Mikroniek

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Volume 50

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Active vibration isolation technology • Cure and care robotics in the USA
Fast ALD • Thermomechanics • Optical improvement for laser material processing
High-end, low-cost motion control • Dynamic characterization of microresonators

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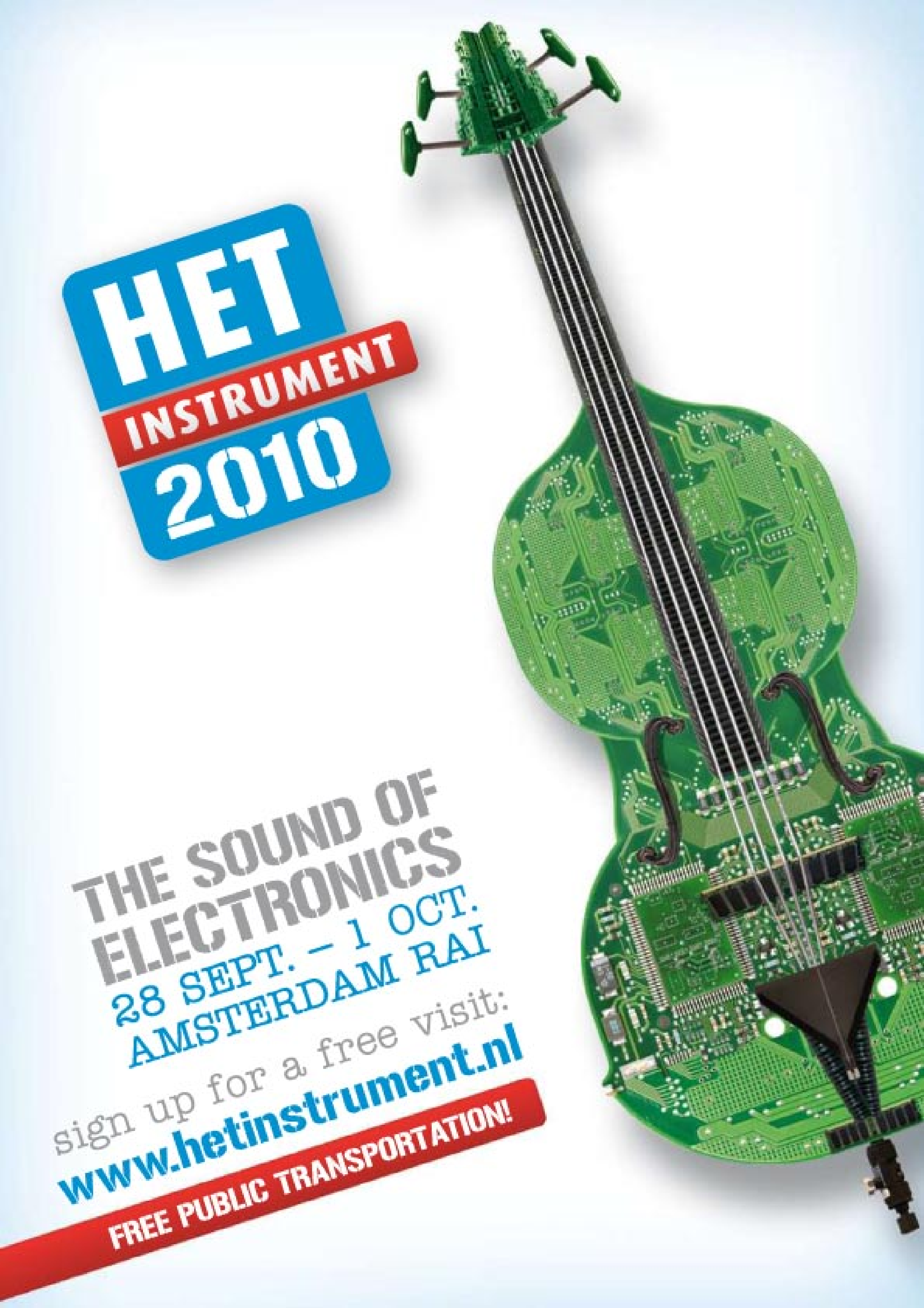

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Mikroniek - 2010

In this issue

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editorial

Point-One: People in Mechatronics

The Point-One innovation programme for nano-electronics, embedded systems and mechatronics (www.point-one.nl) aims at creating an ecosystem of Dutch high-tech industry, SMEs and knowledge institutes. It is supported by the Ministry of Economic Affairs, and by far is the largest of its kind in the Netherlands. This segment of the Dutch high-tech industry significantly contributes to our economy in terms of export. Besides a vast amount of technology development projects, the Point-One innovation programme also invests in projects contributing to the broader development of this unique Dutch high-tech ecosystem. Point-One understands the need of investing in technological innovations as well as the urgency of creating an inspiring business environment where many highly qualified people find and enjoy lifetime careers.

One of the main concerns related to this successful ecosystem is the long-term availability of highly educated and skilled people. The Human Capital (HC) Roadmap, set up by the High Tech Systems Platform (HTSP) in co-operation with Vanderlande Industries, identifies three main concerns: an insufficient number of highly educated engineers and scientists; increased demands on R&D personnel in terms of continuously upgrading their technological knowledge; and a lack of co-operation among the HR departments of the large companies (mostly the OEMs). The HC roadmap suggests various solutions to these concerns.

Looking from the human capital perspective, not only the technical skills and knowledge, but also personal competences and general business skills (leadership, entrepreneurship) are crucial for a flourishing high-tech ecosystem. One of the HC initiatives worth mentioning is the programme for Innovation and Entrepreneurship in Mechatronics, by TSM Business School (www.tsm.nl). Engineers and/or scientists who feel the need to improve their business and personal competences can now boost their career potential by participating in this programme.

Another ecosystem development initiative is the development of technology roadmaps. By the end of this quarter, the Mechatronics Long Term Investment Roadmap will be published. This roadmap analyzes the mechatronics technology needs of the main OEMs, as well as technology developments at research institutes and universities and their long-term vision. The idea is that the mechatronics community, supply chain and professionals, initiate those business or personal actions that help them to prepare for the future.

Hans Dijkhuis, Member Point-One Ecosystem development Core Team
Rik Savelsbergh, HR Coordinator HTSP

Design Principles

The field of Design Principles has an impressive list of Dutch pillars, such as A. Davidson, Wim van der Hoek and Rien Koster. But what is it that connects these people? Not only their passion for mechanics, revolutionary calculations and constructions, but, in my opinion, also how they created their mechanical designs. They stimulated creativity and out-of-the-box thinking. They showed that designing is about teamwork. They let designers solve design problems by asking the right questions. A design process full of brainstorming and collective reviewing. In this article I will explain that Design Principles is a Way of Working. "It is not only about the end result, but about how you get there."

• ***Krijn Bustraan*** •

A. Davidson was the authority in the field of high-precision mechanical engineering at Philips in the 1950s and 60s. He was the author of a handbook of precision engineering that formed the basis for the engineering community at Philips [1,2].
Wim van der Hoek made machines in the factory faster, more accurate and more silent by analyzing amongst others cam drive mechanisms. This led to a mechanical design that combined stiffness, dynamics, 'mechanical software' and input/output relations (mathematics) for converting actuator movement into end effector movements. He summarized his multi-disciplinary knowledge in lecture notes [3]. Later, one of his successors, Rien Koster, published the famous and widely taught book "Constructie-principes" [4], full of design choices often based on thinking in parameters such as the height/diameter values of hole flexures. Recently, Herman Soemers included dynamic aspects in his English-language lecture notes [5].

It is difficult to give an exact definition of Design Principles. My definition in one sentence is:
"Combining a fundamental understanding of mechanisms with a creative way of designing."

A multi-disciplinary technology field

'Mechanisms' not only includes mechanics but also physical principles such as wear, friction, hysteresis and damping. Design Principles is not only about mechanical design, but is a broad scope of disciplines including dynamics, actuation, control, metrology, physics, optics and thermomechanics. In my opinion the Way of Working that will be described in this article cannot be learned from a book or in a course, but only by working together in the design process with Design

Author

Krijn Bustraan works at Philips Applied Technologies on the High Tech Campus Eindhoven, the Netherlands, as a mechanical designer. He graduated in 2001 at Eindhoven University of Technology in the field of precision engineering under the supervision of Prof. Piet Schellekens. He is active in promotion and development of Design Principles. In December 2009, he won the Ir. A. Davidson award, which is an initiative of DSPE (see the February issue of Mikroniek).

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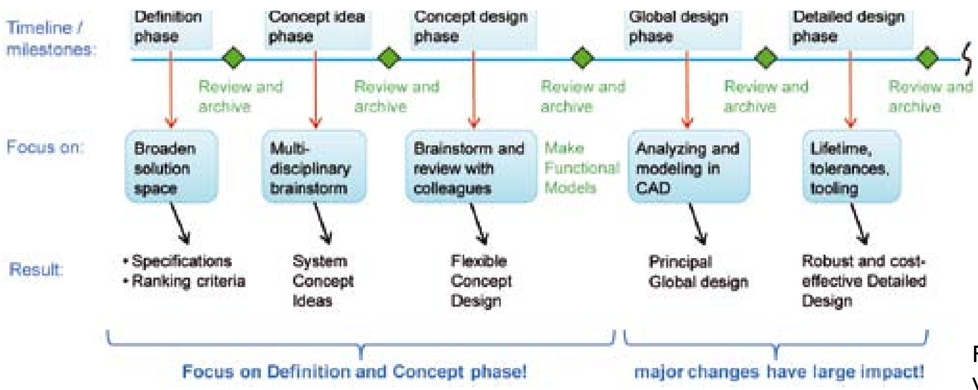


Figure 1. Proposed Way of Working in the design process.

Principles oriented engineers. Mechanical design is about teamwork. Use your colleagues as sparring partners to continuously reflect on your ideas and generate new ones. Designing together also means putting your ego aside. Stop the "not invented here" syndrome. In a brainstorm it does not matter who's idea it was!

Proposed Way of Working: include the right concepts by brainstorming

Mechanical designs are mostly not created by sudden brilliant ideas. Brainstorming can be used to stimulate creativity in a systematic way. Figure 1 shows the proposed systematic Way of Working for design projects with sufficient complexity. There are five phases in the design process that always have to be followed: definition, concept idea, concept design, global design and detailed design. The phases will be explained in the next section about the creation of an opto-mechanical design. Each phase ends with a review and archiving of the results.

The definition phase is about getting the right specifications and ranking criteria by interviewing the client. What is important for the customer, determines the mindset in the design. This can be for example accuracy, CoGS (Cost of Goods Sold), reliability, lifetime (prediction) or easy assembly and maintenance. When the specifications and ranking criteria from the definition phase are clear, the concept phase can start.

An important step is to split the concept phase in a concept idea phase and a concept design phase. Figure 2 shows a way to come to a flexible concept design using brainstorming and ranking. This phase is about architecture and a multi-disciplinary team should be used. Brainstorming techniques such as mind mapping help to think out-of-the box and to enlarge the set of concepts. The large set of ideas should be filtered on feasibility and client's scope. It is recommended to compose two or three different system concepts from all the ideas: for example A, B and C. For each concept the design issues must be written down: α, β, γ. This gives insight in the complexity and design effort for each system concept idea.

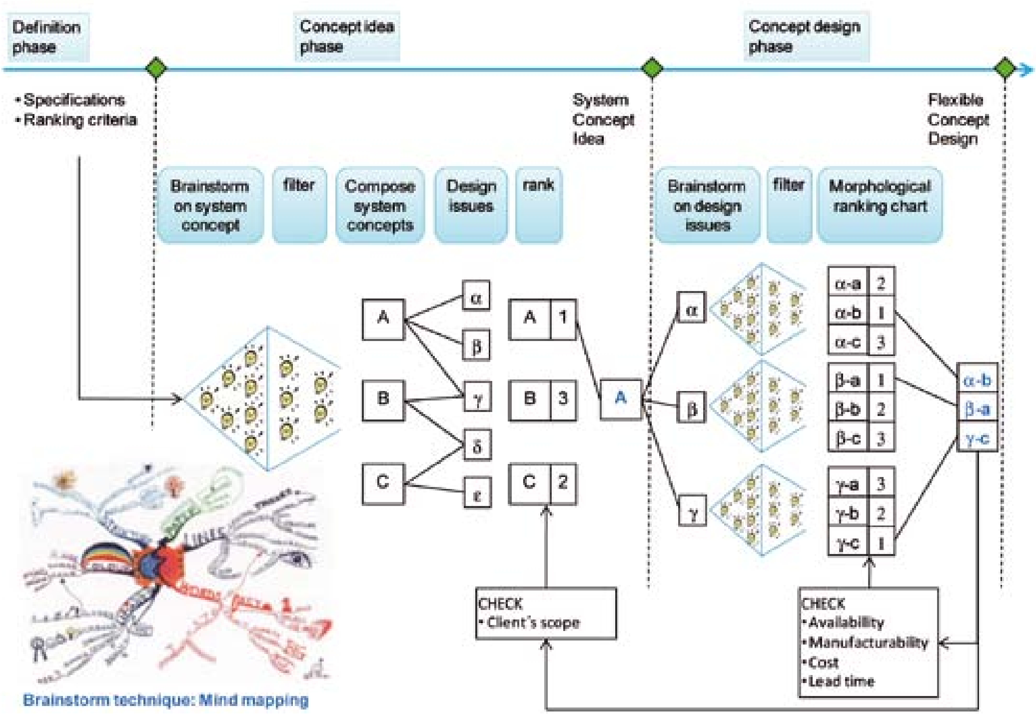


Figure 2. Concept phases with brainstorming and ranking towards a flexible concept design.

After the concept ideas are ranked, one system concept can be chosen and the concept idea phase is finished. To give a generic example: for Lorentz actuation, moving coil (A) or moving magnet (B) can be chosen. System concept idea A has design issue water cooling on the moving world due to energy

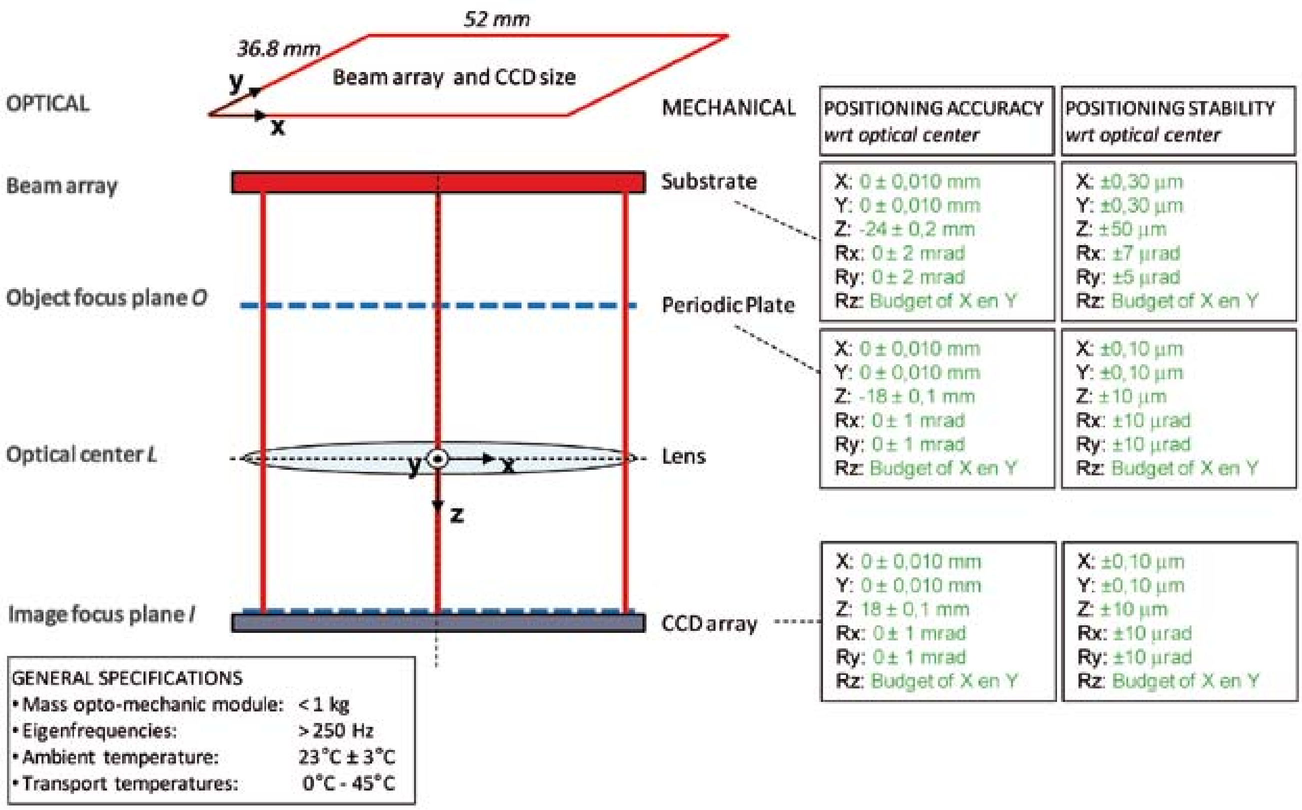


Figure 3. Specifications for an opto-mechanical module.

dissipation in the coils (α) and a cable slab with disturbance forces varying with stroke (β). System concept B has a design issue on reaching eigenfrequencies by large moving weight (δ). Both system concept ideas have a design issue on magnet stray field (γ).

The concept design phase is to solve the various design issues for the chosen system concept. The mechanical, electronical and software teams, for example, can solve their 'own' design issues. For each design issue, the set of ideas from the brainstorm must be filtered to two or three concepts (α-a,α-b,α-c). These concepts can be combined in a morphological chart and will be ranked. The proposed concept designs should be checked on, for example, availability, manufacturability, cost and lead time. If showstoppers arise, the next best concept design can be chosen without brainstorming again. All the best concept designs for all design issues together form the proposed concept design which is reflected to the customer to see if it is in line with his scope and expectations.

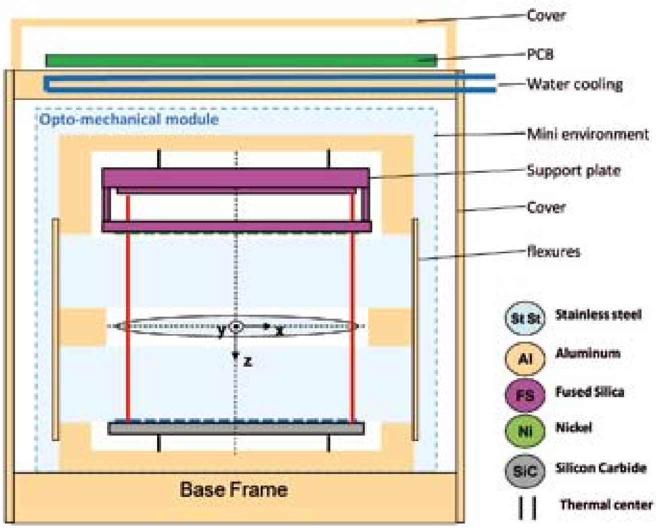
This proposed way of working with doing brainstorms, expanding the solution space and then narrowing the number of concepts, leads to a concept design with a large confidence that the *right* concept is chosen. Keeping two to three concepts alive leads to a flexible concept design that can easily be changed.

Usually a large design effort and many costs are made after the concept choice: global design, detailed design, detailed calculations and tests. In my opinion, often too little time is planned for the concept phase. Choosing the right concept increases the probability that the global and detailed design phase can be executed in a straightforward and efficient way without further iterations.

Example of Way of Working: creating an opto-mechanical design

Definition phase: towards specifications and ranking criteria

Figure 3 shows a generic opto-mechanical system consisting of a periodic plate with a beam array coming from a substrate as backlight, a lens and a CCD array. The lens is imaging the periodic plate onto the CCD array. The components have to be aligned and fixated with respect to each other with an accuracy of 10 µm. After calibration, the system has to be robust for (transport) accelerations and geometrically stable within 100 to 300 nm, see the positioning accuracy (initial alignment accuracy) and positioning stability (after calibration) in Figure 3. Other specifications are a maximum weight of 1 kg, minimum eigenfrequency of 250 Hz, an ambient temperature range of 6 °C and transport range temperature. The system will be made in series of about 100 each year.



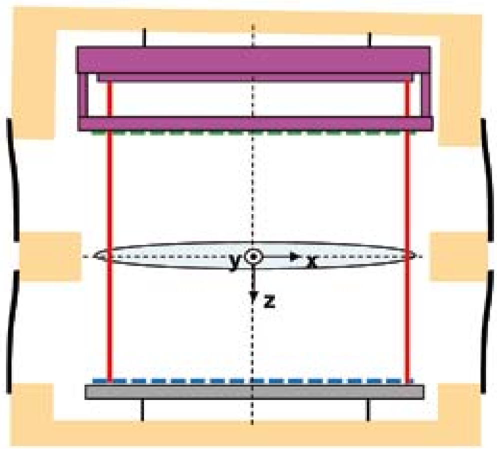


Figure 4. Concept idea phase.
(a) System concept idea.
(b) Opto-mechanical module with alignment principle.

The most important criteria for the customer in this case were: opto-mechanical quality, easy assembly, CoGS and design lead time. For the design team an added criterion was design flexibility, since the client had the alignment tolerances and alignment procedure not ready in this phase. These criteria were used to rank the concept ideas.

Concept idea phase: towards system concept ideas

The system concept idea is shown in Figure 4a. It was created by a multi-disciplinary team of mechanical, optical and electronical designers and reviewed by the client and manufacturing and assembly engineers as well. Alternative system concepts will not be discussed here. The concept idea is presented as a simple basic picture. In this phase no CAD design is needed.

The material for three optical components was given: a fused silica substrate, a quartz lens and a SiC CCD. The substrate is mounted on a support plate of the same material to increase rigidity. The material of the periodic plate was selected as fused silica for thermal expansion matching. Each (group of) optical component(s) with the same CTE (Coefficient of Thermal Expansion) is mounted in an aluminum frame with a thermal center. The outcome of the system concept idea brainstorm was three possible materials for the frames: fused silica, stainless steel or aluminum. Aluminum was chosen for thermal stability, to obtain homogenous temperatures. Thermal gradients in the frames or flexures can disturb the positioning stability.

The periodic plate and backlight array were regarded as one optical component that will be pre-aligned. Then three frames (subassemblies) were created that have to be aligned with respect to each other. The frames can be aligned and fixated by aluminum flexures between the frames, see Figure 4b. A flexible and modular design was created from conventional frame materials to limit production lead times and CoGS. The alignment stroke could be designed in the frames using monolithic structures with adjustment screws, parallel guides and virtual rotation points by elastic hinges. However, in this phase the idea was born to use alignment tooling to reduce product complexity, cost and weight.

The opto-mechanical module of three subassemblies can be mounted into a water-cooled mini-environment. The beam array is activated by electronics on a PCB. From now on, only the opto-mechanical module will be discussed in detail as an example to explain the design process phases.

Concept design phase: towards flexible concept design

The concept design phase is to solve various design issues one by one by brainstorming in small (mono-disciplinary) teams. Exploring (hand) calculations can help ranking the concepts from the brainstorms and to estimate whether the specifications can be met.

Design issues for the opto-mechanical module were material choices for the frames, the mounting and material choice of the periodic plate and the alignment and fixation of the frames.

Starting with the first design issue, thermomechanical calculations showed that the temperature variations and gradients within the mini-environment were very small compared to ambient temperature fluctuations. Hence stainless steel seemed a better option than aluminum, since stainless steel flexures have a higher yield strength and no

MOUNTING PERIODIC PLATE	1. INTEGRATED PACKAGE WITH BEAM ARRAY	2. ON STEEL FRAME, WITHIN BACKLIGHT FRAME	3. ON STEEL FRAME SANDWICHED
Optical quality	☺	☺	☺
Risk of damaging parts	☹	☺	☺
Thermal stability	☺	☺	☹
Tolerance sensitivity	☺	☺	☹
Weight	☺	☺	☹
Ease of assembly	☹	☺	☺
Number of parts	☺	☺	☺
Tolerance range	☹	☺	☹
Complexity	☹	☺	☺
CTE Match -> thermal center	☺	☹	☺
Material cost	☹	☺	☺
Manufacturability	☹	☺	☺
Supplier can do alignment	☺	☺	☹
Manufacturing time	☹	☺	☺
Design flexibility	☹	☺	☺

Ranking Criteria			
Opto-mechanical quality	5	4	3
Ease of assembly	1	4	3
Cost of BOM	1	5	4
Lead Time	1	5	4
Design flexibility	1	5	3
RANKING	9	23	17

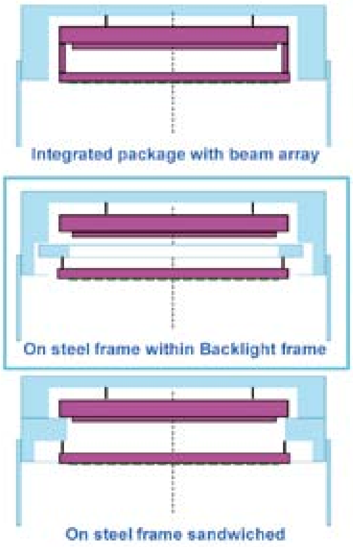
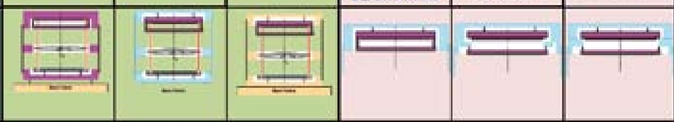


Figure 5. Brainstorm and ranking on mounting the periodic plate.

Design issues	Frame material choice			Mounting Periodic Plate			Periodic plate material			
Concept options	FS	SST	AL	INTEGRATED FS PACKAGE WITH BEAM ARRAY	ON SST FRAME, WITHIN BACKLIGHT	ON SST FRAME SANDWICHED	FS	INV	SST	AL
Concept options							With etched layer NI	etched/lasered	etched/lasered	etched/lasered
Ranking Criteria: Opto-mechanical	4	4	3	5	4	3	5	N/A	N/A	N/A
Ease of assembly	1	5	3	1	4	3	1	3	4	4
Cost of BOM	1	5	4	1	5	4	1	3	5	5
Lead Time	1	5	5	1	5	4	2	3	5	5
Design flexibility	1	5	5	1	5	3	2	3	5	5
Concept choice										
Ranking	8	24	20	9	23	17	11	12	19	19

N/A: Not Applicable
FS: Fused Silica
INV: Invar
SST: Stainless Steel
AL: Aluminum
NI: Nickel

Figure 6. Morphological ranking chart.

inserts have to be used for screws. See also Figure 6, where the frame material choice is ranked with the ranking criteria.

The design issue of mounting the periodic plate was tackled with three colleagues and a whiteboard, filtered to three concepts and archived using simple basic pictures. The feasible concepts were ranked, see Figure 5: an integrated fused silica package with the beam array, mounted on a steel frame within the backlight frame, or sandwiched. The second concept design was chosen from the ranking.

The same way of working was followed to tackle all other design issues. The results were combined in a morphological ranking chart, see Figure 6. For the periodic plate material stainless steel or aluminum are not feasible due to thermal expansion outside the stability specification of 0.1 μm. Invar is stable enough but the manufacturing process is a showstopper: the holes cannot be etched or laser cut accurately enough regarding diameter and positioning. Hence, the only feasible option seemed fused silica with an etched metal (nickel) coating, although this option has the lowest ranking.

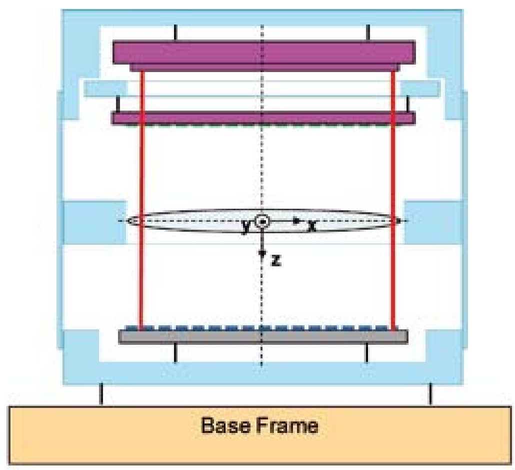


Figure 7. Concept design for the opto-mechanical module

Figure 7 shows the concept design for the opto-mechanical module. Note the differences with the system concept in Figure 4.

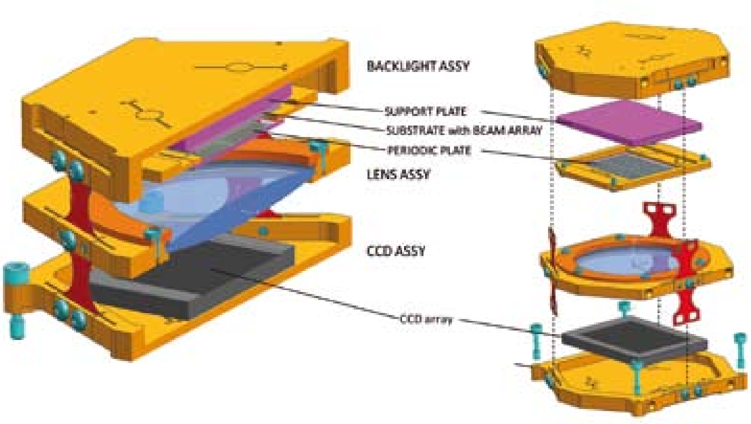


Figure 8. Global design of the opto-mechanical module.

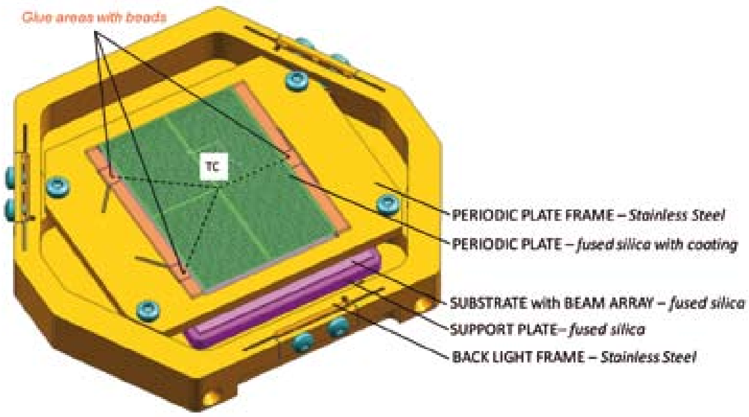


Figure 9. Backlight assy with periodic plate.

Global design phase: towards a principal global design

The global design phase is where the CAD design starts to fit all parts and functions in the required volume. Geometry is optimized to balance low weight, high stiffness and eigenfrequencies on one side, with decoupling for thermal expansion differences and low alignment stroke forces on the other side.

Figure 8 shows the global design consisting of three frames: a backlight assy with the periodic plate mounted on a separate stainless steel frame and the beam array as backlight, a lens assy and a CCD assy.

The periodic plate can be glued with beads as spacers onto the periodic plate frame using a spark-eroded Thermal Center (TC), see Figure 9.

The backlight assy has to be aligned in three Degrees of Freedom (DoFs) to the object plane of the lens. The CCD assy has to be aligned to the image plane of the lens (z, Rx, Ry) and to the periodic plate (x, y, Rz), a total of six DoFs to align. Figure 10 shows the statically determined tooling interface for alignment in six DoFs. Each frame has three conical holes that serve as interface for the tooling. The tooling consists of an external manipulator that is coupled to the upper and lower frame by three pins with a spherical front surface. Pin 1 constrains three DoFs, pin 2 constrains two DoFs by decoupling the horizontal positions for manufacturing tolerances by an elastic hinge. Pin 3 is retractable (play-free) and constrains only the z-direction by using an elastic hinge and radial preload. The six DoFs alignment can be performed by many different manipulators, either sourced or by dedicated design.

After alignment the position has to be fixated. Figure 11 shows the three sheet flexures that are used to provide alignment stroke and exactly constrained fixation after clamping the flexures using screws.

Three possible phenomena can cause fixation errors:
1. Reaction forces of the flexures in bent position will cause small elastic movements after removing the alignment tooling.
2. Tool clamping forces can deform the frames, which will cause small elastic movements after removing the alignment tooling.
3. Disturbing moments on the frame by screw fixation torque. When fixating the first of six screws that clamp the flexures, the screw torque can be led into the frame and can lead to elastic deformation by finite stiffness of the tooling.

Ad 1) Fixation errors by flexure reaction forces are minimized by a high compliance of the flexures, see Figure 11. For the chosen configuration of three flexures at 120 degrees, a uniform horizontal stiffness is obtained of 1.5 times C_y. This implies that the frame on the flexures will have an alignment stroke dependent fixation error of 0.8 µm per mm.
Ad 2) The flexures are 'cut' to reduce the radial stiffness to a minimum: 6 N/mm. For 1 mm alignment stroke, pin 3 has to be preloaded with 9 N only.
Ad 3) Screw fixation torque is prevented to be led into the tooling stiffness by shorting the moment directly into the flexure. The flexures are clamped into a monolithic spark-eroded slot. The hold moment between flexure and frame (on two sides) is always larger than the disturbance moment between screw head and frame, even for varying friction coefficients. This way, the frames with optical components can be constrained in a stress-free and hysteresis-free way.

Detailed design phase: towards a robust and cost-effective detailed design

The detailed design is amongst others about robust tolerance trains and stretching the tolerances. In this case, for example, the frames holding the optical components can be water-cut and milled with tolerances of ±0.1 mm.

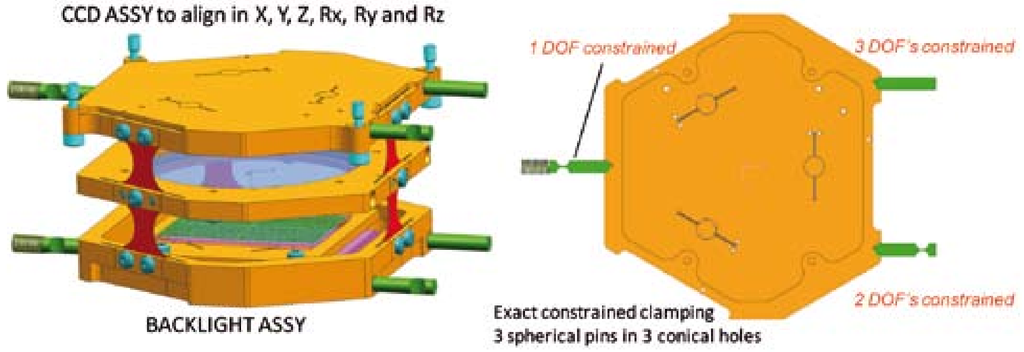


Figure 10. Exact constrained tooling interface for alignment in six DoFs.

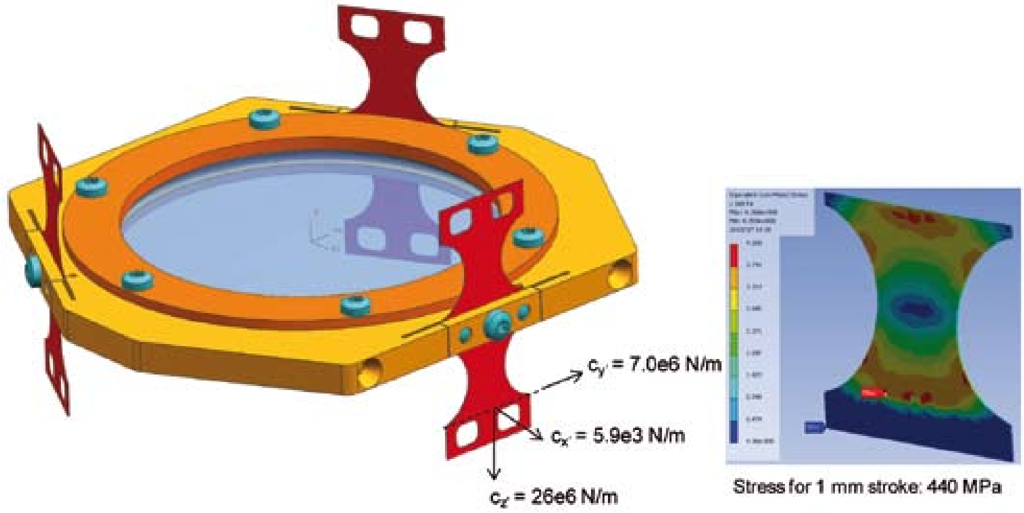


Figure 11. Flexure stiffness ratio $C_{y'}/C_{x'}$ = 1 : 1,200; stress level for 1 mm deflection: 440 Mpa.

The only accurate features are the spark-eroded thermal centers and the flexure clamping blocks. This results in relatively cost-effective parts.

Summary

Design Principles is about thinking in Degrees of Freedom, thinking in functions and parameters, and being creative and analytical. Design Principles is also about a Way of Working using brainstorms and continuously reviewing design ideas with colleagues. It is not only about the end result, but about how you get there. A Way of Working was proposed consisting of five phases with the focus on concept design. This proposed Way of Working leads to a concept design with a large confidence that the *right* concept is included. Keeping two to three concepts alive and creating a modular design leads to a flexible design that can easily be changed if showstoppers arise or if the client's scope changes. Choosing the right concept design accelerates the global and detailed design phase without further iterations. It leads to a relatively short and straightforward design process. Ultimately, it may result in improved customer satisfaction because of shorter time-to-market and cost-effective and robust products.

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Focus on opto-

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.

Case work during the Summer school is done on the design of an optical delay line, such as the one developed by Dutch Space and TNO, for the ESO Very Large Telescope (VLT) on Cerro Paranal in Chile. (Photo: ESO)

Summer school Opto-Mechatronics
Precision Technology

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, the Netherlands.

Programme

The preliminary course programme outlined below each day offers a combination of theory and practice.

Monday 5 July: Systems Engineering
Opto-mechanical instruments are always co-existing with other equipment. So, before starting their design, the essence of the systems engineering has to be considered. What is critical and what are the margins? How to approach such a project and how to gain insight in the background of the requirements?

-mechatronics

Tuesday 6 July: Optical Design
The case starts with an introduction to the optical design and its use in optical aperture synthesis applications. Next, in teams, several delay line designs will be compared, in order to select the best design with respect to the optical requirements. Also, an effective optical design has to be found for measurement of the optical path differences. Zemax will be used to analyse the optics in the delay line. Further work pertains to wave-front analysis and pupil imaging while moving the delay line, and assessment of alignment accuracy.

Wednesday 7 July: Control Design
Based on the functional requirements of the optical delay line, the challenges for control will be discussed. These include actuation for a high dynamic range, servo behaviour, vibration rejection, sensor noise, closed-loop stability and others. An introduction of suitable control design methods is presented to achieve nanometre positioning accuracy.

Thursday 8 July: Opto-Mechanical Design, statically
The trade-off made for a linear guiding of 66 metres, with sub-millimetre accuracy, will be presented. The students are requested to design and assess, in a team effort, the performance. The finite-element method programme ANSYS will be used to gain insight in the mounting of (aberration-free) optical components, and some smart construction principles.

Friday 9 July: Mechatronics
Designing an actively controlled delay line that is stable enough to perform interferometry over large distances, is far from trivial. For the last day, some still missing elements will be presented that are necessary to realize high-performance active positioning and control systems for optics. First of all, an overview is given of electromagnetic and piezoelectric actuators, optical position measurement systems and capacitive sensors. Further, also attention will be given to the performance-determining mechanical system dynamics and vibration isolation. The new field of adaptive optics will also shortly be touched upon.

Impressions of the 2009 Summer school: lectures, practical exercises and social activities.

Information and registration

www.summer-school.nl

The revolutionary

The Hummingbird technology was developed by MECAL and TNO in response to the growing need for highly effective, robust and affordable vibration reduction systems. It combines new and existing technologies to significantly reduce floor vibrations and also suppress disturbances caused by machine movement, ranging from very low to high frequencies. This article discusses the basics and common concepts – with their possibilities and limitations – for (active) vibration isolation. The underlying technologies provide the context for a concise description of the Hummingbird.

• *Bernhard Bakker and Johan van Seggelen* •

With increasing demands in terms of accuracy and speed in modern production equipment and imaging instruments, there is a growing need for highly effective, robust and affordable vibration reduction systems. The major challenge is the need to reduce external vibration sources (mostly floor vibrations), while suppressing disturbances inflicted by the accurate equipment itself. Especially at low frequencies, most technologies currently available are not capable of effective reduction of vibrations.

The basic vibration isolation problem

Figure 1 shows a table connected to the floor via a machine frame with stiffness c_{base}. Vibrations of the table can be caused by floor vibrations, via the machine frame, and by disturbance forces acting directly on the table.
The amplitude and frequency of floor vibrations are determined by vibration sources (such as adjacent machines, traffic, etc.) and by the dynamic properties of the building (stiffness, mass, eigenfrequencies). The disturbance forces are normally caused by processes and accelerating stages mounted on the table. On this table, an accurate component, for instance a lens or another precise instrument, is mounted. The position error between this accurate component and the table is designated as Δ. This error determines the machine accuracy.

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Hummingbird technology

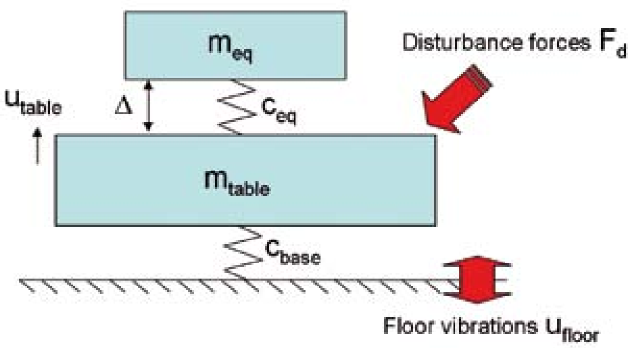

Figure 1. The basic vibration problem.

Normally, the mass of the accurate components (the equipment) on the table is much smaller than the mass of the table ($m_{eq} << m_{table}$). In that case, u_{table} is related to position error Δ through:

$$\Delta = u_{table} \cdot \left[\frac{c_{eq}}{-\omega^2 \cdot m_{eq} + c_{eq}} - 1 \right] \qquad \text{(Equation 1)}$$

This means that the error Δ is proportional to the table movement u_{table}. The challenge of vibration reduction therefore is to keep the table still in spite of the disturbance forces and floor vibrations. The effect of floor vibrations (u_{floor}) on movements of the table (u_{table}), in other words the degree of isolation of the table, is given by the transmissibility function:

$$\frac{u_{table}}{u_{floor}} = \frac{c_{base} + d_{base} \cdot j\omega}{-m_{table} \cdot \omega^2 + d_{base} \cdot j\omega + c_{base}} \qquad \text{(Equation 2)}$$

In this equation, ω is the frequency of the disturbance and c_{base} and d_{base} represent the stiffness and damping, respectively, of the table supports.

The sensitivity of the table for disturbance forces acting on the table (F_d) is given by the compliance function:

$$\frac{u_{table}}{F_d} = \frac{1}{-m_{table} \cdot \omega^2 + d_{base} \cdot j\omega + c_{base}} \qquad \text{(Equation 3)}$$

The optimum, leading to minimised table movement, is the design with minimal transmissibility (i.e. maximum isolation of floor vibrations) and minimal compliance (i.e. minimum sensitivity to disturbance forces). An important value governing both transmissibility and compliance is the eigenfrequency of the table with respect to the floor:

$$f_n = \frac{1}{2\pi} \sqrt{\frac{c_{base}}{m_{table}}} \qquad \text{(Equation 4)}$$

This frequency is in effect the cut-off frequency for the transfer of floor vibrations and disturbance forces to motion of the table: for frequencies higher than f_n the table becomes increasingly less sensitive to disturbance forces and floor vibrations. However, decreasing the stiffness between floor and table will increase the sensitivity to disturbance forces below f_n. This means that to reduce the effect of disturbance forces, the most effective way is to decrease f_n by increasing the mass of the table instead of decreasing the stiffness of the support.

Equations 2 and 3 show that around f_n both compliance and transmissibility become very high for low values of d_{base}. This means that a high damping is needed to prevent amplification of vibrations around eigenfrequency f_n. However, for higher frequencies the transmissibility increases with d_{base}, which means that low damping is needed for optimal isolation at high frequencies.

The error Δ is also decreased by minimising the mass m_{eq} and maximising the stiffness c_{eq} of accurate objects mounted on the table. This is an important part of the design of the machine itself and not part of the vibration reduction issue; therefore, it is outside the scope of this article.

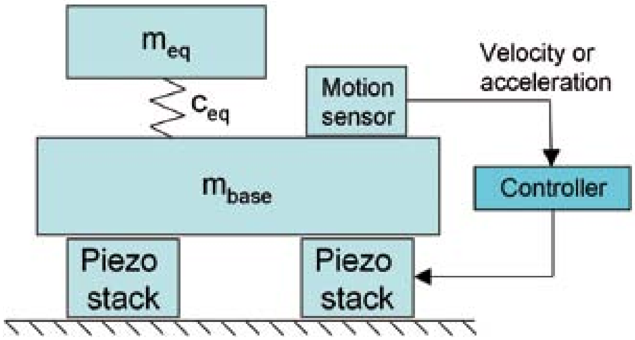

Figure 2. Piezo-based active vibration isolation.

Passive isolation

A first concept for vibration reduction is passive isolation, which means that no active components, such as sensors and actuators, are used. To minimize both compliance and transmissibility, these systems normally consist of a heavy table, as a basis for the accurate process, supported with reasonably soft supports with high damping. This means a low eigenfrequency f_n, resulting from a high mass m_{table} and a low support stiffness c_{base}.

In practice, these numbers are limited. First, the allowable mass of the table is limited for practical reasons. Second, in order to function properly, any application must be robust enough to handle a certain degree of disturbance forces, which means that the stiffness of the table supports can not be decreased too much. In practice, stable supports with a frequency lower than about 2-3 Hz are very difficult to design without active components.

An example: a 100 kg table at 2 Hz. A small force of 10 N (= 1% of the gravity force acting on the table) will already induce a displacement of 0.6 mm. In practice this means that the table is very sensitive to drift and ‘feels’ very unstable to the user.

High damping is needed to prevent the amplification of floor vibrations and disturbance forces at frequencies close to the eigenfrequency, but it reduces the isolation performance at higher frequencies.
Overall, passive vibration isolation is a very straightforward technology and can be effective to solve vibration issues for frequencies higher than 3-5 Hz, where a modest reduction of amplitude is sufficient.

Active isolation

If a reduction of floor vibration amplitude with a factor 2 or more at 3 Hz is required, passive isolation will be insufficient. In that case active vibration isolation can be used. This means that sensors and actuators are used to measure and counter vibrations, often in combination with a passive isolation system. Today, various solutions for active vibration isolation (or reduction) are based on three concepts as discussed below.

Piezo solutions

In a piezo actuator system (Figure 2), motion sensors are used to measure vibrations of the table. The table is mounted on stiff piezo actuators that are used to counter these vibrations. A motion controller interprets the motion sensor output and calculates the optimal counter forces.

In most piezo systems there is no passive isolation whatsoever. Therefore, the compliance is determined by the stiffness of the piezo support. This yields a very low compliance compared to other solutions. As there is no passive isolation, the reduction of floor vibrations is provided in the frequency range where the controller is active. The lower boundary of this range is determined by the resolution and noise of the sensors, the upper boundary by the controller bandwidth.

A high controller bandwidth is therefore essential. To enable this, sensors must be used with good performance at high frequencies (> 100 Hz), such as accelerometers or specific geophones. The penalty is that these sensors do not have low sensor noise and good resolution at low frequencies, e.g. below 5 to 10 Hz. Sensor noise easily exceeds floor vibrations, causing the controller to increase the vibration level rather than reduce it. Therefore, it is very difficult to reduce vibrations at low frequencies using a piezo system.
In some commercially available configurations, passive isolation is added between the piezo mounts and the supported table. In effect a table with passive isolation is mounted on top of the piezo mounts. In this way the isolation performance is enhanced at higher frequencies, but the compliance is limited by the passive system.

Note that, because of the stiff connection between table and floor, the controller bandwidth can be limited by floor dynamics. This means that for an effective piezo solution a very rigid floor is needed.

Separate reference mass

In the solution of Figure 3, a reference mass is suspended separately from the isolated table. Sensors measure the displacements of the isolated table relative to the reference mass. The controller forces the table to copy the movements (or lack thereof) of the reference mass.

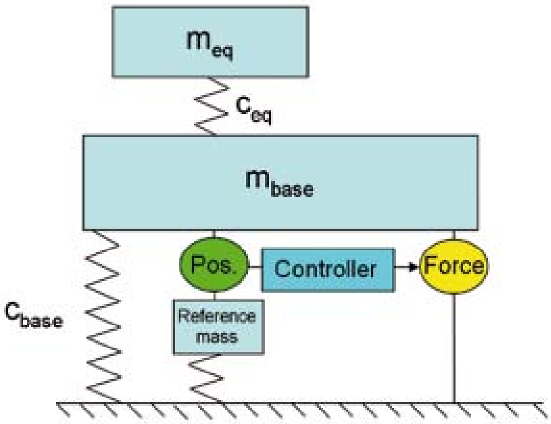

Figure 3. Active vibration isolation based on a separate reference mass.

The basis of this concept is that the reference mass is suspended with a passive support having very low stiffness. This means that the transmissibility of floor vibrations to the reference mass is very low. The major disadvantage of passive isolation, namely the sensitivity to disturbance forces, is not a problem, because the process forces act on the table, not on the reference mass.

Note that amplification of floor vibrations to motion of the reference mass will occur around the natural frequency of the reference mass system. This is directly transferred by the controller to table motion. Considerable damping of the reference mass suspension is therefore essential.

In this design the table is supported with a 'classic' passive isolation system at a reasonably low frequency. The compliance of the passive isolation system can be greatly enhanced between 0 Hz and the controller bandwidth. For higher frequencies, the characteristics of the passive table supports apply. This means that with this concept passive isolation can be applied in situations with large disturbance forces acting on the table.
An important aspect of this solution is that vibration isolation is impossible below the natural frequency of the reference mass on its suspension (e.g. a 2.5 Hz support). Below this frequency, the amplitude and phase of reference mass movement are (almost) equal to those of the floor vibrations. Hence, in this case the controller will force the table to copy floor vibrations.

Inertial control

The basis of the inertial control configuration (Figure 4) is a table suspended by passive isolators. A motion controller is used to minimize motion of the table; actuators between the floor and the suspended table are used to counter table vibrations measured with the motion sensors attached to the table.

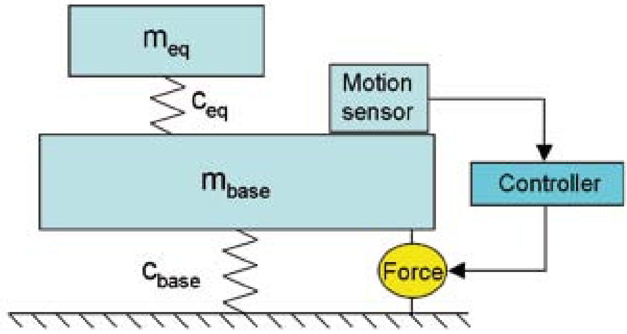

Figure 4. Active vibration isolation based on inertial control.

Compared to passive isolation, compliance and transmissibility are significantly reduced in the frequency range where the controller is active. The upper boundary of this range is determined by the controller bandwidth, and the lower end is determined by the resolution and noise level of the sensors: higher resolution and lower noise means this boundary can be close to 0 Hz, but never at 0 Hz, because then no motion occurs. Furthermore, sensors that are designed to measure horizontal motion at frequencies below 1 Hz, suffer from the 'tilt-to-horizontal coupling' effect. In short, because of gravity, the sensors cannot distinguish tilt from horizontal motion at low frequencies. This effect will be explained below.

The controller will delete the amplification of floor vibrations around the eigenfrequency of the suspension. Therefore, damping of the passive suspension is not necessary. For frequencies higher than the controller bandwidth, the vibration isolation is determined by the passive isolation system, with low damping, and therefore still is considerable.

The major disadvantage is that systems based on inertial control are sensitive to disturbance forces with low-frequency content. For static forces (0 Hz) active levelling can be added. The levelling will react to disturbance forces in the frequency range between 0 Hz and the lowest frequency at which the inertial controller is active. In principle such a levelling system is slow to react and has a reasonably high compliance.

Hummingbird technology

The Hummingbird vibration isolation technology is an enhanced version of the inertial control concept. In existing inertial control systems the motion of the table is measured with geophones or accelerometers. In the Hummingbird concept, motion of the table is determined by measuring position changes between the table and a reference mass that is suspended on the table. This technology is patented.

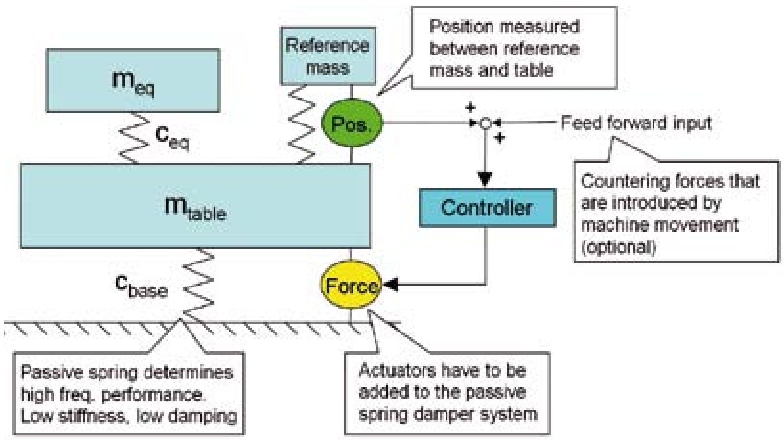

Figure 5. Hummingbird vibration isolation technology, in one DoF.

By measuring position instead of velocity, the noise levels and resolution of the motion sensors at low frequencies are greatly improved. This lowers the start of the frequency range in which the controller is active to about 0.2 Hz, compared to 1 Hz for inertial control systems based upon velocity sensors. As a result, Hummingbird is the only vibration isolation system capable of a vibration reduction of -30 dB at 1 Hz, in six degrees of freedom (DoFs). Also, the low-frequency band where the system is sensitive to disturbance forces is minimised to a small band around 0.2 Hz, which greatly reduces the impact of the major disadvantage of inertial control systems (see above).

Figure 5 shows a one-dimensional representation of the basics of the Hummingbird concept. The technology can be used for isolation in three or six DoFs. The figure shows the passive vibration isolation, provided by soft springs supporting the table. These are air mounts or mechanical springs. The supports have a very low damping << 1%.

Solution for tilt-to-horizontal-coupling

In solutions that are based on inertial control, such as the Hummingbird technology, the problem of ‘tilt-to-horizontal-coupling’ occurs. If the table tilts, the gravity force acting on the reference mass will cause it to move (Figure 6). Theoretically, it is impossible for the sensor to distinguish this effect from acceleration. This means that the controller will misinterpret tilt as a horizontal motion, and will try to correct for it by accelerating the table in opposite direction. At low frequencies the tilting effect will become dominant over actual horizontal motion. Therefore, the tilting effect will limit the performance of the controller below the first eigenfrequency of the reference mass.

In order for reduction of vibrations to be effective at low frequencies, the tilt-to-horizontal-coupling problem needs to be solved. Figure 7 shows the patented solution used in Hummingbird. The sensor, including the reference mass, is

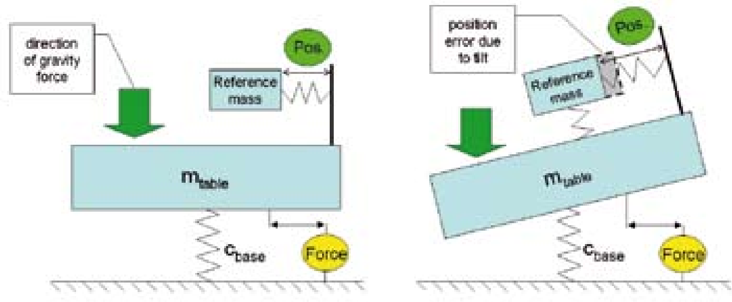

Figure 6. The tilt-to-horizontal-coupling problem in inertial control systems using reference mass-based motion sensors.

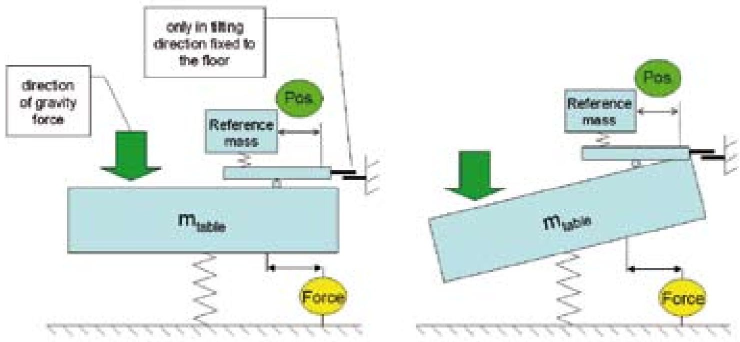

Figure 7. Hummingbird solution for tilt-to-horizontal-coupling.

fixed to the table in all directions except the tilting rotation. The sensor is attached to the floor with a fixation that is rigid only in the tilting direction and very compliant for the other five degrees of freedom.

Sensor behaviour at high frequencies

The motion sensor measures movement of the reference mass, which means that its sensitivity is directly linked to the movement amplitude of the reference mass. To enable sufficient movement of the reference mass at low frequencies, the eigenfrequency of the reference mass on its suspension needs to be as low as possible. However, the second and higher eigenfrequencies, the so-called spurious modes, will induce motion of the reference mass in unwanted directions. This movement is detected by the sensor and interferes with the feedback controller used for active isolation, causing instability of the controller. Normally, this limits the maximum controller bandwidth to about a quarter of the second eigenfrequency of the reference mass.

The mechanical design of the Hummingbird reference mass has been optimised to maximise second and higher modes. In practice, it is extremely difficult to realise a second mode more than 100 times higher than the first mode. For a reference mass with a first eigenfrequency at 2 Hz, the second mode can be elevated to about 160-200 Hz, which limits the controller bandwidth, and therefore the effective range of the active vibration isolator, to 40 Hz.

To enable higher controller bandwidths, and therefore lower compliance and transmissibility over a wider frequency range, the Hummingbird technology includes sensor fusion (patent pending). In this concept, a second sensor (for position, velocity or acceleration) is aligned with the position sensor. This second sensor corresponds with a reference mass at a much higher frequency. For low frequencies the controller uses information from the position-based motion sensor, for higher frequencies the information from the second sensor is used. This results in high resolution over a very large frequency range without problematic higher spurious modes.

Measurement results

Figure 8 shows the 6-DoF isolated Hummingbird platform presented on the Precision Fair in Veldhoven, the Netherlands, in December 2009, including the new technologies as described above. Measurement results show the transmissibility functions of the system (Figure 9) and the vibrations measured on the table (Figure 10). Note that these measurements were obtained with a separate set of sensors, not with the Hummingbird motion sensors used for the controller.

Figure 8. The Hummingbird platform.

The graphs in Figure 9 show the measured transmissibility functions of the platform (i.e. transfer functions from floor vibrations to table vibrations), in X-, Y- and Z-direction. Although the sensors used typically are not suitable to measure below 3 Hz, the measurements clearly show strong reduction of vibrations in the entire frequency range, in both vertical (Z) and horizontal (X, Y) directions. In vertical direction suppression of floor vibrations reaches a factor 100 in the frequency range around 3 Hz.

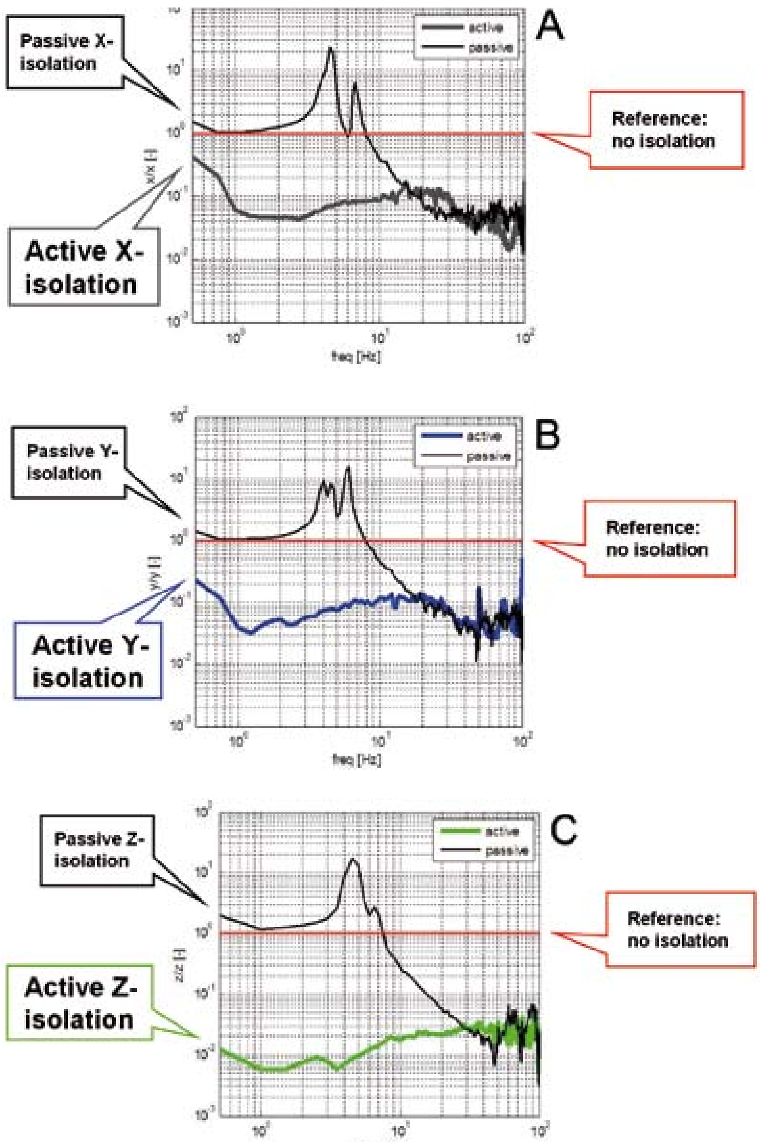

Figure 9. Transmissibility measured in X-, Y- and Z-direction.

The performance of the Hummingbird platform with respect to the NIST A1 vibration isolation standard was independently measured by VSL, the Dutch national metrology institute. Results presented in Figure 10 show that vibration amplitudes of the table, either caused by sensor noise or by transfer of floor vibrations, are well below the very strict NIST A1 specification. Note that below 5-10 Hz the accelerometers used for this measurement are not capable of measuring vibration amplitudes below the NIST A1 specification.

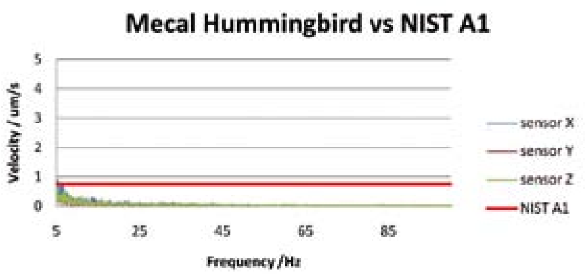

Figure 10. Hummingbird performance with respect to NIST A1.

Conclusion

In the Hummingbird vibration isolation concept three patented technologies were used to enable a considerable performance improvement compared to existing passive and active vibration isolation technologies. The position-based Hummingbird motion sensor enables active isolation starting as low as 0.2 Hz, with measurements showing -30 dB vibration suppression at 1 Hz in 6 DoFs. Overall, the test results show very low transmissibility of floor vibrations to the platform over a broad frequency range and very low vibration levels induced by sensor noise. The Hummingbird technology solves the problem of unwanted tilt of horizontal sensors at low frequencies and the effect of the spurious sensor modes at high frequencies, resulting in a very robust system in the entire frequency range.

The Hummingbird technology is offered by MECAL as a stand-alone supportive structure for a variety of sensitive equipment, or as a design-in for high-accuracy manufacturing and testing equipment.

Acknowledgement

The authors would like to thank the employees of TNO who contributed to the successful implementation of Hummingbird technology into a 6-DoF isolated platform.

High-end, low-cost motion control

In addition to its core business education, Fontys University of Applied Sciences, based in the Southern Netherlands, also conducts research in a number of specific subject units. One of these research groups – Mechatronics – is headed by lector Henk Kiela in Eindhoven, the Netherlands. Mechatronics focuses its research on high-end applications. One of its projects - "Low Cost Motion" - is about developing a high-end, low-cost motion controller.

• *Mark Stappers* •

The "Low Cost Motion" project ran from 2008 to spring 2010. Funded by RAAK, the Ministry of Education's Regional Attention and Action for Knowledge circulation scheme, the project was a spin-off of Paul Verstegen's Ph.D. research on a new concept for a pick & place machine. Despite using advanced techniques, not all solutions turned out to be easy to implement. For example, the controller used did not meet signal processing speed requirements. As a possible solution to these problems, the implementation of certain tasks by a Field Programmable Gate Array (FPGA) was considered. An FPGA makes it possible to describe hardware. Because the description is on the hardware level, it is possible to carry out processes in parallel. By doing calculations simultaneously, the FPGA information output can be many times higher than for microprocessors.

FPGA-based controller

A survey of high-tech companies in the Eindhoven region revealed that they had encountered similar problems and had decided to build their own motion controller. Their choice for a custom-made board was based on technical and/or financial grounds. The question arose whether Fontys could find a solution for these common problems by combining the knowledge of various companies (such as Assembléon, Bosch Rexroth, CCM and Philips Healthcare) into one project to develop a high-end, low-cost motion controller.

It was decided to make the design of the controller fully FPGA-based, which required custom-built hardware for driving motors and collecting information from sensors, as well as custom-built software; see Figure 1 for a general overview. In the project, several types of boards were

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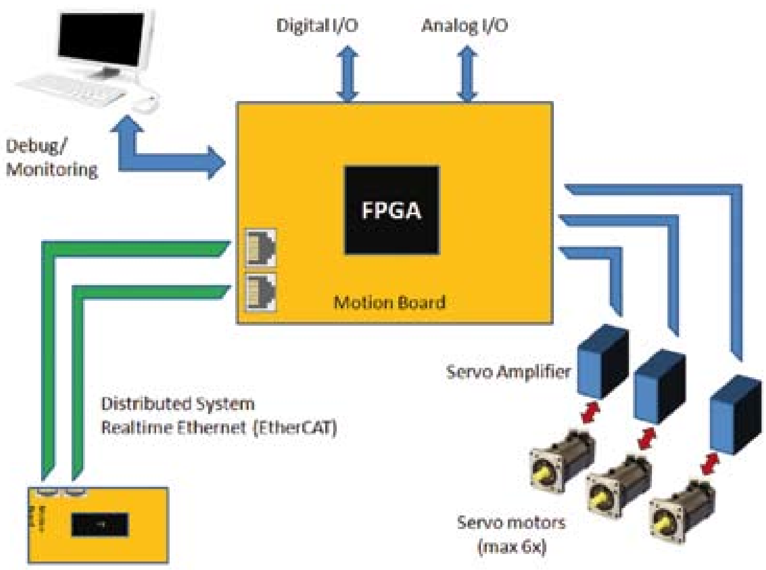

Figure 1. Overview of the FPGA-based motion controller design.

developed for motion control. Exploring the possibilities of the FPGA, a board was initially developed that could control a single axle. The board was able to handle signals at TTL level (S0/S90) or analog signals (sin/cos), and the output was an analog signal between -10V and +10V.

Open source

FPGA programming is done at hardware level, which means that logical AND and OR ports are connected in order to generate functions. These functions can be stored as a "black box", so the user should be able to use these blocks without knowing the underlying code. In this respect, it is similar to an IC: the function can be used without knowledge of the underlying electronics. Alternatively, functions can be made "open source". The main advantage of this is the possibility of seeing the underlying code. Most of the code in this project is open source and available to the participants. By combining different functions from a library, a dedicated motion controller for a particular device can be compiled; see Figure 2.

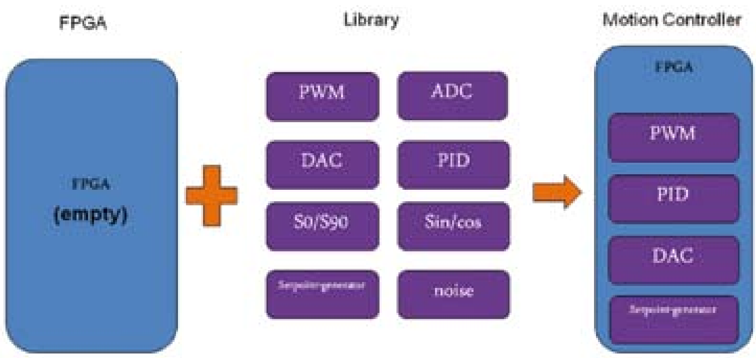

Figure 2. FPGA-based programming of a motion controller.

Configuration

Examples of functions developed include a control loop that was designed to work at an update frequency of 50 kHz. Another development involved an adaptive setpoint generator capable of positioning with an accuracy of 1 µm, with a 2 m/s maximum velocity and 35 m/s^2 maximum acceleration.
The general idea was that a non-technical person should be able to handle the motion controller. Therefore, software was developed for a PC-based user interface that allows easy configuration of the controller; see Figure 3. The serial communication between the PC and the motion controller allowed a data rate of 921,600 kB/s. The resulting controller was used to control an Assembléon pick & place machine. This proved that it was possible to build a high-end, fully FPGA-based motion controller.

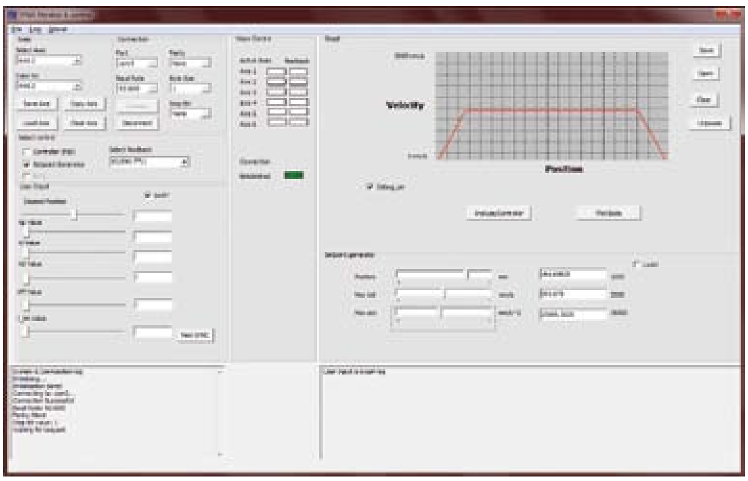

Figure 3. Snapshot of the user interface.

Multiple axles

The next step was to design a board for the control of multiple axles. Starting from a single-axle control board, the number of axles was expanded to six. To be able to implement more algorithms, an FPGA with multiple gates was selected. To showcase the latest techniques for communication between devices, besides the standard RS232 connector, the board was equipped with a realtime EtherCAT fieldbus; see Figure 4.

EtherCAT is an ethernet-based full-duplex protocol. The primary advantage of the EtherCAT protocol is that all information runs through a standard ethernet cable.

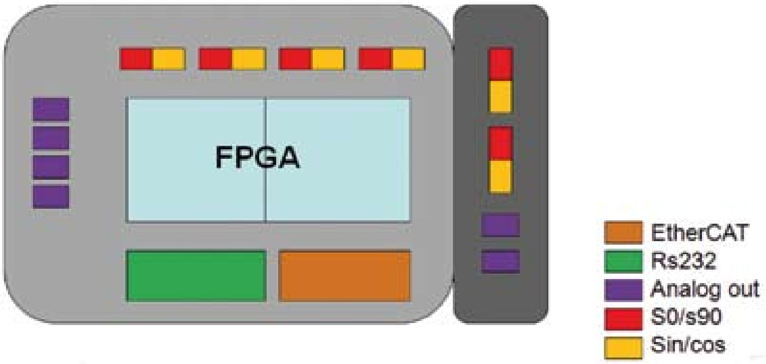

Figure 4. Schematic of the board with its I/O ports.

Moreover, it provides space for existing network protocols such as email, http, etc. To illustrate how fast the EtherCAT protocol is, 1000 I/O ports can be updated in 30 μs. In addition, this protocol's high level of flexibility means it can work with all types of network topologies.

Conclusion

The 6-axle motion controller is now being tested. As a preliminary conclusion, it may be stated that FPGA-implementation allows the development of a high-end motion controller at a reasonable cost; see Figure 5. Applications may be found in pick & place machines, robotics and the automotive sector. The project has encouraged several participating companies to integrate EtherCAT technology into their products.

At Fontys, the research results will be incorporated in both the education programme and new research projects on topics such as remote robotics.

Information

www.fontys.nl/mechatronica

Figure 5. The final result: a high-end, low-cost motion control board.

Millions of stacked

Traditionally and physically, glass and spherical shapes are the preferred parameters when designing and manufacturing lenses. But miniaturization, imaging quality improvement and price-reducing mass production demand for aspherics as forms and plastics as materials. Examples of this trend are the optics in modern mobile phones, which are able to take and transmit pictures and video films. Thanks to its unique WaferOptics® process, Anteryon in Eindhoven, the Netherlands, succeeded in producing such optical systems in huge quantities at challenging cost prices.

• *Frans Zuurveen* •

Anteryon started as a spin-off from Philips Electronics and excels in the ins and outs of replication technologies. These skills originate from the design and production of lenses for optical pick-ups for reading compact discs. This activity was the logical consequence of the successful introduction of the Compact Disc Digital Audio system by Philips and Sony at the beginning of the eighties. The replication technology made it possible to compensate image forming errors that are inherent to spherically formed lenses. The processes from those early CD days are still in use in the Anteryon clean rooms, see Figures 1 and 2.

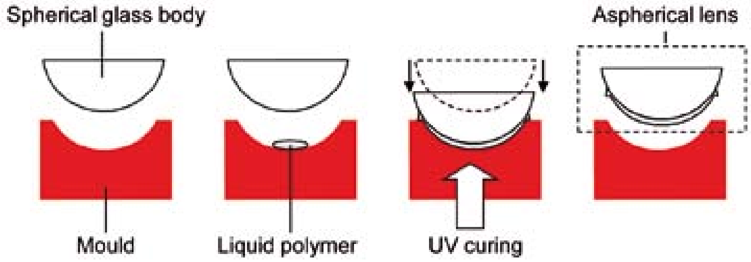

Figure 1. The Anteryon single-lens replication process for the production of aspherics.

Figure 2. One of the Anteryon clean rooms in Eindhoven.

lenses a week

Anteryon – with a staffing of about 120 persons – has many optical machining abilities in house, including sand blasting, grinding, lapping and etching. And as a consequence of the replication process, Anteryon is an expert in the chemistry of UV hardening glues and UV curing resins. Of course, it also masters physical technologies for the deposition of special coatings, like sputtering and evaporation. Moreover, the WaferOptics process requires thorough knowledge of reproduction and aligment procedures. And last but not least, Anteryon is able to predict whether glues and resins adhere to a surface or – reversely – easily loosen from a substrate.

The basic process for aspherics

Figure 1 shows how aspherical lenses are born by correcting spherical glass lenses. In a one-by-one replication process a one-sided flat spherical glass body is being pressed into a droplet of liquid polymer in a UV transparent mould that, negatively, has the aspherical form desired. After that, UV light cures the resin. The crux of the Anteryon replication process is the exact transfer of the lens shape in the mould to the glass surface, thereby ensuring adhesion of the hardened resin to the glass and allowing release of the product from the mould. In other words: the glass body with a thin layer of polymer that gives the glass lens the optical properties necessary to function in the CD and DVD reading process, can easily be taken out of the mould.

Of course, realizing the right aspherical form is an essential condition, in the above-mentioned procedure as well as in the manufacturing process to be described next. Anteryon's optical experts therefore calculate the mathematical data with appropriate computer programs, resulting in the right image of a diode laser on the memory disc. Or, in the WaferOptics case, to find the required characteristics of one element in an optical objective system, i.e. for mobile phones. These mathematical data are translated into a master model. Unfortunately, details of the Anteryon mastering method are not available because the master process tricks are regarded as company secrets.

WaferOptics

Figure 3 shows an 8-inch glass wafer (in future 12-inch wafers will be used) with about 4,000 lenses for objectives to be used in – for example, Nokia – mobile phones. On one hand, such objectives must be very small, on the other hand, they have to comply with stringent optical requirements. This means that mobile phone objectives consist of an assembly of several, nearly always aspherical, elements; see Figure 4.

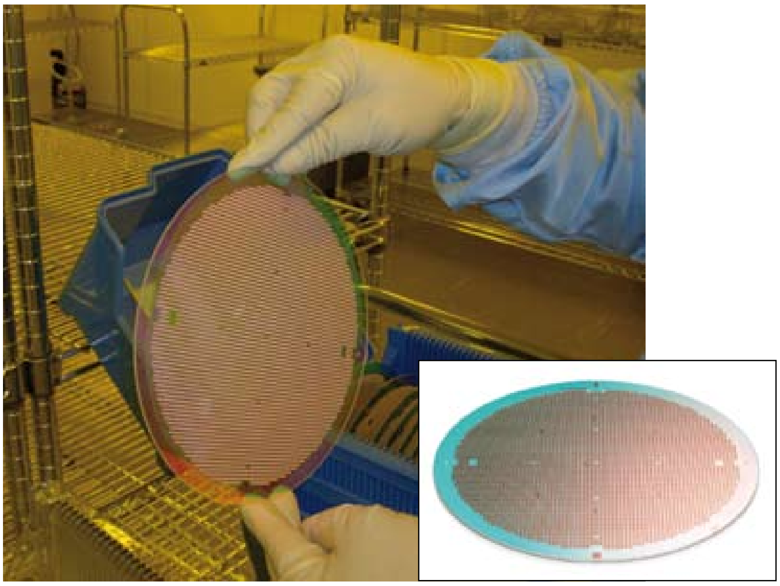

Figure 3. 8-inch glass wafer with about 4,000 lenses for mobile phone objectives.

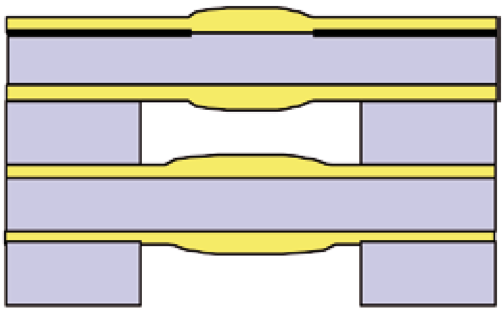

Figure 4. Thanks to the WaferOptics process, a mobile phone objective combines several aspherical elements.

The WaferOptics process resembles IC manufacturing processes, with the difference that UV- and visible light-transparent glass with a thickness of 0.3 to 1.5 mm forms the substrate and not – still thinner – monocrystalline

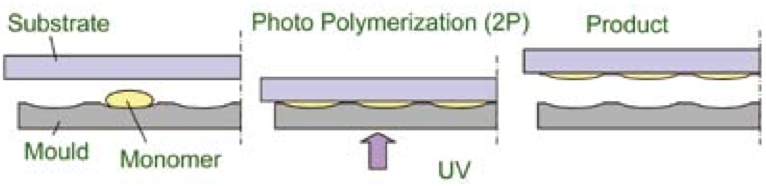

Figure 5. The process starts with the replication and photo polymerization of lots of optical elements at one side of a glass wafer.

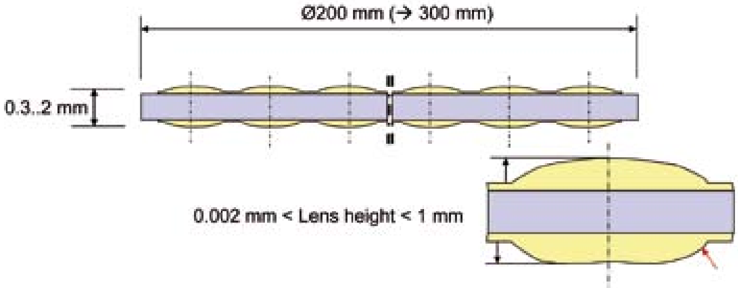

Figure 6. After turning the wafer around, a set of elements is applied to the other side of the wafer.

silicon. Figure 5 shows the replication and photo polymerization process for a wafer with a set of one-sided optical elements, each being > 20 µm thick. Then the wafer is turned around, after which a set of elements for the other side is applied, see Figure 6. Here again, control of the adhering or releasing properties of resin and surface is essential for a successful manufacturing process.

Then sets of optical systems are realized by combining one or more spacer plates in glass with one or two glass wafers with optical elements in resin at both sides. By a powder blasting process the spacer plates have been provided with diaphragms beforehand. UV curing glue is used to connect wafers and plates. Finally, the individual optical systems are separated by dicing with a diamond saw, which results in the products depicted in Figures 7 and 8.

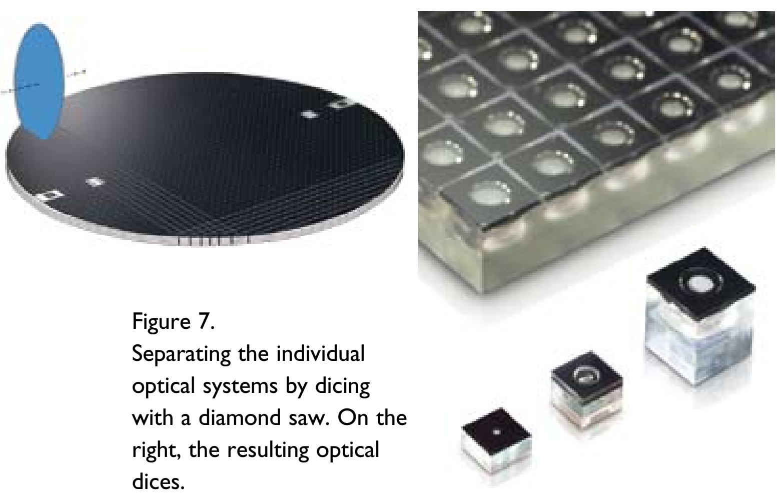

Figure 7.
Separating the individual optical systems by dicing with a diamond saw. On the right, the resulting optical dices.

Figure 8. Optical dices are real precision products.

The WaferOptics process differs from the single-lens process in the huge quantity of the same – mostly aspherical – forms in one wafer-sized mould. Anteryon produces such moulds with an in-house designed highly accurate machine that resembles an ASML wafer stepper in many respects. The machine multiplies the lens shape in UV sensitive resin on an appropriate substrate. After resin curing the acquired product can directly be used as a tool for producing optical wafers or – when mass production is the case – as a mastering tool for daughter tools. This choice determines whether the basic model has to have a positive or negative form.

Precision aligment

It will be clear that manufacturing a precision optical product as shown in Figure 8 requires the utmost precision in aligning the elements at two sides of a glass substrate, and in aligning two (or more) substrates mutually. Therefore tools and substrates are provided with optical aligning marks comparable with the ones used in IC wafer steppers. The foregoing applies to alignment in the x,y-plane, but optical properties also depend on the position accuracy of the various elements in the z-direction. This means that control of the thickness of glue layers is very important too.

How these precision demands are being fulfilled in the Anteryon clean rooms, again has to stay in the haze of company secrets. But citing some of the tolerances may give an idea of the problems Anteryon had to solve before WaferOptics products could be produced with today's yield of 95% after individual MTF inspection in Eindhoven. (MTF stands for Modular Transfer Function, a key parameter that determines the imaging quality of the lens stack.) The concentricity of the various elements in one lens stack is better than 5 µm, roadmapped to below 2 µm. The total thickness variation is smaller than 10 µm, roadmapped to 3 µm. The shape variation of each lens amounts to 100 nm RMS, roadmapped to below 50 nm.

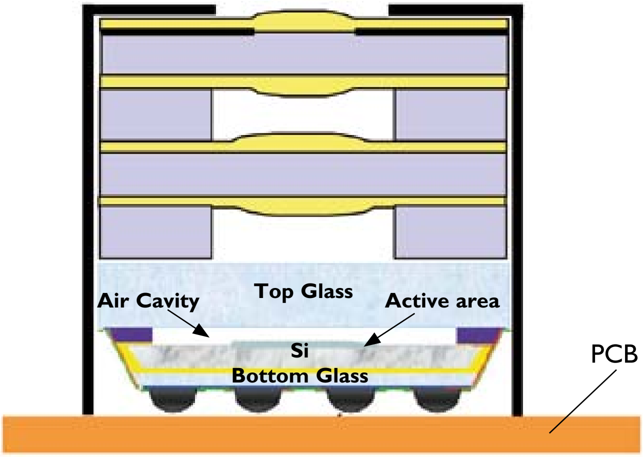

Figure 9. After being provided with a protective cap, the optical dices must be integrated with a CMOS sensor to make them suitable for surface mounting on a PCB.

The absolute position accuracy of one stack on a wafer assembly is better than 5 µm, roadmapped 1 µm.

SMD product

The stacked objective lens of Figures 7 and 8 is not the finished product. It has to be integrated with an optical CMOS sensor and thereafter made suitable for surface mounting. So it becomes an SMD, Surface Mounted Device; see Figure 9.

The stacked Anteryon lenses are quality controlled in Eindhoven, after which they are transported to China for the mounting of a protective top cap. Integration of the lens stacks with packaged image sensors occurs at the camera module assembly plant. There, the customer has to choose from a variety of sensor packaging solutions that can provide the electrical contacts between the sensor and the underlying soldering contacts. Finally, the units are put into

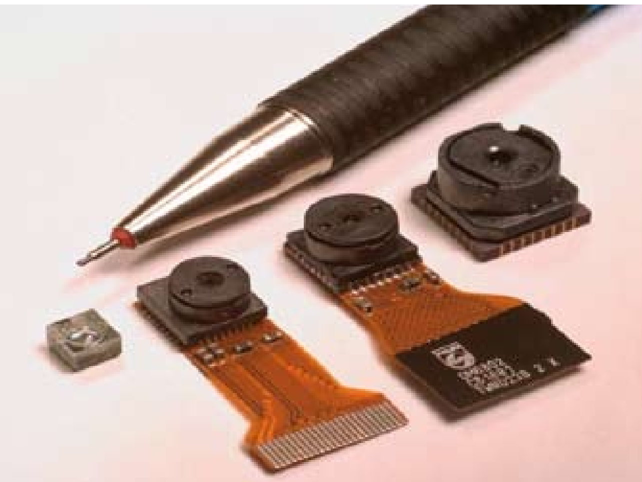

Figure 10. Size reduction of optical units for mobile phones during subsequent generations.

Figure 11. The Anteryon production programme includes a wide range, from sub-millimeter miniature lenses for Blu-ray players to large glass prisms.

casings that comply with the customer's SMD machines for producing PCBs for mobile phones. Figure 10 shows the size reduction of these optical units for mobile phones when compared with the products from earlier generations.

MEMSland

The foregoing description of the successful WaferOptics process for optical units in mobile phones is only part of the Anteryon story. The company also produces many other optical parts, see Figure 11, from large glass prisms to submillimeter miniature lenses for Blu-ray players.

New challenges showed up in the MEMSland project, in which many partners – besides Anteryon, also Philips, NXP, TNO, Boschman and the universities of technology of Eindhoven and Delft – cooperated to find practical solutions for integration of micromechanics, electronics and optics. MEMSland was one of the largest programmes under the flag of the Point-One innovation programme for nano-electronics, embedded systems and mechatronics; see the February issue of Mikroniek for a report on the MEMSland Closing Symposium.

To conclude

Manufacturing optical systems for mobile phones in huge quantities has much to do with a passion for precision. Recently, Anteryon celebrated the delivery of the 25,000,000th optical unit of one type within a time span of one and a half year. This milestone could be achieved due to the enthusiasm of the complete Anteryon crew – which provides a sunny outlook on volume production of other types of lens stacks for new customers.

Author's note

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Information

www.anteryon.com

Thermal effects

In precision engineering, thermal effects have always been important in reaching high precision. Yet, over the years little attention has been given to this subject. Therefore, Mikrocentrum, in cooperation with Tegema Group, decided to organise a second seminar on thermomechanics, following the first one held four years ago, which attracted considerable interest. This year, the seminar focused on the control of thermal behaviour of precision systems. Once again, attendance was above average, underlining the topicality and relevance of this issue.

• ***Ronald Lamers*** •

In precision systems, thermal effects have a large influence on the desired accuracy and throughput, especially when these systems have to perform under extreme thermal conditions (for example, vacuum or cryogenic). Therefore, it is very important to give this aspect sufficient attention in the design phase. Examples are machine tools that are crossing the submicron boundary for machining accuracy, and measurement machines that can reach accuracies in the order of nanometers. Printing systems often work with fluid temperatures above 100°C and position accuracies of micrometers over a large range. The chosen system concept in most of these cases is strongly cost-driven.

Author

Ronald Lamers works as a systems architect with Tegema Group in Eindhoven, the Netherlands. He was co-organiser of the seminar, which was held on 16 March 2010, hosted by Mikrocentrum.

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Figure 1. Impression of the information market that was part of the seminar.

Control of thermal behaviour

Wafer steppers, electron microscopes and space instrumentation can only function properly if the thermal stability is guaranteed in the order of nano- or even picometers. The seminar looked more closely at the control of thermal behaviour of precision systems. Topics included design principles such as the thermal centre, the right

in precision systems

choice of material, passive or active temperature conditioning and the compensation of thermomechanical deformations. Furthermore, attention was given to the modelling and analysis of thermomechanical systems during the design phase and to performing measurements during the test phase.

An historical overview

Theo Ruijl, concerned with thermal effects in engineering within FEI Company, acted as the chairman of the day. In his introduction, he gave an historical overview, going back as far as 1600. Marine chronometers were one of the first precision systems for which thermal aspects were considered: the differences in thermal expansion of materials were used to neutralise thermal effects. The period 1800-1900 showed some achievements in early precision manufacturing and metrology.

Recent examples are ultra-precision diamond turning, where subnanometer surface finishes and submicron form accuracies are achieved. Current opinion on the international status of thermal error research is best described by citing James Bryan from his 1990 paper [1]: '*…In spite of some excellent research…thermal effects are still the largest single source of dimensional errors and apparent non-repeatability of equipment*'. Furthermore, it can be observed that thermal effects are everywhere in all relevant market areas of Dutch precision engineering, such as precision manufacturing and the semiconductor, space, automotive, medical, pharmacy, printing and energy industries.

Large-format inkjet printers

A presentation of the thermal aspects in large format inkjet printers was given by Jos Gunsing of NTS Mechatronics. Positioning errors of the ink droplet can severely disturb the printed image, which may cause banding and colour shifts. The subject of the presentation was the Agfa M-Press Tiger Inkjet Printer, which has a print format of 2.6 x 1.6 m^2; see Figure 2. The system consists of 64 print heads, and the printing motion and substrate handling functions are separated. The overall dot positioning accuracy is 20 µm, the motion errors are smaller than 8 µm and the overlay is 50-100 µm. The main heat sources are the print heads (max. 30 W each), UV sources and the linear motors. In order to achieve the desired accuracies, the temperature conditioning of the system needed to be better than ±0.1°C during one print cycle and ±1°C over longer periods. The accuracy is reached by applying design principles, thermal conditioning techniques such as water cooling and software compensation. Thermal effects were a substantial part of the design effort and thermal lumped-mass modelling gave results that could be used quite well. However, one of the major challenges for future generation printers will continue to be thermal stability.

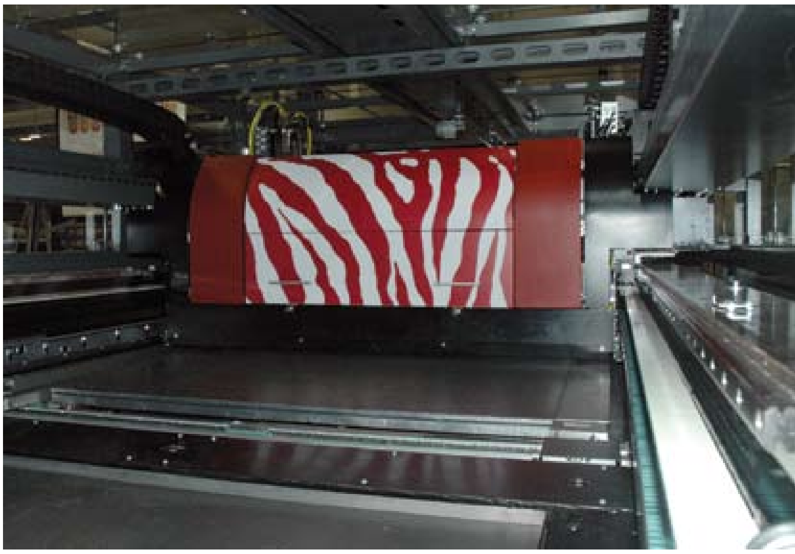

Figure 2. The large-format Agfa M-Press Tiger Inkjet Printer.

FEM simulations

Willem Dijkstra of Mecal gave a presentation on the use of FEM simulations (Finite Element Method). His topic was the effect on overlay as a result of 'wafer heating' in wafer steppers. The total allowable error for the production of chips with features of 45 nm is 15 nm. Approximately 1 nm of this budget is allocated for thermomechanical effects. Heat dissipation during the lithographic production of chips can lead to errors. A wafer is divided into fields that are exposed several times one after another. 95% of the light is transformed into heat and absorbed in the wafer. Due to this absorption, the wafer, and the table and chuck holding the wafer, heat up and deform due to thermal expansion. The mirrors on the chuck, which are used for interferometric position control, also deform. Optimisation was realised by using an FEM model and a good understanding of the thermal interactions between wafer, table and chuck. This complex, large model was kept manageable by the use of submodels of certain complex interactions (for example, thermal contact properties) within the system. Dijkstra underlined that FEM simulations are a tool, and not a goal. A design optimisation can only be realised by understanding the real physics.

Tuning thermal constants

Rens Henselmans of TNO presented the thermomechanical design of an Optical Tube Assembly (OTA). The ESO (European Southern Observatory) is expanding one of its Very Large Telescopes in Paranal (Chile) with the '4 Laser Guide Star System', which creates artificial stars to serve as a reference for their adaptive optics systems. Air turbulence causes blurring of the stellar light, which is arriving as a perfect wave front at the earth's atmosphere. Mirrors can be deformed to correct these turbulence errors. To that end, a 'reference star' is created. A 25 W laser (Continuous Wave, 589 nm) projects its beam into the sky, where it excites sodium atoms in the atmosphere between 90 and 100 km high, which in turn start emitting light.

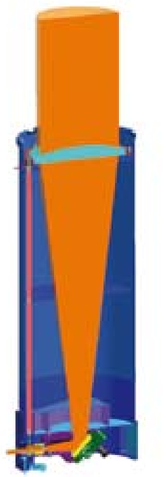

Figure 3. The Optical Tube Assembly expands a 15 mm input laser beam to a steerable 300 mm output beam.

The OTA expands a 15 mm input beam to a steerable 300 mm output beam with strict wave front requirements (50 nm rms wave front quality); see Figure 3. The beam expander should not defocus over 8 hours as a function of the ambient air temperature (0-15 °C; -0.7 °C/hr gradient). The design was therefore passively athermalised in the steady state as well as the transient state by tuning the thermal time constants of the different components, and by matching the expansion coefficient of the structure to the varying properties of the lenses. Different materials were used to gain suitable compensation coefficients. Because steady-state as well as transient behaviour has to be considered, both static and dynamic properties are important aspects of the design solution.

Cheap and reliable micrometers

For printer manufacturer Océ, it all comes down to cheap and reliable micrometers. Rob van Loon presented some of the thermomechanical effects in Océ's new Colorwave 600 colour printer. He underlined that thermal effects are often the largest disturbance and are often very complex. It is important to map out the sources and the effects, both steady state and transient. Within the Colorwave 600, design principles have been applied to gain reproducible behaviour, since the system's error is its sensitivity multiplied by the disturbance. By minimising the sensitivity, the error is also minimised. Correction by means of temperature measurements is also applied. Temperature gradients, which cause bending deformations, are minimised by choosing a material with a low α/λ ratio (for example, aluminum), where α is the coefficient of thermal expansion and λ is the thermal conductivity. One major issue is paper buckling during paper transport, which is caused by thermal, hygroscopic (for example, climate) and mechanical interaction. This subject is still under investigation.

Heat transfer visualisation

Flow visualisation is often used as a technique to gain insight into fluid flows, for example in the aerodynamic design of vehicle bodies, weather predictions, and optimisation of mixing processes. Michel Speetjens of Eindhoven University of Technology showed that heat transfer can be made visible in a comparable way, which allows for thermal analysis with well-known flow visualisation methods. In his presentation, he demonstrated the mathematical equivalent of fluid motion and heat transfer. Some very illustrative 2D and 3D examples where given, for instance for heat transfer in fluids with high and low Péclet number Pe (~ convection / conduction). The vivid discussions afterwards showed that the subject was interesting and this new technique will offer new perspectives.

Thermal drift measurement

Besides design and analysis, measurements on precision systems for validation are also very important. Guido Florussen of IBS Precision Engineering presented some aspects of performing measurements on the spindle of machine tools. Typical heat sources in machine tools are linear drives, motors, spindle drives, hydraulic pumps, gear transmissions, bearings, electronics and, last but not least,

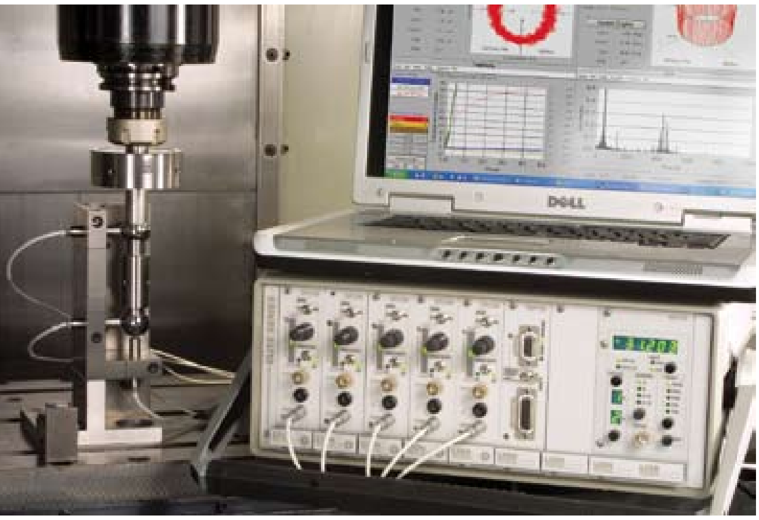

Figure 4. Double-ball set-up for IBS's Spindle Error Analyser.

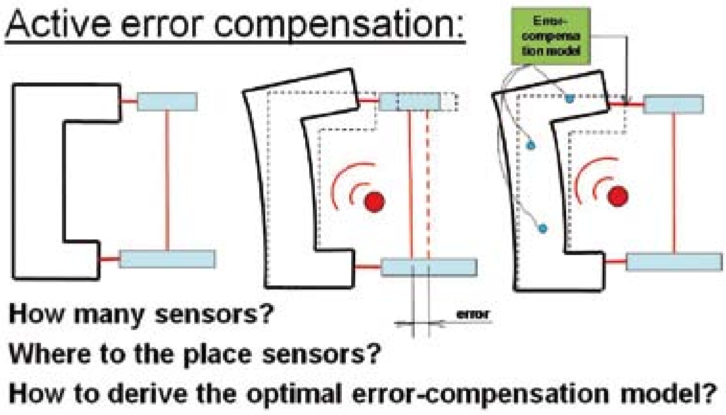

Figure 5. Schematic of a thermomechanical compensation model for position control.

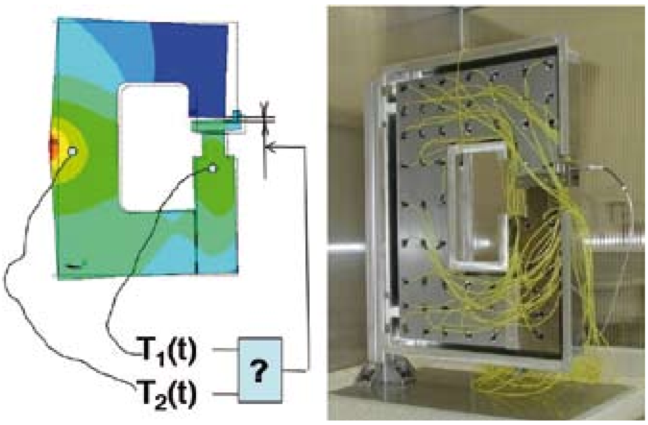

Figure 6. Optimisation of the location of temperature sensors.

the environment. The effects of these heat sources on the expansion of the spindle can be measured with a so-called Spindle Error Analyser. With this method, a very accurate (single) ball is placed inside the spindle, the machine is started and the x, y and z displacement of the ball is measured accurately with three capacitive sensors. With a double ball, see Figure 4, it is possible to also measure Rx and Ry rotations. Some specific measurement results where presented, which clearly show whether a machine is (not) compensated for thermal expansion. Compensation can be realised by active closed-loop cooling techniques or by software compensation. Florussen also mentioned some do's and don'ts regarding these types of measurements.

Model reduction techniques

Marco Koevoets of Philips Applied Technologies discussed thermomechanical compensation models for position control; see Figure 5. Model reduction techniques such as modal analysis, Arnoldi and proper orthogonal decomposition can be used to determine the thermal state of a system based upon measured temperatures. The selection of the right model reduction technique depends on the pre-knowledge of the corresponding system: for example, are the loads known?

With knowledge of the thermomechanical behaviour of the system, the corresponding time-varying thermal deformations can be calculated real-time and compensated for. The performance gained depends on the uncertainty of the thermomechanical model, the configuration of the temperature sensors and the uncertainties in the temperature measurements. With the use of these techniques, the location of the temperature sensors can be optimised; see Figure 6.

Conclusion

The seminar topics covered an interesting and diverse range of aspects, from design and analysis to measurements. The diversity in the attendance showed that thermal effects are relevant to many different applications. The issue will remain hot, as evidenced, for example, by a forthcoming special issue of the Mechatronics journal. See the call for papers on page 57.

Reference

[1] Bryan, J.B., 1990, "International Status of Thermal Error Research". CIRP Annals, Vol. 39/2.

Information

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Optical improvement for

Even after years of industrial use of lasers, there is still room for new concepts and increased flexibility. The reason why laser technology is used in a wide variety of applications, is not the laser system itself but the ability to tailor optical energy to the demands of the production processes. The full potential of the laser technology is becoming available when combined with optical elements such as polarizers, cameras, lenses and sensors. The use of all these optical tools makes laser technology as a production technology adaptable to almost any situation.

• *Johan Bosman, Robert Molenaar, Henk Kettelarij, Martijn de Keijzer and Corné de Kok* •

Serving as an example of the potential of laser technology, a new camera system was developed that co-axially views through a laser scan lens enabling new solar cell designs to be produced more efficiently. And the marking of optical moulds benefits from this new camera option as well. It allows the repair of existing marks on optical moulds. This camera lens system was designed by Sill Optics in close corporation with Molenaar Optics, ECN and Philips Applied Technologies. The new lens enables a scan angle independent view through the scan lens with an integrated illumination of the work piece. Another problem that can be solved by adding optical elements to the laser system, is its inherent change of pulse width and intensity distribution when changing the pulse energy electronically with the power supply of the laser.

Authors

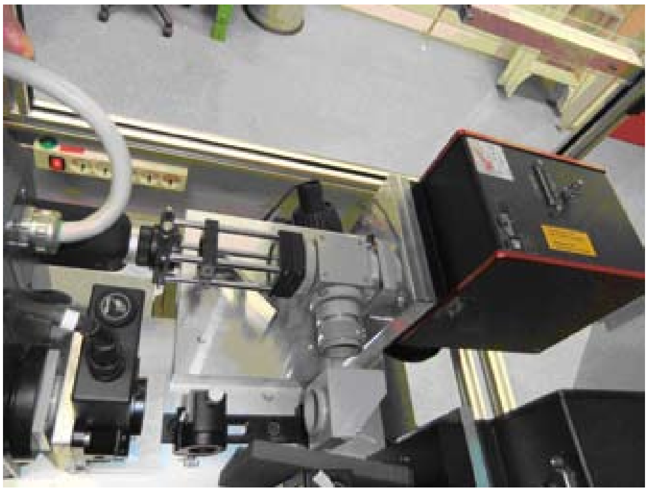
Johan Bosman is scientist/coordinator, and Martijn de Keijzer and Corné de Kok are scientists, all at ECN (Energy research Centre of the Netherlands), Engineering & Services Departement, Eindhoven/Petten, the Netherlands. Robert Molenaar is director of Molenaar Optics, Zeist, the Netherlands. Henk Kettelarij is scientist at Philips Applied Technologies, System in Package/Thermal Processing Department, Eindhoven.

Attenuation

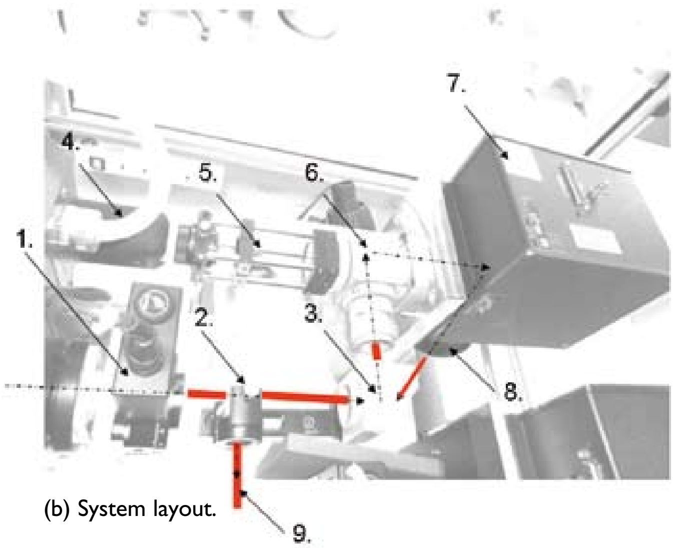
The nature of most laser systems makes the use of attenuation into an efficient production tool. Attenuation is a known solution for many experiments, see Table 1. It allows to change the pulse energy without changing the pulse shape and divergence. A laser is usually most stable at high pulse energies, while selective layer ablation and engraving merely demand moderate pulse energies. Accurate attenuation by computer-controlled polarization variation then provides the necessary reduced pulse energy, while the laser still can be operated at its most stable point. Attenuation can also be used to measure threshold values of laser processes. It is even used as a method to control product quality. A good attenuation system only changes the pulse energy, without any change to the beam quality and pulse duration. Several attenuation methods exist, see Table 1.
The use of modern laser systems such as pulsed fiber lasers, makes external attenuation at first sight less important. These systems are using amplifiers to enable the high pulse energies and have much better cooling due to their higher surface-to-diameter ratio. Therefore, for

Table 1. Overview of attenuation methods.

Attenuation method	Specific features
Angle dependent reflection	Thermal effects, separate cooling is required.
Neutral density filters	Good for low intensities, higher intensities tend to damage the filter.
Polarization dependent transmission	No absorption in the optical elements. Used with half-lambda plates and electro-optical polarization rotation. Suitable for high pulse energy.
Surface reflection	Used for beam measurements, a small part is reflected. Polarization dependent.
Acousto-optical deflection	Full attenuation at Bragg angle. Introduces small angle in the system. Used for fast attenuation.



(a) Overview



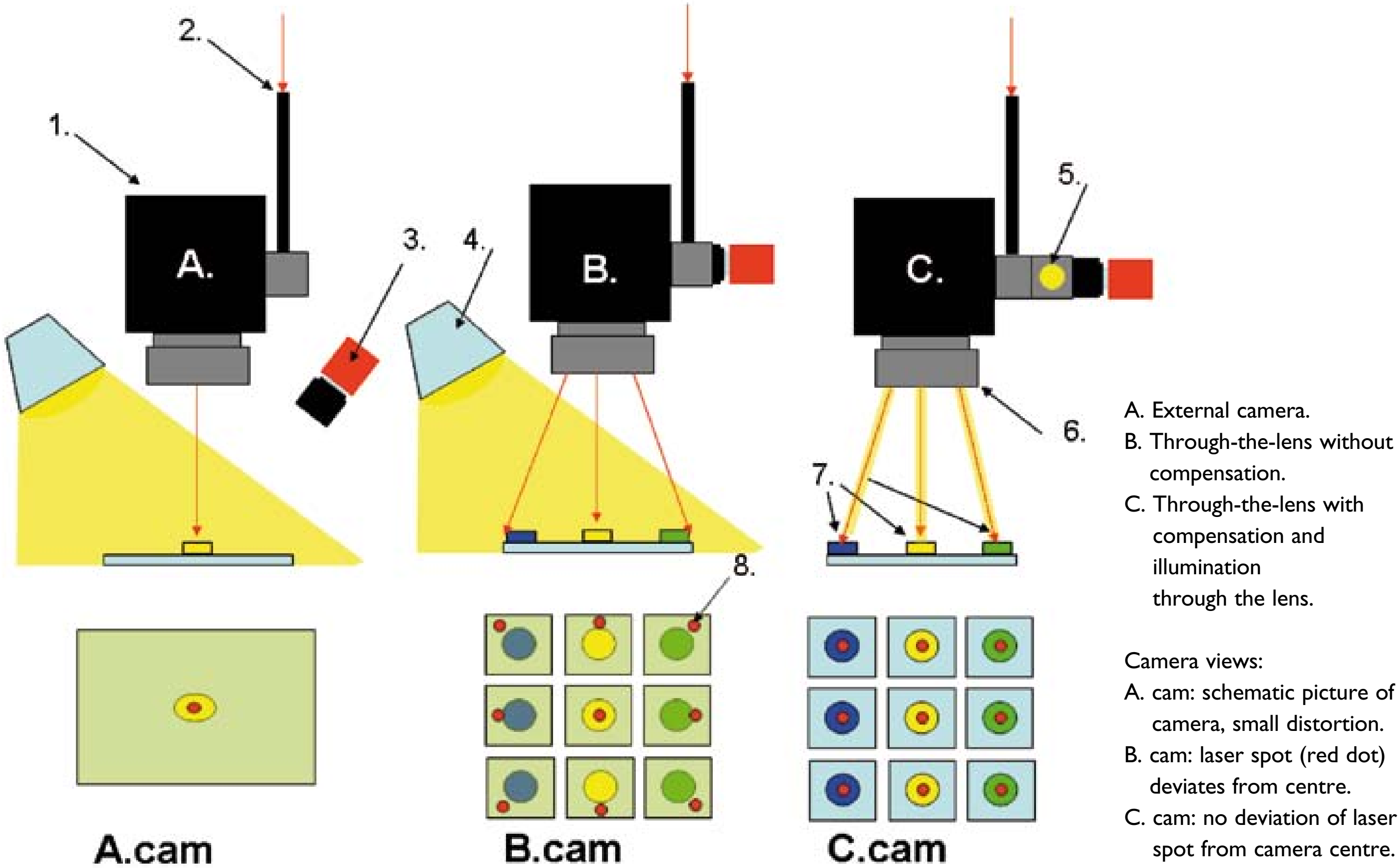
(b) System layout.

1. Rotating half-lambda plate, 2. Polarizing beamsplitter cube, 3. 45° mirror, 4. Camera, 5. Projection optic camera, 6. Infrared 45° mirror, 7. Scanner, 8. Flat-field focusing optics, 9. Laser beam to beam dump. Dashed and red lines: optical path of the UV laser through the system.

Figure 1. UV attenuation system using polarization with camera setup.

nanosecond systems the pulse shape is less dependent on the pulse energy. However, the use of external attenuation is quite helpful in determining the intensity threshold of processes. This does not mean that attenuation is only limited to the design phase. The new picosecond fiber lasers all use internal attenuation to ensure efficient and stable running of the laser under industrial conditions. The attenuator used, see Figure 1, comprises of an accurate computer-controlled steppermotor-rotated quartz halfwave retardation plate from OptoSigma (Figure 2) to rotate the polarization direction of the laser beam. This controls the power output of a high-power laser polarizing cube beamsplitter before it enters the flat-field scanner system.

Figure 2. OptoSigma motorized rotation stage.



1. Scanner, 2. Laser in, 3. Camera, 4. Illumination, 5. LED coaxial (inline) illumination, 6. Scan lens, 7. Objects, 8 Laser spot in camera view.

Figure 3. Three different camera and scanner combinations.

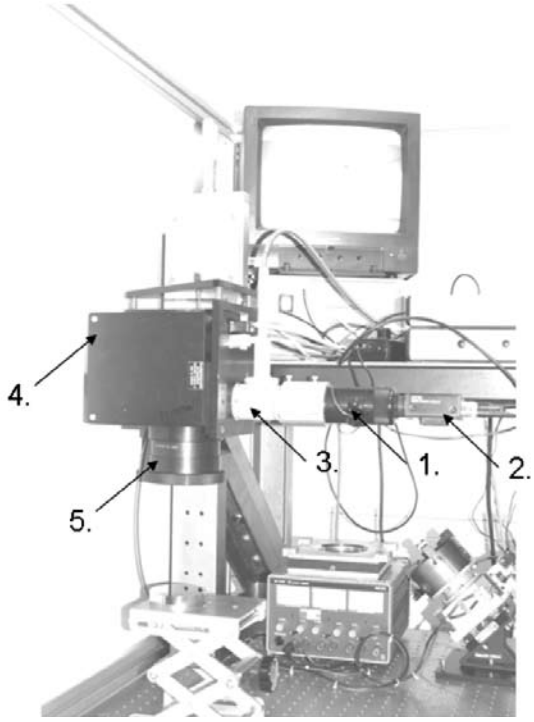
Through-the-Lens Camera System

The repeatability accuracy of optical galvo scanners is very high, 3.5 μm for a 160 mm scan lens. But the absolute position accuracy is not as good. Thermal drift often causes problems when high absolute accuracies are needed (for example, Intelliscan: 0.6 mrad/8 hours * 160 mm = 96 μm). Some systems can calibrate the mirrors internally to ensure a better performance of the scanner. Another, novel scanner design uses less energy and subsequently generates less heat for improving the absolute accuracy. But, these systems are not the answer for measurement of production line variations of part dimensions or errors in positioning systems. In such cases a camera system is the solution.

Cameras are often placed alongside the scanner and communicate with the software of the scanner system. A camera that can look through a complex scan lens is more accurate but only in the centre of the field (see Figure 3). To overcome this position limitation, a calibration can be used to compensate for the errors the scanner lens introduces. This so-called compensation table solution is used in baseline solar cell production at ECN for edge isolation and via drilling. However, it is very time consuming and the complete scan field has to be illuminated. Because the compensation is position dependent, the actual angular position of the mirrors is needed to calculate the real compensation.

Philips, Molenaar Optics, Sill Optics and ECN worked together to enable a more generic solution with a system that eliminates the need for the position feedback and solves another problem, the illumination; see Figure 4. A dual-wavelength scan lens from Sill Optics was used to simultaneously enable vision in the green and a laser process in the near infrared. The lens was originally designed for simultaneous infrared and green laser processing, so it has the same focal length and F-theta condition for both wavelengths. Adding a camera and a telecentric objective lens with coaxial illumination (a green LED) completes the system.

(a) Overview.



(b) System layout.

1. Camera optic and illumination source, 2. Camera, 3. Infrared 45° mirror and incoupling of the fiber laser beam, 4. Scanner, 5. Telecentric lens

Figure 4. Position-independent through-the-lens camera system with illumination.

Going through the objective lens, the green LED illuminates the camera field only, not the surroundings. A polarizing beamsplitter transmits the reflected light with the image of the processed part to the camera while keeping the illumination source away from it. This system has no need for a compensation table. If an automatic camera system is used, the measurement of the camera can be directly fed to the scanner card. This makes fast calibration possible. The system can even measure parts and can act actively when combined with an intelligent camera. The same system can also be used for the green processing wavelength with infrared illumination. The integrated illumination is more efficient because only a small area of the product is illuminated. For some materials like polymers and biomaterials, a full illumination can change the product temperatures through absorption. This could cause melting and deformation of the product.

Conclusion

The cooperation between Molenaar Optics, Sill, Philips Applied Technologies and ECN made it possible to define the needs for a new through-the-lens optical system. This lens system enables a higher absolute accuracy while using scanners and compensates for the thermal scanner drift and displacement of the part during production. The position-independent compensation enables a larger working area. The old system was limited to the centre of the lens. But this optical system can even be used, with an intelligent camera, to find the part and calculate the compensation directly. This reduces the need for accurate positioning.

The other system discussed, computer-controlled optical attenuation, is a good example of simplification. It makes laser operation easier by adding a direct power knob. The user does not have to think about all the other parameters of the laser, while normally changing the pulse energy would automatically lead to a change somewhere else in the laser beam.

Information

www.ecn.nl
www.apptech.philips.com
www.molenaar-optics.nl
www.silloptics.de

A benchtop tool micromechanical

A compact tool, based on a magnetomotive transduction technique at room temperature and pressure, was developed for the characterization of the dynamic properties of micromechanical systems. Using a permanent magnet that generates up to 2.5 Tesla in an adjustable gap, mechanical resonances at megahertz frequencies can be measured. The driving force is strong enough to drive microresonators into nonlinearity, and to detect microresonators vibrating in liquids.

• ***Warner Venstra*** •

For several decades, lithographic processes originally developed for the integrated circuits industry have been used to fabricate tiny mechanical structures. Commercial applications of these micro-electromechanical systems include accelerometers, as shown in Figure 1, force and pressure sensors, switches and motion detectors. Mechanical systems with micro- and nanometer dimensions are extremely responsive and this has led to new instruments that enable, for example, mass sensing on the scale of single atoms, manipulation of individual atoms on a surface, and detection of displacements in the femtometer range.

Author

Warner Venstra, Ph.D., is a researcher at the Kavli Institute of Nanoscience in the Faculty of Applied Sciences, Delft University of Technology. After receiving his M.Sc. in Mechanical Engineering, he worked on the development of the first generation of DVD video recorders at Philips Components in Eindhoven, the Netherlands. He returned to university for a Ph.D. project on micromachining techniques with applications in DNA-sensors. His current research focuses on nonlinearities in nanomechanical structures, and low-power nanomechanical computing.

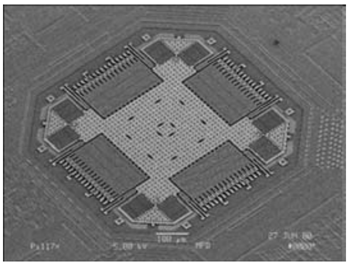


Figure 1. MEMS accelerometer commercialized by Analog Devices in airbags and game consoles.

The principle of mechanical sensing often involves determination of a mechanical resonance frequency, which is affected by the quantity that has to be measured. In Figure 2, the resonance frequency of the V-shaped beam changes as a result of mass adsorbed on its surface. As with electronics, lithographically produced micro- and nanomechanical systems can be integrated on a large scale, and this will enable new applications such as high-speed imaging and manipulation of surfaces on atomic scale by

for characterizing systems

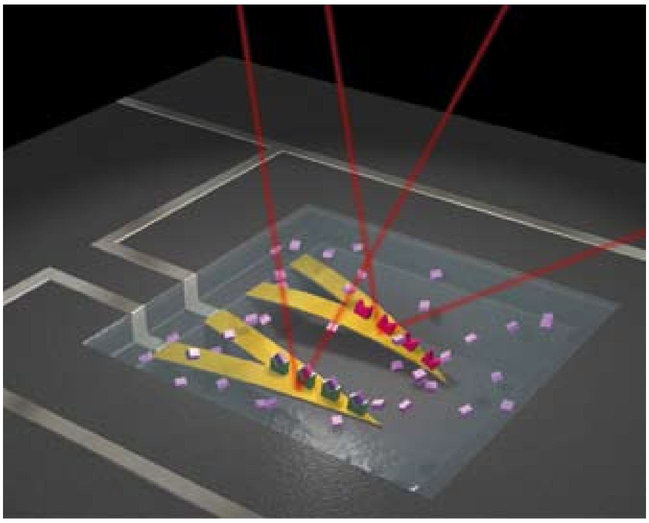


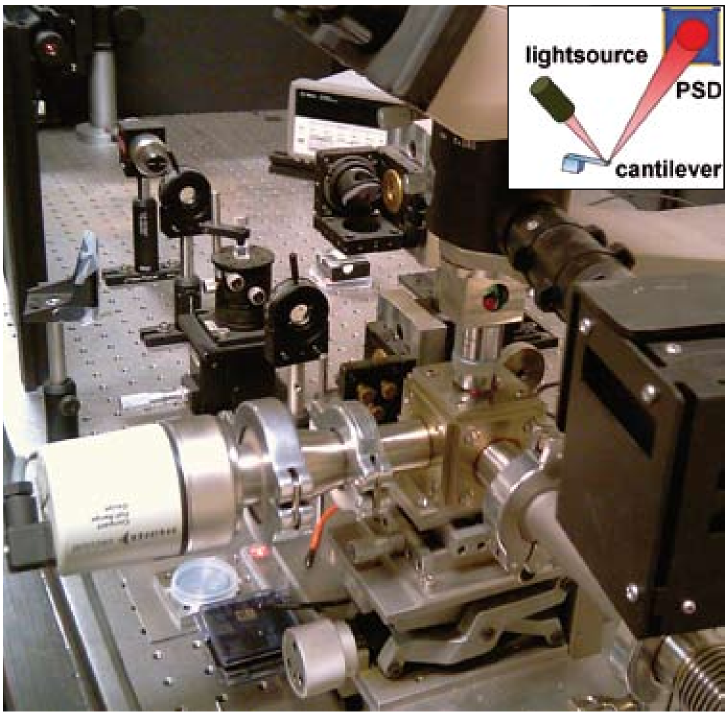
Figure 2. Microresonators for biomolecule sensing.

scanning probes, mechanical memories and logic, and sensor arrays for the simultaneous detection of multiple chemical compounds. Most of these devices operate at atmospheric pressure, in air or in water. Characterization of the dynamical properties in these environments is essential for their development.

Characterization

Optical techniques are often used to characterize the dynamical properties of micro- and nanomechanical systems. Commercial tools are available, such as the laser vibrometer shown in Figure 3a, which detects the Doppler shift of an optical beam reflected from the vibrating micromechanical device. Another popular method is the optical deflection technique. An optical beam is reflected off the vibrating structure and captured on a position sensitive detector (PSD). This scheme, shown in Figure 3b, is often applied in scanning probe microscopes.

(a) Commercial laser Doppler interferometer.



(b) Optical deflection setup for characterization in vacuum, air and water.

Figure 3. Optical tools for the dynamic characterization of micromechanical systems.

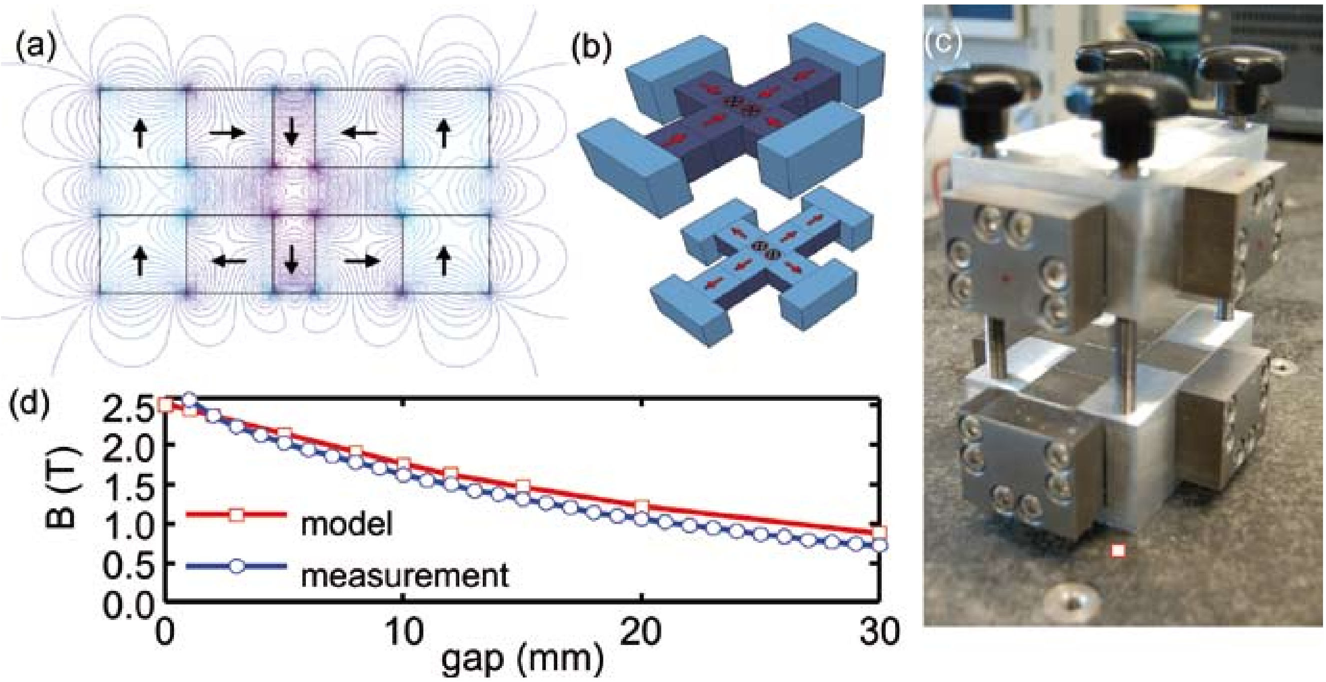


Figure 4. Development of a 2.5 Tesla permanent magnet.
(a) Magnetic field of a Halbach array, calculated by finite element analysis. The arrows indicate the polarization of the magnets.
(b) Implemented magnet arrangement.
(c) The resulting magnet; the gap can be adjusted by four screws.
(d) Measurement of the magnetic field as a function of the gap.

Optical techniques are straightforward to implement, but they have several drawbacks. The minimum dimension of the devices that can be characterized is limited by diffraction. The structure should also be accessible by the optical beam. The optical axis should be aligned with the displacements to be detected. This is not the case for a range of micromechanical devices, such as the electrostatic actuator shown in Figure 1, which are designed to move in the plane of the wafer. Although microscopic imaging under stroboscopic illumination can be used to visualize these lateral movements, the resolution of such measurements is limited. Optical techniques are also inadequate to measure the response of multiple devices simultaneously. Positioning multiple optical beams and capturing the reflections on one or more detectors is a complicated task.

Many of the limitations connected with optical techniques can be overcome by a technique based on electromagnetic induction. This magnetomotive technique can be used to simultaneously drive and detect conducting micromechanical structures.

Magnetomotive drive and detection

To drive the resonator, an alternating current I is applied in the presence of a static magnetic field B. A Lorentz force ($F = B \times I$ per unit length) is acting on the resonator and causes a displacement. Movement of the resonator changes the flux Φ through the current loop, and this generates an electromotive force (EMF) equal to $E = -\mathrm{d}\Phi/\mathrm{d}t$, proportional to the velocity of the resonator. When the frequency of the driving current matches the mechanical resonance frequency, the displacements are amplified and the induced voltage peaks. A mechanical resonance can thus be detected by measuring the generated EMF as a function of the frequency of the driving current.

In micro- and nanomechanical systems, the displacements and the corresponding flux changes are very small. Moreover, the driving currents are limited as the devices easily heat up and resistances are relatively high. However, the extremely low mass results in very high resonance frequencies, and as a result the magnetomotive transduction technique scales favourably when shrinking the device dimensions. It appears that the technique is particularly well-suited for the characterization of micro- and nanomechanical structures.

A quadratic relation exists between the generated EMF and the applied magnetic field, and to detect resonators with lengths in the micrometer range one needs a high magnetic field. Fields that are strong enough can be generated by cooling a Niobium-Titanium coil to below the critical temperature, usually at 4 K, the temperature of liquid

Helium. Once the coil is superconducting, a large current can circulate without dissipation. Magnetic fields over 15 T can be generated in this way, which is more than ten times the remanence of today's strongest permanent magnets. Although these cryogenic systems have been used to explore the dynamics of nanomechanical resonators [1], they are expensive and take great effort to operate and maintain. This makes them impractical for routine characterization purposes.

A 2.5 Tesla permanent magnet

The remanence of state-of-the-art Neodymium permanent magnets is approximately 1.5 T, but the field rapidly diminishes when the magnetic circuit includes an air gap. To obtain a strong field inside a gap which is large enough to accommodate a variety of experiments, the magnetic flux can be concentrated by using a special arrangement of piece-wise rotated magnets, known as a Halbach array [2]. Several implementations of such a magnet array were simulated using a two-dimensionsal finite element analysis. Figure 4a shows a simulation of a Halbach array. The field is maximum in the center of the air gap, and rapidly diminishes outside the magnet. Figure 4b shows the implemented magnet arrangement, slightly different from the Halbach configuration to facilitate the assembly procedure. Each magnet pole is constructed from six 1 $inch^3$ NdFeB cube magnets and two 1 x ¼ x ¼ $inch^3$ rods. The magnets are forced in an aluminum holder by following a special procedure, invented to withstand the huge repulsive forces. Figure 4c shows the realized magnet. The gap distance can be adjusted by four screws, rotating on pivots formed by silicon nitride bearing balls.

Figure 4d shows the magnetic field measured as a function of the gap distance. Also shown is a 2D simulation for this composition of magnets. For a large gap, the simulated field is slightly higher than in the experiment. This is due to fringe fields at the magnet boundaries; these boundaries are absent in the 2D model. For a small gap, the simulation underestimates the field and here the effect of the side magnets is prominent. The measured field in a 6 mm gap is 2 T, and when the gap is a millimeter, still enough to accommodate a silicon wafer, the magnetic field exceeds 2.5 T. For a gap of 6 mm, the field was measured as a function of the position. In a volume of 6 x 6 x 6 mm^3 around the center of the magnet the field varies less than 5%. The devices to be characterized can be placed anywhere within this relatively large volume. In contrast to optical systems, alignment of the sample is not critical.

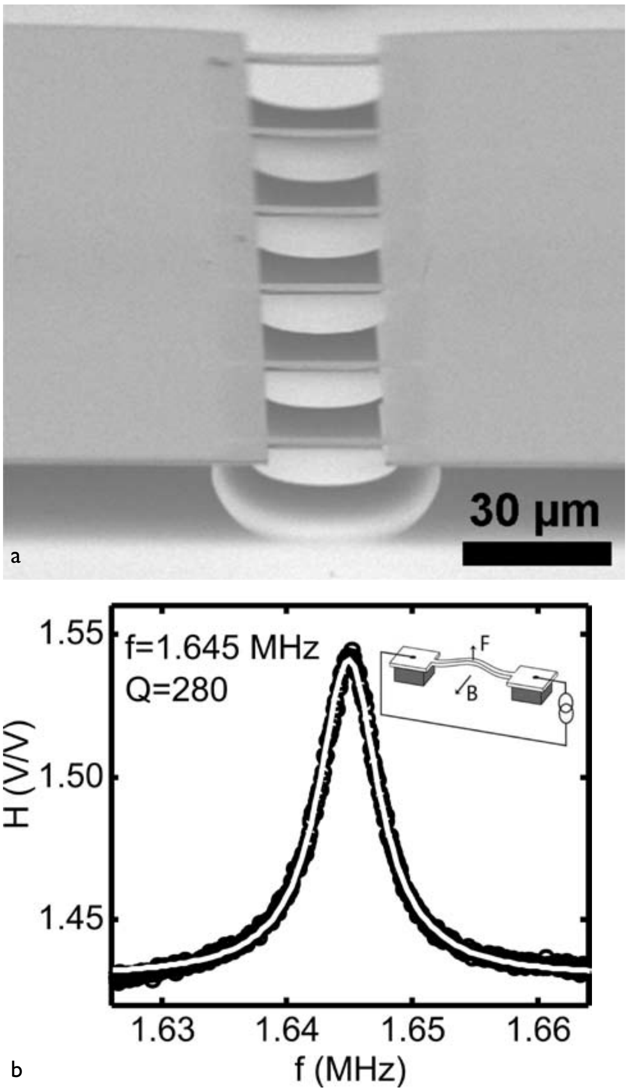


Figure 5. Resonator fabrication and characterization.
(a) Clamped-clamped resonators fabricated from a silicon nitride film by electron beam lithography. (b) Frequency response of one of the resonators at room temperature and atmospheric pressure.

Detection of mechanical resonances

The magnetomotive setup was used to characterize various types of microresonators, including crystalline silicon beams and silicon nitride beams and strings. Depending on the flexural rigidity and the residual tension, the resonator behaviour is governed by beam equations or a wave equation. The resonators shown in Figure 5a were fabricated from a 200 nm thick film of silicon nitride with a residual stress of several tens of MPa, and the behaviour is near the cross-over between a beam and string. A thin layer of gold was evaporated on top of the resonators to create a conductive path.

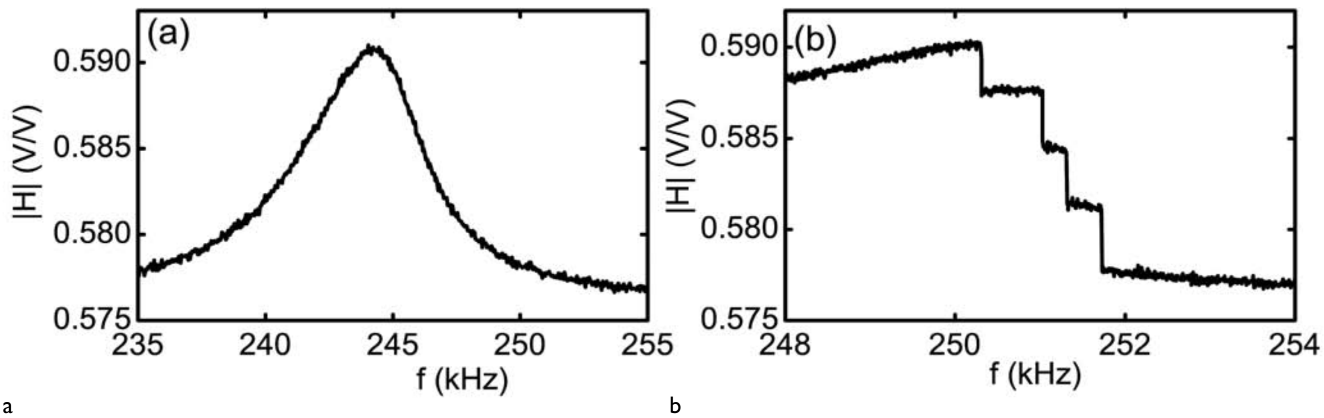
Figure 5b shows the frequency response of one of the resonators, measured with the magnetomotive technique at room temperature and atmospheric pressure. The mechanical resonance frequency is 1.645 MHz. Another important parameter, which represents the amount of damping, is the width of the resonance peak. A narrow peak means low damping, and a large displacement amplitude at resonance. It allows accurate determination of the resonance frequency. The damping can be quantified by the quality factor (Q-factor), defined as the energy stored in the resonator divided by the energy loss per movement cycle. It is related to the velocity dependent damping force by $Q = 1/(2\gamma)$. In addition to the viscous drag, the resonator is damped by the current passing through the detector circuit. To minimize this current, the EMF is measured using a high-impedance input amplifier. For the present resonator, the Q-factor is around 280, limited by the viscous drag from the ambient air molecules at atmospheric pressure.

Multiple resonators

Unlike optical techniques, the magnetomotive method is suitable for the simultaneous detection of multiple resonators. To characterize an array of resonators, all the elements are connected in series and driven by a single frequency sweep. This results in a response with multiple peaks, each peak representing a resonator. When the separation between the resonance frequencies in the frequency spectrum is less than the width of the resonance peak, individual resonators can not be resolved. This situation easily occurs in viscous environments, such as air and liquids, where the damping is high. As an example, Figure 6a shows the response of a series circuit of four resonators with nearly identical resonance frequencies. The responses add up and form a single peak, and no discrimination can be made between the resonators. Damping thus limits the number of resonant sensors that can be used simultaneously in a given frequency band.

This problem can be circumvented by making use of the nonlinear properties of the mechanical resonator [3]. When the driving force on a clamped-clamped resonator is large, the resonator behavior qualitatively alters, and the frequency response strongly deviates from the damped-driven harmonic oscillator. At large vibration amplitude the beam stretches significantly, and in addition to the flexural rigidity now the *axial* rigidity starts to play a role as well. This effect inserts a cubic stiffness term in the equation of motion, and the frequency becomes amplitude-dependent.

In the case of a clamped-clamped resonator, such as shown in Figure 5, the resonance frequency is pulled to a higher value. At sufficiently large amplitudes, typically in the order of the resonator thickness, the resonator amplitude can become bistable. Instantaneous transitions between high and low vibration amplitude can then occur, and the frequency response curve is hysteretic. The forces developed in the magnetomotive setup are large enough to access this interesting regime.



a b

Figure 6. Simultaneous detection of multiple resonators.
(a) Collective linear response of four nearly identical resonators.
(b) When strongly driven, the resonators can be discriminated by making use of their nonlinear properties.

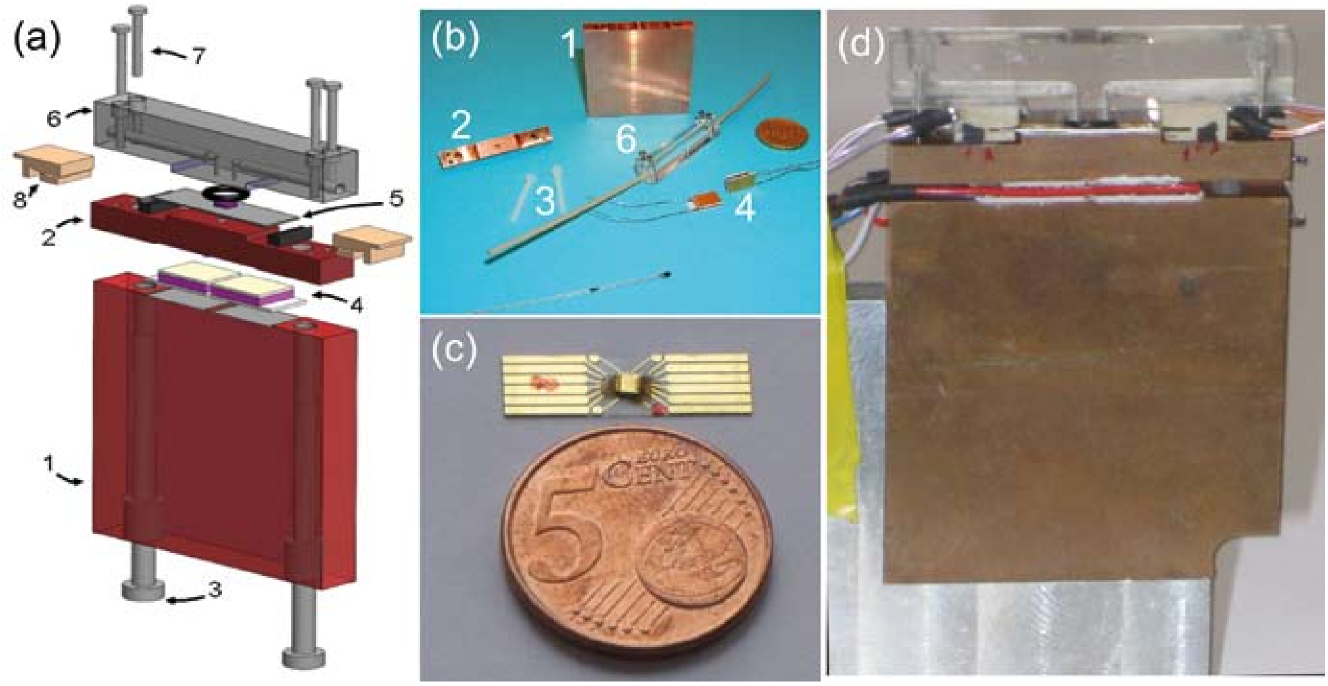


Figure 7. Construction of a flow cell.
(a) Exploded view of the flow cell.
(b) Collection of fabricated parts.
(c) Resonator chip bonded on carrier glass plate.
(d) The resulting flow cell.

The sudden jumps in the vibration amplitude can be used to discriminate resonators that could not be resolved in the linear regime of Figure 6a. This is shown in Figure 6b, which represents the same four resonators but with the drive strength increased up to the point where the resonators become bistable. In this regime, individual transitions are clearly visible for each of the four resonators. Adding or releasing mass at the surface of one of the resonators induces in a shift of the transition correspondig to that resonator, whereas the location of the other transitions remains unaffected. This principle allows the simultaneous operating of multiple resonant sensors in environments with high damping.

Flow cell

Sensing applications related to biology require operation of the microresonators in water, and to investigate the dynamic behaviour of immersed resonators, a flow cell was developed. To maximize the magnetic field, the height of the cell should be minimized. The sample is mounted upright to detect the flexural modes, using both the magnetomotive technique and a reference optical deflection technique.

Figure 7a shows the flow cell design. A heat sink (1) is connected to a sample holder (2) by isolating screws (3). Peltier elements (4) acting as heat pumps are placed in between. The sample is bonded on a carrier glass plate (5), an O-ring is placed, and a transparent cover (6) equipped with fluid in- and outlets is mounted (7). The transparent cover gives optical access to the resonators. Figure 7b shows an overview of the fabricated parts. Electrical contacts are made by two connectors (8) clamped on the carrier plate. Figure 7c shows a carrier plate, fabricated by photolithographic patterning of a gold-coated glass wafer. The sample containing the resonators is bonded on top. Figure 7d shows the flow cell that was realized. The building height is 6 mm, it contains a volume of 3 microliters, and using the Peltier elements the temperature can be stabilized to within a few mK.

Detection in liquids

With this setup, the heavily damped motion of clamped-clamped micromechanical resonators in water was detected [4]. For this experiment, 200 µm long string resonators were used. The fundamental resonance mode was first measured in air at $f_{1,air}$ = 213 kHz with a Q-factor of $Q_{1,air}$ = 50. The flow cell was then filled with water, and the measurements were repeated using the magnetomotive detector and an optical deflection technique as a reference.

Figure 8 shows the responses of the immersed resonator, as obtained by both detectors. The resonance frequency and Q-factor were $f_{1,water}$ = 53 kHz and $Q_{1,water}$ = 2. The magnetomotively detected resonance was confirmed by the optical measurement. The observed shifts in resonance frequency and Q-factor are the result of mass added by a water layer moving together with the resonator, and the

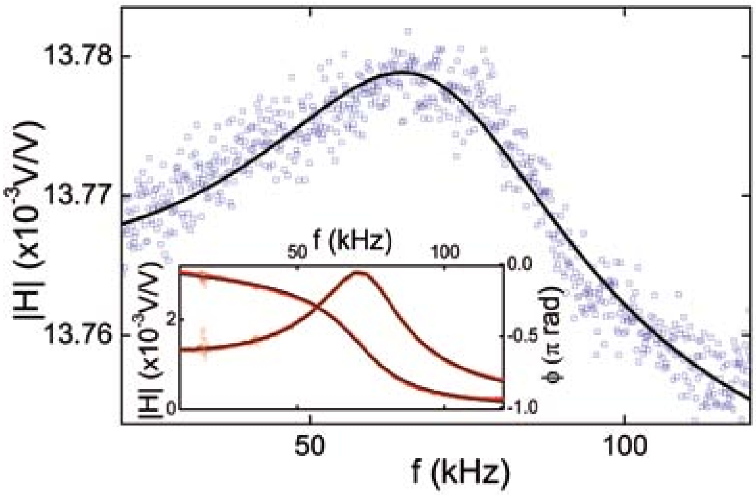


Figure 8. Magnetomotive detection of a micromechanical resonator in water. The upper inset shows the resonator, the lower inset shows the control measurement by an optical deflection technique. The solid lines represent damped-driven harmonic oscillator fits.

friction associated with the viscosity of the water. A theory was developed that quantitatively describes these effects for clamped-clamped resonators in water for arbitrary mode number [4]. Both the theory and the experimental data obtained for the fundamental and higher modes indicate that the Q-factor of immersed resonators increases with the mode number. This suggests that higher modes are less susceptible to viscous drag, and more suitable for resonant sensing in liquids.

Conclusion

An instrument was developed for the characterization of the dynamic properties of micromechanical systems. The tool uses a magnetomotive transduction technique, operating at room-temperature and atmospheric pressure. A permanent magnet was constructed that generates up to 2.5 Tesla in an adjustable gap. Mechanical resonances at megahertz frequencies can be measured, and the driving force is strong enough to drive microresonators into nonlinearity. The tool was equipped with a flow cell to allow the characterization of micromechanical systems in liquids.

The instrument has a number of advantages over optical techniques. The dimensions of the devices to be characterized are not limited by diffraction, no optical access is required, and there is no need for a separate actuator to drive the device. The magnetomotive technique allows multiple devices to be detected simultaneously, while the positioning of the samples is not critical. An alignment microscope is not needed, which this makes the tool compact and inexpensive. These features make the apparatus very convenient for fast and routine characterization of micromechanics.

Acknowledgment

The projects reported here were carried out at Delft University of Technology, within the Molecular Electronics and Devices group in the Faculty of Applied Sciences, and the Mechatronics group in the Faculty of Mechanical, Maritime and Materials Engineering (3mE). The author acknowledges collaborators Khashayar Babaei Gavan and Hidde Westra.
Also acknowledged are John Compter of Philips Applied Technologies for discussions regarding the magnet, Lex Molenaar of SKF for the silicon nitride pivots, Carel Heerkens of Mapper Lithography for providing glass wafers, John Dukker of the Precision and Microsystems Engineering department (3mE) for fabricating flow cell parts, Jan Groeneweg and Wim van der Vlist of Dimes (Delft Institute of Microsystems and Nanoelectronics) for fabricating the optical mask, dicing and bonding, and, from the Faculty of Electrical Engineering, Mathematics and Computer Sciences, C.K. Yang for assistance with optical lithography.
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Information

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Fast ALD revolutionizes solar cell manufacturing

A novel disruptive concept in Atomic Layer Deposition (ALD), developed by Dutch research organization TNO, can achieve breakthrough ultrafast Al_2O_3 deposition rates of 1 nm/s (currently limited to 0.1 nm/s). Using spatial ALD, instead of temporal (i.e. time-switched) ALD, TNO researchers deposit 30 nm of Al_2O_3 in 30 seconds. Compared to 20 minutes in an R&D single-wafer reactor, this opens up a wide range of industrial-scale applications with high industrial throughput and cost-effective manufacturing. A very promising application is to improve solar cell efficiency by depositing Al_2O_3 as a backside passivation layer.

In recent years, research institutes such as Eindhoven University of Technology, IMEC in Belgium and the German Fraunhofer Institute, have been working on backside passivation of Si solar cells. Backside passivation by Al_2O_3 deposition may increase a single cell's efficiency in absorbing energy. An observed increase in efficiency from 16% to 17% represents a 5-year leap on the solar industry roadmap, according to a TNO representative. He demonstrates the profitability: assuming a 60 MW/year solar cell manufacturing plant, the efficiency increase yields another 3,75 MW/year. At €1.25/Wpeak this generates M€4.7 additional annual revenue. With an estimated investment of M€4-5, return on investment is achieved within approximately 12 months.
An additional advantage of passivation is that it allows for thinner silicon wafers in solar cell manufacturing. Because of the high material costs of silicon, thinner wafers, besides efficiency improvement, is an important direction on the solar roadmap.

Too slow

So far, the main drawback was that there was no cost-effective high-volume production tool available for depositing Al_2O_3 with Atomic Layer Deposition. Currently, industrial ALD production is mainly used in high-end semiconductor manufacturing, where the key application is high dielectric constant gate oxides in CMOS transistors and DRAM trench capacitors, and where high throughput is not essential. With a 100 wafers/hr throughput, this process is too slow for solar applications, whereas the alternative, PECVD (plasma-enhanced chemical vapor deposition), yields a lower quality passivation layer, which spoils the efficiency increase. The new technology now offers a fast process for high-quality passivation, so TNO claims.

Time-sequencing

Conventional ALD is based on the time-sequencing of self-limiting half-reactions, each separated by purge steps; see Figure 1. In the case of Al_2O_3 deposition, alternatingly

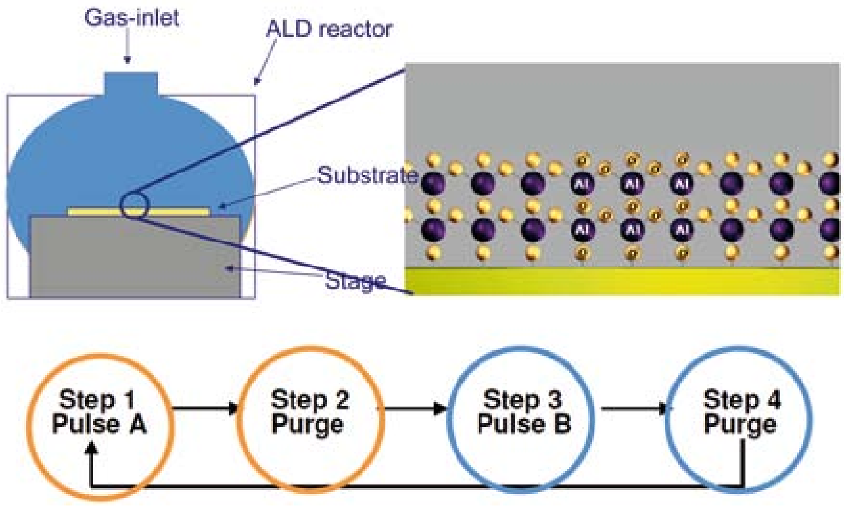

Figure 1. Schematic of Al_2O_3 deposition in a conventional ALD reactor.

trimethylene aluminum and water are exposed to the substrate/wafer, and as a result of two consecutive reactions (half-reactions), a single atomic layer of Al_2O_3 is deposited, after which the cycle can be repated for deposition of a second layer, etc.

Spatial separation

TNO's new ALD concept is based on spatial separation of these half-reactions: the reactor has separate zones, each exposing one of the precursors (in this case trimethylene aluminum and water) to a substrate. By rotating the wafer underneath the corresponding feeder nozzles, this spatial separation is translated into (periodic) time-sequencing. Gas bearings between the zones eliminate cross diffusion, hence there is no need for purge steps. An additional advantage of the gas bearing-based design is that it operates under atmospheric conditions, eliminating the need for vacuum loadlocks. Half-reaction timescales are

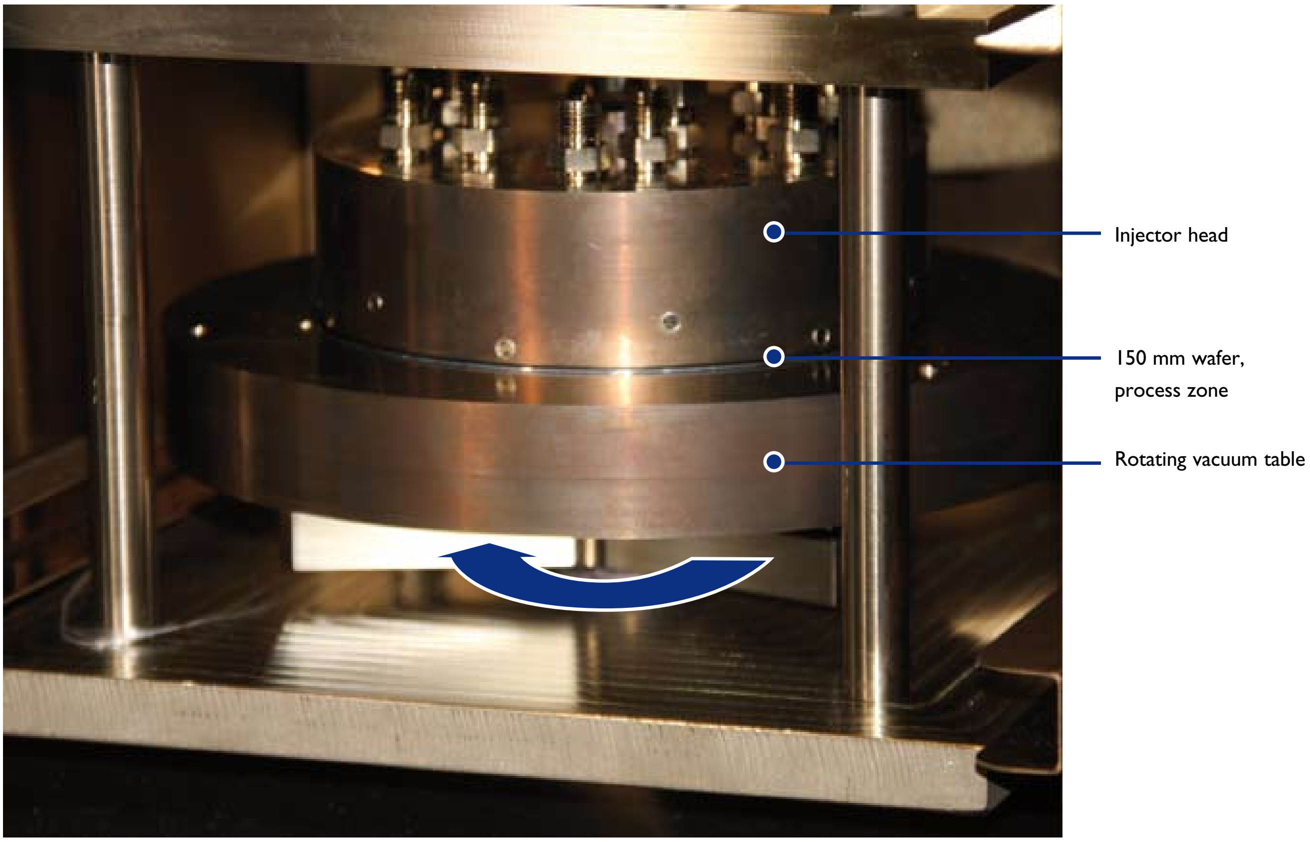

Figure 2. The ALD reactor for 150-mm substrates.

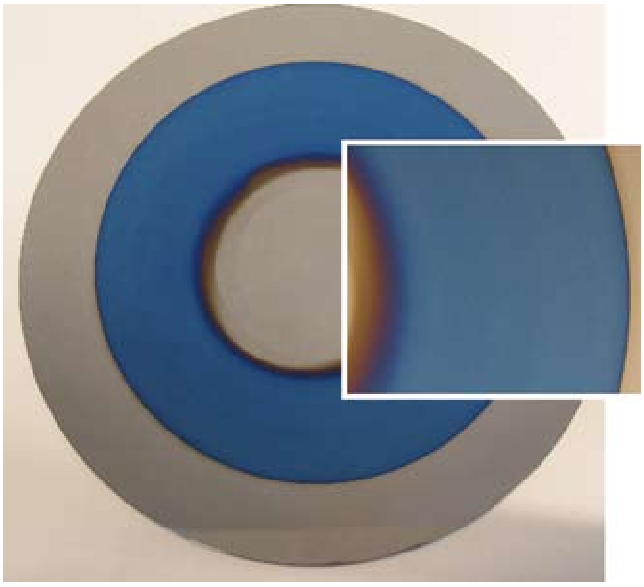

Figure 3. A 150-mm Si wafer with a 30-mm ring-shaped track of 100 nm Al_2O_3 deposition.

~10 ms, enabling ultrahigh deposition rates, while maintaining typical ALD film quality.

As a demonstrator, an ALD reactor was built that can handle 150-mm wafers. On a rotating vacuum table, a wafer is placed below a stationary injector head that contains the feeder nozzles for the precursor gases and the separation gas (nitrogen); see Figure 2. In one rotation of the table, a single layer is deposited, with a thickness in the order of 0.1 nm. At a moderate 600 rpm (10 rotations per second), the deposition rate is 1 nm/s. In fact, Al_2O_3 layer deposition rates of ≥1.2 nm/s have already been demonstrated. These films show excellent surface passivation; see Figure 3.

Linear set-up

For in-line industrial application, it is practical to replace the rotational process by a linear process. In that case, the substrate will move back and forth below the stationary injector head. The mechatronic solution for this linear set-up is one of the tricks of TNO's new ALD concept. An additional advantage, next to the higher industrial throughput (targeted at 3000 wafers/hr), of this industrial in-line solution is its small footprint (2.5 x 3 m^2), as compared to the alternative ALD set-up with a sequence of vacuum reactor chambers.

New applications

Ultrafast ALD will also open up new applications in the manufacturing of LEDs (deposition of buffer layers), organic LEDs (deposition of barrier layers), flat panel displays, sun-protection glass, and of course semiconductors. Al_2O_3 is more and more becoming an important material for many applications. For instance, to enhance the quantum efficiency of silicon in metal-insulator-semiconductor devices, to encapsulate humidity- or oxygen-sensitive materials and devices. Or to enhance the Q-factor of Si-based cantilevers to enable functionalization on hydrophobic graphene and carbon nanotube surfaces for application in nanoelectronics. Of course, also other binary, multi-component oxides and other compounds like nitrides, sulfides, coatings that are now being deposited by CVD, may soon transfer to a high deposition rate ALD production environment.

SoLayTec

TNO has already taken steps to develop cost-effective, high-volume production batch systems for solar cell manufacturing. Tests show throughput numbers for cost-effective production are feasible.
At the moment, all efforts are aimed at further maturing of the technology. For development towards industrial-scale production, a large R&D project has been set-up by TNO in collaboration with some eight companies within the Eindhoven region. Funding was solicited from the Dutch Ministry of Economic Affairs, Peaks in the Delta programme. For commercialization, a TNO spin-off company is about to start, called SoLayTec. Once more, perspectives are sunny for solar energy.

Note

This article was in part based on information published on the TNO website.

Information

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"Going to the rehab"

During a trip to the USA (Boston area, Baltimore area and Chicago), a Dutch delegation of robotics researchers and entrepreneurs discovered a lot of "interfaces" for R&D and business collaboration. Common interests include surgical robotics, robotic-assisted rehabilitation training of stroke survivors, and development of advanced prostheses. Based on the delegation's impressions, this article offers a glimpse of cure and care robotics in the USA.

• *Hans van Eerden* •

Nowadays, consensus exists that robotic technology has the potential to address social and economic issues related to an ageing population and a decreasing workforce. As the emerging technology in health care fields such as surgery and rehabilitation, robotics can offer new and improved surgical procedures, better training results and enhanced comfort and safety for patients. This trend is founded in mechatronics, with mechanical, electronic and software engineering as the underlying disciplines. After many years of fundamental research and clinical trials, robotic technology will now have to mature and enter the operating theatre and the clinic for routine application.

Revolutionizing Prosthetics

A large proportion of American robotics research – as well as research in many other fields – is (in)directly funded by the Department of Defense. Currently, Iraq and Afghanistan act as "drivers" for robot-related research. For example, DARPA (Defense Advanced Research Projects Agency) has initiated the Revolutionizing Prosthetics (RP) research programs. Preceded by the RP2007 program, the $70 million RP2009 program aims to restore limb function and quality of life to military and civilian amputees by developing a fully integrated upper extremity prosthesis; see Figure 1.

Figure 1. Non-invasively controlled advanced prosthetics developed under DARPA's RP2007 program. (Source: www.darpa.mil/news_images/prosthetics.html)

One of the participants is the Applied Physics Laboratory (APL), a research and development division (4,500 staff members) of Johns Hopkins University, Baltimore, Maryland. The RP2009 work is performed by members of the Biomedicine Branch of APL's National Security Technology Department. APL is the lead system integrator for the more than thirty national and international research groups who are involved in the RP2009 program. Recently, the APL team demonstrated the first fully integrated prosthetic arm that can be controlled naturally, provide sensory feedback and allow for over twenty degrees of freedom.

Surgical robots

With a nearly 15 years of history in robotics research, Johns Hopkins University (JHU) in 2007 founded the Laboratory for Computational Sensing and Robotics (LCSR). The lab (95 staff members) is characterized by a "horizontal" collaboration on robotics, including JHU's medical school.

The research focuses on robotics for health care and biomedical applications, autonomous systems for safety and surveillance, and human-machine interaction. Subjects include the design of sensor-based robot control systems based on how animals process sensory information to control their motion; haptics to enable robots to explore the world through touch, and also to add the sense of touch to virtual and tele-operated environments for humans; computer integrated interventional systems (surgical robotics, anatomical modeling, and treatment planning, ultimately aimed at achieving "closed-loop interventional medicine"); and visual imaging and surgical robotics; see Figure 3.

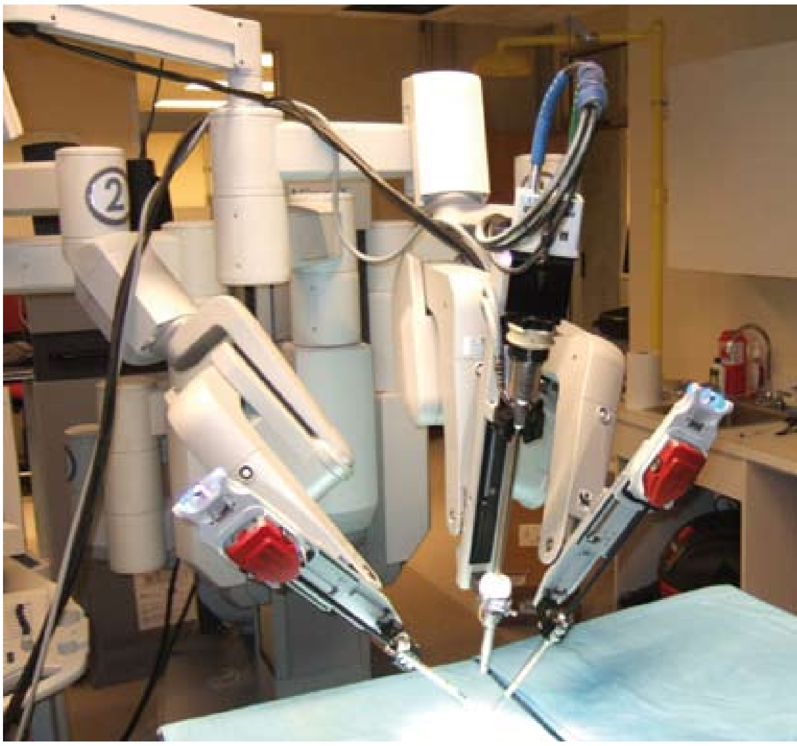

Figure 3. In the LCSR research, extensive use is made of the Da Vinci surgical robot.

Dutch delegation visits USA

Scientists, entrepreneurs and business developers of various organisations from Twente / the Eastern Netherlands participated in the Cure and Care Robotics Mission USA 2009, which was organised last November in close collaboration with the Netherlands Office of Science and Technology in Washington, DC. One of the driving forces behind this trip was the Advanced Robotics & Mechatronics Foundation (Romech), which in 2008 launched an initiative to strengthen education, research and business collaboration in the area of robotics, especially humanoids and home robotics, in the Twente region.

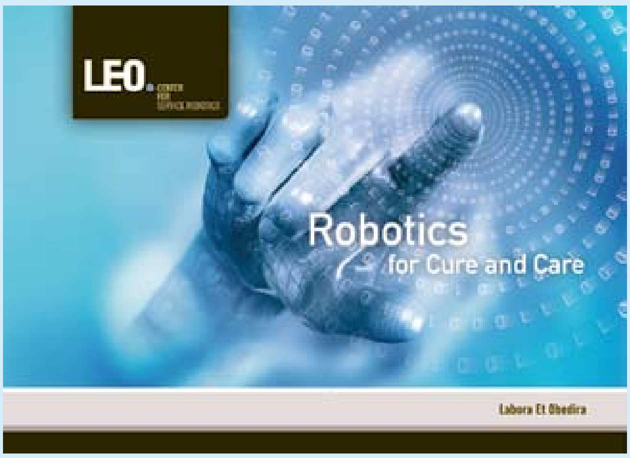

Figure 2. The full report on the Cure and Care Robotics Mission USA 2009 will be available through the Romech website.

As the framework for this initiative, the LEO Center for Service Robotics will serve. LEO will have Twente / the Eastern Netherlands as a natural home base, because of its many key players (University of Twente, Roessingh Rehabilitation Centre R&D, high-tech mechatronic and medical companies), its advanced facilities (such as for medical imaging, rapid prototyping, and virtual reality), and – with respect to medical robotics – the unique discipline of Technical Medicine at the University of Twente.

www.romech.nl
www.leo-robotics.eu
www.twanetwerk.nl (Netherlands Office of Science and Technology)

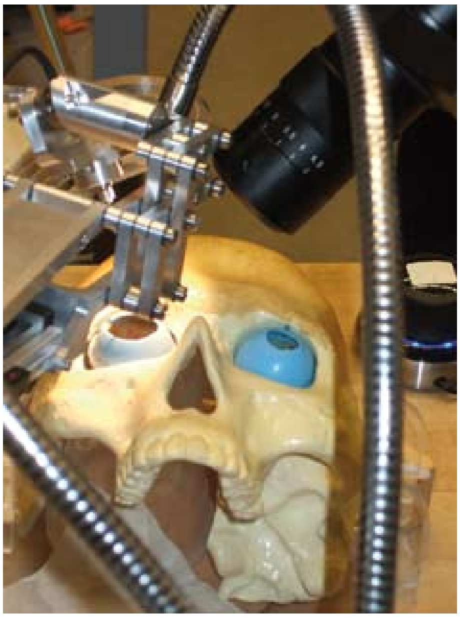

Figure 4. Experimental set-up in LCSR for robotic-assisted retinal microsurgery.

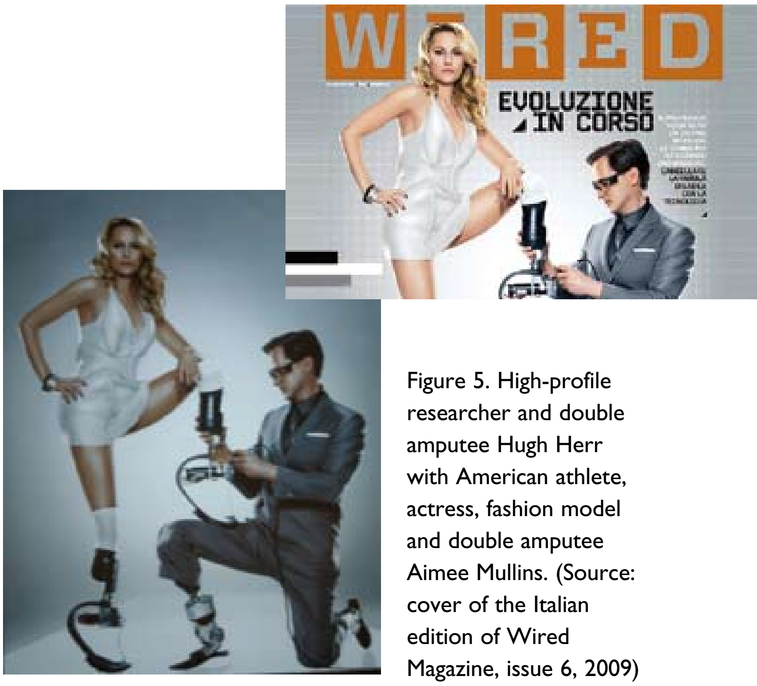

Figure 5. High-profile researcher and double amputee Hugh Herr with American athlete, actress, fashion model and double amputee Aimee Mullins. (Source: cover of the Italian edition of Wired Magazine, issue 6, 2009)

For example, research on robotic-assisted retinal microsurgery focuses on micro-force sensing for giving the surgeon feedback; see Figure 4. To that end, optical fibre Bragg grating strain gauges were enclosed inside the instrument. 3D tremor compensation is achieved with piezo-electric actuators.

Biomechatronics

Prosthetics development is also undertaken at the Massachusetts Institute of Technology's Media Lab, in the Biomechatronics group, directed by high-profile researcher and associate professor Hugh Herr, who is wearing two knee-foot prostheses of his own make; see Figure 5. The scientific programs of the group, based in Cambridge, Massachusetts, center on organismal biomechanics and control, and on skeletal muscle biomechanics and control. Key issues, with respect to the design of artificial limbs or limb supports, that have been studied include angular momentum regulation in human walking, and humanoid balance control using contact and non-contact limbs. The technological programs include prostheses, orthoses, and exoskeletons.

The basic architecture of an active (powered) foot-ankle prosthesis was designed as a unidirectional spring, configured in parallel with a force-controllable actuator with series elasticity. With this architecture, the ankle-foot prosthesis matches the size and weight of the human ankle and foot, and is also capable of delivering high mechanical power and torque as observed in normal human walking. A biomimetic control scheme was proposed to allow the prosthesis to mimic the normal human ankle behavior during walking.

PowerFoot One

The technological work on active ankle-foot prostheses is commercialized through Cambridge-based iWalk. Founded in 2006, it started with introducing PowerFoot One, the world's first actively powered prosthetic ankle and foot; see Figure 6. PowerFoot One is a completely self-contained robotic system, equipped with two microprocessors and six environmental sensors for continuous evaluation and adjustment of ankle position, stiffness, damping and power. Control algorithms generate human-like force while traversing level ground, slopes and stairs, providing active amputees with near-normal gait and lower energy expenditure compared to state-of-the-art passive prosthetics, so iWalk claims. Series-elastic actuators and energy control strategies allow for efficient use of light, high-power batteries. Novel materials have been included in the design, such as metallic crystals and carbon fibers for lightweight, high-strength springs and structural components.

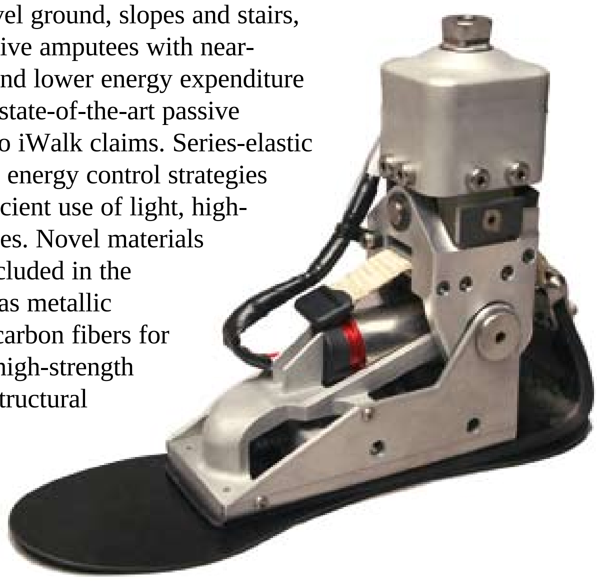

Figure 6. The PowerFoot One ankle-foot prosthesis was developed in the Biomechatronics group at MIT's Media Lab and was commercialized by iWalk. (Source: www.iwalkpro.com/products.html)

Robot therapy

MIT's Newman Laboratory for Biomechanics and Human Rehabilitation, led by Prof. Neville Hogan, is dedicated to technology for enhancing human performance. The initial focus was on stroke, resulting in the development of the well-known MIT Manus, used for assessing the feasibility of robot therapy for stroke survivors. Current research is devoted to the development of other robots (for example, for robot-aided wrist and grasp rehabilitation), therapy design, movement analysis, motor learning, and semi-active variable-impedance materials (for shock absorption in biomechanical applications).

Much attention is devoted to new designs of actuators for neurological rehabilitation robots and similar "high force haptic" devices. These applications require actuators with high force/weight ratio and low mechanical impedance. Conventional actuators with high force capacity generally either are extremely heavy (e.g. electromagnetic actuators) or have high endpoint impedance (such as geared actuators), and in general are inadequate when the device kinematics are complicated.

Another "research product" of the Newman Lab is the MIT-Skywalker, a device that delivers gait therapy without imposing rigid kinematics patterns of normal gait on impaired walkers, as opposed to previous approaches in mechanized gait therapy. Instead, the MIT-Skywalker takes advantage of the concept of passive walkers and the natural dynamics of the lower extremity in order to deliver more "ecological" therapy.

Stroke survivors

At Northwestern University, research in the Chicago-based NeuroImaging and Motor Control Laboratory, led by associate professor Jules Dewald, is dedicated to understanding motor recovery following stroke. The aim is to conduct basic science before designing robots, making the use of robotics in rehabilitation science-underpinned. The focus is on learning the role of brain plasticity in recovery, and on developing novel therapeutic training techniques to improve arm function following a cerebrovascular accident. The lab's biomechanics research is concerned with the basic mechanisms of movement disorder following stroke. Closely related to this approach is the research on rehabilitation and neurotherapeutic training, aimed at developing and validating novel training programs to enhance functional recovery after stroke.

Figure 7. A test subject using the ACT3D.
(Source: www.dlrehab.com/rehab.htm)

ACT3D robot

Projects involve the development and validation of training programs that seek to diminish abnormal constraints on torque generation in the impaired limb. Providing feedback to the subject via a virtual arm displayed on a monitor in front of them, a robot system creates a virtual environment for the subject to interact with, and can be programmed to provide varying levels of support/gravity compensation, shoulder torque load (as if the subject were lifting an object), or to prescribe alternate planes of motion. The spin-off of this research is being commercialized as the ACT3D robot (Arm Coordinated Training Device in Three Dimensions) through D.L. Rehab Technology. ACT3D is based on Moog FCS's HapticMaster, a force-controlled robot acting as a haptic interface, in combination with a chair belonging to Biodex Medical Devices's single-link robotic system, which is often used for sports rehabilitation; see Figure 7.

Rehabilitation Institute of Chicago

The Sensory Motor Performance Program (SMPP) at the Rehabilitation Institute of Chicago (RIC) counts 29 faculty, mostly from Northwestern University (see above), and 200 staff in total. SMPP is devoted to the study of musculoskeletal, neuromuscular and sensory disorders that are associated with abnormal control of posture and movement. The research is aimed at understanding the sensory-motor system through close interaction with artificial systems and determining how the brain acquires, organizes and executes motor behaviors. Robotic

Figure 8. The Lokomat rehabilitation training robot in Spaulding's Motion Analysis Laboratory.

technologies are being used to investigate how humans adapt to radical changes in body mechanics.

The ultimate aim is to help restore motor functions in individuals with neurological disorders and to create systems that can learn and adapt to their users. Over fifteen laboratories/centers participate in the SMPP research, covering, amongst others, robotics, biodynamics, upper-extremity mechanics, biomechatronics development, neural engineering for artificial limbs, and neuromechanics of impaired locomotion. The Neurolocomotion Lab, for example, comprises three Lokomat rehabilitation training robots, for clinical use (motion/gait analysis), neuro-research and research on the effect of training and medication. Other research equipment includes the KineAssist (see below, Kinea Design) and the MACARM (see below, Intelligent Automation, Inc.).

Lokomat therapy

The Motion Analysis Laboratory in Spaulding Rehabilitation Hospital, Boston, Massachusetts, combines laboratory and field assessments to enhance mobility in individuals with mobility limiting conditions caused by age, illness, or trauma. This lab also works with the Lokomat, see Figure 8, which not only has a positive effect on the recovery of stroke survivors but also relieves the physical load of their therapists during training. Further, the device is used in studies of motor learning paradigms, and in collaboration with its supplier, Hocoma, motivational graphics for biofeedback during Lokomat training are being developed.

Biorobotics

At Harvard University, Cambridge, research in the BioRobotics Laboratory, directed by Prof. Robert Howe, focuses on the role of sensing and mechanical design in motor control, in both robots and humans. Applications of the research are found in biomedical instrumentation, tele-operated robots, and intelligent sensors.
In collaboration with the Boston-based Children's Hospital, research is conducted on image-guided intra-cardiac surgery for mitral valve repair in a beating heart. A handheld, lightweight robotic motion compensation instrument was designed, see Figure 9, that has sufficient bandwidth to compensate for the fast-moving structures in the heart, as well as a sufficient force output to perform suturing and stapling tasks on heart tissue. This instrument, operating within the limited confines of the heart, has made valve repair, which compared to valve replacement is more difficult but has a lower mortality, a more viable option. To enable motion compensation during operation, real-time instrument and tissue tracking is performed using 3D ultrasound. Because of the time delay introduced by data processing, a dynamic feedforward is introduced in the procedure.

Figure 9. The lightweight robotic motion compensation instrument for mitral valve repair.

As a supplement to the visual feedback that is, for example, provided by 3D ultrasound images, the introduction of force feedback is studied. Haptic (or force) feedback can improve task performance during surgical tele-operation using a master-slave system with non-ideal properties. For example, tip sensors may offer benefits during tele-operation with a flexible slave (because surgical instruments are becoming very thin).

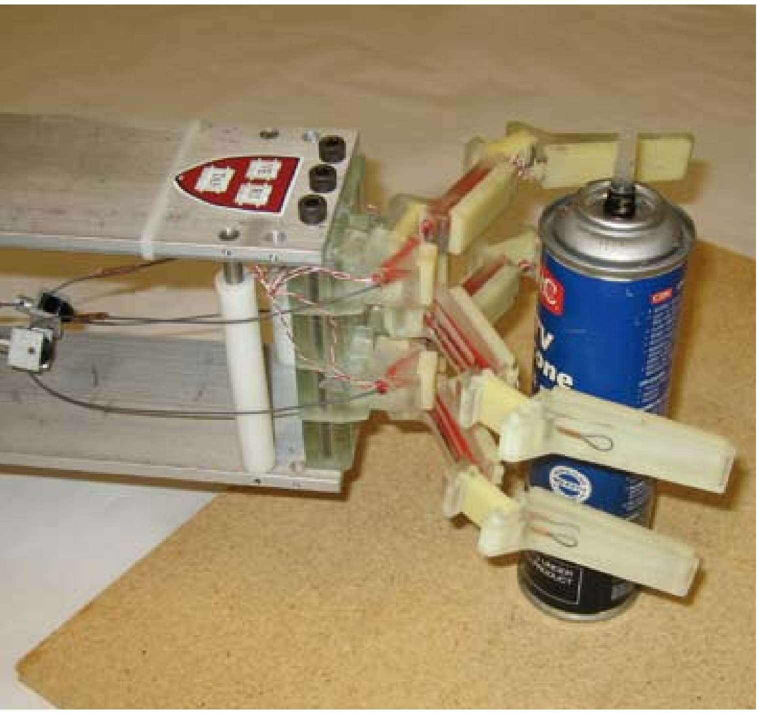

Figure 10. The one-piece, one-motor robot finger can be incorporated in a gripper.

Fingers

Another research subject is the design of a general purpose, robust robot hand, a simple gripper, having fingers each coming in one piece (combining hard plastic and soft rubber) with one motor; see Figure 10. Using Shape Deposition Manufacturing, which can alternate material deposition and machining, robot structures with compliant joints and embedded sensing and actuation elements can be produced. This contrasts with the anthropomorphic approach, which has been very popular, but to date primarily has yielded complex systems without much result. The design is now being commercialized by Barrett Technology; see below.

Whole Arm Manipulator

Barrett Technology, based in Cambridge, developed a highly dexterous, naturally backdrivable, haptic robot arm; see Figure 11. The WAM™ arm (Whole Arm Manipulator) has direct-drive capability supported by Transparent Dynamics™ between the motors and joints, using low-mass, high-tensile steel cables for transmission. Its design makes the control of contact forces robust – independent of mechanical force or torque sensors. The arm is available in two main configurations, having either 4 or 7 degrees of freedom, both with human-like kinematics. The joint ranges exceed those for conventional robotic arms. The redundancy of 7 instead of 6 degrees of freedom gives the arm's movements a natural "graceful" character instead of the conventional "robot jerkiness".

Figure 11. The WAM Arm demonstrating its skills. The arm on the left belongs to Barrett Technology founder and CEO, Bill Townsend.

Puck and Hand

The arm comes with the highest performance servo-electronics available in the world today, so Barrett Technology (now 15 employees) claims, referring to the so-called Puck™, an ultra-miniature brushless servo-electronics module that makes controller cabinets (internal or external to the arm) redundant. This Puck ("powerful universal controller") features ultra-low power consumption for safety and environmental benefit, as well as superior brushless-servo performance allowing applications such as force-field enabled medical surgery.

The WAM Arm can be equipped with a BarrettHand™, a low-weight, multi-fingered programmable grasper; see Figure 12. It has the dexterity to secure target objects of different sizes, shapes, and orientations. Of its three multi-jointed fingers, two have an extra degree of freedom with 180 degrees of synchronous lateral mobility supporting a large variety of grasp types. Because of its flexibility, a BarrettHand offers an attractive alternative to cheap parallel-jaw grippers, as these have to be custom-designed and require exchange during work for different tasks.

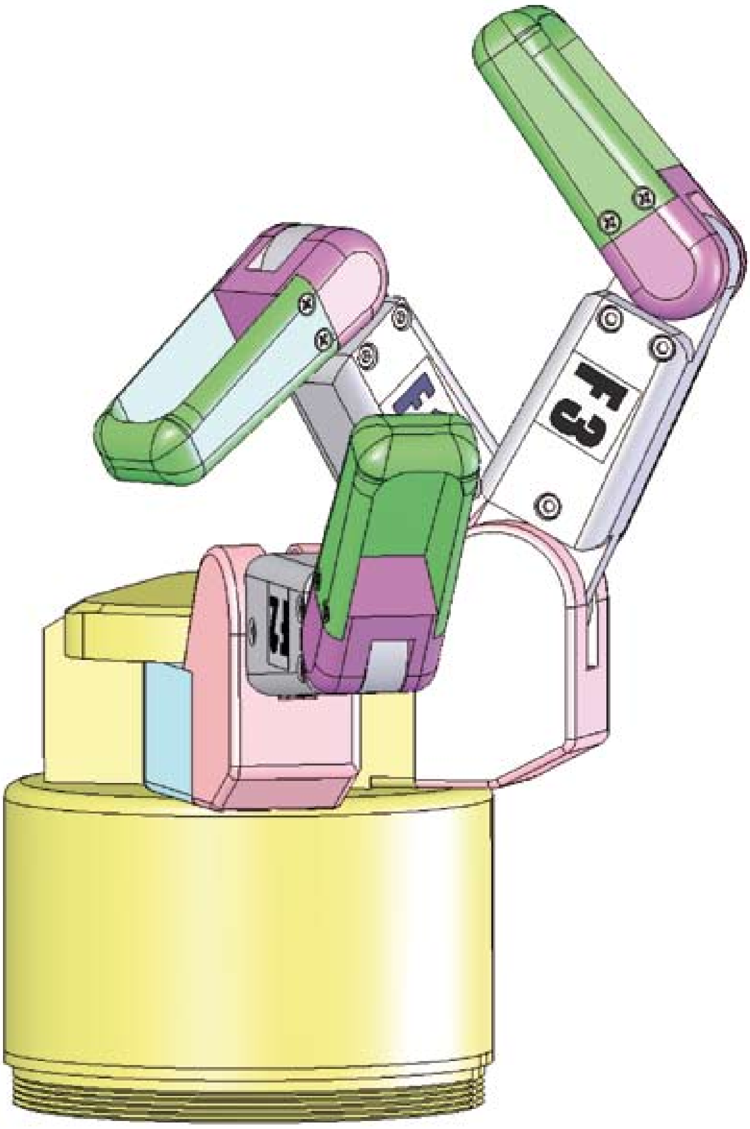

Figure 12. Design of the BarrettHand.
(Source: www.barrett.com/robot/products-hand.htm)

Up to now, Barrett's 100,000 US$+ robot arms are mainly used for research purposes, for example in the study of trends in emerging robotics applications and in understanding human/primate learning and motor control. Medical applications have also been developed, such as neuromuscular rehabilitation after stroke (at RIC), or providing assistance to a surgeon for improving knee-implant surgery (at Mako Surgical, Inc.).

Human-interactive mechatronics

Other companies consulted by the Dutch delegation, included Kinea Design, Intelligent Automation, Inc. (IAI), and AnthroTronix. Kinea Design, "innovators in human-interactive mechatronics", is based in Evanston, Illinois, and currently employs twelve people. As a design services firm collaborating with external engineering consultants and clinicians, they develop electro-mechanical devices, sensors, controls systems, haptic interfaces, and purely mechanical systems. A fine example of the Kinea design approach is the KineAssist™ for walking and balancing retraining of stroke survivors that was developed for RIC.

Arm Rehabilitation Machine

IAI, headquartered in Rockville, Maryland, counts over 120 researchers and technical staff, and primarily serves as a R&D provider to the US government, major first-tier (defense-related) integrators, as well as to commercial firms within the USA and abroad. One of their products is the Multi-Axis Cartesian-based Arm Rehabilitation Machine (MACARM), used for therapy on stroke survivors in RIC. The unique feature of the MACARM is that it can provide full six degrees of freedom control over the patient arm's trajectory and mechanical environment, and thus enables the application of virtually any conceivable movement or force pattern to the impaired limb.

Interface technology

Founded in 1999, AnthroTronix has been working since as an engineering research and development firm focused on optimizing the interaction between people and technology. AnthroTronix is specialized in the development of advanced interface technology, wearable computing and robotic control systems, and simulation tools for training applications. The company, located in Silver Spring, Maryland, currently employs twelve people and has commercial as well as governmental customers in the fields of defense, space, medical rehabilitation and education.

AnthroTronix's first commercial product is the AcceleGlove™ (or iGlove™) instrumented gesture recognition glove; see Figure 13. The iGlove is a low-cost gesture recognition system that can detect the individual motions of finger, hand, wrist, and arm. It may serve as a robot controller, using the natural movements of the operator's hand/arm as the input to control both the movement of a robot (such as an unmanned vehicle) itself, as well as the movement of ancillary devices such as grasping and lifting arms.

Figure 13. AnthroTronix's first commercial product, the AcceleGlove. (Source: www.mydigitallife.info)

Clusters
The trip offered various opportunities to meet with regional robotics clusters. One example is the Massachusetts Robotics Cluster, facilitated by the Mass Technology Leadership Council (MassTLC). In 2009, MassTLC published a report on the robotics industry in the region: "Achieving Global Leadership: A Roadmap for Robotics in Massachusetts". The analysis revealed the cluster to contain the largest concentration of robotics companies in the USA, counting some 80 enterprises, 2,500 people and 1 billion US$ annual sales. Success factors that were identified included the total of 11 universities featuring 14 robotics research groups as well as the first-ever undergraduate robotics engineering program (Worcester Polytechnic Institute), the entrepreneurship culture (including companies spinning out spin-outs) and the region's strength in industry, with health care, defense and manufacturing driving robotics development.

Quality of Life Technology
The Technology Collaborative (TTC) aims at accelerating digital & robotics innovation. It is based in Pittsburgh, Pennsylvania, home to the Southwest Pennsylvania Robotics Cluster, which is centered around Carnegie Mellon University's Robotics Institute, featuring 8 research centers, 44 labs, 500 people, and a 55 million US$ annual budget. The cluster includes some 40 robotics companies, well-established companies such as Bombardier and McKesson Automation Solutions, as well "second generation" companies such as Redzone, Interbots and MobileFusion.

A fine example of interdisciplinary collaboration within the cluster between researchers, industry partners, clinicians and users, can be found in the Quality of Life Technology (QoLT) Center, an initiative of Carnegie Mellon University and Pittsburgh University. The center's mission is to improve the quality of life of people with reduced functional capabilities due to ageing or disability. So-called compassionate intelligent QoLT systems (including robotic systems) will be designed to monitor and communicate with a person, understand his or her daily needs and tasks, and provide reliable and happily-accepted assistance by compensating and substituting for diminished capabilities.

Author's note
Hans van Eerden is a freelance text writer in Winterswijk, the Netherlands, and editor of Mikroniek. At the invitation of Romech he participated in the trip to the USA. Photos without statement of source were taken by participants Bianca Screever, Stefano Stramigioli and Hans van Eerden.

Information

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www.atinc.com

Benelux Laser Event 2010 focuses on applied laser processing

The key objective of the Benelux Laser Event 2010, to be held on 18 and 19 May in Mol (Belgium), is to create awareness of the existing know-how of applied laser processing. Laser technology offers an abundance of opportunities in both the design and the production process.

Rapid developments in laser technology offer the manufacturing industry new opportunities for product development and process improvement. This is based on the precondition that developers and engineers are familiar with the possibilities of laser technology and adjust their designs accordingly.

BENELUX LASER EVENT'10

This had led the organiser of the Benelux Laser Event 2010, Mikrocentrum, to introduce "applied laser processing" as the central topic. Profound knowledge of laser processing methods and feasibility offers new application possibilities, improvement of product and material features, and simplification of parts design for equipment and machines. The automation and robotisation of processes allow faster, more flexible and more reliable implementation of laser technology in the areas of cutting, welding and cladding.

Increasing possibilities

Lasers are still known for their high-tech image. During the two-day event in Mol, all the ins and outs of laser technology will be addressed. The first laser used to process materials was the glass laser. This was followed by the Nd:YAG and the CO_2 laser, and later the diode laser. Now, we have the disc laser, the fibre laser, and, of course, the CO_2 laser, without which life seems impossible today. Processing time shifted from Continuous Wave (for cutting) to the millisecond (welding), microsecond (drilling), nanosecond (engraving, ablation) and now to the femtosecond range. The ongoing development in power, efficiency, bundle quality and controllability enables the laser to retain its high innovative value, now and in the future.

Laser welding.

Information

The Benelux Laser Event 2010 will be held on Tuesday 18 and Wednesday 19 May 2010 in the VITO Lasercentre, Mol (Belgium). The event – organised by Eindhoven-based independent competence centre Mikrocentrum – includes exhibits, lectures and demonstrations focusing on applied laser processing. Visitors are offered free admission, parking, coffee, tea, soft drinks and lunch.

www.beneluxlaserevent.com

Towards an MBA in Mechatronics

TSM Business School, based in Enschede, the Netherlands, and Festo have developed a new management training programme, Innovation and Entrepreneurship in Mechatronics. The programme comprises personal development, including leadership and entrepreneurship competences, special mechatronics topics and related business management disciplines, including marketing, strategy and innovation management. The overall aim is to strenghten the position of mechatronics in the global market. The 2-year programme will start in September 2010 and it offers the first step towards an Executive MBA in Mechatronics.

www.tsm.nl

Sixty years of glass manufacturing

The year 2010 marks the 60th anniversary of Pulles & Hanique, the "Glass & Ceramics for High-Tech Applications" company based in Veldhoven, the Netherlands. The company, which started in 1950 in Eindhoven and now employs a staff of forty, is specialised in thermal and mechanical engineering and manufacturing of components, instruments and systems of glass, quartz glass and technical ceramics. It works in close cooperation with renowned partners such as TNO Science and Industry, Eindhoven University of Technology, Philips and the Laser Zentrum Hannover (Germany).
Pulles & Hanique used to manufacture mainly laboratory equipment for analytical applications, but over the years broadened its scope to the opto-electronics, semiconductor, petrochemical, laser and biomedical industries. Using borosilicate glass, quartz glass and technical ceramics, precision parts can be manufactured for the high-tech industry. In 2008, Pulles & Hanique moved to new 4,000 m^2 engineering and production facilities.

www.pulleshanique.com

Modern precision engineering in quartz glass.

Industrial inkjet applications

MuTracx, a technology spin-out from Océ Technologies, recently announced they have secured additional funding of US$ 11.3M for the Lunaris project. Lunaris is an industrialized solution for the jetting of etch resist for printed circuit board inner layers. The additional funds were raised from multiple sources and bring the total post spin-out funding to US$ 17.5M. MuTracx, based in Helmond, the Netherlands, will produce a fully digital inner layer printer based on inkjet technology. This machine, called Lunaris, is designed to offer exceptionally high yield and productivity. The goal of 100% correct panels going into the subsequent process steps will be enforced with the introduction of inline process validation. As such, MuTracx claims to provide the world's first true industrial inkjet application.

www.mutracx.com

Invited: 'critical' products for milling

Last year, TNO Science and Industry in Eindhoven, the Netherlands, installed the Hembrug Nano-Focus 425, a fully hydrostatic 5-axis hard-finish milling machine. TNO uses this machine in its new test laboratory to explore the feasibility limits of ultra-precise machining with submicron tolerances.
Recently, TNO and Hembrug started a project in which they invite companies to make available complex products made of hard materials that are difficult to machine. Using these 'critical' work pieces, TNO aims to develop optimal machining and programming strategies and to investigate their effects on geometrical accuracy and surface roughness.

www.hembrug.com
www.tno.nl

The Hembrug Nano-Focus 425.

Training system architects

In the high-tech industry, innovation effort increases due to the growing complexity of (mechatronics) systems. Hence, there is a growing need for professionals on the (sub-) system level, ranging from designers (components), to domain architects (disciplines, subsystems, functions) and system architects. To meet that need, the Executive Competence Development Program for High-Tech Systems architects was started, targeted at high potentials from industry with a B.Sc. or M.Sc. degree and a minimum of five to seven years of work experience. The programme is based on the so-called 'Industry as classroom™' concept.
On 3 March 2010, the first graduates from the domain architect training received their diploma. Amongst them employees from ASML, Philips, Océ, PANalytical and Vanderlande Industries. The programme is an initiative of the High Tech Systems Platform (HTSP) and the Embedded Systems Institute (ESI), funded in part by the Dutch 'Peaks in the Delta' programme. Partners include Eindhoven University of Technology and Stevens Institute of Technology (New Jersey, USA).

Another training programme in this field is System Architecting. After Philips Centre for Technical Training (CTT) ceased all its activities as of 31 December 2009, the systems engineering and software training programmes, including the popular System Architecting training, were taken over by Sioux. Sioux is a specialist in embedded software and technical automation, based in Eindhoven, the Netherlands. Recently, it was announced that Sioux will market the System Architecting training through Techwatch Hightech Training, part of Techwatch, the well-known publisher of Bits&Chips and Mechatronica Magazine.
The System Architecting training includes the crucial role of the system architect in the communication with all stakeholders (customers, suppliers, management, marketing, engineering, manufacturing and maintenance). The 5-day training is in English and will start in the week of 31 May 2010, with a maximum of sixteen participants.

www.hightechtraining.nl/sysarch

Call for papers - Mechatronics

A special issue of Mechatronics, supported by the European Society for Precision Engineering and Nanotechnology (euspen), is intended to bring together contributions from authors active in the field of controlling the thermal effects on mechatronic systems. For the relevance of this subject, see the article on page 28 in this Mikroniek issue. The guest editors are involved in a Special Interest Group on “Thermal Effects in Precision Systems” set up by euspen. Papers are sought from all relevant disciplines, whereas application areas are expected to be the machine tool industry, metrology instruments, space instruments, semiconductor manufacturing and many others. The schedule is tight, with 30 April 2010 as the due date for papers submission, but one of the guest editors, Gert van Schothorst of Philips Applied Technologies, can be contacted for consultation: gert.van.schothorst@philips.com.

www.elsevier.com/framework_products/promis_misc/mechthermal.pdf

New HTS website

Initiated by Johan van Seggelen (MECAL), a website was started that aims to provide the latest news on products and technology of Dutch OEM companies, suppliers, upcoming innovators and knowledge institutes. Furthermore, it offers access to key people that work in the Dutch High Tech Systems industry. This industry is a major global contributor to development in technology fields such as mechatronics, precision engineering, embedded systems, microsystems and nanotechnology.

www.dutchhts.nl

2010 Summer school Opto-Mechatronics

Following the success of the Summer school Opto-Mechatronics in 2008 and 2009, each edition with over forty participants, DSPE and TNO Science and Industry decided to organise a Summer school again. The 2010 Summer school Opto-Mechatronics will take place from 5 to 9 July 2010 in Eindhoven, the Netherlands; see also page 12 in this Mikroniek issue.

www.summer-school.nl

Euspen 10th International Conference

In 2010 euspen is delighted to be returning to the Netherlands for its annual international meeting, including a conference and an exhibition. This will provide a leading forum to research and communicate latest advances and market developments in precision processes and manufacturing, as well as fabrication, metrology, sensing applications and cutting-edge materials. From 31 May to 3 June 2010 at Delft University of Technology.

www.delft2010.euspen.eu

Vision & Robotics

Mikrocentrum organises the ninth edition of the Vision & Robotics trade fair on 26 and 27 May 2010 in Veldhoven, the Netherlands. The fair includes lectures, demos and an exhibition, and is focused on robotics, machine vision, safety, intelligent cameras, 3D solutions, optical sensors and software.

www.vision-robotics.nl

Introducing DSPE board members: Bart Dirckx

In the rapidly changing world of online social networks such as LinkedIn and Hyves, there seems little need for 'yet another network'. However, in the case of DSPE, the opposite is true. DSPE represents the long and rich history of Dutch precision engineering, something worth investing time in. These days, it is not enough to only excel in one thing. Progress tends to lie ever more in the combination of disciplines, to take the next step in the innovation process, for which terms like 'mechatronics' have been widely accepted.

As a graduate from Dr. Nick Rosielle's Precision Engineering group at Eindhoven University of Technology, I was raised with the mechatronic approach and the use of 'design principles', something that will probably remain with me forever. After graduation, I started with Philips Machinefabrieken (now VDL Enabling Technologies Group), where I learned the manufacturing as well as the project management side of this technology. Switching to Philips CFT (currently Philips Applied Technologies), I headed numerous inspiring and innovative projects. During this period I also got in touch with the Philips RoboCup team, of which I was team leader for three years. In this period we managed to finish third at the World Championships in Osaka, Japan, in the Middle Size League.

Having gained more than ten years' experience, I decided to leave Philips and I am now working as a business developer for my current employer TMC at TNO Science and Industry. In this role I enjoy getting companies together in different Dutch and EU projects as well as helping companies take their next step in the innovation process.

For DSPE, I took over the activities of my TMC colleague Ad Vermeer in coordinating the Mikroniek editorial board led by Herman Soemers. The first step was to change the content of the magazine to English, a decision that was made at the end of last year. We are now facing the challenge of further improving the overall quality of a magazine that is already abundant and fascinating, while adapting it to today's needs. I hope you will enjoy the changes.

Mikroniek 2010 schedule

Issue	Deadline	Publication date	Special theme
3 (June)	21 May	25 June	Opto-Mechatronics
4 (September)	30 July	3 September	Metrology
5 (October)	10 September	15 October	-
6 (November)	15 October	26 November	2010 Precision Fair

TT-Groep provides knowledge and experience for technical problems

The engineering and secondment firm TT-Groep has built up a high-quality customer base within various branches of industry such as the aerospace, automotive, machine building and shipbuilding sectors, providing solutions to a variety of knowledge and capacity-related problems. TT-Groep achieves this by deploying highly qualified and very experienced technical specialists and generalists. TT-Groep has been "sterk in techniek" [strong in technology] since 1988.

Head of Technical Drawing Office, CAD Engineer, Assistant Manager, Technical Writer; these are a few of the jobs currently being carried out by TT-Groep engineers for customers. These support services are offered from three business units: TT-Engineering, TT-Safety Solutions and TT-Technical Team.

Three business units

The engineers from the TT-Engineering business unit provide customers with services ranging from engineering support to expertise and capacity in mechanical engineering and electrical engineering. The engineers have a thorough command of CATIA V4 & V5, SolidWorks, NX, Pro/E, Inventor and/or AutoCAD. TT-Engineering also provides PDM (Product Data Management) implementations and advice, process support and support in the development of a business case.

Employees from the TT-Safety Solutions business unit provide assistance and advice on safety issues and the writing of technical documents.

The TT-Technical Team business unit takes care of the recruitment and selection and/or outplacement of technical engineers with backgrounds in mechanical engineering, electrical engineering, automobile engineering, technical automation and industrial engineering and management.

Informal atmosphere

TT-Groep is an independent organisation and has an informal atmosphere where attention and involvement are key. It operates in areas undergoing continual change and, as a result, aims to retain the small-scale nature of its activities. Short lines of communication between departments and people, informal contact, appreciation of one another's work, and an eye for personal circumstances ensure a pleasant working atmosphere in which everyone can provide a positive contribution to the success of the company.

Areas of work

TT-Groep is based in the Dutch cities of Zwolle and Enschede and is active in the aerospace, automotive, machine building and shipbuilding industries, as well as providing services to other sectors requiring the support of highly qualified technical engineers, such as the energy engineering and processing industry.

Information

www.tt-groep.nl

TT-Groep is active in areas such as the aerospace, automotive, machine building and shipbuilding industries.

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