I am honoured to distribute Mikroniek among the precision engineering communities in Taiwan. Also, I appreciate DSPE's interest in publishing Taiwanese articles on precision engineering in Mikroniek. I helped to establish contact with ITRI's Mechanical Engineering Laboratory. This lab focuses on processes and equipment for new applications in the technology area of LEDs, OLEDs, lighting and energy harvesting by photovoltaic devices, for example.

I am pleased that DSPE is looking forward to exploring the precision engineering relationship between the Netherlands and Taiwan with a view to extending our historical affiliation.

Shuo-Hung Chang
Professor and department chair, Department of Mechanical Engineering, National Taiwan University

# High performance and reconfigurable design at moderate cost

*A design has been made for a high-end telescope system aimed at the amateur astronomer market. The design goal was to achieve high optical performance, while keeping the telescope structure light-weight and dividable so that the system is portable. Special attention was paid to the mechanical performance of the telescope structure, making the system robust and extremely reliable. Finally, the telescope was given a modular setup, making the optical characteristics adjustable for specific applications.*

• *Raimondo Cau, Nick Rosielle and Maarten Steinbuch* •

## Backyard astronomy

Amateur astronomy is a hobby, whose participants enjoy watching the night sky and the wide variety of objects found in it, mainly using telescopes or binoculars. In some cases, amateur astronomy is focused on day sky as well, e.g. for viewing solar eclipses, sunspots, etc. Amateur astronomy is sometimes referred to as “backyard astronomy”, after the most common viewing location.

Amateur astronomers observe the sky from a variety of locations, ranging from a person’s backyard to special public areas where light pollution is limited. The latter category comprises open spots in forests, mountain tops, or

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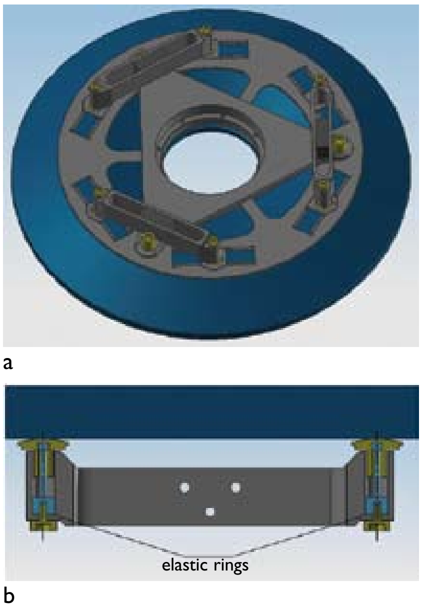


Figure 2. Primary mirror suspension.
(a) Overview.
(b) Section view of a linked pair of rods.

desert locations. For this reason, amateur astronomers like their optical system to be portable, robust and low-maintenance.

Common targets of amateur astronomers include the moon, planets, stars, comets, meteor showers as well as deep-sky objects, such as nebulae, galaxies and star clusters. Many amateur astronomers like to specialize in observing particular (types of) objects or interesting astronomic events. One of the branches of amateur astronomy is astrophotography, and involves taking photos of the night sky. This has become especially popular since high-quality CCD cameras have become affordable.

Furthermore, amateur astronomers are highly dependent on atmospheric conditions for the performance of their optical system. It is essential that the night sky is clear and the weather is calm. Atmospheric turbulence is a common cause of optical aberrations. These effects, combined with the fact that most optical systems owned by amateur astronomers are relatively low-tech (compared to the giants in scientific astronomy), allow the amateur to make high-quality observations only a few times a year.

Amateur astronomers pay high regards to reliable and easy-to-use telescope systems, which do not require frequent calibration. Most amateur astronomers consider astronomy as a mere hobby, which is why they are particularly interested in low price-to-quality ratios. Following the above requirements, a design has been made for a high-end telescope system aimed at the amateur astronomer market.

## High performance versus low cost

Among amateurs, Cassegrain systems are appreciated for their relatively short length compared to the focal ratio. The short length makes it easy to move the telescope to different viewing locations, as opposed to refractor systems which are generally long and slender. The Dall-Kirkham variant has an elliptical primary mirror surface and a spherical secondary mirror, which makes the mirrors easier to grind than in the “classic” system, greatly reducing the costs [1]. An unfavorable side effect is that the image quality quickly degrades off-axis. Since this is less noticeable at longer focal ratios, a Dall-Kirkham design is particularly suitable for planetary and deep-space applications.

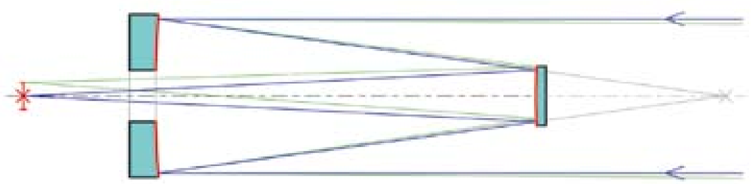

Figure 1. Cassegrain light path.

The primary mirror in a Cassegrain telescope system is one of the most important components, as it directly defines the light-gathering power and the resolution for the entire system. The proposed design contains a Ø300 mm primary mirror made of Pyrex 7740, with a silver reflective coating on the front surface, as well as a secondary coating to protect the mirror against detrimental external influences.

All individual light rays reflecting through the system ideally have an equal length, creating a perfect image on the focal plane; see Figure 1. Any misalignment of optical components or deflection of mirror surfaces will result in an aberrated image. A commonly used telescope specification [2] defining the maximum allowable variation in light-path lengths is set to

$$E_g \leq \lambda / 20$$

where $\lambda$ is the wavelength of light. A system suitable for applications in the near UV spectrum is therefore limited to maximum geometrical deviations of around 18 nm. To be able to meet this demand, static deflection of the mirror surfaces under various viewing angles is a vital issue.

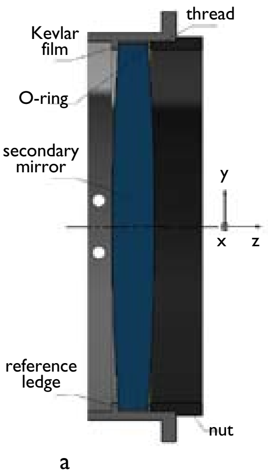



Figure 3. Secondary mirror mount
(a) Section view.
(b) Mounting on a series of elastic line hinges, crossing at the mirror apex, with two differential screws used to set the rotation angles.

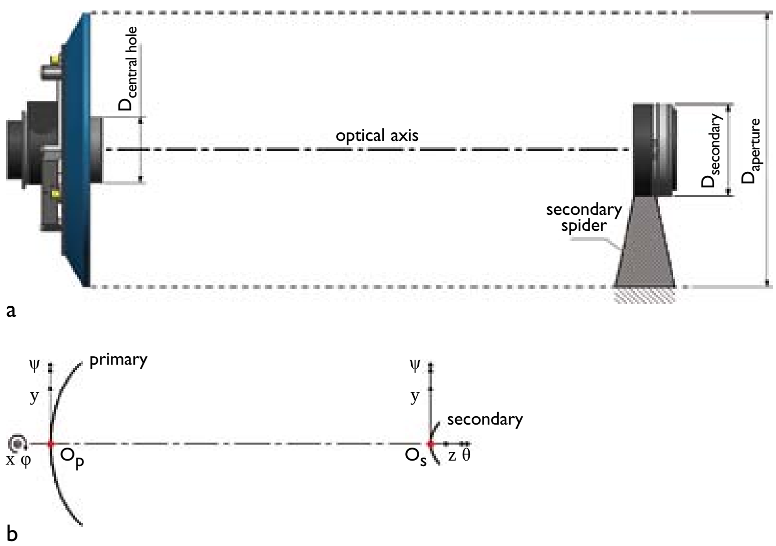


Figure 5. Simplified representations of the optical components and their mounts.

## Thermal stability versus simple design

Mirror mounts should provide a stable and controlled environment for an optical component, regarding its position, static and dynamic behavior, and any thermal influences [3]. Inevitably, any mounting system will have a negative effect on the optical performance. Yet a well-thought-out suspension can reduce this to a minimum. A stress-free and statically determined design can avoid internal forces. Using a whiffle-tree offers a suspension for the primary mirror, where axially orientated rods offer support in $z$, $\varphi$ and $\psi$, pairwise linked to a rigid base; see Figure 2. The remaining degrees of freedom are independently defined by a sheet-metal ring containing tangentially orientated rods, again connected to the base of the whiffle-tree. Radial expansion of the mirror is left free, which means that the suspension has no influence on system performance due to slow homogeneous thermal effects.

Considering the relatively small dimensions of the secondary mirror, a simpler mount can suffice; see Figure 3. The secondary mirror is suspended above the primary mirror by a C-shaped frame, supporting the mount in $x$, $y$, $z$ and $\theta$. Rotations $\varphi$ and $\psi$ around the apex of the mirror can be adjusted by manipulating two differential screws on the backside of the mount. The hollow CFRE (Carbon Fibre Reinforced Epoxy) frame runs along the bottom of the telescope and can be connected to any regular commercially available tripod. The result is an open structure (Figure 4), allowing air to flow through the system, hence thermally balancing all optical components with ambient conditions. When viewing in breezy weather, forced convection reduces thermal boundary layers or dew formation on the mirror surfaces.

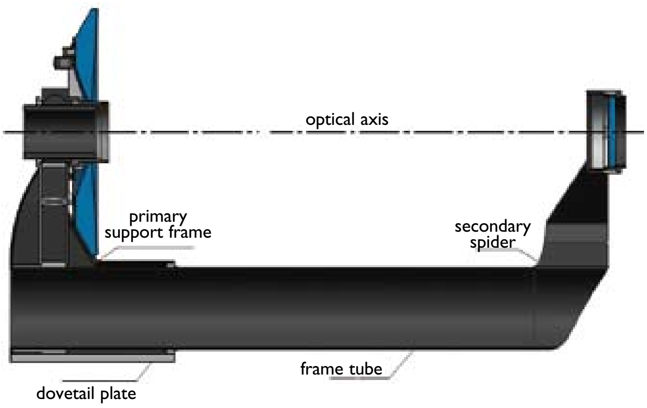


Figure 4. Section view of the CFRE C-frame

## Accurate alignment versus reconfigurable setup

Using Zemax [4], all optical components have been modeled with parametrized variables. With the primary mirror rigidly fixed, the effects of deviations in the secondary mirror position and orientation (Figure 5) have been analyzed and qualified in terms of image aberration type. Referring to the geometrical aberration limit $E_g$, the numerical results have been used to define the relative positioning tolerances of all optical components. Accordingly, throughout the design process these values have been used as a benchmark; see Table 1.

Table 1. Relative positioning tolerances between primary and secondary mirror.

| | | |
|---|---|---|
| Defocus (z-translation) | 1 | µm |
| Decenter (*xy*-translation) | 30 | µm |
| Tilt ($\phi\psi$-rotation) | 100 | µrad |

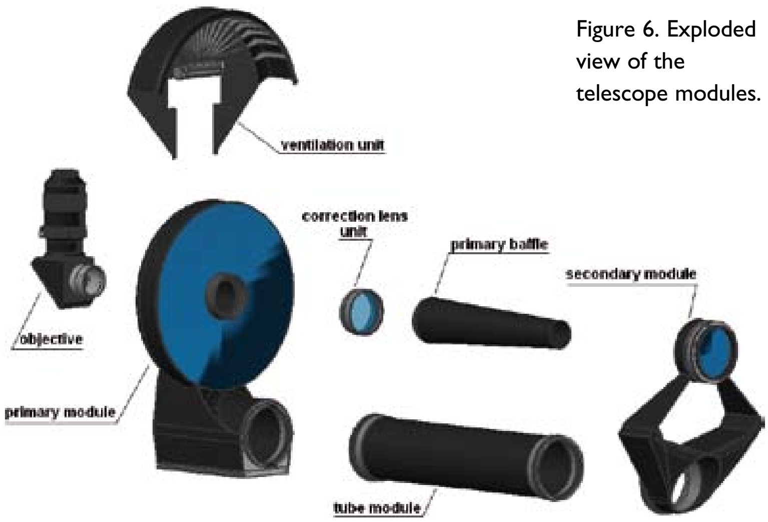


Figure 6. Exploded view of the telescope modules.

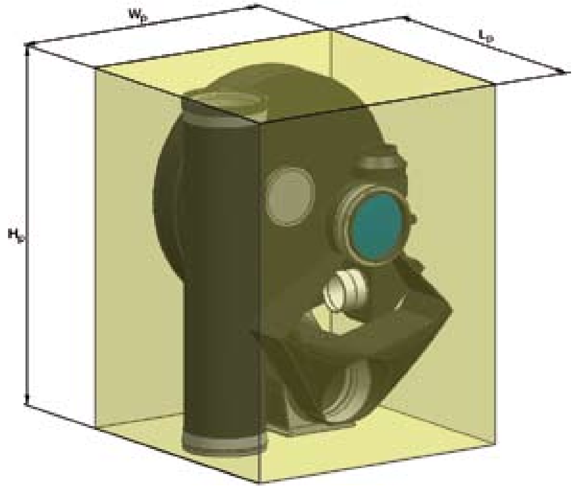


Figure 7. Packaged telescope.

## Dynamic response versus portability

The structural frame can be disassembled into several modules (Figure 6), being the primary and secondary support frame, and the frame tube. The connection between the modules and the tube is made by frame connectors. To enhance packaging, the frame connector has a universal design for each module. Apart from this, there are several other demands; see Table 2.

Table 2. Additional demands.

| | |
|---|---|
| Accuracy | Upon assembly, the structural frame needs to position the optical components within the calculated tolerance limits. |
| Reproducibility | When assembled, the system components should not need recalibration. |
| Rigidity | The frame needs to provide adequate stiffness to maintain system dynamic performance. |
| Controllability | All joints must be free of play. |
| Durability | A connector can be used numerous times before losing performance or requiring maintenance. |
| Stability | The relative position of the modules imposed by the connectors has to stay constant at least for the duration of use. |
| Ease of use | Attaching/detaching modules should be quick and easy for non-technical users. |

The proposed connector design is based on a male-female interface, with insertion along the frame tube centerline. Consequently, the connector consists of two parts, either of which is rigidly fixed to one of the opposing modules. The circular frame tube calls for an axisymmetrical design, with material concentrated along the edges as much as possible. An elastic centering mechanism between the connector halves, compressed by a union nut, provides the required pre-loading force to ensure adequate stiffness and correct radial and axial positions.

The secondary mirror unit is suspended from the frame tube by a two-legged straight spider, specifically designed to weaken the effect of spider diffraction, reducing the obstructed area while maintaining proper stiffness. This causes the first eigenmode (frame tube flexure) of the entire system to be at 180 Hz.

Another demand is portability, such that it is allowed in an airplane as carry-on luggage. This implies the telescope should be packaged according to airline restrictions, i.e. regarding weight and overall dimensions; see Figure 7 and Table 3.

Table 3. Casing properties (as in Figure 7).

| | | | |
|---|---|---|---|
| Dimensions | | | |
| | Length | 350 | mm |
| | Width | 350 | mm |
| | Height | 450 | mm |
| Volume | | 55 | l |
| Mass | | 11 | kg |

## State of affairs

A proposal has been made for the design of a 300mm Dall-Kirkham Cassegrain, incorporating basic essentials for high performance and features desired by most amateur astronomers as much as possible. The modular setup allows changing the optical configuration while using the same primary mirror, greatly reducing the costs.

Moreover, this creates a universal telescope system suitable for a wide variety of applications, dependent on the modules used. During the design process, all variables have been made parametric, allowing easy recalculation of dimensions and relative positions of components for different configurations.

Dedicated accessory components such as primary and secondary baffles, correction lenses and a ventilation unit have been designed to further enhance optical performance. Current prospects are that a full-scale model and an extensive series of experiments will ultimately provide a valuable product for the amateur astronomy market.

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[1] H. Rutten and M. van Venrooy, 2002. Telescope Optics, A Comprehensive Manual for Amateur Astronomers, fifth printing. Willman-Bell Inc, Virginia.
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# Smart mounts

***A novel active vibration isolation approach using stiff supports (called hard mounts) is discussed. The objective of this vibration isolation system is to combine high support stiffness with excellent isolation of floor vibrations. The support stiffness is realized by mechanical design and the floor vibration isolation performance is realized by means of feedback and adaptive feedforward control. This constitutes a novel approach to vibration isolation, which is not offered by manufacturers of vibration isolation systems.***

• ***Tjeerd van der Poel, Johannes van Dijk, Ben Jonker and Herman Soemers*** •

Vibrations due to environmental disturbances can cause a loss of accuracy in high-precision equipment. This is illustrated schematically in Figure 1. In many cases, floor vibrations are the dominant mechanical disturbance source. To reduce the vibration levels due to floor motion, the equipment is commonly mounted on vibration isolation systems with relatively low support stiffness. However, the low stiffness of such soft suspension systems may introduce difficulties in the response to direct disturbances (e.g. reaction forces due to stage motion or cable-transmitted forces) and with the levelling of the equipment. The high support stiffness in hard mounts circumvents these difficulties.

In a recent Mikroniek article [2], an overview of the basics and common concepts in (active) vibration isolation systems was presented. The active hard mount vibration isolation approach discussed here is an extension of the "piezo solution" that was briefly touched upon in that article. However, the key element in this approach is the

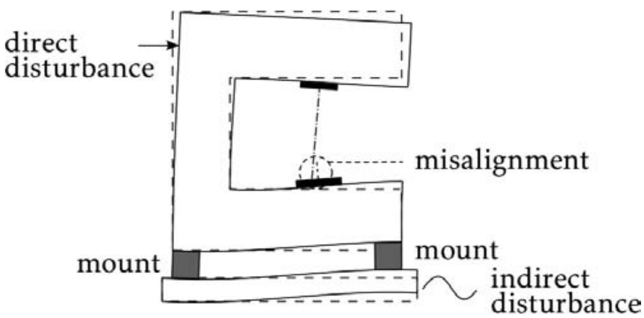


Figure 1. Illustration of deformations in a machine due to various disturbances, leading to a reduction in the machine accuracy.

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Herman Soemers is part-time professor of Mechatronic Design, Ben Jonker is full professor of Machine Dynamics and Robotics, and Johannes van Dijk is assistant professor of Mechatronics. All are with the Laboratory of Mechanical Automation and Mechatronics at the University of Twente, Enschede, the Netherlands. Tjeerd van der Poel has obtained his Ph.D. degree [1] on the topic of active hard mount vibration isolation in the same research group.

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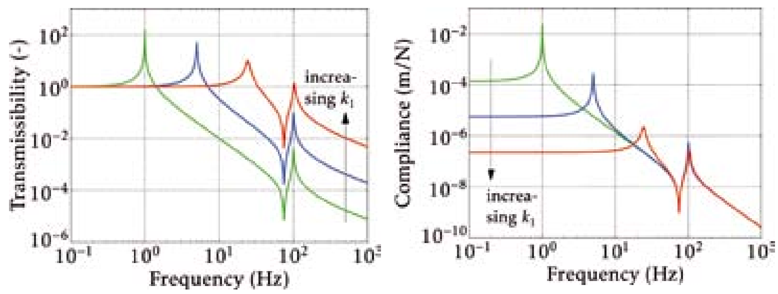


Figure 3. Design trade-off for the support stiffness $k_1$: effect on the transmissibility $T(j\omega)$ and the compliance $C_1(j\omega)$.

high suspension stiffness, which need not necessarily be realized by piezoelectric actuators.

## Design guidelines

Figure 2 shows a mass-spring-damper model of a suspended machine, which captures the basic features of a vibration isolation problem. Note that this machine model contains a structural resonance mode, because such structural modes typically occur within the frequency range of interest. In many cases, the internal deformation ($\Delta x = x_2 - x_1$) determines to a large extent the machine accuracy. At frequencies up to the first structural resonance, this deformation is proportional to the acceleration level of the machine $\ddot{x}_1(t)$. Therefore, the response of the supported machine to floor vibrations and direct disturbance forces is usually considered. This response is described in the frequency domain by the transmissibility function $T(j\omega)$ and the dynamic compliance $C_1(j\omega)$:

$$T(j\omega) = \frac{x_1(j\omega)}{x_0(j\omega)} = \frac{\text{machine motion}}{\text{floor vibration}}$$

(Equation 1)

$$C_1(j\omega) = \frac{x_1(j\omega)}{F_{d_1}(j\omega)} = \frac{\text{machine motion}}{\text{direct disturbance force}}$$

(Equation 2)

The support stiffness offers a distinct trade-off in the design of a vibration isolation system. This trade-off is illustrated in Figure 3 in terms of the transmissibility and

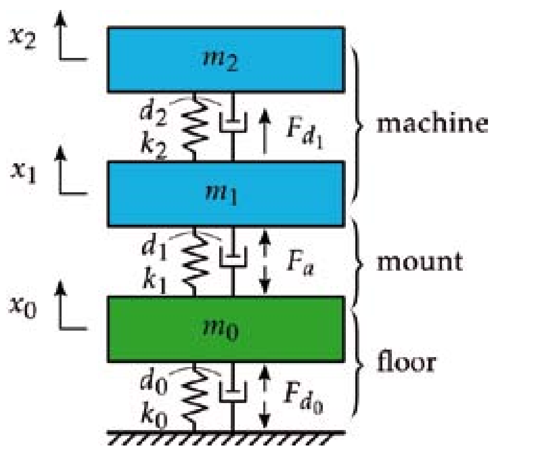


Figure 2. Basic model of the vibration isolation problem.

compliance. In words, low stiffness offers good isolation of floor vibrations, but increases the sensitivity to direct disturbance forces. For hard mounts, the opposite is true.

Due to the relatively high support stiffness of hard mounts, an exact constraint design of the support system is necessary. This means that all the "rigid body" degrees of freedom of the machine (i.e. three translations and three rotations) are constrained exactly once. Otherwise, difficulties with thermal loads and manufacturing and assembly tolerances are likely to occur [3].
Moreover, deviating from the exact constraint design can have a significant effect on the realizable vibration isolation performance. The so-called parasitic stiffness in the mount offers additional transfer paths for vibration energy, which are extremely difficult to suppress using active control. Figure 4 shows the effects of parasitic stiffness in the mounts on the transmissibility of the active hard mount system; see [1] for details. As a rule of thumb, the parasitic stiffnesses must be at least 100 times lower than the principal stiffness.

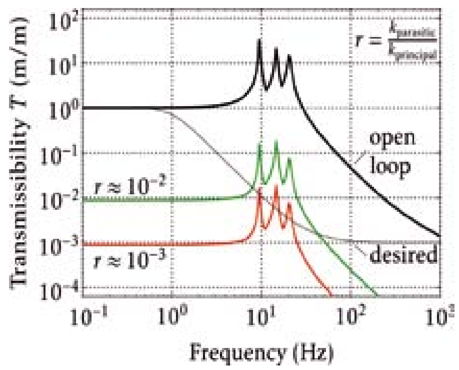


Figure 4. Effect of parasitic stiffness on the (best case) floor vibration transmissibility.

## Active control strategy

From Figure 3, it is clear that the transmissibility of a hard mounted system has to be improved significantly to achieve the same vibration isolation performance as a soft suspension system. For this purpose an active control system is used that combines feedback control of the

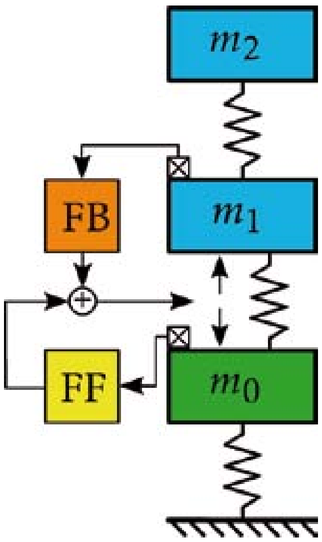


Figure 5. Combined feedback (FB) and feedforward (FF) control using absolute motion sensors (geophones or accelerometers).

machine motion with feedforward compensation of the measured floor vibrations; see Figure 5. Note that all active components (sensors, actuators) are placed in the mount, resulting in a modular system. The feedback control aims at adding active damping to the suspension and relevant structural resonances in the system. The transmission of floor vibrations is then reduced further by the feedforward compensation. This feedforward controller generates anti-forces based on the measured floor vibration, attempting to cancel the machine vibrations induced by the floor vibrations.

## Active damping

The feedback control strategy is based on Direct Velocity Feedback (DVF) [4], which uses collocated actuator/sensor pairs to effectively add viscous dampers at the actuation points in the system. Due to the collocation, the decentralized feedback loops are robustly stable.
The theoretical maximum damping ratio for a carefully tuned DVF controller is given by

$$\zeta_{max} = \begin{cases} \frac{1}{2}\left(\frac{\omega_r}{\omega_a} - 1\right) & \text{if } \omega_a < \omega_r; \quad \frac{1}{2}\left(\frac{\omega_a}{\omega_r} - 1\right) \quad \text{if } \omega_a > \omega_r \end{cases}$$

(Equation 3)

where $\omega_r$ is the natural frequency of the structural resonance mode to which the DVF controller is tuned and $\omega_a$ is the anti-resonance frequency closest to $\omega_r$. As a result, the spacing (in the frequency domain) of the structural resonance and anti-resonance frequencies is of key importance for the achievable damping.

In view of this result, it can be shown that either geophones or accelerometers are the preferred choice of sensors (compared to force sensors and displacement sensors). Throughout this research project, accelerometers have been used. These sensors provide the largest spacing of $\omega_a$ and $\omega_r$. Moreover, with these sensors it is possible to achieve skyhook damping of the suspension modes of the supported machine. This means that damping can be added while retaining the –40 dB/decade roll-off in the transmissibility function. When using relative damping, the roll-off would reduce to –20 dB/decade, leading to an increase in transmissibility at high frequencies.

## Feedforward compensation of floor vibrations

A block diagram of the feedforward control system is shown in Figure 6. The components in the block diagram have the following interpretation:

- $P(z)$: primary path; describes the system dynamics relating the disturbance source $d(k)$ and the machine acceleration $\ddot{x}_1(k)$. (or an equivalent sensor signal)
- $S(z)$: secondary path; describes the system dynamics relating the control force $F_a(k)$ and the machine acceleration $\ddot{x}_1(k)$.
- $T(z)$: tertiary path; describes the system dynamics relating the disturbance source $d(k)$ and the floor acceleration $\ddot{x}_0(k)$. (or an equivalent sensor signal)
- $W(z)$: feedforward controller
- $d(k)$: disturbance source, assumed to be a white noise signal; the colouring of the floor vibration spectrum is achieved by including a spectral factor into $T(z)$ and $P(z)$.
- $r(k)$: reference signal for the feedforward controller; this signal represents the floor acceleration $\ddot{x}_0(k)$ due to the disturbance source $d(k)$.

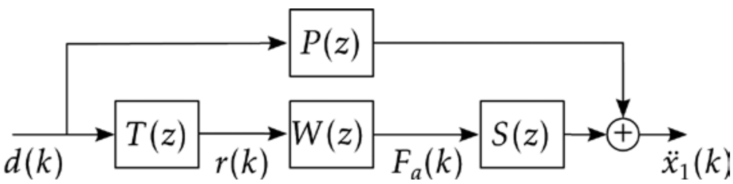


Figure 6. Block diagram of the feedforward control system.

The transfer functions $P(z)$, $S(z)$ and $T(z)$ represent the closed-loop system dynamics, i.e. including the feedback control. Moreover, the reference signal $r(k)$ is obtained from the measured floor acceleration $\ddot{x}_0(k)$ by compensating for the effect of the control force $F_a(k)$ on the floor acceleration, using internal model compensation (IMC). The IMC is required to prevent instability of the feedforward compensation. Furthermore, the signals and transfer functions are presented in the discrete domain, because the feedforward controller is implemented digitally.

Theoretically, the optimal feedforward controller $W_o(z)$ is given by:

$$W_o(z) = -S^{-1}(z)P(z)T^{-1}(z) \quad \text{(Equation 4)}$$

However, the inverses indicated in Equation 4 may result in an unstable and/or acausal optimal controller, which can not be implemented in practice. Moreover, the system dynamics $P$(z) and $T$(z) are difficult to obtain in practice. Therefore, an adaptive algorithm is used to find an approximation of the optimal feedforward controller. Moreover, the adaptive nature of the controller offers (to some extent) tracking capabilities for time-varying disturbances.

Commonly, the feedforward control force $F_a(k)$ is computed as a weighted summation of delayed samples of the reference signal $r(k)$, see Equation 5.

$$F_a(k) = \sum_{l=1}^{L} w_l(k) r(k-l+1) \quad \text{(Equation 5)}$$

This is called a Finite Impulse Response (FIR) parametrization because the weight vector $\boldsymbol{w}(k)$ contains the impulse response coefficients of the controller and its length is limited to the user-defined number $L$. The controller weights are updated using the filtered-reference least mean squares (FxLMS) algorithm [5], resulting in a convex adaptation (i.e. a unique global minimum exists). Several extensions to the standard FxLMS algorithm have been implemented to further improve the convergence rate as well as the robustness of the adaptation; see [1] for details.

A significant drawback of the FIR parametrization of the feedforward controller is the large number of coefficients that is required to accurately describe systems with long impulse responses (i.e. systems with poorly damped resonances). Unfortunately, this is typically the case in precision equipment. As a result, the achievable performance can, in practice, be limited by the real-time computational capabilities of the digital controller, especially for multi-channel vibration isolation systems.

As an alternative, an infinite impulse response (IIR) parametrization with fixed poles has been considered, see Figure 7. Its basic structure is a cascaded connection of second-order sections (SOS) and first-order sections (FOS). Each SOS and FOS is an all-pass state-space system, which ensures that the signal power of the reference signal is transferred to all sections. The actuator force $F_a(k)$ is now formed by the weighted summation of the states of the second- and first-order sections, combined with a direct feedthrough term $w_0$. This summation can be written in a similar form as Equation 5, albeit with a different reference signal. Consequently, the same adaptive algorithms can be used to update the IIR filter coefficients, and the adaptation still has a unique global minimum.

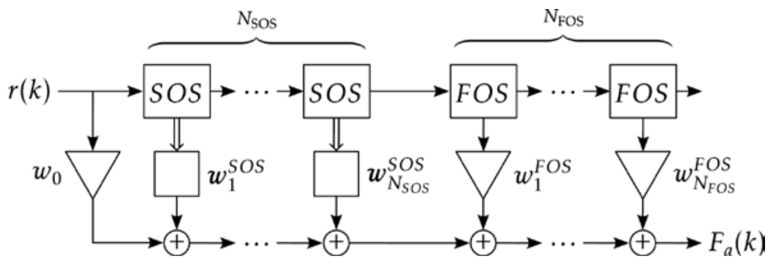


Figure 7. IIR filter parametrization: cascaded connection of $N_{SOS}$ second-order and $N_{FOS}$ first-order filter sections with user-selectable fixed poles. Each section is implemented as a state-space system, whose states are used to compute $F_a(k)$.

The IIR pole locations are not updated, thereby preventing the stability and convergence problems of fully adaptive IIR filters. The user should closely match all the SOS/FOS poles to the pole locations of the optimal controller. In practice, these pole locations can be chosen based on model studies, system identification and/or experimental tuning. When these pole locations are chosen correctly, a significant reduction in filter parameters (and computational complexity) can be achieved without notable degradation in performance.

As an illustrative example, assume that the optimal controller is given by the discrete transfer function

$$W_o(z) = \frac{1}{z^2 - 1.896z + 0.9937} \quad \text{(Equation 6)}$$

which is a discrete, second-order, low-pass filter with poles at 0.9481±0.3080i. These poles have a 1% damping ratio and a resonance frequency at 0.05 $f_s$, where $f_s$ is the sample frequency.

When the IIR parametrization is taken to consist of one second-order section with the exact poles of $W_o(z)$, only two controller coefficients are required. Moreover, the IIR filter is then capable of exactly describing the optimal controller. On the other hand, the 1% settling time of this filter is 1,466 samples, i.e. it requires 1,466 samples to accurately describe the optimal controller with a FIR parametrization. Moreover, this FIR description is still only an approximation of the optimal controller.

## Experimental results

The feedback and adaptive feedforward control strategies have been tested on an experimental setup, which is shown in Figure 8. The setup has only one dominant direction of motion as it is designed to mimic the basic model of Figure 2. A voice coil actuator is used as the control actuator. The linear guidance of the coil with respect to the permanent magnet is designed such that the suspension frequency of this setup is approximately 17 Hz. Therefore, the support stiffness is almost 300 times higher compared to a 1 Hz soft suspension system.

Figure 9 shows the results of various control experiments. In open-loop operation (only passive isolation, blue line), the floor vibrations mostly excite the suspension mode at 17 Hz as well as the structural resonance mode at 80 Hz. Due to the additional damping in both modes that is realized by the feedback control (red line), the machine vibration level is reduced by a factor six to 1.5 mm/s$^2$ (0-1,600 Hz). When the feedforward control is turned on, the machine vibration level is reduced further to 0.5 mm/s$^2$ (0-1,600 Hz). There is no significant difference in vibration isolation performance between the FIR (green) and IIR (purple) parametrization. However, the IIR parametrization is six times more efficient due to the significantly smaller number of coefficients, see Table 1. This table also lists the measured internal deformation.
The dominant limiting factor in the vibration isolation performance has been found to be the noise that is injected by the accelerometers and the voice coil actuator amplifier.

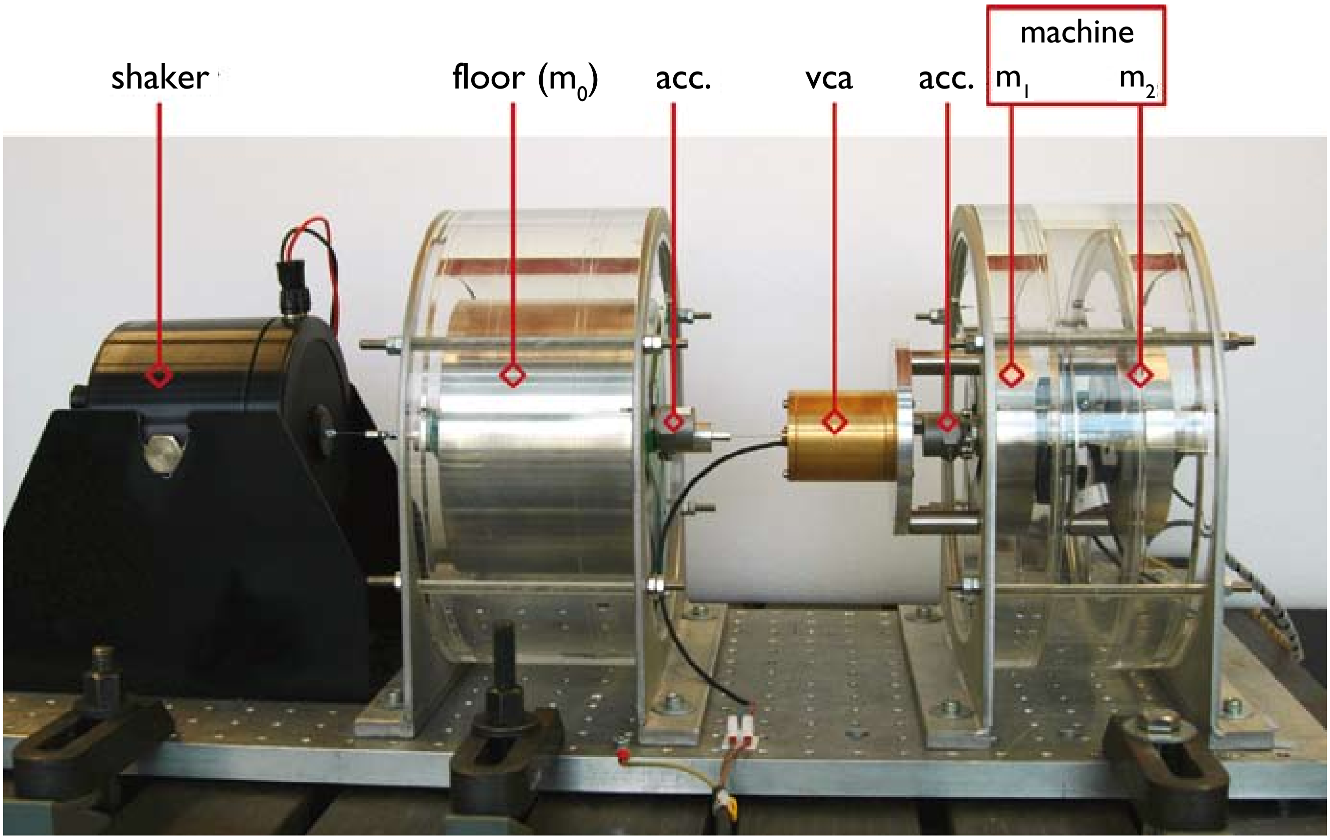


Figure 8. Experimental setup for control experiments. (acc. = accelerometer, VCA = voice coil actuator)

Table 1. Summary of control experiment results.

| | Passive | Feedback | FB + FF [c] FIR | FB + FF [c] IIR | Units |
|---|---|---|---|---|---|
| $\ddot{x}_0^{a}$ | 7.4 | 6.2 | 6.2 | 6.2 | mm/s² |
| $\ddot{x}_0^{b}$ | 17 | 16 | 16 | 15 | mm/s² |
| $\ddot{x}_1^{a}$ | 9.4 | 1.4 | 0.25 | 0.14 | mm/s² |
| $\ddot{x}_1^{b}$ | 9.5 | 1.5 | 0.57 | 0.48 | mm/s² |
| $\Delta x^{a}$ | 69 | 10 | 2.9 | 2.7 | nm |
| $\Delta x^{b}$ | 69 | 11 | 5.2 | 5.5 | nm |
| # of FF coefficients [c] | – | – | 2,000 | 58 | – |
| computational time | 20.4 | 20.9 | 200 | 31 | μs |

[a] RMS 0-100 Hz; [b] RMS 0-1,600 Hz; [c] FB (feedback) + FF (feedforward).

## Conclusions and future research

An active hard mount vibration isolation system has been discussed that allows to realize a stiff suspension system, while simultaneously offering floor vibration isolation.
A combination of feedback control and (adaptive) feedforward control is used, in order to actively add damping to the suspension and structural modes and reduce the transmissibility of floor vibrations. The feasibility of this active vibration isolation concept has been demonstrated on an experimental setup with one dominant direction of motion, resulting in a 20-fold reduction in the machine acceleration level.
Future research activities will focus on implementing the control strategies on a six degrees-of-freedom hard mounted setup and further improvement of the control performance.

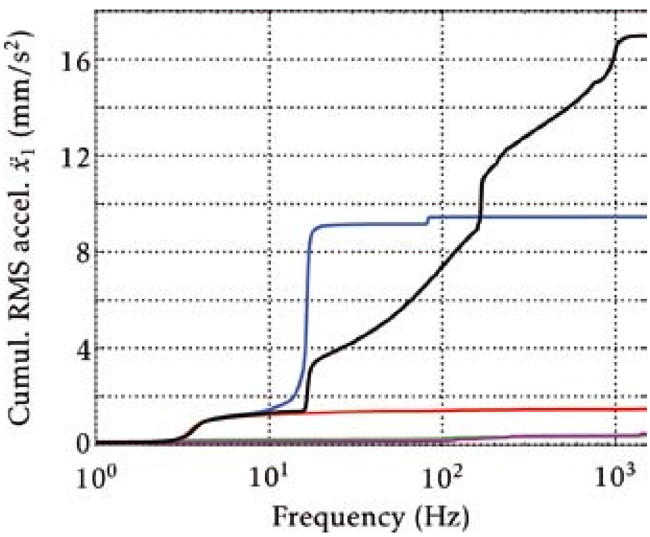


Figure 9. Cumulative spectrum of machine acceleration (mm/s²). (black: floor vibration; blue: passive; red: feedback; green: FF FIR; purple: FF IIR)

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**Acknowledgement**

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# The difference between

***Unlike other engineering disciplines, software (methodology) does not have enough precision to allow any formal reasoning about the software itself. Consequently, most requirements and design errors ("details") are discovered typically too late, when the system has been built. One improvement is to introduce mathematical methods in such a way, that they scale, are economic to use, and that the key stakeholders remain involved and are still able to validate the specifications based on such mathematical methods. Analytical Software Design meets these requirements.***

• ***Leon Bouwmeester*** •

Precision and detail: two small words that are often used as if they have the same meaning, but which differ greatly. Precision refers to the ability of a measurement to be reproduced consistently; key factors are predictability and exactness. Detail, on the other hand, refers to something small or trivial enough to escape notice; it has a flavour of "not important" about it.

The Eindhoven area is home to several companies that are involved in building high-precision mechatronic equipment. Precision – next to accuracy (degree of closeness of measurements to the actual value) – often affects their core business (in)directly. Therefore, one can assume that all disciplines related to mechanics, optics, physics, and electronics are well coordinated and aligned within these types of companies. The combination of these disciplines is directly related to the overall precision and accuracy of the resulting equipment they build. Any failure in this area is directly visible – sometimes even literally, as explained by the Hubble example.

## Hubble telescope

On 24 April 1990, the Hubble telescope was launched into orbit from aboard the Discovery space shuttle. Almost immediately afterwards it became clear that something was wrong. While the pictures taken with Hubble were clearer than those of ground-based telescopes, they were not the pristine images promised. Analysis of these flawed images showed that the problem was caused by the shape of the primary mirror. Although it was probably the most precise mirror ever made, with variations from the prescribed curve of only 10 nm, it was too flat at the edges by about 2.2 μm, which caused severe spherical aberration: light bouncing off the centre of the mirror focuses in a different place than light bouncing off the edges. Figure 1 shows a schematic overview of the internals of the Hubble telescope.

Fortunately, scientists and engineers were dealing with a well-understood optical problem (although in a unique environment). For which they had a solution: a series of

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# precision and detail

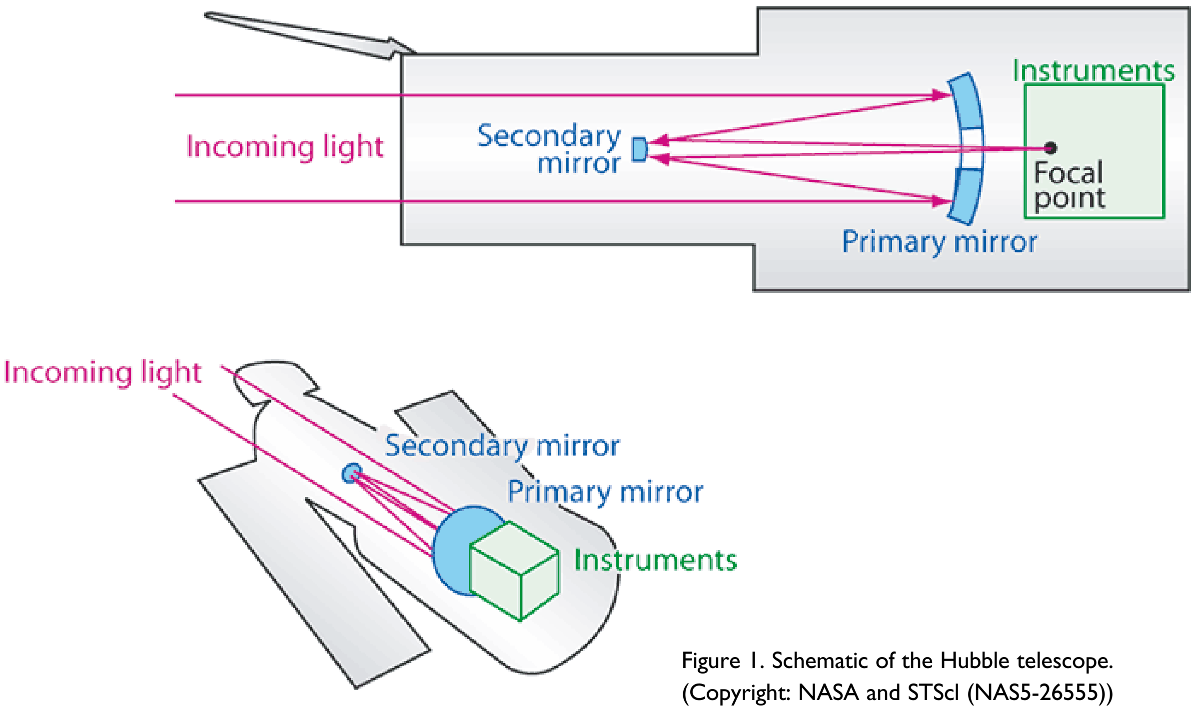



Figure 1. Schematic of the Hubble telescope.
(Copyright: NASA and STScI (NAS5-26555))

small mirrors were used to intercept the light reflecting off the mirror, correct for the flaw, and bounce the light to the telescope's science instruments. Several of the telescope's cameras were replaced by newer versions containing small mirrors to correct the aberration [1]. As the Hubble was already in orbit, the costs to resolve the spherical aberration were about $150 million [2] [3]; a figure that does not even include the cost of the shuttle repair mission itself – which may easily have been about three times higher [4].

## The root cause

A commission was established to determine how the error could have arisen [5]. They found that the main null corrector, a device used to measure the exact shape of the mirror, had been incorrectly assembled: one lens was wrongly spaced by 1.3 mm. During the polishing, the surface of the mirror was analyzed with two other null correctors, both of which correctly indicated that it was suffering from spherical aberration. However, these test results were ignored as it was believed that these two correctors were less accurate than the primary one that showed that the mirror was perfectly figured.

## Observations

A couple of observations can be made about the Hubble telescope and its flaw in the primary mirror. First, it was a well-understood optics problem for which the mathematics were known and described *precisely*. Hence, it was "easy" to figure out a solution to resolve the spherical aberration of the primary mirror. Second, it was this same mathematics that allowed the engineers to verify their designs during design time. They did not need to construct the entire Hubble telescope and check whether the images produced met the required quality. Third, as a consequence all testing that was performed on the telescope was intended to determine the quality of the telescope and not to establish it. Fourth, an expensive mistake was made during the verification of the primary mirror: the engineers missed an important aspect, which was considered a *detail*. They should have investigated more carefully the difference between the main null corrector and the other two null correctors. Fifth, engineering requires one to work *precisely* while not losing sight of important *details*; any mistake may lead to catastrophic failures and most of the time costs a lot of money to fix. In the end, the suppliers of the telescope agreed to pay $25 million to settle claims over the defects after which they were freed of further liability claims [6].

## Software

What about software? Is it as precise as the other engineering disciplines? Unfortunately, the answer is no. Most software (methodology) lacks a sound mathematical foundation, which makes it impossible to reason about it with sufficient precision; let alone perform design-time verification like other engineering disciplines do. Typically, only after implementation it can be determined by testing whether the software is correct (verification: does the software contain errors) and whether it is the correct software (validation: does the software fulfil its intended purpose). This means that only very late during the development process – perhaps even too late – feedback is obtained about the completeness and the correctness of the requirements (including software), architecture and design; paradoxically, the feedback only refers to what can be expected – the unexpected is never tested and therefore makes testing insufficient. Testing is also more than testing code; it is also testing the requirements, architecture, and design. Further, testing is also more than *determining* the quality: it is also often the phase where quality is *established* by resolving all errors that were found and, as a result, testing becomes unpredictable in terms of quality, progress, and cost. Consequently, the decision to release software is often made in a subjective manner [7].

But it gets even worse: during the requirements, architecture, and design phases, reviews are organized to get feedback and improve the quality of the specifications as much as possible. Everybody knows that it is the most cost effective to find and to resolve errors during these phases. However, since most errors are *injected* during the requirements, architecture, and design phases [8], but only a small number are *detected*, a false impression is given about the quality and the progress a software development team is making. In practice, remarks on requirements and architecture are often hand-waived as being *details* that can be resolved later on, whereas in reality such remarks refer to specification points that are not *precise* enough. The consequences only become apparent when it is typically too late: during testing.

## A paradigm shift is needed

Is there a solution? Projecting the development of the Hubble telescope onto software development implies the introduction of mathematics or, more precise, formal methods. However, formal software methods in industry were never really successful: they did not scale very well, they were expensive to use as highly-skilled people were needed, and often the solution was more complex than the original problem statement. Lastly, key stakeholders were excluded from the development process as they were not able to read the difficult mathematical notations and judge whether what was described was what they intended. However, when taking a closer look at other disciplines, it can be seen that indeed mathematics are involved, but that most, if not all, of the mathematics are hidden from the engineers. For example, a construction engineer creates a CAD/CAM model of a bridge from which automatically the mathematics is generated needed to check whether the bridge withstands earthquakes, the traffic, strong winds, etc. A similar approach is desired for software development: create a model, automatically generate the mathematics and verify it for design errors and resolve them until the design is error-free, but in such a way that it can be applied in industrial-scale development, that it is general purpose, easy to use and understand, and it is indeed more economic to do so.

## Analytical Software Design

The above requirements are met by Analytical Software Design (ASD), a patented technology developed by Verum Software Technologies. ASD is a component-based technology that enables software specifications and designs

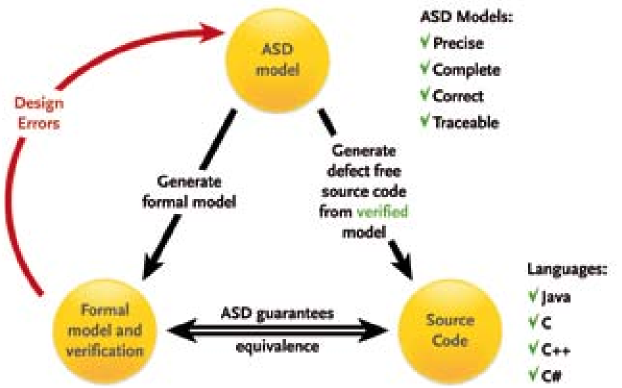
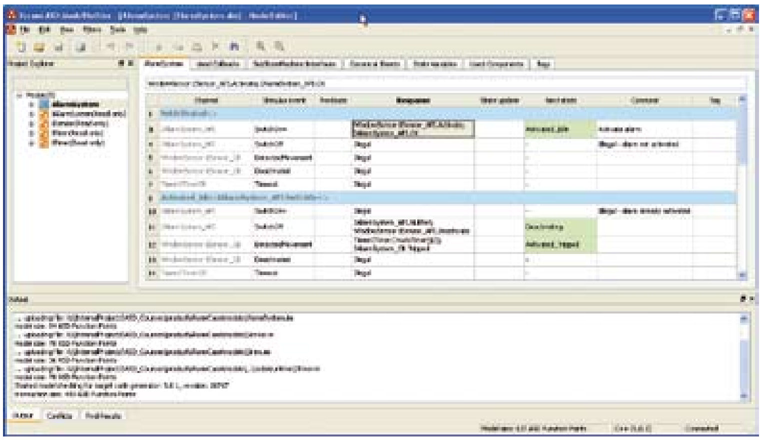



Figure 2. ASD technology provides design verification and code generation.

Parts of an ASD model.
(a) ModelBuilder.
(b) ModelChecker.



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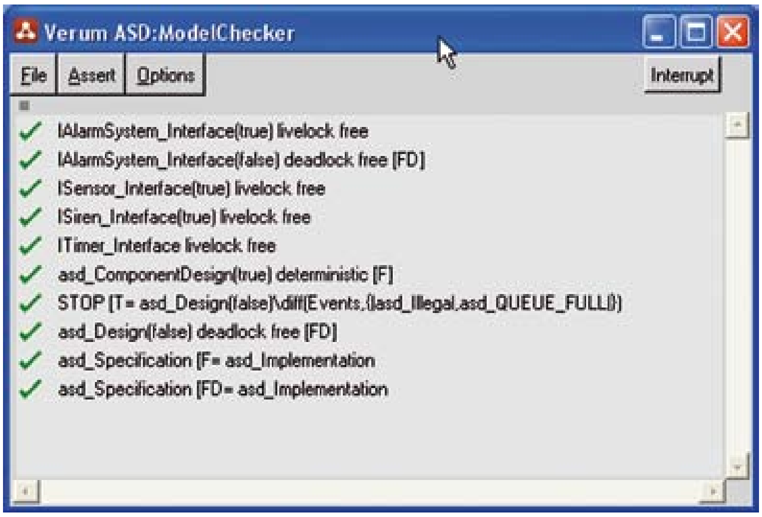


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to be mathematically verified at design time. After the design has been verified, code is generated from the verified design; see Figure 2. This technology is incorporated in a tool chain called the ASD:Suite.

ASD uses two kinds of component models: first, interface models that serve as the functional specification of the component which is externally visible. Second, design models that specify the internal design of this component. Although ASD models have no visible mathematical notation and are thus accessible to all project stakeholders, they are sufficiently *precise* so that mathematical models can be automatically generated from them. Where the construction engineer uses tools to generate a finite-element analysis model of a design, the software designer uses the ASD:Suite to generate a process algebra model. The process algebra model is then mathematically verified against the functional specifications by the ASD:Suite by means of model checking. Design errors uncovered by this verification, such as race conditions, deadlocks, and livelocks, are then easily removed by the designer by updating the ASD models. These models are then verified again, the process being repeated until all errors have been removed. At the end of the process, the ASD design model is *correct* and *complete*. The ASD:Suite is then used to generate the corresponding implementation in MISRA C, C++, C#, or Java, in such a way that the execution semantics as described in the models are equivalent to the mathematical model as well as the generated code. Since ASD is component-based, it can be applied to all software components that have discrete control behaviour; rather than specifying and verifying an entire system, the steps above are applied on the individual components. The compositionality rules of the mathematics guarantee that the composition of all these components together also works, and therefore these rules provide the scalability needed for industrial-size systems.

Figure 3 shows two fragments of an ASD model. Using ASD, all behaviour of a component is explicitly described, including all error scenarios. An ASD model is based on a Sequence-Based Specification (SBS) methodology. This methodology ensures that for all possible events in each state that a system finds itself in, proper responses are defined for all the events as well as the next state to go to. During this rigorous specification process, new states can be discovered where again proper responses and next states have to be defined for all stimulus events. This process ensures the completeness, whereas the model checking provides the correctness.

## A case: Philips's prototype digital pathology scanner

At the beginning of 2009, CCM (Centre for Concepts in Mechatronics) in a consortium of companies embarked upon an ambitious project to build a prototype digital pathology scanner for Philips's Digital Pathology business venture. Besides the technological challenges, as it had to be a fast scanner with the highest resolution and image quality, it had to be realized in a time span of 12 months where both software and hardware were developed concurrently by several companies leaving only a short period for test and integration.

CCM chose to use ASD for modelling, verifying, and generating the code for the control software of the digital pathology scanner for various reasons. First, at the time the contract was awarded, the customer requirements were good, but like in most other projects, certainly not complete. ASD enabled CCM and the other consortium


Figure 4. Philips's prototype digital pathology scanner, for which the control software was designed using the ASD:Suite.

members to *precisely* specify all possible behaviour of the prototype scanner. Second, during the requirements and architecture phase ASD was used to specify all external interfaces completely and correctly. These *precise* specifications enabled concurrent engineering of the hardware and software with the net result that integration of the graphical user interface was performed within hours and worked first time right, and that integration with the hardware was also successfully performed within a couple of days. Further, the first prototype of the scanner was to be shown at an exhibition for pathologists. The scanner had to be operational during the entire exhibition – even when visitors would push the scanner's buttons in all possible combinations. Another effect of using ASD: all exceptional behaviour has to be specified.

Initially, CCM had estimated to deliver about 70K lines of code and to realize this with a team of 8-12 people; in the end, the software was developed with 7 people while at the same time the code size grew to over 200K lines of code as the actual functionality increased. CCM would not have met the demanding deadlines and quality without the use of ASD, as the benefits went beyond producing defect-free software; it also increased CCM's productivity and facilitated the concurrent engineering.

## Conclusion

ASD has been successfully applied to various industrial-scale projects where the digital pathology scanner is the most recent one. It provides the necessary balance between precision and detail since ASD identifies the minimum level of detail required to satisfy its completeness property, which in turn provides the level of precision required for the purposes of formal verification. The only question that remains is which company will be the first one that develops software based on formal methods and accepts liability for the software like other engineering disciplines? Only then will software be a true engineering discipline.

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# Design of the Matchmaker

***The driving force behind the ever-increasing density of components on printed circuit boards (PCBs) is the miniaturisation of handheld equipment for component placement. PCB technology went from Thru Hole to Surface Mount and currently there is a growing presence of components that have the contacts on their blind side, as is the case with Ball Grid Arrays (BGAs). This article describes the design and use of a semi-transparent mirror in component placement for superimposing the image of the contact side of a component with the image of the corresponding tracks on the PCB.***

• ***Hans van den Brink and Ruud Bons*** •

In the early 1990s, the first vision systems for component placement based on a semi-transparent mirror appeared on the market. In March 1992, an article was published in the IBM Technical Disclosure Bulletin [1] that described an ingenious cube beam splitter with an additional mirror that allowed for simultaneous looking up and down. Pick & place equipment based on this principle was sold by, among others, Zevac. At about the same time, Finetech introduced the Fineplacer, a joint development with the Fraunhofer Institute, which employs a cube beam splitter. Because the view is at right angles, the placement arm rotates over 90 degrees and the prism is in a fixed position.

## Matchmaker

In 1994, a patent was granted on a novel beam splitter, a semi-transparent mirror sandwiched between two identical optical substrates. When looking under an angle, the apparent displacement in transmission is equal to the one in reflection. Placement is done by rotation, the angle of rotation typically being in the order of 2 x 20 degrees, a compromise between ease of handling and optical aberration. At the time, a semi-transparent mirror deposited upon a membrane was considered the state of the art, but it was not suitable for application in a taxing atmosphere.

**Authors**

Hans van den Brink (M.Sc. Physics, Delft University of Technology, the Netherlands) worked with E.G.&G. in the USA and with Philips. After retirement he became self-employed in the area of laser systems and consultancy. In the 1990s he conceived the idea of the Matchmaker. Ruud Bons is a mechanical engineer at Technobis Mechatronics in Uitgeest, the Netherlands.

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The system was baptised 'Matchmaker'. The three systems are shown schematically in Figure 1.

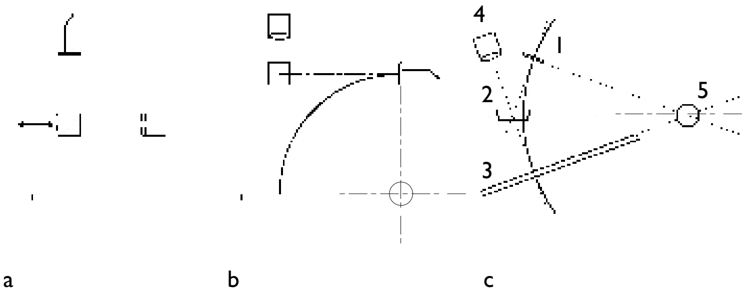


Figure 1. Schematics of component placement vision systems based on a semi-transparent mirror.
(a) IBM.
(b) Finetech.
(c) Matchmaker: 1. component, 2. semi-transparent mirror, 3. PCB, 4. objective, 5. rotation axis.

An initial series of four Matchmakers was produced for testing, demonstration and evaluation. The accuracy was adequate for the then current BGAs. For reasons that go beyond this article, no follow-up was conducted until 2004. In the meantime, miniaturisation progressed ever further and lead was being banned from solder. Lead-containing solder in the liquid phase has a high surface tension, as a result of which a poorly placed BGA will align itself during soldering. With the new lead-free solder, accurate positioning prior to placement becomes necessary – preferably at an affordable price.

## Rotatory versus linear placement

The overwhelming majority of pick & place systems employ a vertical movement of the component. The exceptions are Finetech and Matchmaker. Placing along a straight line can be looked upon as using an infinitely long arm. In a rotating system, the component lands along the tangent of the circle and as such has a limited depth of 'mechanical focus' compared to the straight movement. To give an indication: with a 150 mm placement arm, a premature landing of 1.2 mm in the vertical direction will cause a horizontal placement offset of 5 µm.

## Superimposing images

A perfect match in component placement requires that object and image are at exact opposite positions of the mirror. To assess the required accuracy, the tolerance budget has to be calculated (see below). When a component is picked up at its top side and it is the image of the bottom side that should be 'at the exact opposite position', then there is a complication: components vary in thickness, up to several millimetres. The Matchmaker solves this problem, as shown in the cycle of the process steps in Figure 2. Here the mirror holder is multifunctional, acting also as a loading platform for the component.

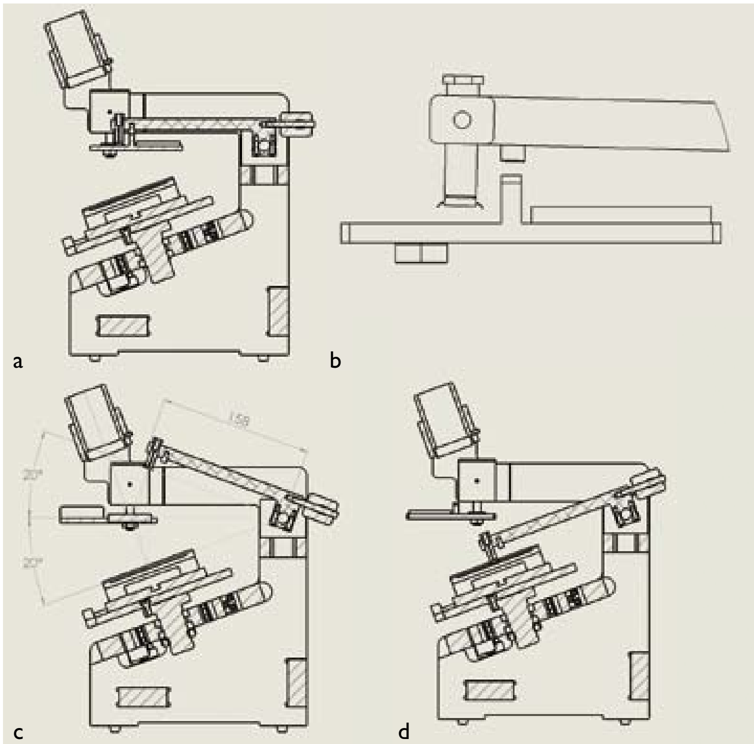


Figure 2. Operation of the Matchmaker.
(a) After rotation of the mirror holder, the component is picked up.
(b) The downward rotation of the pick-up arm is stopped by a limiter; the vacuum pick-up then goes down until it meets the top of the component.
(c) The position of the vacuum pick-up is fixed relative to the head of the pick-up arm and the arm is lifted to its upper position. The semi-transparent mirror in the optical path, the image and the objective are aligned.
(d) The mirror holder rotates to clear the way for the pick-up arm with the component on its way to the PCB. This is also the start of loading the next component.

## Tolerance budget

To facilitate a design that meets the required accuracy, the allowable tolerances in position and/or orientation of the various parts or subassemblies with regard to one another were considered in a systematic fashion. At the outset of the design phase, the target for placement accuracy was set at +/-5 µm. Here, placement accuracy is defined as follows: if the operator achieves a perfect match between the image and the object, after placement the match should be within +/-5 µm. It is understood that with the eye as detector the actual match depends on the operator's care and skill.
In the following analysis of a selection of potential 'errors' it is assumed that all other conditions are met perfectly. As this is not realistic, the requirements for orientation and position should be a factor 10 tighter. An approach to get at least partially around this problem is offered below (section on Design philosophy). This is the result of progressive insight.

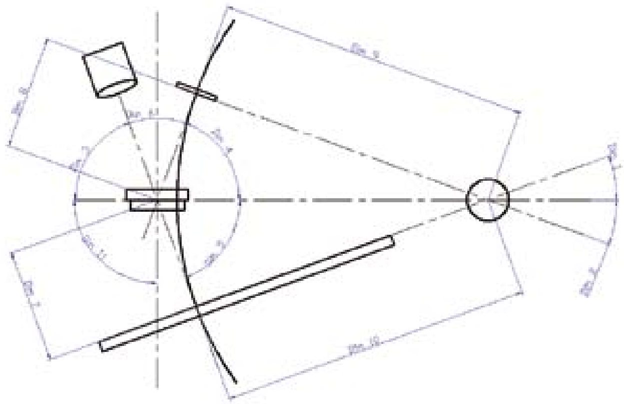

Figure 3. Definition of the dimensions and their nominal values as used in the tolerance budget exercise.

| Dimension | Nominal value |
|---|---|
| 1 | 20° |
| 2 | 20° |
| 3 | 70° |
| 4 | 70° |
| 5 | 70° |
| 6 | 40° |
| 7 | 54.60 mm |
| 8 | 54.60 mm |
| 9 | 150 mm |
| 10 | 150 mm |
| 11 | 90° |

## Error conditions

This section discusses several relevant 'error conditions' emerging from the tolerance budget calculations. As stated before, the acceptable mismatch of a BGA component on the PCB is 0.005 mm.

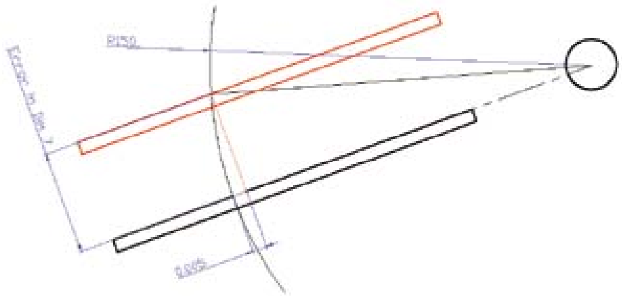

Figure 4.

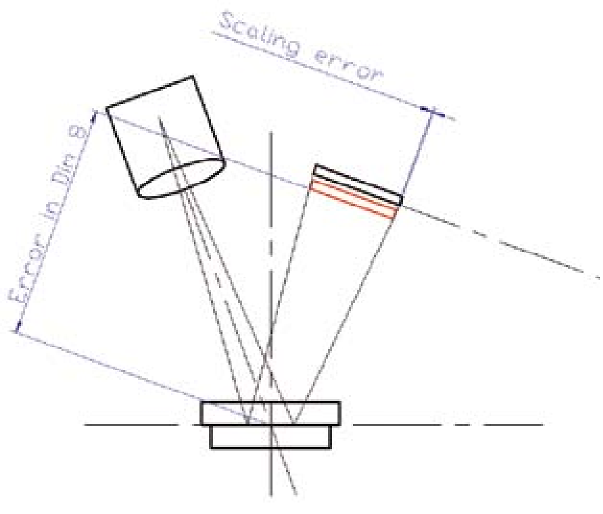


Figure 5.

- The PCB is not in line with the rotation axis (see Figures 4 and 5)
  An error of 1.2 mm in Dim 7 causes Dim 10 to go from 150 mm to 149.995 mm, a mismatch of 5 µm. This 1.2 mm error constitutes the 'mechanical depth of focus'. For a number of applications this is sufficient. However, Figure 5 shows what will happen in the field of view if the image of the contact side of the component floats 1.2 mm above the PCB.

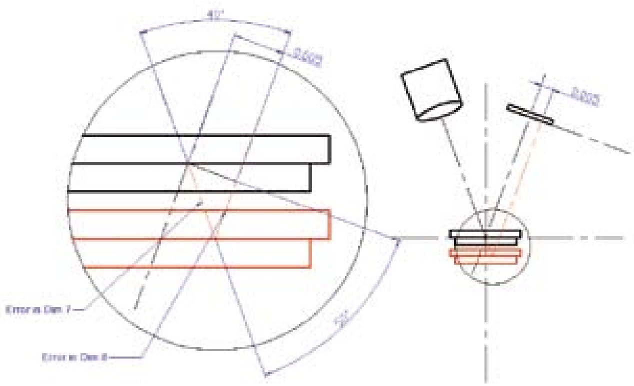

Figure 6.

- The mirror is not in line with the rotation axis (see Figure 6)
  If the mirror for instance has been lowered by 0.008 mm (Dim 7 decreasing, Dim 8 increasing), Dim 9 decreases from 150 mm to 149.995 mm. It can be concluded that the position of the mirror relative to the centre line through the rotation axis is the most critical aspect.

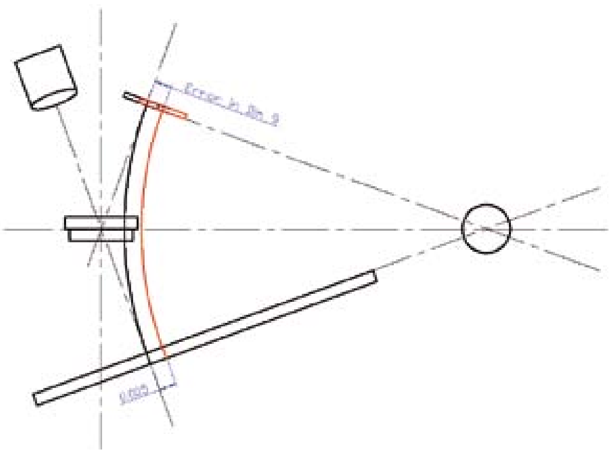

Figure 7.

- The placement arm is too short (see Figure 7)
  Dim 9 and Dim 10 are each other's mirror image; there is no effect on placement accuracy. This in itself is interesting since it means that effects of, for instance, temperature change on the length of the arm do not affect accuracy.

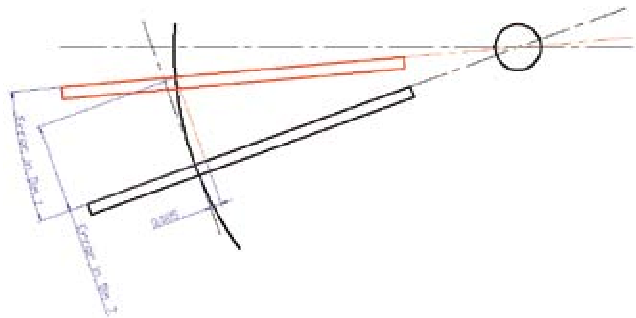

Figure 8.

- The mirror does not bisect the BGA and PCB planes (see Figure 8)
  This situation is similar to the one in Figure 4. Incorporated into the design is the feature that the upper position of the placement arm has an adjustable limiter, enabling the mirror to bisect the two planes.

## Conclusions

Some of the most relevant results of the calculations regarding the 5 μm placement accuracy target have been presented. It has become evident that the position of the mirror relative to the rotation axis is the most critical aspect. In the analysis of an individual potential error it was assumed that 'everything else' was perfect. As this does not represent reality, the effect is that the tolerances have to be tighter than presented. The effect of temperature changes has not been taken into account, as it is assumed that the axis is positioned in some kind of thermal centre. The effect of optical drift is shown in Figure 5. If the PCB is flat and the component has been picked up from the plane of the mirror, the drift should be minimal.
To meet the required accuracy, there is just one realistic option and that is to assemble the Matchmaker in such a way that parts and subassemblies are put into position by means of calibration.

## Design philosophy

The placement arm rotation axis (axis 1) should be straight. Its position is determined by the frame and it should be mounted free of play. Axis 1 is dominant. On the adjusting platform, the reference plane of the PCB holder should point at the centre line of axis 1, say with an accuracy of 0.1 mm. The mirror holder assembly rotates free of play around axis 2 and is perpendicular to this axis. Two

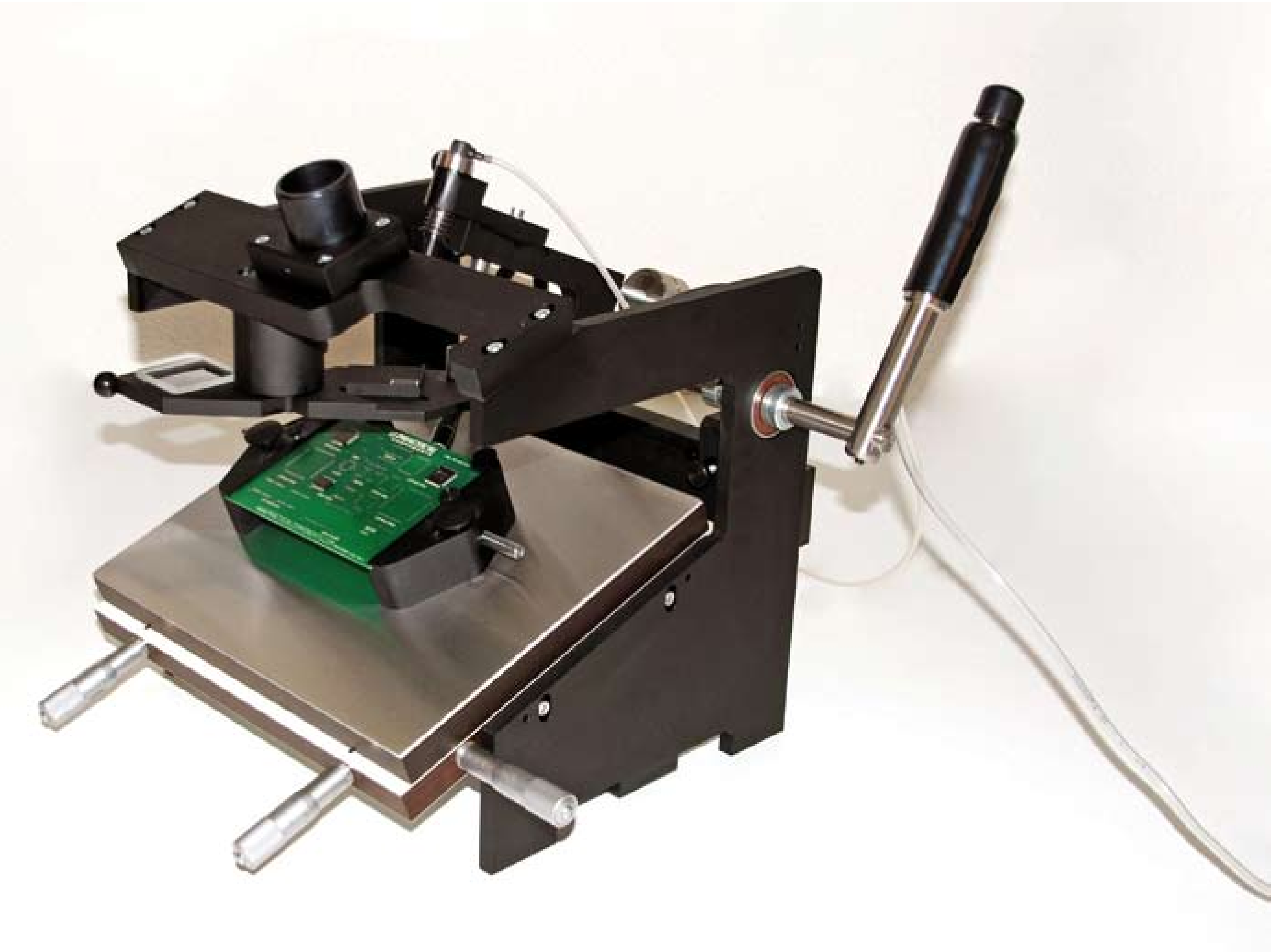

Figure 9. Current version of the Matchmaker. (Photo: Technoprint)

conditions must be met: axis 2 should be perpendicular to axis 1 and the plane of the mirror should point at the centre line of axis 1.
In order to avoid unrealistic demands on the accuracy of the production parts, it was decided to make the mirror housing adjustable in height and direction relative to axis 1. This may be at the expense of Dim 7, but this can be compensated by making Dim 8 equal to Dim 7 by means of the adjustable limiter that controls the upper position of the placement arm.

## Epilogue

As mentioned in the introduction, there are three different approaches to 'splitting the beam'. The tolerance budget drawn up for the beam splitter of the Matchmaker is basically applicable to all three systems. The pick-up procedure of the Matchmaker with its automatic compensation for the thickness of the component is, so far, unique. Figure 9 shows the current version of the Matchmaker, built by Technoprint in Ermelo, the Netherlands.

## Reference


[1] *Precision superposition component placement tool for endpoint sensing*, IBM Technical Disclosure Bulletin, 1992, Vol. 34, No. 10B, pp. 4-6.

# Gravitational wave

*Detection and observation of gravitational waves requires extremely accurate displacement measurement in the frequency range of 0.03 mHz to 1 Hz. The Laser Interferometer Space Antenna (LISA) mission will attain this by creating a giant interferometer in space, based on free-floating proof masses in three spacecrafts. Due to orbit evolution and time delay in the interferometer arms, the direction of transmitted light changes. To solve this problem, a picometer-stable Point-Ahead Angle Mechanism (PAAM) was designed, realized and successfully tested.*

• *Joep Pijnenburg and Niek Rijnveld* •

The picometer-stable scan mechanism is a crucial element in the Laser Interferometer Space Antenna (LISA) mission [1] [2]. The objective of the LISA mission is to observe and measure gravitational waves. Because of the extreme stability and low disturbance requirements, the detector will be created in space. The detector will consist of a giant interferometer with three measurement arms, travelling between three spacecrafts each at a distance of 5 million kilometers from each other; see Figure 1. Each spacecraft holds two free-floating proof masses, which provide the absolute reference for the interferometer arms. Because the disturbances acting on the proof masses have been absolutely minimized, any path length changes measured by the interferometer arms can be attributed to gravitational waves.

Due to the evolution of the orbit during its trip around the sun, the laser beam angles have to be corrected for constantly. Not only the in-plane angles are affected, but also the so-called point-ahead angles, which correct for the offset caused by the time delay of the travelling light. The Point-Ahead Angle Mechanism (PAAM) is designed to perform the task of correcting the point-ahead angle. The PAAM was developed and tested by TNO Science & Industry, with the help of the Albert Einstein Institution in Hannover, Germany. As an Elegant Bread Board (EBB), it has successfully gone through all performance and environmental testing and is ready to be integrated in a functional breadboard of the Optical Bench for a LISA spacecraft.

**Authors**

Joep Pijnenburg and Niek Rijnveld are members of the Precision Motion Systems Department of TNO Science and Industry in the Netherlands. The LISA mission is a combined ESA NASA space mission. The Point Ahead Angle Mechanism was developed by TNO in a technology development programme under contract of the European Space Agency (ESA).

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# detection in space

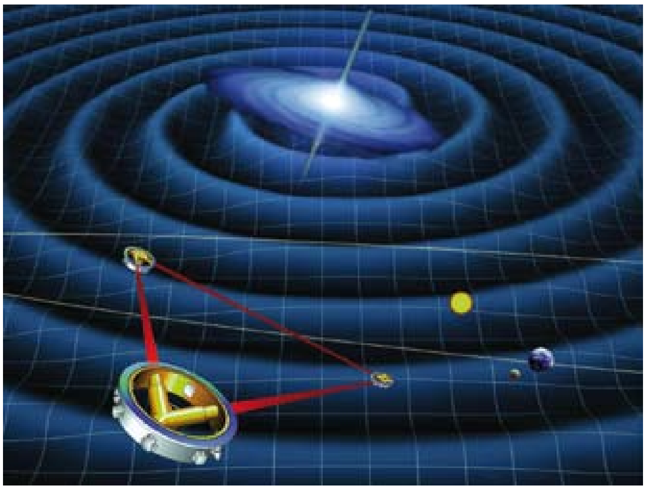


Figure 1. Artist impression of the LISA mission. (Illustration: NASA)

## Driving requirements

The PAAM is required to steer the incoming laser beam through a range of ± 824 µrad, while contributing minimally to the optical path delay (OPD) as well as to the angular jitter of the laser beam angle. During operation, the mechanism will follow an annual trajectory that runs through the entire range twice.

### *Performance requirements*

Both the specification for the optical path delay (OPD) and the angular jitter were described using a noise shape function, as shown in Equation 1.

$$n(f) = \sqrt{\left(1 + \frac{2.8\,mHz}{f}\right)^4} \qquad (1)$$

The requirements for OPD and angular jitter, defined in terms of amplitude spectral density (ASD), were multiplied with this noise shape function. It has been designed such that the requirements are relieved below 2.8 mHz, and constant above this frequency. The requirements only apply within the LISA measurement bandwidth, which is defined to be between 0.03 mHz and 1 Hz. Table 1 shows the requirements for OPD and angular jitter.

Table 1. Performance requirements for the PAAM.

| Description | Requirement | Unit |
|---|---|---|
| Optical Path Delay | $1.4 \cdot n(f)$ | pm/Hz$^{½}$ |
| Angular jitter | $16 \cdot n(f)$ | nrad/Hz$^{½}$ |

### *Environmental requirements*

Several additional requirements made the design of the PAAM quite challenging. First of all, due to the sensitivity of the measurement set-up on the Optical Bench, no magnetic materials were allowed. This ruled out the use of any electromagnetic actuators or bearings. Second, due to the strict requirements on stray light, the contamination requirements on the Optical Bench were extremely strict. Any outgassing materials, as well as mechanisms containing moveable parts with frictional contacts were to be avoided. Third, the mechanism will have to survive launch loads of 25 g RMS, without the use of a launch locking mechanism.

## Design description

The PAAM consists of a mirror on a flexible rotational hinge, which can be actuated individually by either one of two piezo stacks. The angle is measured by a capacitive sensor. The system operates in closed loop. The overall design is shown in Figure 2, and its realization is shown in Figure 3. In the paragraphs below, the optical, mechanical and electrical design is described in detail.

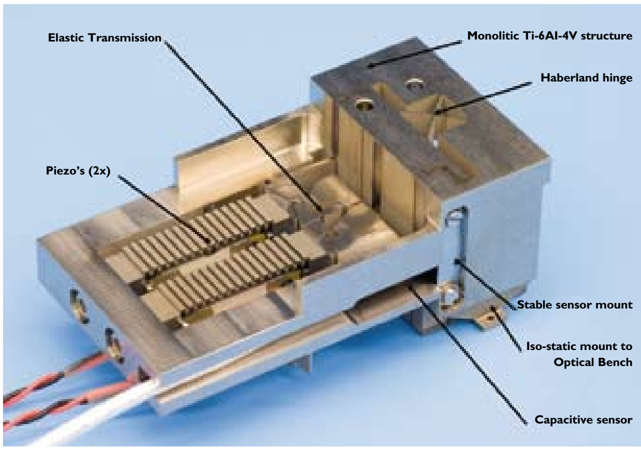



Figure 2. Elegant Bread Board of the Point-Ahead Angle Mechanism as designed by TNO Science and Industry, including all its components. (Photo courtesy of Leo Ploeg)

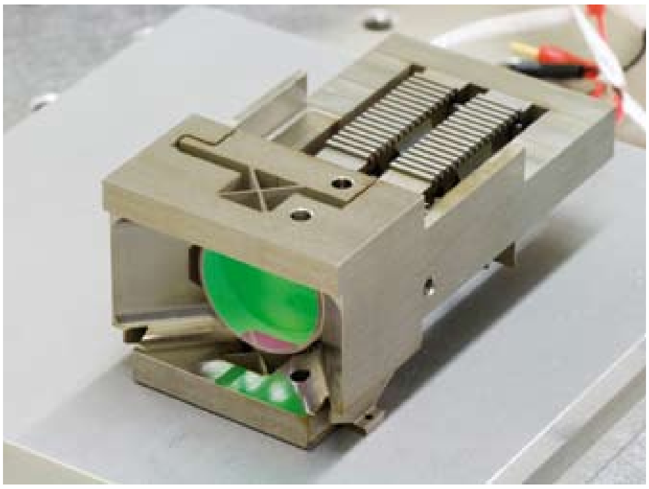


Figure 3. Realization of the PAAM. The mirror is glued to a monolithical structure featuring a Haberland hinge. The mirrors can be actuated by one of two piezo stacks. (Photo courtesy of Leo Ploeg)

### *Optical design*

The optical concept for the PAAM is a mirror rotating around an axis in the mirror plane. This concept was chosen over alternatives due to its low transmission losses and low complexity. The mirror is coated for the wavelength of 1064 nm and for the incoming angle of 45º. The reflectivity is specified as more than 99.9%, and its flatness is better than 12 nm RMS over its entire diameter of 19.05 mm.

The Optical Path Delay (OPD) has been identified as the most critical requirement. If the laser beam and the reflecting surface are perfectly aligned with the rotation, the OPD due to rotation is theoretically zero. Figure 4 schematically shows the optical path delay due to a rotation of the mirror, when the beam and surface are not perfectly aligned.

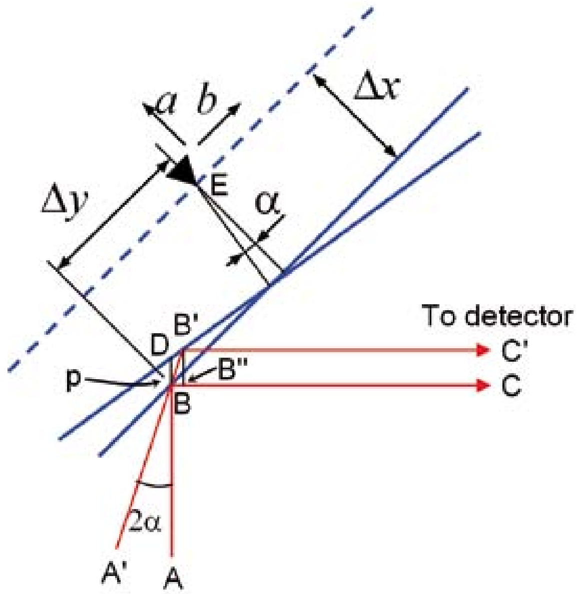



Figure 4. Schematic representation of the influence of alignment and jitter parameters of the mirror on the optical path delay of the incoming laser beam.

From Figure 4 it can be seen that the OPD equals the distance BB' - BB''. For small angles, this can be approximated by BD. The sensitivity of the distance BD, and hence the OPD, to the most relevant parameters is listed in Table 2. These parameters are the angular jitter, caused by rotation of the mirror around the optical axis in combination with an alignment offset, the longitudinal jitter, caused by piston sensitivity and angular jitter, and the rotation axis longitudinal jitter, caused by parasitical actuation forces through the Haberland hinge. Other misalignments of the optical axis and cross-couplings were shown to have negligible contribution to the optical path delay.

### *Mechanical design*

The rotation of the mirror is guided by a so-called Haberland hinge, a monolithical elastic cross hinge. Due to the restrictions on magnetic materials and contamination, magnetic, hydrostatic or contact bearings are not favored. The axis of rotation of the Haberland hinge is aligned with the mirror surface. As the material $Ti_6Al_4V$ was selected, due to its high allowable stress and high dimensional

Table 2. Sensitivity of the OPD to relevant parameters

| Parameter | Description | Budget | Relation | Effect on OPD (pm/Hz$^{½}$) |
|---|---|---|---|---|
| $\Delta x$ | Static longitudinal misalignment | ±1000 µm | - | 0 |
| $\Delta y$ | Static lateral misalignment | ±50 µm | - | 0 |
| $\Delta\alpha$ | Angular jitter | 8 · $n(s)$ nrad/Hz$^{½}$ | $\delta BD = 2^{½} (\Delta x\alpha + \Delta y)\delta\alpha$ | 0.57 · $n(s)$ |
| $\delta\Delta x$ | Longitudinal jitter | 0.28 · $n(s)$ pm/Hz$^{½}$ | $\delta BD = 2^{½} (1 + 0.5\alpha^2)\delta\Delta x$ | 0.40 · $n(s)$ |
| $\delta a$ | Rotation axis longitudinal jitter | 0.30 · $n(s)$ pm/Hz$^{½}$ | $\delta BD = 2^{½}\ \delta\alpha$ | 0.43 · $n(s)$ |
| Total | | | | 1.40 · $n(s)$ |

stability. The mechanical design is shown in Figure 3. The entire mechanism, excluding the functional components, was wire-eroded in a single fixture configuration; such that optimal production tolerances were achieved.
A compact elastic transmission between the actuator and mirror allows actuation of the mirror angle without introducing parasitic forces. The elastic transmission also enabled the inclusion of a second, independent actuator, such that the mechanism is redundant. The required mechanical stroke of ± 412 μrad can be actuated with an actuator stroke of 20 μm, with minimal hysteresis effects. To minimize OPD due to temperature variations, the thermal centre of the $Ti_6Al_4V$ structure was placed in line with the axis of mirror rotation. This was achieved by strategic placement of isostatic interfaces to the optical bench.

A finite-element model analysis (FEM) of the Haberland hinge was used to predict the longitudinal jitter, caused by the coupling between angular jitter and piston sensitivity. Production tolerances of ± 10 μm were included, which was justified by the accuracy and symmetry of the applied wire-erosion process to manufacture the monolithical mechanism. Figure 5 shows the calculated piston movement of the mirror rotation axis under different actuation angles. The derivative of this curve is the piston sensitivity to angular jitter, which is 2.1 fm/nrad at the maximum angle. With the requirement of 8 nrad/Hz$^{½}$, the predicted longitudinal jitter becomes 0.017 pm/Hz$^{½}$, which is significantly below the allocated budget of 0.28 pm/Hz$^{½}$.

### *Electrical design*

For the actuation, two piezo stacks (PPA20M) of Cedrat Technologies were selected. For the stroke of 20 μm, and with the limitations on magnetic materials, a piezo stack is the most appropriate actuator. The stacks are driven with a high-voltage piezo amplifier (Cedrat Technologies LA75B), which produces voltages between -20 and +150 V.
Because of piezo hysteresis and discharge behaviour, a closed-loop system was required to meet the requirement for angular jitter in the entire range. The controller acting between the sensor and piezo actuator can have a low bandwidth, because only disturbances within the LISA measurement bandwidth have to be suppressed.

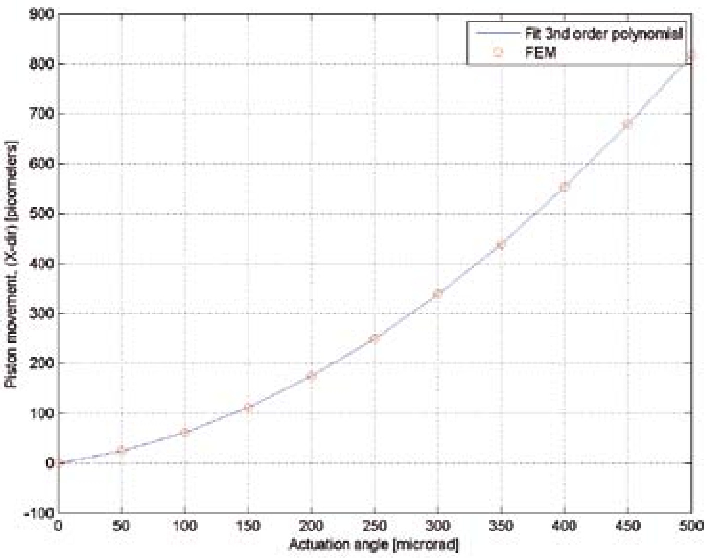



Figure 5. The piston movement of the axis of rotation under different actuation angles. By taking the derivative of the fitted polynomial, the piston sensitivity can be determined for different angles.

The sensor consists of an active target capacitive sensor system, which measures the displacement of the far end of the mirror (see Figure 6). The tilting of the mirror is less than 0.5 mrad, which has only a small influence on the capacitive sensor signal. A one-time calibration ensures that the sensor signal is representative of the mirror angle with high enough accuracy. The active target system is preferred over a passive target system for the following reason: in a passive target system, the cable capacitance is in parallel to the capacitance to be measured, and is typically a few orders higher. This makes it very sensitive to low-frequency environmental changes which dramatically influence the cable capacitance. In an active target system, the target is connected to a virtual ground, which draws the current from the cable capacitance. This way, the system will be much less sensitive to environmental changes.

The capacitive probe is a standard Lion Precision probe, whereas the active target consists of an isolating BK7 plate, coated with a layer of gold. The active target, located on the moving part, was connected to the sensor cable by two thin copper wires, which add negligible parasitic stiffness to the Haberland hinge. The capacitance-to-digital converter (CDC) electronics were chosen to be a custom electronics board, especially for extreme requirements on low-frequency noise. Typically, capacitive sensor electronics introduce 1/*f* type noise in the amplification, but the charge-integration configuration and precision electrical components chosen for the CDC board reduce this effect maximally.

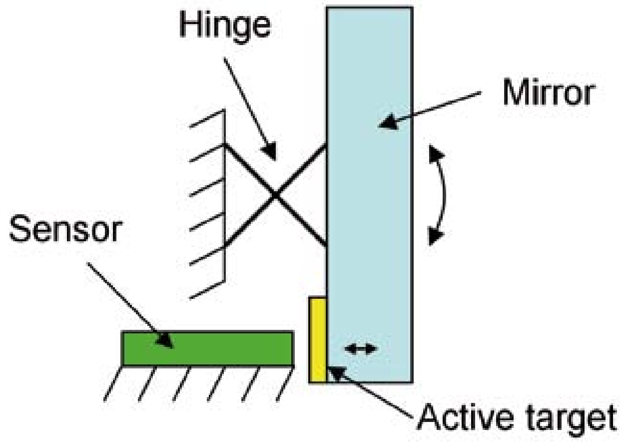



Figure 6. Schematic illustration of the active target capacitive sensor. The sensor measures the displacement of the tip of the mirror. The tilting of the mirror is taken into account by one-time calibration.

## Performance testing

Before and after the environmental test, consisting of 25 g RMS random vibrations and thermal cycling from 0 to 80 °C, the performance of the PAAM Elegant Bread Board was measured. This was done with the help of the Albert Einstein Institution in Hannover, because of their experience with measuring picometer stabilities and the availability of an existing measurement facility [3].

Figure 7 shows the test set-up used for the performance measurements, featuring a vacuum chamber pumped down to $10^{-4}$ mbar that is temperature controlled to less than 14 μK/Hz$^{½}$ · *n*(*f*). The extreme stability required to measure 1.4 pm/Hz$^{½}$ can currently only be achieved with an interferometer, realized with a resonance cavity. Because the nominal incidence angle of the PAAM is 45°, the cavity was made triangular. To keep the cavity resonant, the stabilized laser frequency that is generated in an external cavity is modulated by a controller. The actuator is an Electro-Optical Modulator, which is included in the vacuum chamber. The sensor is a frequency counter, which measures the resonance frequency of the cavity relative to the reference cavity. The feedback signal is a measure of the cavity round trip length change, which represents the contribution of the mechanism to the OPD. The cavity of the measurement set-up inside the vacuum chamber was mounted on a Zerodur base plate, to minimize the influence temperature variations on the cavity round trip length.

### *Test description*

Two of the critical requirements of the PAAM needed to be verified by tests: the OPD and the angular jitter. Both were measured at three different static angles within the range of the mechanism. The LISA measurement bandwidth determines the length of each performance measurement: the lowest frequency to be measured is 0.03 mHz. With several repetitions of this period to obtain a

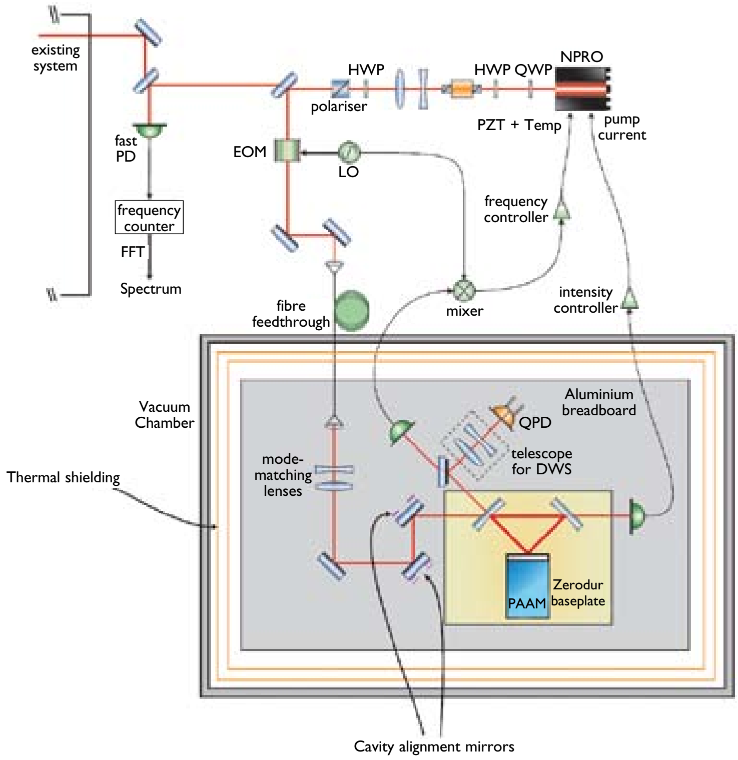



Figure 7. The OPD of the PAAM was measured in a triangular resonance cavity, inside a temperature-controlled vacuum tank. (Courtesy of Albert Einstein Institute, Hannover)

proper spectral estimate, the measurement time per angle was approximately 48 hours.
To measure the OPD, the PAAM had to be aligned accurately in the resonance cavity. To achieve this, a modulation sine wave was used as a setpoint on the mechanism, which followed this signal by rotation of the mirror. Through the amplitude of the sine wave, the misalignment of the axis of rotation with respect to the incoming beam could be estimated.
To measure the angular jitter, the PAAM was deliberately placed at an alignment offset. A modulation sine wave was used as a setpoint for the PAAM. Through the amplitude of the sine wave, the coupling of angular jitter to OPD could be estimated. A long measurement of OPD then provided an indirect measurement of the angular jitter of the PAAM.

### *Test performance results*

The results of the performance measurements of OPD and angular jitter are shown in Figures 8 and 9. For all angles, the performance of the mechanism was exactly according to the requirements. The peak visible at 50 mHz is the modulation sine wave which was used for alignment in the OPD measurements, and coupling estimation in the angular jitter measurements.

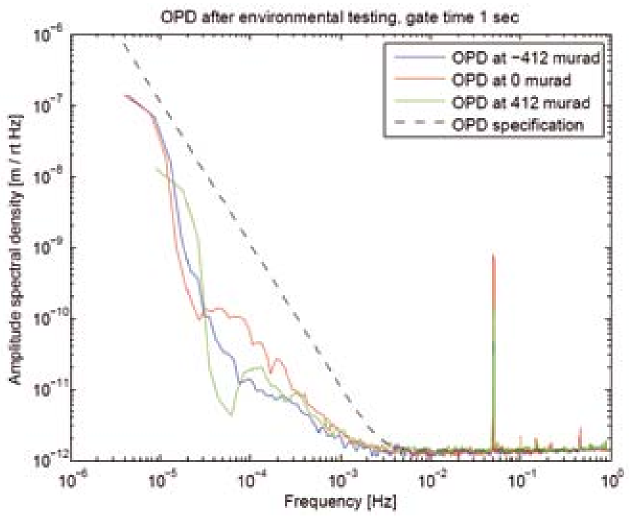



Figure 8. Amplitude Spectral Density of the OPD measurements on the PAAM. For all angles, the result met the requirements. The peak at 50 mHz was introduced for alignment in the cavity.

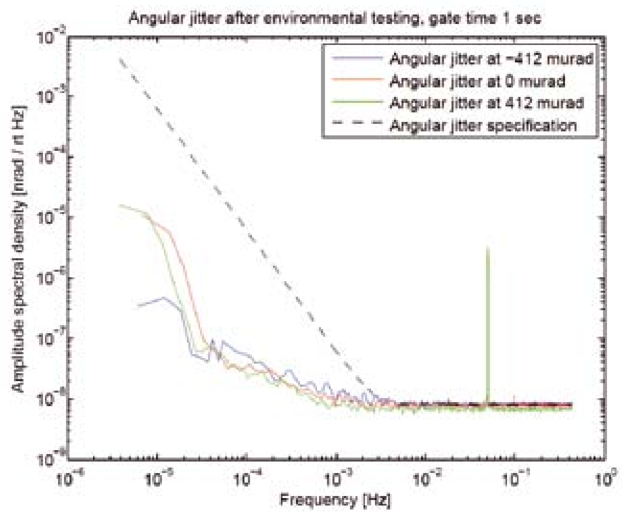



Figure 9. Amplitude Spectral Density of the angular jitter measurements on the PAAM. The PAAM was deliberately placed at an alignment offset, to make the angular jitter dominant in the OPD measurement. For all angles, the result met the requirements. The peak at 50 mHz was introduced to estimate the coupling of angular jitter to OPD.

## Evaluation

The PAAM concept has been based on a rotatable mirror. The critical requirements were the contribution to the optical path length (less than 1.4 pm/Hz$^{½}$) and the angular jitter (less than 8 nrad/Hz$^{½}$). Extreme dimensional stability was achieved by manufacturing a monolithical Haberland hinge mechanism out of $Ti_6Al_4V$, through high-precision wire erosion. Extreme thermal stability was realized by placing the thermal centre on the surface of the mirror. Because of piezo actuator noise and leakage, the PAAM has to be controlled in closed loop. To meet the requirements in the low frequencies, an active target capacitance-to-digital converter was used. Interferometric measurements with a triangular resonant cavity in vacuum proved that the PAAM meets the requirements.

## Conclusion

With the design, realization and testing of the PAAM, TNO Science and Industry has demonstrated that a scanning mechanism with picometer stability that has to operate under extreme environmental conditions is achievable. Performance test measurements have shown that it is compliant with the challenging requirements for optical path delay and angular jitter. The analysis, as well as the measurement results, showed that application of a Haberland hinge in a monolithical structure enables rotation with negligible parasitical motion in terms of optical path delay. The thermal design of the structure proved to be sufficient to guarantee the thermal stability. The angular jitter measurements have shown that an active target capacitive sensor system meets the extreme requirements on low-frequency noise.
The Elegant Bread Board of the PAAM, as used in the performance testing, will be included in a breadboard model of the LISA Optical Bench in the near future.

## References


[1] Danzmann, K., “LISA Mission Overview”, Advances in Space Research Vol. 25, Issue 6, 2000, 1129-1136.
[2] lisa.nasa.gov
[3] Troebs, M., “Laser development and stabilization for the spaceborne interferometric gravitational wave detector LISA”, Ph.D. dissertation, 2005.

# Lasers weld,

*In Ditzingen near Stuttgart, the Trumpf Group organised its Technology Day on February 24 last. The day comprised demonstrations of many Trumpf laser welding and cutting machines, whose names without exception start with the prefix Tru. For example, it was shown how immense sheet metal parts for the automotive industry can be cut and welded on huge TruLaser Cell machines, with TruPulse, TruDisk and TruDiode as versatile laser sources. Also optical systems were shown that distribute laser energy to machining cells: precision technology on a large scale. On a smaller scale, Trumpf engineers showed how precision products that used to be milled from solid, can be realized at much lower prices in sheet metal.*

• *Frans Zuurveen* •

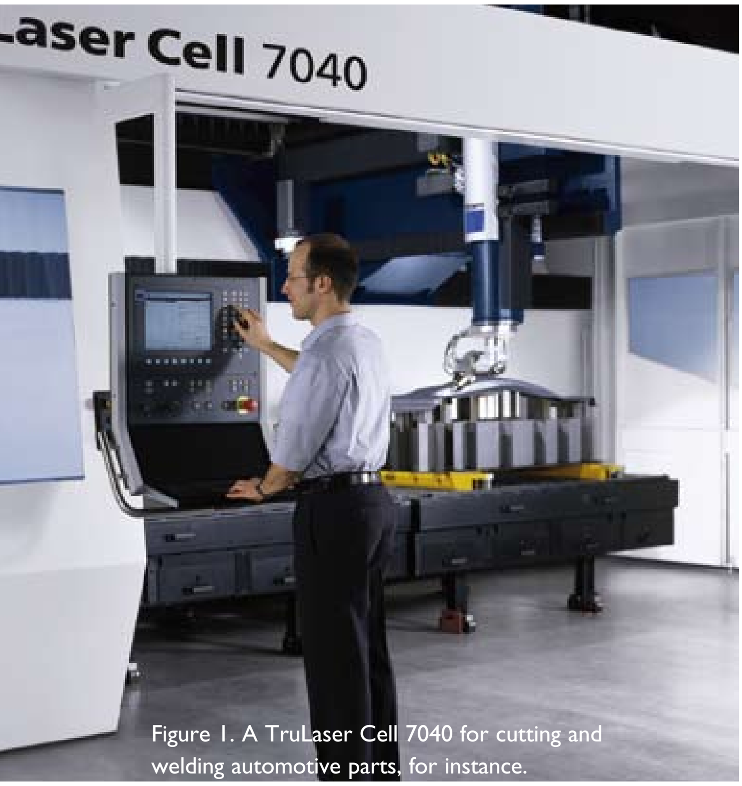


Figure 1. A TruLaser Cell 7040 for cutting and welding automotive parts, for instance.

Albert Einstein seems to have used the term “stimulated emission” in connection with his quantum theory to explain radiation of light. Not much later, in 1923, Christian Trumpf started a mechanical workshop that gradually specialised in the production of machines for sheet metal processing: punching and nibbling.

In 1960, Theodore Maiman constructed the first laser: Light Amplification by Stimulated Emission of Radiation. This invention stimulated the Haas Company in Schramberg to investigate the application of a laser spot for


Figure 2. An example of a laser cut and welded product from sheet steel that replaces a much more expensive piece milled from solid.

# cut and deposit

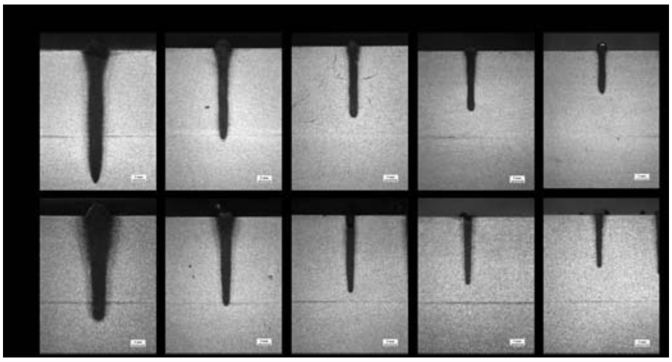


Figure 3. Cross sections that show welding penetration at different speeds (from left to right 2, 4, 6, 8 and 12 m/min) for gas laser TruFlow (upper row) and solid-state laser TruDisk (lower row).

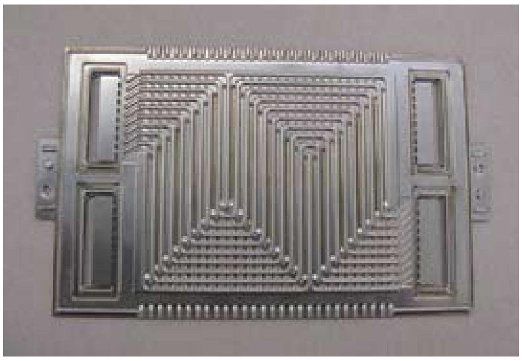


Figure 4. Example of precision welding a 200 μm thick foil with a TruFiber 400 laser.

solving the difficult problem of fastening coiled springs for the German and Swiss watch industry. This resulted in the development of Haas's first solid-state laser in 1970. The renamed Haas Laser GmbH started a co-operation with Trumpf and the latter decided to concentrate on gas lasers, which at that time were able to generate more radiation power. So, in 1985 Trumpf succeeded in developing a 1kW $CO_2$-laser, in 1989 followed by a high-power folded $CO_2$-laser. In 1992, Haas Laser became part of the Trumpf Group and today it has been fully integrated.

In the nineties, gas and solid-state lasers competed in power. In that competition disk-lasers succeeded in multiplying the power of diode-pumped solid-state lasers: today disk-lasers have almost the same power as gas lasers, 16 kW for the TruDisk 16003 and 20 kW for the TruFlow 20000.

This article – drawing from the interesting lectures that Trumpf specialists gave during their Technology Day – aims to explain how Trumpf applies lasers in practice for welding and cutting sheet metal, for the deposition of material and for product marking.

## Laser selection

Many laser types and many applications do not make it easy to choose a laser. Customer requirements that determine the type of laser include strength, material, quality and visual appearance of products. Process parameters are laser power, welding speed, focus diameter and process gas ($N_2$ or Ar to prevent oxidation).

For welding it is interesting to compare a TruDisk solid-state laser with a TruFlow gas laser concerning speed and penetration depth. Figure 3 shows that for large penetration and small welding speed a TruFlow has to be preferred, whereas a TruDisk wins for large welding speeds at small penetration. A real precision product is a 0.2 mm thick foil for fuel cells, welded with a TruFiber 400 laser at 25 m/min, see Figure 4.

For laser cutting it is important to convert as much laser light into heat as possible. The relative quantity depends on the light's wavelength and on the light's incident angle, which is small for small sheet thickness and large for larger sheet thickness, see Figure 5. This means that for small thickness the TruDisk laser is preferable concerning speed and quality, because of its larger absorption at small incident angles. On the other hand, a TruFlow laser can achieve a better quality and larger speed for larger sheet thickness because of its larger absorption at large incident angles.

These examples show that it is necessary to use different laser sources to fulfil the requirements of the various applications, and to consider the complete system from laser source to handling machine.

## Remote laser systems

In TruLaser Cell machines the workpiece moves on guided slides. In a TruLaser Robot the optic system moves by using a robot arm. In both cases the laser light is guided to the cell

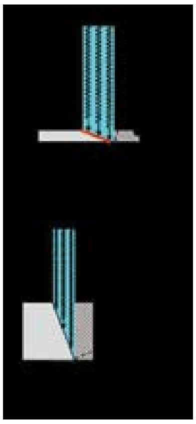


Figure 5. Cutting sheet metal with a small thickness gives a smaller incident angle than when cutting sheets with a larger thickness.

by a glass fibre cable. That cable transports the light from a modular housing that accommodates the beam generator (solid-state or gas laser), the beam guidance system, power supply, cooling and laser control. Some laser modules are provided with mirror systems to divide the laser energy across several machining cells. The distance between cells and laser module may amount to as much as 100 m.

A disadvantage of workpiece or robot movement systems is the unproductive time when travelling from one welding or cutting position to another. In remote laser systems this unproductive time has been nearly eliminated by the introduction of two light-weighted rotatable deflection mirrors. They allow the laser focus point to scan the workpiece, see Figure 6. A work distance of up to 500 mm avoids contamination of the mirrors. A real sophistication is the addition of a camera with image recognition having a resolution better than 30 μm.

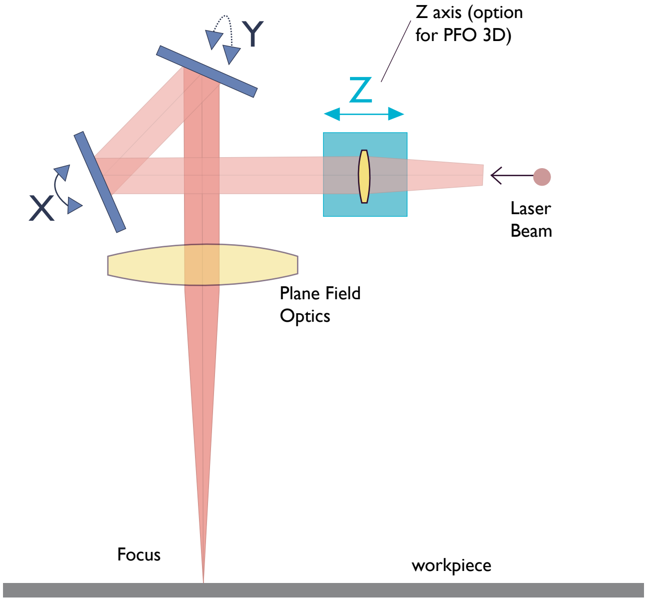



Figure 6. In a remote laser machining system two rotatable deflection mirrors allow the laser focus point to scan the workpiece.


Figure 7. A remote laser system with a PFO 3D (PFO: Programmable Focusing Optics) mounted on a robot for welding a car door. After rough positioning by the robot the PFO focuses the laser spot accurately.

Remote laser systems find more and more applications in the automotive industry, for highly efficient replacement of conventional resistance spot welding. In such systems the combination of a robot and a remote laser system, see Figure 7, provides a very flexible welding system that can yield a process time reduction of a factor three compared with conventional spot resistance welding.

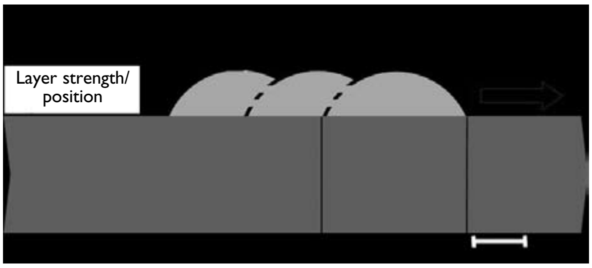
## Highly dynamic 3D processing

TruLaser Cell series 7000 are large machines for 3D welding, cutting and metal deposition, both with solid-state or gas lasers. Off-line programming makes their use more comfortable, also thanks to the user-friendly TruTops Cell Basic software programme package. Maximum working ranges x,y,z are 4,000 x 2,000 x 750 $mm^3$. A gas-laser system is a bit more versatile, as compared to the solid-state laser, and it is able to cut thicker sheet metal.

## Workpiece improvement

Laser deposition welding can be applied to improve surface characteristics of products or to repair them. A laser beam is used to create a melt pool wherein coating material and substrate mix and form a metallurgical bonding in the solid state. The coating material is deposited by spraying powder particles onto the substrate surface.

An abrasion-resistant layer can be created by laying parallel tracks onto a surface with a minimum width of 0.3 mm, a minimum thickness of 0.1 mm and a smallest

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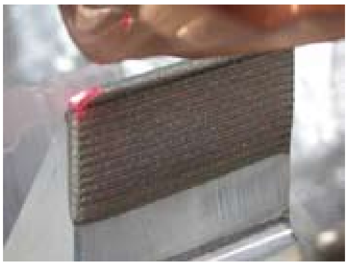

b

Figure 8. Applications of laser deposition welding.
(a) The laying of surface-improving tracks.
(b) A laser coated saw tooth.

overlap of 0.15 mm, see Figure 8. Coating materials for improving resistance against corrosion are nickel alloys (NiCr, NiCrMo) and austenitic steels. Cobalt alloys (satellite) and carbides in a metal matrix (WC, TiC) improve resistance against wear.

The laser deposition process is highly valuable for repairing products like turbine blades and pistons (piston ring grooves). A quite new application is the filling of large gaps, for joining profiles for example.

## Fine-contour processing

Fine 2D cutting with lasers competes with wire eroding and stamping, but laser cutting neither needs a starting hole nor expensive tools and is very flexible when producing pre-series. 3D cutting with lasers is often used for medical technology and for contouring pressed or forced sheet metal parts.

Good examples of products created by 3D laser precision machining (cutting, welding, marking and polishing) are medical transplants, see Figure 9. The only way to design and manufacture such sophisticated products is the application of laser technology.

TruLaser Cell series 3000 machines are applied for 2D and 3D precision cutting and welding, together with TruPulse, TruFiber, TruDiode or TruDisk solid-state lasers. Figure 10 shows how the frequency of pulses from a TruPulse laser can be controlled in curves: fixed pulse frequency or fixed pulse overlap.

## Efficient production

Laser welding of sheet metal parts helps to expand functionality at constant costs, or to reduce costs at constant functionality. Laser welds can be narrow, have a minimal heat-affected zone, are highly reproducible with little distortion, require no filler material and are made without contacting the material.

Welding sheet metal products nearly always requires fixtures. Turnkey systems can be successfully expanded with a TruLaser Robot 5020 with one of the solid-state lasers. A robot positioning accuracy of ± 0.10 mm can be realized at a maximum workpiece weight of 30 kg within a workspace of 2,000 x 1,000 x 700 mm$^3$. For example, savings in time (90%) and cost price (80%) can be achieved by building up a switching frame from two laser cut sheets and laser welding them together, instead of milling it from solid material. Mind that the holes and slots are also realized by laser cutting.

## Laser marking

A CNC-controlled laser in a TruMark machine provides a very flexible and accurate product marking system. Figure 11 shows how marking speed and quality depend on the degree of overlap of successive spots.

Figure 9. A 3D laser cut, welded, polished and marked medical transplant.

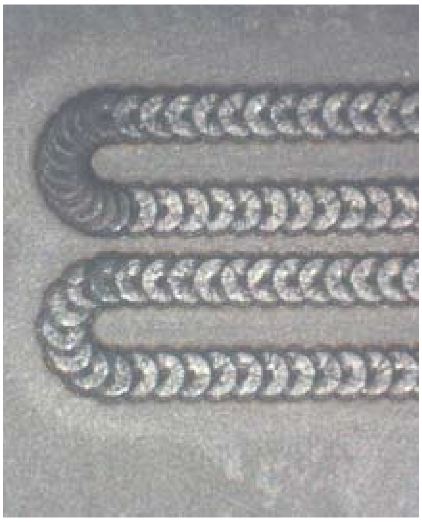

Figure 10. Frequency control of a TruPulse laser in curves. Upper track with fixed pulse frequency, lower track with fixed pulse overlap.

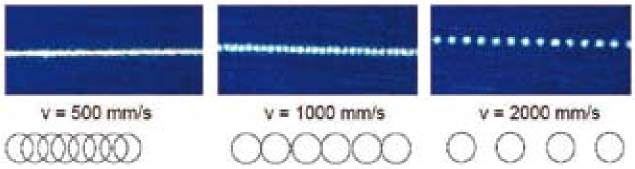


Figure 11. Marking speed and quality depend on the degree of overlap of successive spots.

Various physical phenomena can be applied when marking a product. Most popular is engraving, where surface material (besides metal also some duroplasts or epoxies) is ablated by melting and evaporation, see Figures 12 and 13. Contrast may be increased by oxides in the engraving. Another process is annealing: the material (steels, titanium) is locally heated and changes its structure. Layers of oxide determine contrast and colour. Ablating a coating is a third option, i.e. for marking anodized aluminium or coated surfaces, see Figure 14. The different colours of base material and coating determine the contrast.

Carbonization and foaming are the last processes to be mentioned. Bright thermoplastics can be marked by carbonization, where dark carbon contrasts against the base material. Dark thermoplastics can be marked by foaming, see Figure 15. In this process the marks are bright and contrast against a darker background. Often carbonization and foaming are combined for marking plastics.

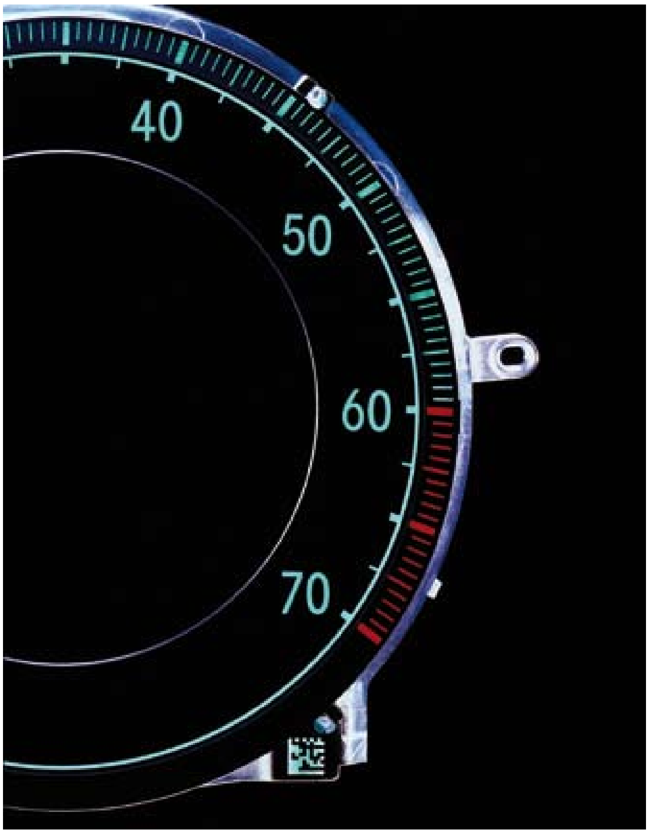


Figure 14. A torque meter as an ablation marking example.

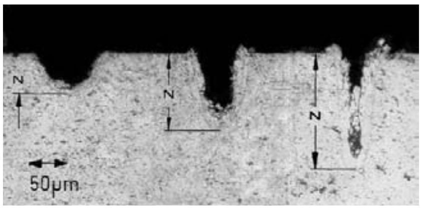


Figure 12. Cross-section of engraved steel.


Figure 13. An engraving example: a punch tool.

## To conclude

The Trumpf Technology Day impressed in two ways. On one hand, laser welding, cutting and deposition machines were shown that combine flexibility with high precision. On the other hand, it was an eye-opener to see how a respected and long-established manufacturer of sheet metal machines has turned its mission into a new direction: innovative laser technology. Nevertheless, to ease the mind of sheet metal workers: the oldest Trumpf branch still flourishes.

## Author's note

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**Information**

www.trumpf.com


Figure 15. An automotive reflector housing marked by foaming.

# The Cornea

***Recent technological developments in vision and imaging will increase the potential for application of optical principles in precision measurement and decision support. This 'vision' had led Dutch engineering company MECAL to extend its portfolio with engineering services and product development support in vision and optronics technology. It now includes automated visual inspections in combination with automated recognition and decision processes, inspections on micron and nanometer level, and development and small-scale production of diagnostic systems. The Cornea Topographer case may serve as an example.***

Technological development leads to an ever-increasing availability of low-cost computing power and CCD-enabled cameras. This broadens the industrial application scope of vision technology in the area of precision inspection and positioning. For example, fully- or semi-automatic 3D shape measurements of precision-engineered parts by full image reconstruction may replace point-to-point measurements by 'conventional' coordinate measurement machines. It helps to speed up inspection considerably.

Figure 1. The Cornea Topographer.

## Inspection

This trend can be applied fruitfully in the area of (defect) inspection. For instance, MECAL has delivered a system for continuous automated inspection of cast parts that are used in car engines. The cast parts have varying shapes with dimensions of up to 50 x 50 $mm^2$. Camera and illumination were developed to meet workshop conditions, an image and learning database was defined, and good/fault recognition algorithms were developed and tested. As a result, deviations (in dimensions) of down to 5 μm can be detected. In general, MECAL expects the accuracy for routine inspection of precision parts to decrease from 10-20 μm to the submicron level within five to ten years. Another factual example is an optical precision scanner, capable of measuring the surface of a 2 x 2 $m^2$ flat object at 10 μm accuracy levels. It will be incorporated in a measurement system, to be used for verifying tolerances of CNC-milling procedures.

Core competences in developing and manufacturing such opto-mechatronic inspection systems are accurate alignment of optical components, optimal control of their positioning, vibration isolation of the mechanical

# Topographer case

construction, and image processing (software). Next to 'still' images, multiple or streaming images may also be inspected, for example in fluid process monitoring (concerning bubbles having dimensions less than 1 mm).

### Medical optics

Interesting medical applications for optical inspection can be found in the field of eye diagnostics. Recently, MECAL has developed two scanning systems for use by (para) medical practitioners. One case involved a collaboration with India, where reaching out to the poor with easy-to-use, high-quality, low-cost medical scanners is a driver for medical technology development. As diabetes has a high prevalence in India, diabetic retinopathy is a logical 'target' for eye inspection aimed at early and easy detection. To that end, an eye scanner and pre-diagnosis system, for analysis of patients' retina and cornea images, was developed in close cooperation with Indian technology partners.

### The Cornea Topographer case

The second medical case involves the Cornea Topographer, which can map the topography of the cornea with higher accuracy and wider range than currently available systems. Mapping the cornea topography is relevant for eye disease detection (such as keratoconus, a degenerative disorder involving changes in the shape of the eye), eye surgery, eye

#### Company profile: MECAL

MECAL is an independent engineering company, offering services and products in various markets. Headquartered in Enschede, the Netherlands, MECAL employs over 100 professionals, working from offices in the Netherlands, USA, and Japan. MECAL analyses, consults, designs, develops and integrates advanced solutions. Having its origin in MEchanical CALculations, MECAL has grown into an engineering company for the semiconductor industry, the wind energy market and mechatronic product development. It can deliver anything from a concept sketch to a complex product in numbers up to 100.

In wind energy, MECAL aims to help customers – major wind turbine manufacturers, developers, utilities, and wind farm owners – to increase performance and enhance the lifespan of the wind turbine(s). In the semiconductor industry, MECAL helps OEMs and fab owners to detect and decrease vibrations in order to enhance the performance of their equipment. Recently, MECAL has extended its scope towards the vision & optronics market.

www.mecal.eu

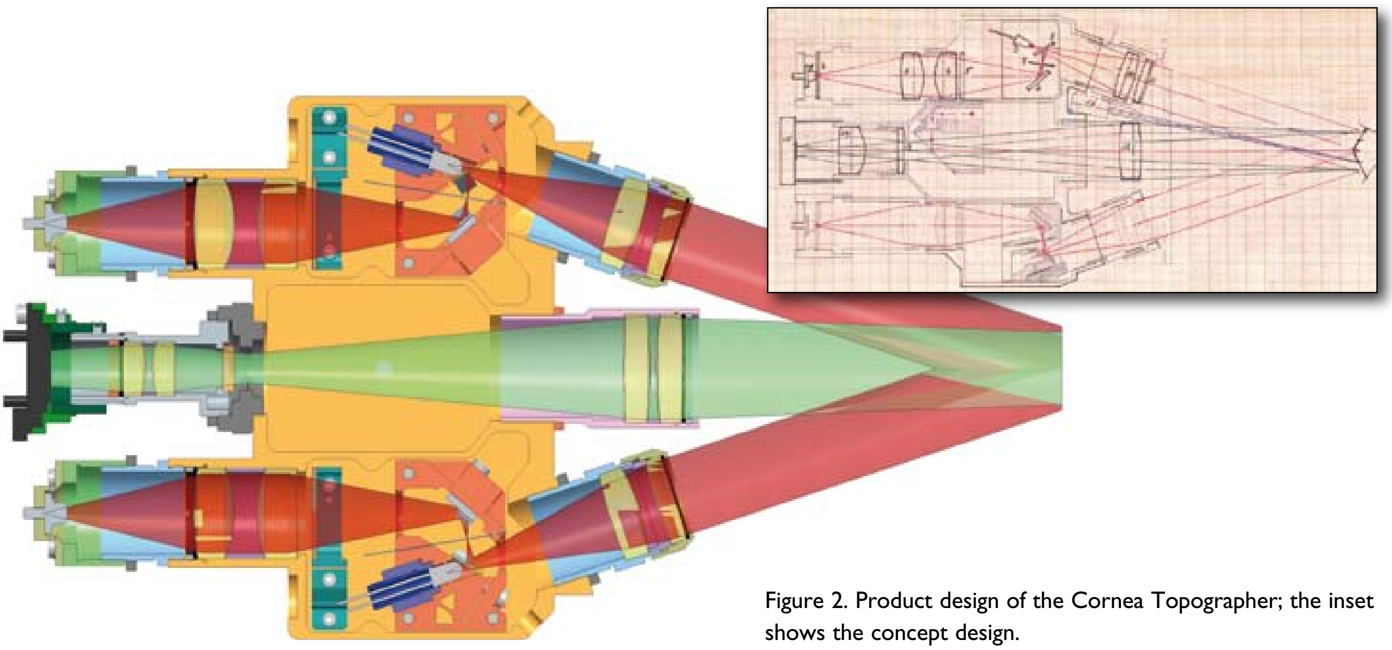

Figure 2. Product design of the Cornea Topographer; the inset shows the concept design.

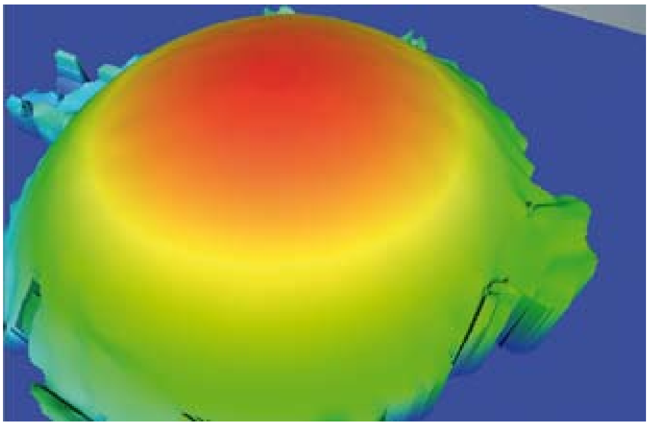

Figure 3. Contour map of the cornea, reconstructed from measurements with the Cornea Topographer.

treatment such as lasering, and contact lense manufacturing (for obtaining a better and more comfortable fit).

## Design

Figure 2 shows the concept design. Two projection units, on both sides of the central imaging unit, are used to project patterns on a circular surface of 20 mm diameter. Interference of the two patterns gives rise to so-called Moiré patterns. These patterns are recorded by a 0.45 million-pixel CCD camera and a software algorim converts the data into contour maps of the cornea; see Figure 3. The uncertainty associated with the data in this map is 25 μm in all three directions.

Figure 4. Detail of the prototype, showing the adjustment of the lenses using elastic hinges.

## Marketing

After MECAL completed the product design, prototypes of the system were built by Nedinsco, based in Venlo, the Netherlands. Figure 4 presents a detailed view of the prototype as show in Figure 1. At the moment, these instruments are being used for clinical studies conducted by Polish medical researchers. Marketing of the commercial instrument, see Figure 5, will be done by Dutch start-up Meyeoptics.


Figure 5. The final version of the instrument for use by clinicians and opticians.

# At the core of our "knowledge society"

***On 27 April 2010, a full-day symposium on microsystems and innovation was held at DIMES, the Delft Institute of Microsystems and Nanoelectronics. The purpose was to offer an overview of the recent achievements in microsystems and the technological challenges that will have to be addressed in the near future. Also, attention was paid to the role that R&D on microsystems can play in industrial innovation and the development of the "knowledge society". The audience consisted of delegates from the academic and industrial communities, as well as of public authorities.***

• *Lina Sarro, Mart Graef and Paddy French* •

Presentations were given by members of the academia and by representatives of large industries and SMEs. They provided the audience with a good overview of the field, the relevance and the impact microsystems are having and will have in many sectors of industry and society, ranging from health monitoring to automotive, and from diagnostics to equipment manufacturing. A panel discussion, which focused on the question how the various stakeholders (large and small industries, institutes and universities, government) can cooperate on microsystems-enabled innovation, followed. During the breaks posters highlighting the microsystems research activities at DIMES were shown. Both during the presentations, the poster sessions and the panel discussion, lively interactions between participants took place.

## Switzerland and Germany

Keynote speaker Oliver Paul, professor at IMTEK (Institute of Microsystem Technology at the University of Freiburg, Germany), gave a clear overview of the research activities in Switzerland and Germany, pointing out where strong research groups are located. He touched upon the

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types and mechanisms of available funding in both countries, and the link to innovation: the “return on investment”. He stated that you never know where innovation is coming from, but you have to be ready when it arrives.
Then he moved on to the microsystems activity at his department. He gave specific examples of research in his group [1]. Interestingly enough, he showed how highly unexpected, but successful applications derived from some basic technological developments and some fundamental studies on 3D silicon structuring and microneedle fabrication his group was engaged in, in the early days. In particularly, he zoomed in on the CMOS-integrated 3D force sensor for coordinate measurements of micro-components (collaboration with Carl Zeiss IMT) and some recent developments in multifunctional probe arrays for brain research (EU project NeuroProbe).

## From ICs to MEMS, from MEMS to ICs

The semiconductor industry has been traditionally driven by cost reduction: more transistors per unit area (Moore’s law), which basically meant more calculations, faster calculations. For microsystems, as pointed out by Reinout Woltjer (NXP), the increase in functionality, the “better” as opposed to “faster”, is the driving force, moving from the “production era” to the “value added era”. The added value is in making life better, providing dedicated functionality. NXP is pursuing MEMS opportunities and focusing research on three types of MEMS devices: oscillators (for timing devices), microphones (mostly for speakers in mobile phones) and galvanic switches (for phones, car networks and radar systems, large data communication).

ASML is, as we all know, market leader in lithography equipment. Lithography is the “heart” of IC manufacturing, the key to smaller and more powerful chips. Innovation is crucial to maintaining such leading position. Maybe surprisingly to some, but less to the microsystems/MEMS researchers, MEMS devices are at the heart of the new lithographic systems. Robert Kazinczi, from ASML, introduced the FlexRay design concept, a fully programmable illuminator for high-NA (numerical aperture) immersion systems; see Figure 1. Illumination source shapes can be generated on demand, by manipulating a large array of MEMS mirrors with electrostatic actuation, instead of the traditional way of inserting optical elements and changing lens positions. The tiny mirrors can be individually tilted, thus optimizing the light path and offering a large flexibility. FlexRay provides on demand (freeform) source availability which allows for reduction in R&D cycle time and device shrink. Moreover, better machine-to-machine matching is obtained through unlimited tuning. This innovative concept which allows scaling down to sub-22nm nodes, has been recently introduced to the semiconductor industry [2], placing once again ASML one step ahead of the competition.

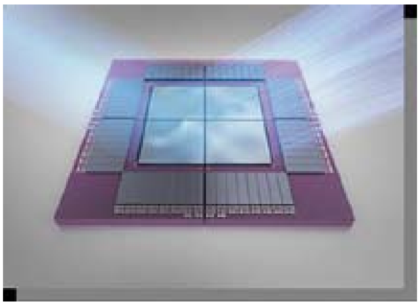

Figure 1. The FlexRay offers flexibility by controllable micromirrors. (Courtesy of ASML)

## Microsystems for automotive

Environmental concerns are becoming a major factor in the development trends in the automotive industry. As illustrated by Paul Gennissen of Sensata Technologies emission legislation and energy availability/climate change dictate both mid- and long-term trends in automotive nowadays. For the long term, alternative fuels and electrical propulsion are the main objectives, while for the mid term the focus is on cleaner diesel, more efficient petrol consumption and more efficient transmission. A giant leap in fuel efficiency can be achieved when the automotive industry converts to closed-loop combustion control where the combustion process is measured by a cylinder pressure sensor. Sensata has been the first to develop a sensor that is affordable and reliable enough to be applied in mass-produced combustion engines. The sensor enables to monitor and correct the combustion process in individual cylinders of both diesel and petrol engines [3]; see Figure 2. In this way engine efficiency is increased and car pollution reduced. The heart of the sensor is a MEMS silicon strain gauge, but the success of the product is in the microsystem approach, i.e. the combination of sensor, dedicated signal processing and clever packaging design. This example once more

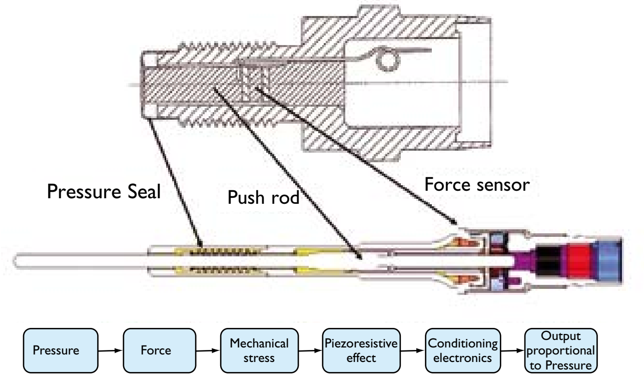


Figure 2. Evolution into a combined cylinder pressure sensor/glow plug. (Courtesy of Sensata Technologies)

underlines the importance of a (micro) system approach, focusing on the “product” that is needed.

## Health: prevention, diagnostics, care

A very interesting parallel between microelectronics and microfluidics was drawn by Albert van den Berg, professor at the University of Twente, to introduce the relevance and potential of the now well-known lab-on-a-chip. As the electronic switch, the transistor, also the “liquid” switch needs to be integrated on a chip to be able to do the necessary complex liquid manipulation at very small scale, down to pico/femtoliter. These manipulations are essential to develop new drugs, to assist in disease diagnostics, in the point-of-care market. The lab-on-a-chip is a technology platform for a number of measurement instruments for the point-of-care segment. Examples include monitoring of ions in liquids, such as lithium content in blood, sodium content in urine, etc. [4] Accurate and easy measurements can help chronic patients to monitor their health, but also to spot and possibly prevent infections.

Cees van Rijn, professor at Wageningen University, pointed out that diagnostics are quite relevant also in the food and beverage industry. His company Aquamarijn Microfiltration [5] develops, fabricates and implements membrane technology for bulk filtration (milk fractionation, beer clarification, etc.) and microanalysis for fast and simple on-line diagnostic applications, based on nano- and microsystems technologies.
As smaller and smaller samples need to be analyzed, membranes with tailored porosity are required. Miniaturized systems which have the advantage of small dead volume and thus hardly any loss of sample, provide a much improved detection limit for cells and bacteria (10 $ml^{-1}$ vs 10,000 $ml^{-1}$). The Aquamarijn microsieves are particularly suited for these analytical applications. Thanks to the high flux, narrow pore size distribution, and smooth pores, a large amount of fluid can be checked on the presence of cells and bacteria.

The fluid under study is concentrated on a small, optically flat surface, suitable for microscopic scanning and fluorescent counting methods. Research in this area deals with the proper material choice for the microsieves (including strength, biocompatibility, possibly “disposable” for some applications); the design of the complete analysis module; improved lab testing methods. Also the automation for continuous filtration systems, for example for drinking water equipment, requires analytical methods to be able to guarantee the reliability of the filtration.

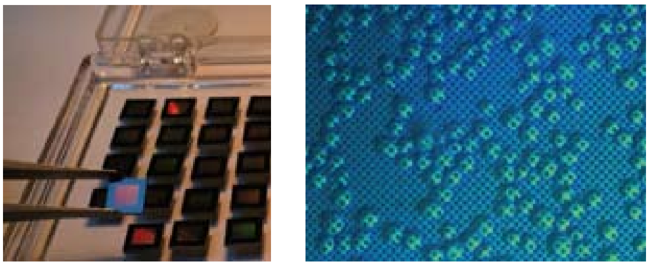

Figure 3. Microsieves, with on the right a close-up of a microsieve with yeast cells. (Courtesy of Aquamarijn Microfiltration).

## The Delft perspective

In his presentation, prof. French showed how microsystems technology started in Delft under the leadership of professor Simon Middelhoek, and which initiatives were taken since then to put Delft on the world map of the field. The start of the STW Technology Foundation was an important step in stimulating applied research in this field in the Netherlands, leading to many successful developments. Since the early days, Delft has seen the importance of having a cleanroom to validate new concepts, ideas and devices. Through these developments, Delft became a major player on the microsystems world stage. A second important step was replacing the initial small cleanroom with a new facility, DIMES. DIMES has since expanded into a large research school encompassing four faculties.
A wide range of microsystems developed in DIMES were presented to illustrate the Delft approach: increased functionality, system integration and new measurement concepts, etc. These included medical research performed in collaboration with a number of major hospitals, fundamental materials studies, environmental and industrial applications along with the technologies specifically developed to support these applications. The goal of


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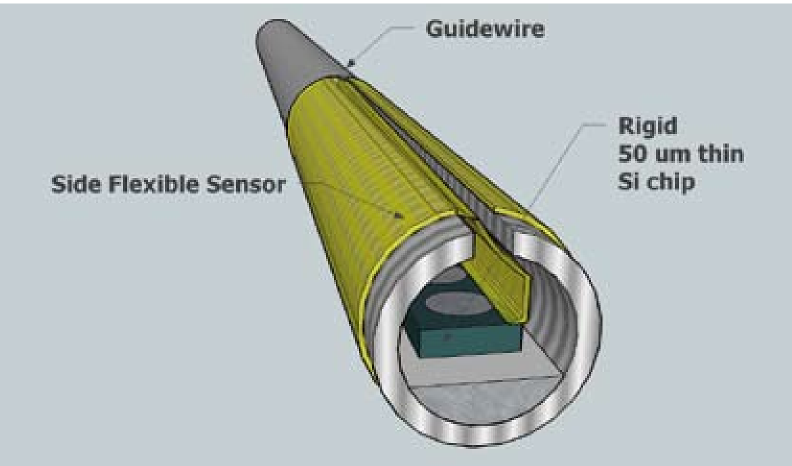


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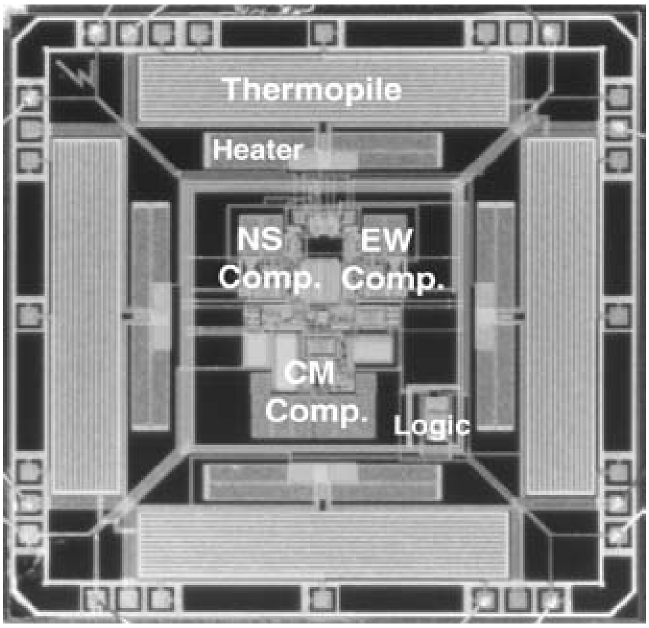


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Figure 4. Examples of DIMES devices.
(a) Blood impedance measurement system [6].
(b) Flexible blood pressure sensors for guide wires [7].
(c) A fully integrated thermal wind sensor [8].

increased functionality and the integral system approach continue to be the driving forces for future development in microsystems.

## Panel discussion

Microsystems constitute the essential building blocks for virtually every domain that defines modern society, such as communication, transport, health care, energy management, safety and security. None of these domains would have developed as they have without the availability of reliable, sophisticated and affordable microsystems, enabled by nanotechnology. Consequently, nanotechnology is a strategic asset for industrial innovation and the knowledge-based society in general. It is clear that, within this landscape, important roles have to be played by large and small companies, universities, institutes and governmental organizations.

These considerations were the starting point for a panel discussion in which the following questions were addressed:

- What are the respective roles of industries, academia and government in the creation of a “nano-electronic ecosystem” in the Netherlands and in Europe?
- Are these roles subject to change? (e.g. industrial vs. academic research; role of SMEs for innovation)
- Which cooperative models would be most effective for the stimulation of innovation?
- Which application domains offer the best opportunities, in view of the Dutch and European capabilities and experience in nanotechnology?
- Are subsidies important? If so, how can these be allocated in the most efficient way? By whom?

The panel agreed that innovation in the emerging “More than Moore” domain strongly depends on cooperation between all partners in the supply chain. They have to provide the multidisciplinary expertise within the consortia, but they are also needed to generate the critical mass in order to bring the technology to the market. SMEs play an increasingly important role in these consortia, but the involvement of and guidance by large companies remains essential. Some people in the audience expressed their concern about the new financial models of various large companies, which could limit their long-term innovative capabilities.

The panel shared the opinion that innovation can not be planned, but that the ground can be prepared for it. In this respect, governments can help by stimulating cooperation and the exploration of technical frontiers. There were some critical remarks about the complexity of the (Dutch) subsidy system, which was judged to be insufficiently transparent. Some panelists expressed the view that the role of government in defining the innovation programme should be limited to the identification of key areas, rather than trying to control a comprehensive innovation process.

It was acknowledged by both the panelists and the audience that invention is still at the core of innovation. The multidisciplinary domain of microsystems offers a unique opportunity for the future of our “knowledge society”, and its importance for the preservation of the European competitiveness can hardly be underestimated.

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# MEMPHIS: a smart

*The Memphis project, funded by the Dutch Smart Mix innovation programme, focuses on developing an integration platform for high-frequency electronics with micro- and nano-photonics. The consortium with 23 partners from SMEs, multinationals, universities and institutes brings together the best players in the Netherlands. The limitations of present electronics require a new massive converging technology based on complementary characteristics of "micro- and nano-electronics" and "micro- and nano-photonics", utilizing the best of both technology worlds. A low-cost combination of the processing power of classical CMOS IC technology, the high-frequency capabilities of modern high-frequency (HF) electronics, and the large bandwidths offered by integrated photonics creates the technology for novel broadband miniaturized electronic-photonic devices. This article focuses on the Production Processes and Equipment subprogramme of the Memphis project.*

• *Lis Nanver, Ruud Polmans, Arne Leinse, Lorraine Flannery and Hans Mulders* •

The partners in Memphis investigate new complex miniaturized devices with vastly increasing functionalities against the lowest possible cost price, which cannot be fulfilled with present micro-electronic technology alone. In order to balance the "market-driven" and the "technology-pushed" technology developments within the Memphis project, several subprogrammes have been defined, focusing on Applications, Technology, Devices and Systems, and Production Processes and Equipment. This article is mainly concerned with Production Processes and Equipment, thereby highlighting the impressive

# mix of electronics and photonics

contributions of Dutch companies in building machines and production equipment for high-tech systems as well as paying specific attention to concrete results in the Memphis project.

## Introduction

Most authoritative scenarios for the development of technology show optimistic views on how our life will be changed by an ambient, intelligent, comfortable and safe environment, by continuous health monitoring, by personal communication and by early detection of threats from


### Authors

Lis K. Nanver, Ph.D., in 1988 joined the Delft Institute for Microsystems and Nanoelectronics (DIMES). She is now a professor in the Faculty of Electrical Engineering, Mathematics and Computer Science, of Delft University of Technology, the Netherlands. Ruud Polmans worked with ASML and Philips Lighting and is now manager engineering at Tempress Systems, based in Vaassen, the Netherlands. There, he is in charge of all engineering activities (mechanical, electrical and software). Arne Leinse, Ph.D., joined LioniX (based in Enschede, the Netherlands) in 2005 and works as a project leader on several integrated optical projects, including Memphis. Lorraine Barbara Flannery, Ph.D., is an applications engineer for Demo Lab Europe at ASML in Veldhoven, the Netherlands. She is currently working in the Opto-Electronics Devices (OED) group at Eindhoven University of Technology, the Netherlands, on ASML Lithography for Optical Integration Technology. Hans (J.J.L.) Mulders, Ph.D., is application development scientist at FEI Company in Eindhoven, the Netherlands. His current specialism is focused beam induced chemistry.

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nature, technical failures and human activities. These areas of interest require the aforementioned new complex miniaturized devices. The limitations of present electronics require a new massive converging technology based on complementary characteristics of “micro- and nano-electronics” and “micro- and nano-photonics”, utilizing the best of both technology worlds. A low-cost combination of the processing power of classical CMOS IC technology, the capabilities of modern high-frequency (HF) electronics and the large bandwidth offered by integrated photonics creates the technology for novel broadband miniaturized electronic-photonic devices. This will open the way to major new applications for the use of light: in medical diagnostics, for healthcare, entertainment, telecommunications, tracking and positioning; see Figure 1. Underlying technologies are ultra-fast signal processing, terahertz imaging, broadband communication technologies, sensor technology, Raman spectroscopy, laser imaging and light sources.

## Consortium

In 2006, Dutch government stimulated the convergence between and the development of nano- and

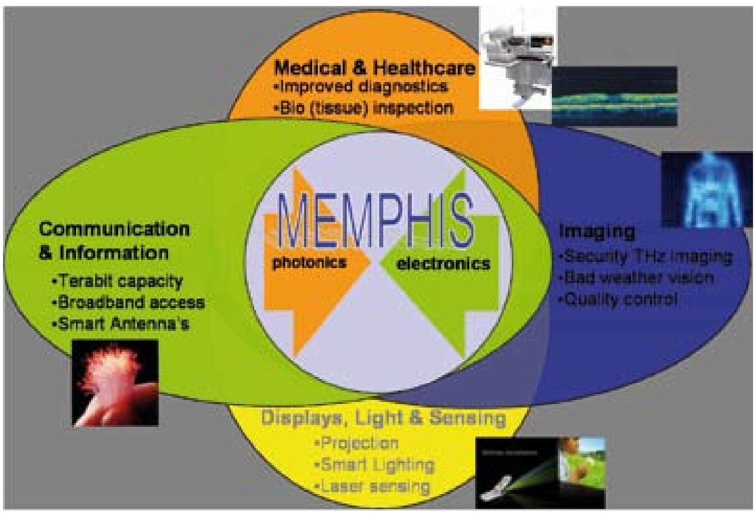


Figure 1. Memphis application areas.

microelectronics and -photonics by disposing subsidy from the Smart Mix innovation programme to the Memphis project. The MEMPHIS project, being an acronym of Merging Electronics and Micro & nano PHotonics in Integrated Systems, is constituted by an excellent consortium consisting of five multinationals, like Philips, ASML and Alcatel, six SMEs, including LioniX, Genexis and Tempress, six university-related research groups, amongst others from the Erasmus Medical Centre and the three Dutch universities of technology, and five research institutes, like AMOLF, TNO and IMEC. This eminent and complementary character of the consortium corresponds to the ambition and the challenge of the project.
The ambition of the Memphis project is to create and exploit synergy effects between the disciplines of electronics and photonics or, in other words, to combine the best of both worlds. This challenge can best be appreciated against the historical background of the main technological force boosting the market for electronics, Moore's law. In the mid-1960s, Gordon Moore, one of the founders of Intel, argued that the capacity per area of electronic integrated circuits (ICs) was doubling every 18 months. However, this miniaturization principle of Moore's law will not be perpetuous, so the concept of "Beyond Moore" has been introduced.

## Beyond Moore

Apart from miniaturization, enhancement of functionality of micro-devices can also be achieved by diversification, i.e. the introduction of new technologies which will generate even more opportunities than Moore's law. Extending the opportunities of basic micro-electronic designs by other physical phenomena and other materials will therefore be of great interest in the years ahead. The most promising option is the merger of micro- and nano-electronics with micro- and nano-photonics. Whereas the classical CMOS IC technology (logic) offers a huge data processing power and modern high-frequency electronics has outstanding wireless connection capabilities, micro-optics is a very versatile technology offering complementary properties. The usage of micro-optical technology is best known in ultra-broadband (data) communication. Also extremely fast signal processing is strongly related to photonics. Additionally, interaction of light and matter offers unique options, for example for materials characterization and processing, for data stream handling by photon manipulation, future illumination and display techniques.
The option of merging the complementary technologies of micro- and nano-electronics and micro- and nano-photonics, being extremely promising for the achievement of outstanding properties for a large amount of applications suited for many markets, therefore constitutes the heart of the Memphis project.

## Production machines

Within the Memphis project, the role of the Applications subprogramme is to create a structure in which the technological research and development activities are continuously linked to the market demands for future applications. The Technology research and development subprogramme is the foundation of the project enabling the various levels of integration of electronic and optical circuits and functions. Because a project as substantial and profound as Memphis, has to cover the total supply chain, the subprogramme Devices and Systems addresses new physical phenomena in advanced structures which will be the basis for new electronic-photonic building blocks. Finally, to create and produce novel electronic-photonic devices and systems, new production processes and associated new production equipment must become available – this is covered by the Production Processes and Equipment subprogramme.

With respect to this final subprogramme, it is interesting to note that Dutch companies have significantly contributed to an impressive history of building machines and production equipment for high tech systems. Apart from the participation of ASML, as the world-leading manufacturer of lithography systems for the semiconductor industry, the activities of companies like Tempress, Lionix, FEI and Alcatel as well as universities like Delft University of Technology have in particular been focused on the world of electronics. It is one of the main challenges in the Memphis project to extend this expertise and experience to the development of production equipment for photonic devices as well. The remainder of this article will highlight some of the progress made in the Memphis project regarding this development of production equipment for photonic devices. The focus will be on impressive results from, respectively, Alcatel, Delft University of Technology Delft, Tempress, ASML and FEI. As a result, it will become clear that the Memphis project contributes greatly to merging the worlds of micro- and nano-electronics and micro- and nano-photonics.

### Etch depth control in Inductive Coupled Plasma etching – Alcatel

In the fabrication of micromechanical structures, Inductive Coupled Plasma (ICP) etching is a good technology to etch anisotropically in different types of material. In these etchers the plasma is induced by electrical currents which are produced by electromagnetic induction, that is induced by time-varying magnetic fields. These etchers can be used for different types of materials, like Silicon (Si), Silicon On Insulator (SOI) as well as for III-V materials like InP and GaAs; see Figure 2. Within the Memphis project, Alcatel supplied an ICP etcher offering superior process performance including very high etch rates, high mask selectivity, excellent etch uniformity and profile controls. However, these ICP etchers until very recently have most often been used for “deep” etching in Si, SOI or glass wafers, i.e. for the world of micro- and nano-electronics. Using the ICP equipment, however, for e.g. so-called TriPLeX™, i.e. for photonic applications, very different demands are set regarding the equipment. In optical waveguides the etch depth is very often small (~ microns) while the demands for footprint control and sidewall roughness are very strict.

Within the Memphis project, an ICP etcher has been developed which is particularly valuable for the realization of TriPLeX™ waveguide structures. Whereas in some applications the challenge for the etcher is to etch in a material as deep as possible, in the realization of TriPLeX™ the exact process control is much more important. Since the exact etch depth determines the performance of the waveguide, etch depth control better than 50 nm is needed.
In order to develop equipment for proper usage in optical waveguide etching, Alcatel has varied several parameters to find the specific relations between the etched structures and these parameters. For example, experiments have been done by varying (bias) power, gas flow, temperature, pressure, sample distance and mask material. Results of these experiments now lead the further development of specific ICP-etchers for optical devices.

### Epitaxy of III-V compounds and Si/SiGe – Delft University of Technology, DIMES

The success of merging photonics with electronics will to a great extend depend on the degree to which the materials used in the two realms can be merged. Basically, this means merging III-V semiconductors such as GaAs, GaN and InP with silicon, being the “workhorse” of the CMOS industry. In the Memphis project, the accessibility of this merger is brought closer by the development of a new tool for III-V Chemical Vapor Deposition (CVD).
Conventionally, CVD of these materials is achieved from high concentrations of gases, including metal-organics, in equipment referred to as MOCVD epitaxy systems. The high gas concentrations, particularly of the highly toxic gases arsine ($AsH_3$) and phosphine ($PH_3$), mean that severe safety precautions must be implemented when running MOCVD. For this reason, most MOCVD III-V material fabricated today is produced in dedicated laboratories not directly connected to Si cleanroom facilities.

In the Memphis project, for the first time the growth of both III-V compounds and Si/SiGe has been demonstrated in one and the same CVD system. A commercial CVD system (of ASMI, see Figure 3) has

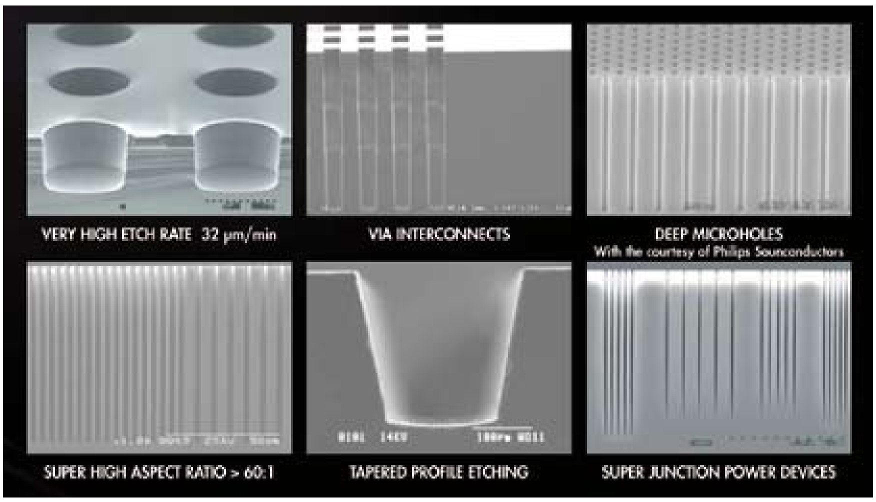


Figure 2. Silicon etching process examples obtained on Alcatel’s Inductive Coupled Plasma etcher.


Figure 3. The ASMI Epsilon 2000 CVD system and its reactor chamber (inset). In Delft, this Si/SiGe epitaxy system has been specially equipped for the growth of III-V compounds in a manner that does not exclude use for Si-based depositions.

been developed for the growth of III-V compounds in a manner that does not exclude the use of the system also for Si-based depositions. For this purpose, the Si system was extended with a TriMethylGallium (TMGa) bubbler and extra tubing to allow the deposition of III-V semiconductors such as GaAs and GaN in addition to the standard Si and SiGe depositions. A very low arsine concentration is applied: 0,7% as compared to the values normally used in MOCVD, which are at least ten times higher. The correspondingly low concentration of TMGa means that contamination of the reaction chamber with Ga or As is so low that standard high-quality low-doped Si and SiGe depositions can still be performed in the same chamber. Moreover, the low gas concentrations permit the system to be run with the same safety precautions that apply to a normal Si/SiGe reactor. Thus there is no issue with respect to adding this equipment to a CMOS cleanroom environment. Finally, it should be noted that, in spite of the very low $AsH_3$ concentration resulting in a correspondingly low growth rate, GaAs growth rates of 1 to 5 nanometer per minute have been achieved. Such values are acceptable for many of today's device applications for which layers in the 100-nm range are required.

### Optimizing atmospheric and LPCVD equipment – Tempress

In order to be able to produce high-quality, low-price and high-volume products with integrated optical and electronic devices, existing production equipment has to be optimized. Within the Memphis project, Tempress researches and develops atmospheric and LPCVD (Low-Pressure CVD) equipment for the fabrication of the optical waveguides based on the TriPLeX$^{TM}$ structures.

The new equipment enables achieving optimal material characteristics. For example, fine tuning is possible with respect to layer thickness, refractive indices, uniformities, reflow characteristics and compatibility with other processes. Another specific challenge for Tempress is to design and build a new horizontal LPCVD furnace that has much tighter specifications than a normal LPCVD furnace. In order to achieve these results a new furnace frame has been developed. This frame contains a new loading system for the ATM (atmospheric) oxidation furnace that makes faster loading possible. Also, cleaner process results can be achieved because no unwanted materials stay in the process tube. Moreover, to get cleaner LPCVD furnaces a new way of vacuum line heating has been designed: individually controlled heated sections ensure that particle formation is minimized. These kinds of optimization of the existing atmospheric and LPCVD equipment enable the definition of an improved CMOS-compatible optical backbone circuit.

## The specific requirements of complex photonic devices – ASML

The photonics market has a unique set of challenges that need to be addressed on equipment that was originally driven by the manufacturing needs of the Si-oriented semiconductor industry on 8- and 12-inch substrates. The photonics market consists of a plethora of devices, manufactured from a variety of material systems and using a wide range of technologies, each with their own set of application-specific requirements. This translates into system adaptations needed to take into account the physical properties of the material systems (e.g. substrate type, size, fragility) and the consideration of the application requirements of a large number and variety of components to find the best overall lithography solution.

Imaging solutions down to a (half pitch) resolution of ≤ 150 nm for 3- to 8-inch substrates and to ≤ 90 nm for 8-inch substrates are available on the PAS 5500 platform; see Figure 5. ASML is collaborating with the COBRA


Figure 4. Tempress equipment developed within the Memphis project: the LPCVD and atmospheric oxidation furnace. From left to right: touchscreens for process control; loader units (the upper one for the newly developed ATM process, the lower three for LPCVD); and four gas systems, one for each process (behind them, not visible, the process chambers).

Institute at Eindhoven University of Technology to facilitate the development of a special carrier to allow Deep UV lithography solutions down to ≤ 100 nm on 2-inch substrates and wafer pieces for R&D purposes in InP Photonic Integration Technology. In order to reduce prototyping cycles for photonic and electronic integrated circuits, ASML has developed Compound Image Design (CID) software which enables the easy creation of compound images as large as the wafer itself, giving maximum flexibility for multi-product wafers. It also allows stitched designs that are larger than the lithography systems imaging field or contain more than one occurrence of a pattern.

In addition to the different material systems and device design considerations, the lay-out of planar photonic components does not adhere to the same design rules as used in Si-based micro-electronics, where similar structures are imaged on the same layer and the size of the feature never exceeds the half pitch. Most of the patterns used in photonics are non-orthogonal (curved geometries) and require precise critical dimension (CD) control. In addition, to meet strict alignment criteria, photonic components which are incompatible from an imaging perspective are printed on the same layer. All ASML PAS 5500 systems can be configured with a number of different imaging, overlay, productivity and focus improvement options depending on the application requirement to extend manufacturing for challenging layers.

## Deposition of gold by Electron Beam Induced Deposition – FEI Company

For photonic and plasmonic structures a thin film of gold is one of the most relevant base structures. Local functionality can then be achieved by creating a micro- and nano-scale structure within this film. The main reasons for this interest in gold are its optical behavior as well as its good conductivity. Unfortunately, that same element of gold is a forbidden material in any CMOS factory due to its high mobility in the semi-conducting base material and its capability to reduce the junction performance, and hence kill the device locally. As a consequence, gold patterning has not been of major relevance in the CMOS industry. When merging micro- and nano-electronics with micro- and nano-photonics, the issue of creating and modifying small structures of gold becomes however very relevant.


Figure 5. The PAS 5500/1150 193-nm Step-and-Scan system enables cost-effective 90-nm ArF mass production.

Figure 6. The Magellan is FEI Company's latest commercial instrument in the high-end range of SEM. It can be used for imaging the latest challenges in electro-optic structures, and its development was supported by the Memphis project.

Standard patterning of gold is done by optical and electron beam lithography, using resist patterning and lift-off generation of a suitable mask. However, in the early development phase of creating and modifying plasmonic structures, these methods are not very flexible, require a multi-step approach and only offer a 2D patterning capability. Moreover, lift-off using electron beam lithography also easily suffers from inhomogeneities in structures, when looking at the nanoscale.

Another solution for direct deposition of gold is by Electron Beam Induced Deposition (EBID). This technique is relatively new and recent developments focus on direct deposition of conducting (platinum, tungsten) or non-conducting ($SiO_2$) materials. The basis of this technique is the in-situ gaseous delivery in a SEM (Scanning Electron Microscope; see Figure 6) of a precursor gas that adsorbs on the surface. When the electron beam hits the surface, locally induced electrons decompose the adsorbed layer, creating both volatile and non-volatile parts. The latter is the metal of interest, while the former parts such as CO are pumped off by the vacuum system.

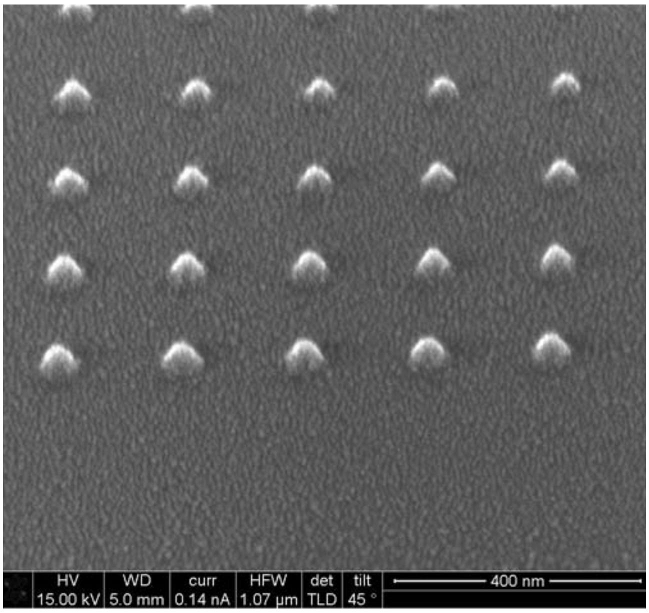


Figure 7. An array of nano-scale gold dots created by direct electron beam induced deposition. The structures are around 35 nm wide and 30 nm high. The purity of the gold is > 95 at% and the creation time of the 10x10 matrix is around 3 minutes.

This direct deposition technique is very promising, but for the deposition of gold the purity of the material is too low. For this reason a new process has been developed within the Memphis program that allows the deposition of nanoscale 100% pure Au by direct-write EBID; see Figure 7. This process can now be used for the creation of complete structures, but also has the capability to locally add gold to a non-homogeneous Au structure created with e-beam lithography. In this way, it is possible to repair non-perfect structures.

## Conclusion

The new processes and equipment developed within the Memphis project will become instrumental for the merging of micro- en nano-electronic functionalities and the micro- and nano-photonic devices that will make up the next generation of products. These new products can be made at lower cost and with increased functionality in a smaller footprint. The Dutch companies that participate in this Memphis project have made a substantial contribution to the new requirements of merged electronic and photonic devices.

**Information**

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# "More than mechatronics"

***On 15 April, the Mechatronics Valley Twente Foundation (MVT) held its seventh TValley conference, entitled "More than mechatronics". The event in Enschede, the Netherlands, was well-attended and comprised a conference and exhibition on innovation and business for the high-tech manufacturing industry. The programme focused on exploring applications of mechatronics in various industrial and societal sectors, including robot surgery and rehabilitation as well as solar cell manufacturing and high-tech materials processing.***

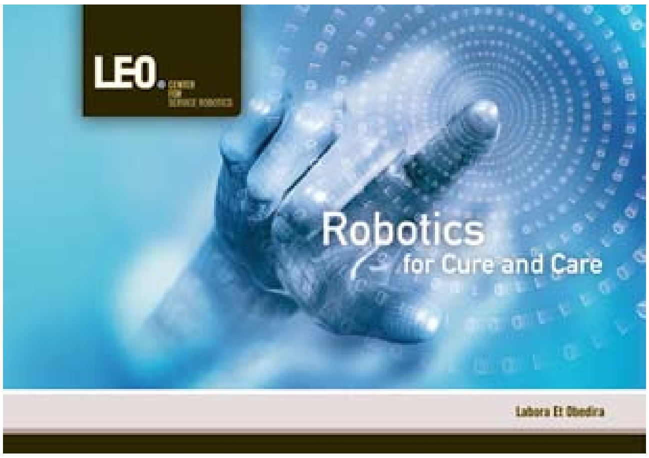
• ***Hans van Eerden*** •

The Dutch high-tech systems industry is renowned all over the world, thanks to mechatronics, the combination of disciplines such as mechanics, electronics and software. The mechatronic approach has resulted in numerous technical highlights, including ASML lithography machines, FEI electron microscopes and Philips medical scanners. However, the application range is much wider. Fertile soil can be found in the Eastern part of the Netherlands in the Twente region, so Arie Kraaijeveld, president of the Innovation Platform Twente (IPT), claimed in his opening statement of the TValley conference on 15 April in Enschede.

**Author**

Hans van Eerden is a freelance text writer in Winterswijk, the Netherlands, working for clients such as Mechatronics Valley Twente Foundation, and editor of Mikroniek.


(Photos, unless otherwise stated: University of Twente)




IPT-president Arie Kraaijeveld (right) has received the first copy of the "Robotics for Cure and Care" report; on the left MIRA managing director Martijn Kuijt.

Kraaijeveld described 'his' IPT as a support system that keeps the regional 'innovation machine' running by defining new projects again and again. For example, promising projects can be found in the area of (medical) robotics. November last year, researchers and entrepreneurs from the Eastern Netherlands visited the US east coast for inspiration. Their findings were published in the "Robotics for Cure and Care" report. Arie Kraaijeveld was handed over the first copy by Martijn Kuijt, managing director of MIRA, the biomedical technology and technical medicine research institute at the University of Twente.

## Surgical robotics

This kick-off nicely introduced the first three presentations, on robotics for surgical and rehabilitation applications. Chairman of the day Herman Soemers, senior mechatronics consultant at Philips Applied Technologies and professor at the University of Twente in the MVT-financed chair of Mechatronic Design, announced as the first speaker Ivo Broeders, professor of Minimally-invasive Surgery and Robotics at the University of Twente, and surgeon in the Meander Medical Centre in Amersfoort, the Netherlands. Robot-assisted surgery has been more than science fiction for a long time already, Broeders stated. Mechatronic solutions provide the accuracy, safety and ease of use that are required for 'keyhole surgery'. Advantages for the patient of this kind of surgery as compared to conventional (large incision) surgery include less pain, better recovery and less scar ruptures. Worldwide, over 1,400 pieces of the well-known Da Vinci surgical robot have already been installed; they are being applied successfully for urological and other procedures.

The latest challenge, according to Broeders, is NOTES, Natural Orifice Translumenal Endoscopic Surgery, that is surgery via natural orifices using a flexible endoscope. At the University of Twente, technical medicine research is devoted to low-complexity, high-volume NOTES procedures, such as the removal of polyps from the gut. With that application in mind, an intuitive control, a kind of 'cockpit', is being developed for a surgical tele-manipulation system based on the flexible endoscope.

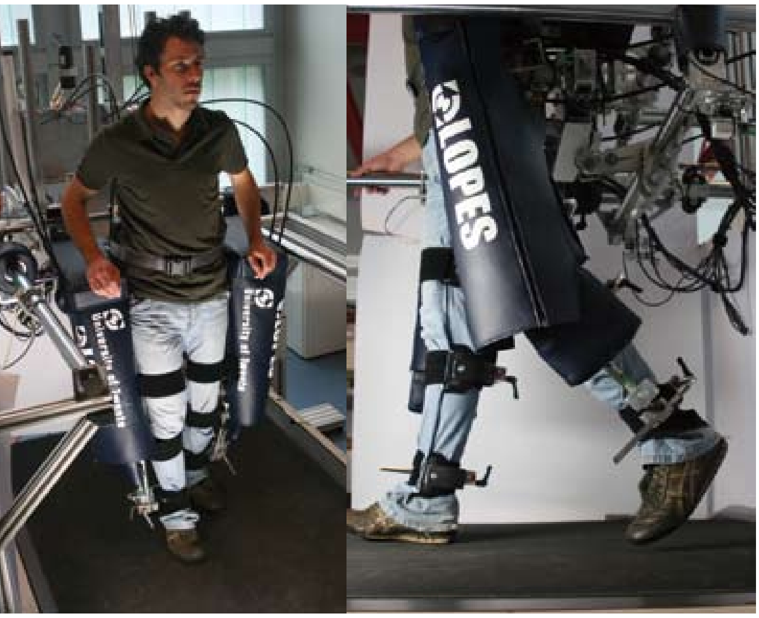
## Rehabilitation robotics

In the area of rehabilitation, robots also are on the rise, for gait training of patients recovering from, for instance, a stroke. On this subject, Twente has hit the spotlights with gait training robot LOPES, that was developed by the University of Twente (MIRA research institute) in collaboration with Roessingh Research & Development, part of the Enschede-based Roessingh rehabilitation centre. Here, the added value of mechatronics lies in patient safety and smart control engineering that allows the patient to do as much active training as possible.

At the TValley event, university researcher Herman van der Kooij discussed the biomechatronics discipline, which views a human being as a mechatronic system, the aim being twofold: learn to understand human locomotion, and provide support in locomotory training. Next, Van der

Kooij addressed the nature of this support, either position-controlled (the patient being passive) or force-controlled (active patient). On this second approach the design of LOPES (Lower extremity Powered ExoSkeleton) was based, according to the 'assistance as needed' principle: the patient himself is moving and the gait training robot only provides the required additional support as determined by a smart algorithm. The effectiveness of this approach has already been demonstrated, but yet has to be substantiated by clinical evaluation.

Therefore, Rik Kruidhof, business developer at MVT member DEMCON, discussed the next phase, the development of LOPES into a commercial product that can be used in the clinic for validation of robotic gait training therapy. This broad application in clinical research requires LOPES to be highly accessible in its use, with simple controls and interfaces, and results that are made available in a simple and quick manner. Kruidhof also addressed marketing: "LOPES is not a robot, but a new way of rehabilitation. The added value when compared to current therapy lies in better reproducibility." In this way, LOPES may become a fine example of high-tech research leading to a clinically relevant product.




A test person using the gait rehabilitation robot LOPES. (Photos: RRD)

Impression of TValley 2010.

## Multi-agent control

Theo de Vries, director of MVT member Imotec and associate professor of intelligent control and mechatronics at the University of Twente, devoted his presentation to modern machine control. His thesis was that in years past progress mainly was achieved in the area of hardware, where controller design more or less has become a matter of 'plug & play', that is configuring a number of standard modules. Whereas with software, design still is a case of 'program & pray'. There has been some standardisation, using function block libraries, but a lot goes wrong in programming, especially in the conditional realm ("if… then…else"). Moreover, the testing is very time-consuming and a lot of software is not re-usable.

The solution according to De Vries lies in multi-agent control: the control of a system is compiled from a number of agents that each perform a specific task (in parallel). This approach yields less code, with less complexity (and hence less errors) and more potential for re-use. The use of agents (or modules) instead of function blocks, De Vries claimed, may turn design on the software level into configuration as well. It may even add new momentum to high-tech machine building in the (Eastern) Netherlands.

## Inkjet printing

A high-tech mechatronic application area on the rise can be found in (inkjet) printing. Twente Fluid Physics professor Detlef Lohse, who last year was named Simon Stevin Master, the highest degree in technical-scientific research in the Netherlands, addressed the hydrodynamics of the printing process. Here, the biggest challenge is in the formation of air bubbles in the print head. These bubbles can grow to such a size that they disturb the ejection of ink droplets. Lohse showed results of high-speed video investigations on the origin of the bubbles. Also, his research group had developed an ingenious, piezo-acoustic method for determining bubble dimensions.

## Collaboration

An example of Mechatronics Valley Twente collaboration was presented by MVT members Masévon Technology and DEMCON. Commisioned by OTB Engineering, it was concerned with the development and realisation, within a very short time span, of a sputter tool, for thin layer deposition in solar cell manufacturing. Masévon director Henk Kieft talked about the systems his company is building for Eindhoven-based OTB, a manufacturer of in-line solar cell production systems. The processes include for example PECVD (Plasma-Enhanced Chemical Vapour Deposition) for deposition of a SiN anti-reflection layer. Kieft stated that 80% of the solar systems built by Masévon end up in China.

The Masévon-DEMCON collaboration involved a tool for deposition of aluminum and vanadium contact layers, with glass acting as a carrier. The OTB commission was to deliver, within a mere twelve weeks, an R&D tool, which at a later stage could be converted into a production tool. To meet this tight deadline, the principle of concurrent engineering was put into practice: design phases were executed in parallel and compressed to the max. This required a truly multi-disciplinary team to work on a common design specification that continued to expand during the project. Therefore, it was mandatory to keep the design plan as flexible as possible, to accommodate changes on the go.

Technical challenges included the design of the large vacuum kettle in which the sputter process takes place, the vacuum loadlock (minimal pumping time) and a vacuum-compatible drive for the product carriers. Finally, the sputter tool was delivered in time. DEMCON team leader Jan Leideman concluded: “Without the close collaboration between Masévon and DEMCON, in which the fortes of both parties were employed optimally, we would not have succeeded in achieving this at such short notice.”

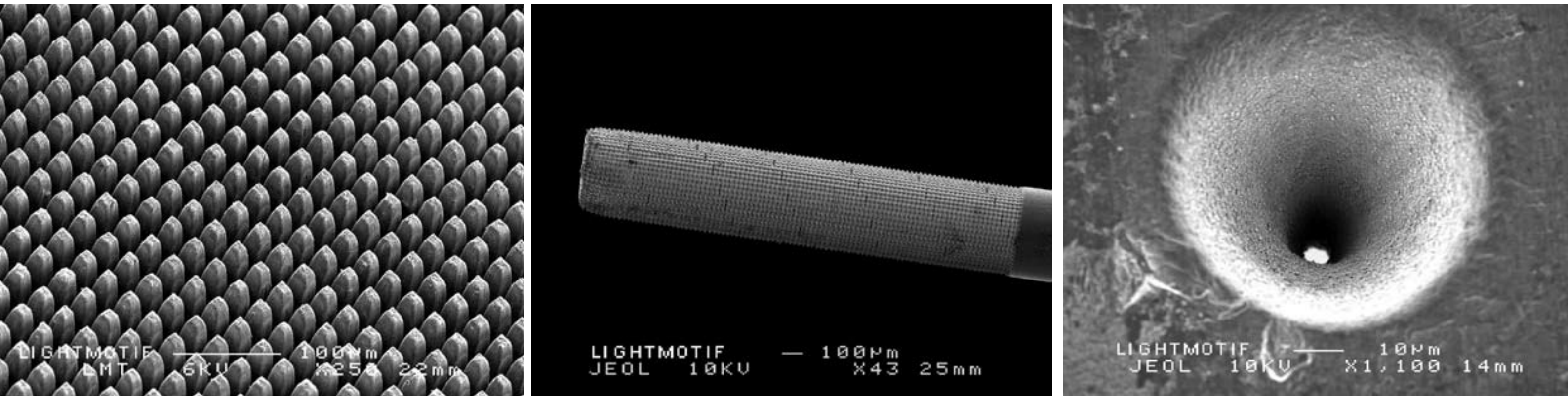
## MVT Mechatronics Award

As an intermezzo in the afternoon of 15 April, the MVT Mechatronics Award was presented. This award of the Mechatronics Valley Twente Foundation for best master thesis in the area of mechatronics was presented for the fourth time. The jury was chaired by professor Herman Soemers and staffed by University of Twente mechatronics-related (associate) professors. Six master theses were judged concerning mechatronic content, quality, creativity and the student’s stimulating effect on fellow junior mechatronic engineers. The winner was Claude Lagoda from Luxembourg, who graduated with Herman van der Kooij and professor Frans van der Helm from Delft University of Technology. The subject of his master thesis was “Design of an electronic Series-Elastic Actuated Joint (eSEAJ) for the gait rehabilitation robot LOPES”.

Herman Soemers, chairman of the de MVT Mechatronics Award jury, addresses winner Claude Lagoda.

## Lightmotif

Next, university spin-off Lightmotif director Max Groenendijk presented the potential of micro- and nano-manufacturing using ultrafast laser pulses (pulse lenght less than 50 ps). The advantage of these ultrafast pulses is the highly accurate machining of a metal surface without affecting the underlying bulk material, as time is lacking for the laser heat to penetrate the material. Moreover, laser machining in general benefits from being contactless (and thus having no tool wear), which further increases the attractiveness of ultrafast laser machining for various applications. For example, moulds for plastic products




a b c

Examples of ultrafast pulsed laser machining. (Photos: Lightmotif)
(a) Textured polymer surface.
(b) Textured needle (used for precision measurements on hydrophobic surfaces).
(c) Nozzle hole in metal foil.

manufacturing can be textured so as to make the resulting plastic surfaces hydrophobic, which can be useful for 'self-cleaning' packagings. Also, the friction properties of surfaces can be manipulated, making them for instance direction-sensitive by laser machining. And a completely different application can be found in the manufacturing of waveguides for opto-electronic components. In short, there are endless possibilities, wich is reflected by the growth of Lightmotif. It started in 2008 on the university campus, moved to the Enschede-based Business & Science Park in 2009 and will open a new laser lab and a cleanroom in the course of this year.

## Warning

After all the inspiring presentations on "mechatronics and more", it was Delft professor Rob Munnig Schmidt's turn to close the conference. He seized the opportunity to express his concerns about the state of mechatronics in the Netherlands. Philips, which had been the leader in Dutch mechatronics for decades, no longer is active in this field, so Munnig Schmidt. Moreover, mechatronics as it is now being pursued in the Netherlands, is biased due to its physics orientation. "It is highly succesful, yes, but there is something missing in the area of manufacturing technology. And, is there any chance that the mechatronics industry can survive without manufacturing? No!" Software-based innovation, such as the TomTom navigator, can not be sustained, the Delft professor issued a warning. On top of that, there is too much internal competition in "our little country". Munnig Schmidt proposed the model of one large virtual company, in which Dutch parties jointly communicate, design, manufacture and market. To conclude, he addressed the problem of 'technology pull': solving (short term) technological problems for companies is detrimental to fundamental research. "In the end, this is killing the Dutch universities of technology."

## Cross-pollination

Luckily, Munnig Schmidt still found justification for a favourable outlook on Dutch mechatronics. To that end, he identified traditional Dutch strongholds, including agricultural technology and the offshore industry. "We have to exploit our market domination in 'agri' and offshore. Here, it is possible to apply knowledge from other areas (such as ASML wafer steppers). This cross-pollination has hardly been put into practice up to now." In this way, the TValley congress on "Mechatronics and more" was concluded with a call for scanning all kinds of markets on their potential for mechatronic applications.

**Information**

www.tvalley.nl

# Seminars, from contamination to aerospace

**The standards for products and materials are being raised due to increasing miniaturization. Cleanliness of materials and components is becoming more and more important: unclean equals unusable. Therefore, contamination is a major challenge for industries such as semiconductor and aerospace. To address this problem, a large number of cleaning techniques is available, ranging from ultrasonic to megasonic to UV cleaning. Mikrocentrum and DSPE are working together to organize an event devoted to contamination, which will take place in the autumn this year.**

Topics of other seminars of interest that will be held this autumn, include micro and precision machining, machining technology in general, materials, corrosion, and aerospace. Pertaining to this last topic, Mikrocentrum has joined forces with NVR (the Dutch Aerospace Association) to bring space to SMEs in a number of seminars in the forthcoming years. In preparation, this autumn a "meet & match" will be organized to discover how both worlds can benefit from each other. Topics to be covered: mechanics and electronics miniaturization, design for low power consumption, emerging technologies such as opto-electronics, and systems engineering.

www.mikrocentrum.nl

### 2010 Precision Fair

This year, the Precision Fair will be held on 1 and 2 December, once again in the NH Conference Centre Koningshof in Veldhoven, near Eindhoven, the Netherlands.

www.precisiebeurs.nl


### Positive result 2010 Fotonica Evenement

On 30 March 2010, the fourth edition of Fotonica Evenement attracted as much as 500 visitors. The participants of the Knowledge Exhibition and the Knowledge and Education Square were satisfied about the attention they received. The seven high-quality tracks of the conference programme were also much appreciated.

The previous editions of Fotonica Evenement have been empowered by the Dutch Ministry of Economic Affairs. The next (jubilee) edition will be organised by Mikrocentrum in cooperation with Photonics Cluster Netherlands (PCN). Because of the success and an expansion to a wider range of topics, it will be a two-day event.
Fotonica Evenement 2011
Tuesday 29 and Wednesday 30 March 2011
Nieuwegein's Business Center, Nieuwegein, the Netherlands

www.fotonica-evenement.nl

# Euspen 10th International Conference

From 31 May to 3 June 2010, the Euspen 10th International Conference was held at Delft University of Technology, the Netherlands. The conference attracted over 400 participants and 45 exhibitors from Europe, America and Asia. Keynotes were delivered by Dr Jos Benschop of ASML, on Extreme Ultra Violet Lithography, and Prof. Rob Munnig Schmidt of Delft University of Technology, on the current international status of Adaptive Optics. Besides, a large number of oral and poster presentations was delivered on the latest advances and market developments in precision processes and manufacturing, as well as fabrication, metrology, sensing applications and cutting-edge materials.
The September issue of Mikroniek will feature a full report on the conference.

www.delft2010.euspen.eu

Euspen president Henny Spaan opens the Euspen 10th International Conference in Delft. (Photo: Nicole Minneboo)

# World record 1.2M rpm from Leuven

Researchers at K.U.Leuven, Belgium, have succeeded in making a shaft rotate at a speed of 1.2 million rotations per minute. The shaft, which is 6 mm in diameter, is suspended in aerodynamic radial air bearings. Due to the fact that the shaft does not touch any other parts, there is no wear, even at 1.2 million rpm. Multiplying rpm with shaft diameter yields that the shaft surface reaches a speed of 377 m/s, or Mach 1.1, a world record in self-acting air bearing technology.

The speed of air bearings is usually limited by instabilities, but the researchers solved this problem by developing a special damping mechanism. Moreover, in contrast to aerostatic air bearings, which operate on a compressed-air supply, this air bearing is aerodynamic (or self-acting) and thus develops sufficient bearing pressure from its own rotation. This is particularly beneficial as the self-pressurising system can operate autonomously. These high-speed bearings will be used in turbos, small gas turbines, compressors and micro-milling cutters.

www.powermems.be/pen_setup.html

# More training

Technical Training for Professionals (T2Prof) has engaged in a collaboration with Techwatch, editor of Bits&Chips and Mechatronica Magazine, to market electronics and optics training programmes. These programmes, a total of thirty, are aimed at experts and engineers that require a fast introduction to a new discipline. The majority of trainers come from companies like Philips, NXP and ASML. T2Prof was started this year by Hans Vink, who was programme manager at Philips Centre for Technical Training (CTT), which ceased all its activities as of 31 December 2009.

www.t2prof.nl
www.hightechtraining.nl

# Obituary: Theo Bisschops

In early March it was announced that Dr Theo Bisschops had died at the age of 53 as the victim of a random murder attack. Theo Bisschops had been working at Philips Research in Eindhoven, the Netherlands, for nearly twenty years. He was a well-respected researcher, working in different fields including vacuum technology, where he contributed to such things as the development of technology for Extreme Ultra Violet Lithography. Theo Bisschops's death is a great loss to his family, his colleagues at Philips and the Dutch precision engineering community.

# Sensors central in society

The possibilities of sensors and their applications are enormous, as was showcased by the twelfth edition of the Sense of Contact. Despite one of this year’s largest traffic jams on the Dutch motorways, some 90 people turned up on 8 April in the Woudschoten Conference Centre in Zeist.

First speaker Leo Schultze Kool, of MiTeC (Minimal invasive Technology expertise Center), delivered a stimulating presentation on the scope of this center. In MiTec, Radboud University Nijmegen and University of Twente have joined forces on a wide range of disciplines, aimed at fast and adequate diagnostics and treatment using the latest techniques to minimize the “damage” sustained by patients.

Next, in parallel sessions, Dutch universities, institutes and industry presented their recent sensor research and development according to challenges in art, safety and autonomous sensors. For a hands-on experience several demonstrations showed the possibilities of sensor applications. Also, real-life cases presented technical challenges of sensor development.

The event, which included an exhibition, was targeted at sectors ranging from high-tech equipment, industrial automation and automotive to laboratory & medical technology, academic hospitals and microsystem and nanotechnology companies. The Sense of Contact 12 was organised by FHI Federation of Technology Branches and STW Technology Foundation.

www.fhi.nl/senseofcontact

Impression of the exhibition during the Sense of Contact 12.

# Micro/Nano Atlas of Germany

Micro- and nanotechnology companies from Germany are successful players on global markets. Areas in which the German industry is particularly strong, are described in a new survey, the Micro/Nano Atlas of Germany. This Atlas is the first survey that gives a complete and unique overview of the micro- and nanotechnology industry in Germany, including research activities, regional concentrations and industry clusters, funding policy, market and application trends, and the current economic situation – all illustrated with numerous maps and figures.

As a supplement to the survey, IVAM Research has compiled the Nano Guide of Germany database. This Guide is an inventory of more than 1,500 enterprises and innovative research institutions engaged in microsystems technology, nanotechnology or advanced materials throughout Germany.

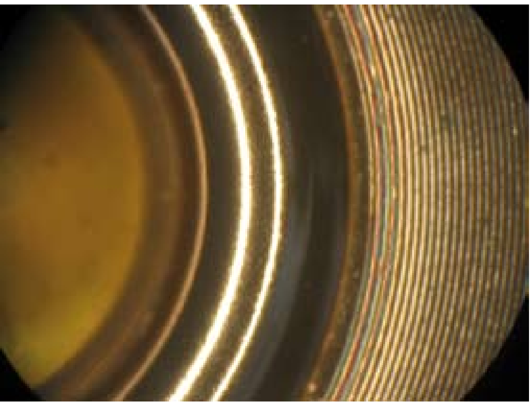
IVAM, based in Dortmund, Germany, is an international association of companies and institutes in the field of microtechnology, nanotechnology and advanced materials. IVAM Research is its economic research division and has been conducting surveys and collecting statistics in the aforementioned fields since 2004.

www.ivam-research.de/en

# Electro Plasma Polishing for processing micro-parts

Galvanic processing of parts is often associated with foul-smelling, poisonous chemical baths, yet it is still extensively used in the industry, if only for electrolytic polishing of stainless steel products, such as small machine parts, jewellery, medical implants and surgical tools. However, engineering company Alliance Technologies from Leeuwarden, the Netherlands, has recently made a breakthrough having developed a new technique and successfully implemented on a prototype machine.

Alliance has managed to create and control a highly unstable plasma, which is like a ball of lightning, in a water tank. The interesting thing about this artificial plasma is that it has multiple functions. Products that are submerged in this plasma are polished, degreased and deburred in a single, short procedure. This Electro



Mechanical seal after Electro Plasma Polishing; critical applications require a surface roughness of $R_a < 50$ nm, which cannot be achieved using alternative techniques such as electrolytic polishing.

Shaver heads processed with EPP to minimise skin irritation for users.

Plasma Polishing (EPP) technique is much more environmentally friendly and the product finish is of a higher quality than with other, competing techniques. Previously, polishing used to decrease the accuracy of the parts that were processed. EPP, however, preserves dimensional accuracy since only a very thin layer at the surface is affected by the plasma. Therefore, EPP can be viewed as a form of precision processing that can achieve accuracies in the nano domain.

Alliance Technologies was established a few years ago by former employees from Philips in Drachten. Using experience gained at Philips in the equipment development process for Electro Chemical Machining (ECM) and Electrical Discharge Machining (EDM), Alliance is now engaged in equipment development and mechatronic problem solving for SMEs. This, as chief engineer Albert-Jan Oosenbrug states, has allowed Alliance to grow into a specialist in unconventional precision machining technologies.

www.the-alliance.eu

# Precision-in-Business day: Bosch Rexroth

**One of DSPE's goals is to facilitate the exchange of knowledge and experience between members. For example through so-called Precision-in-Business (PiB) days, which offer DSPE members the opportunity to be introduced to applied precision engineering at OEMs, (system) suppliers and research institutes. On 4 March 2010, a PiB day at Bosch Rexroth, the 'drive & control' company, in Boxtel, the Netherlands, was attended by some twenty people. Interesting presentations given by Bosch Rexroth Systems and Engineering and Tech Center Europe, profiled Bosch Rexroth as an expert in "big precision engineering".**

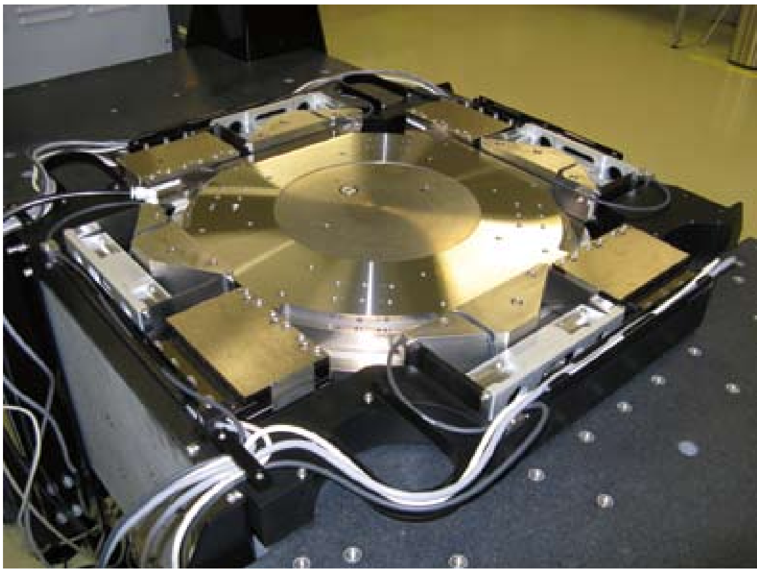


Figure 2. The XY-theta alignment stage developed by Bosch Rexroth.

Bosch Rexroth Systems and Engineering is active in a wide range of application fields, ranging from stages and other motion systems to extremely large offshore, materials handling and energy systems. One of the application examples shown was the motion platform for a flight simulator; see Figure 1. Topics included system design, control strategy, mechanical analysis and component development.

Figure 1. Bosch Rexroth Systems and Engineering developed and realized the motion platform (inset) for a flight simulator.

## Multidisciplinary

Next, Tech Center Europe, located in Eindhoven, the Netherlands, presented itself as a multidisciplinary partner for the semiconductor, electronics, solar and medical industries. As an application example a high-precision XY-theta alignment stage was discussed; see Figure 2. In this project, Bosch Rexroth was in charge of project management, system specifications definition, mechatronic design, and assembly, testing and delivery.

www.boschrexroth.com

# Summer school
## Opto-Mechatronics

**Following the success of the Summer school Opto-Mechatronics in 2008 and 2009, each edition with over forty participants, the Dutch Society for Precision Engineering (DSPE) and TNO Science and Industry decided to organise a Summer school again. The 2010 Summer school Opto-Mechatronics, from 5 to 9 July 2010 in Eindhoven, the Netherlands, once again 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 opto-mechanical instruments that are actively controlled, operating in the non-perfect environment.**

The 2010 Summer school Opto-Mechatronics comprises five days of intensive course, taught by excellent Dutch professors and scientists in the field of precision engineering, combined with hands-on training by TNO specialists. Participants will come from universities and high-tech large companies and SMEs. The programme includes social events. Venue for the Summer school is TNO Science and Industry at the university campus in Eindhoven.

### Programme

- Monday 5 July: Systems Engineering
- Tuesday 6 July: Optical Design
- Wednesday 7 July: Control Design
- Thursday 8 July: Opto-Mechanical Design
- Friday 9 July: Mechatronics

### Information and last-minute registration

www.summer-school.nl

Impression of the 2009 Summer school.

# Nikhef – National Institute for Subatomic Physics

***Nikhef carries out research, coordinates and supports activities in experimental (astro)particle physics in the Netherlands. The mission of Nikhef is to study the interactions and structure of elementary particles and fields at the smallest distance scale and the highest attainable energy, and to connect the findings of today's research in a qualitative and preferably quantitative manner to the processes occurring in the early universe, 13.7 billion years ago.***

This kind of research frequently demands teamwork in a large international collaboration, development of new detection methods and high accuracy in design and manufacturing of complex and unique structures. This requires expertise in design, precision mechanics as well as specific knowledge of materials, thermodynamics, heat transfer, etc. All these skills exist in the Mechanical Technology department of Nikhef.

## Large Hadron Collider

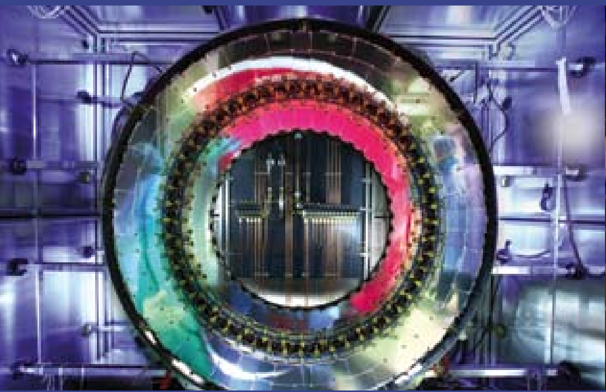
The largest particle accelerator on earth is the Large Hadron Collider (LHC) at CERN in Geneva, Switzerland. The LHC is used to study elementary particles. Two beams of protons are accelerated in opposite directions inside the 27 km long circular accelerator to collide head-on in four complex and gigantic detectors which measure the trajectories of the particles created in the collisions. One of the four LHC experiments is ATLAS. The ATLAS detector contains six different subsystems that identify particles and measure their momentum and energy. Nikhef contributed to the design and construction of one of those subsystems, the ATLAS SemiConductor Tracker (SCT).

## High-precision monitoring

The SCT is a silicon microstrip tracker consisting of 60 $m^2$ detector-grade silicon and has over 6 million implanted readout strips. The total volume of the SCT is 5.6 $m^3$. The readout pitch of the strips is 80 μm, which allows the positions of charged particles to be reconstructed with an accuracy of < 12 μm in the direction transverse to the microstrips.
To minimize the obstruction of particles and to obtain rigid structures, low-mass technologies like carbon fiber and sandwich constructions have been widely applied in the detectors. For radiation damage prevention the detectors are kept cold at approximately -10 °C without influencing the detector alignment. To monitor the alignment accuracy, Nikhef developed a high-precision monitoring system called Rasnik.

## Rasnik

The red alignment system Nikhef (Rasnik) creates an image of a coded mask on a CMOS sensor by means of a lens. The relative position in the X and Y direction of the coded mask is measured with respect to the optical centre. Moreover, the relative rotation and position of the lens along the Z-axis can be calculated. The system has a measurement range of several centimeters with an absolute accuracy better than 1 μm.



The ATLAS SemiConductor Tracker.
(Photo: Peter Ginter/Nikhef)

Rasnik, the red alignment system Nikhef.

**Information**

www.nikhef.nl

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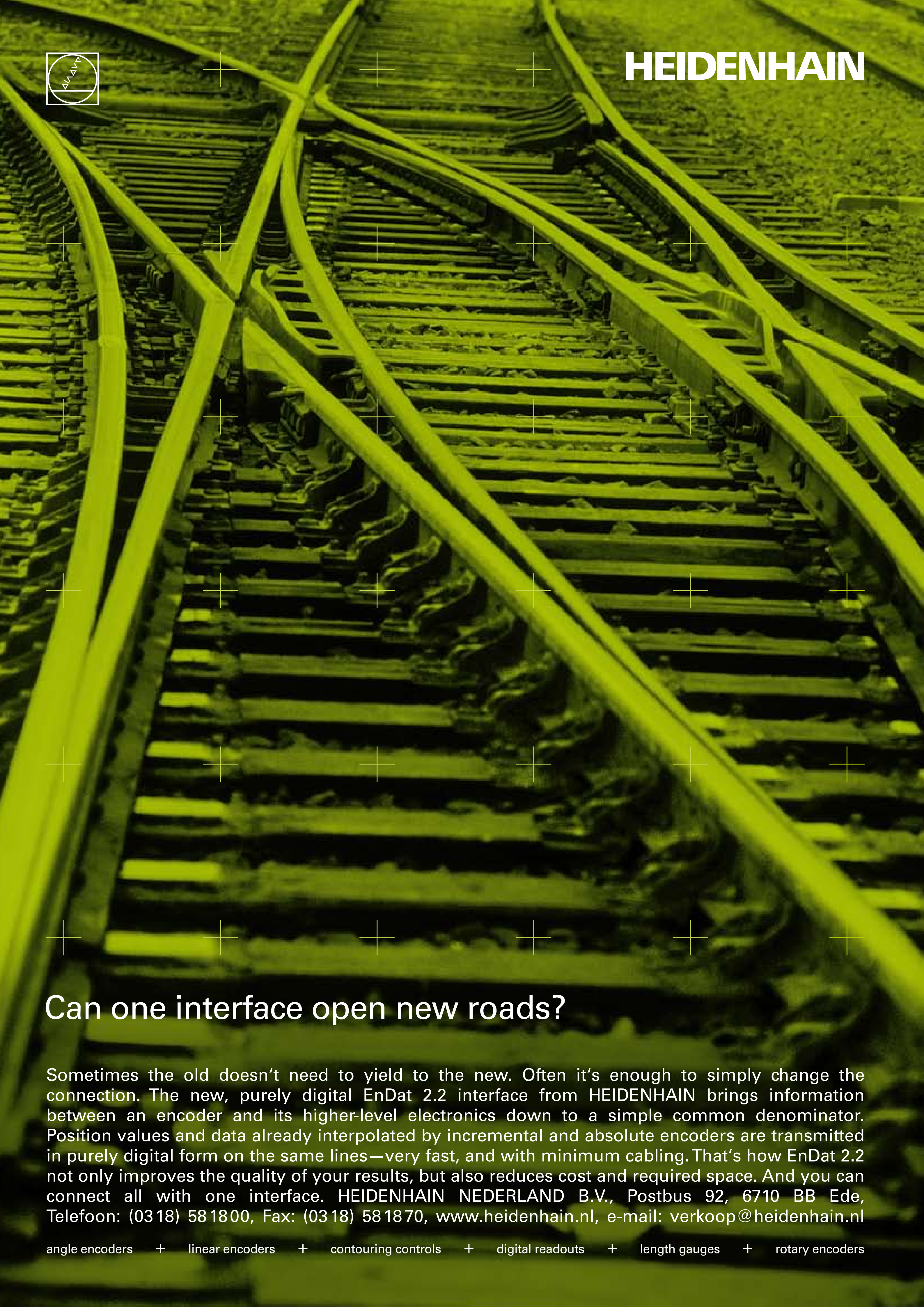
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