Mikroniek

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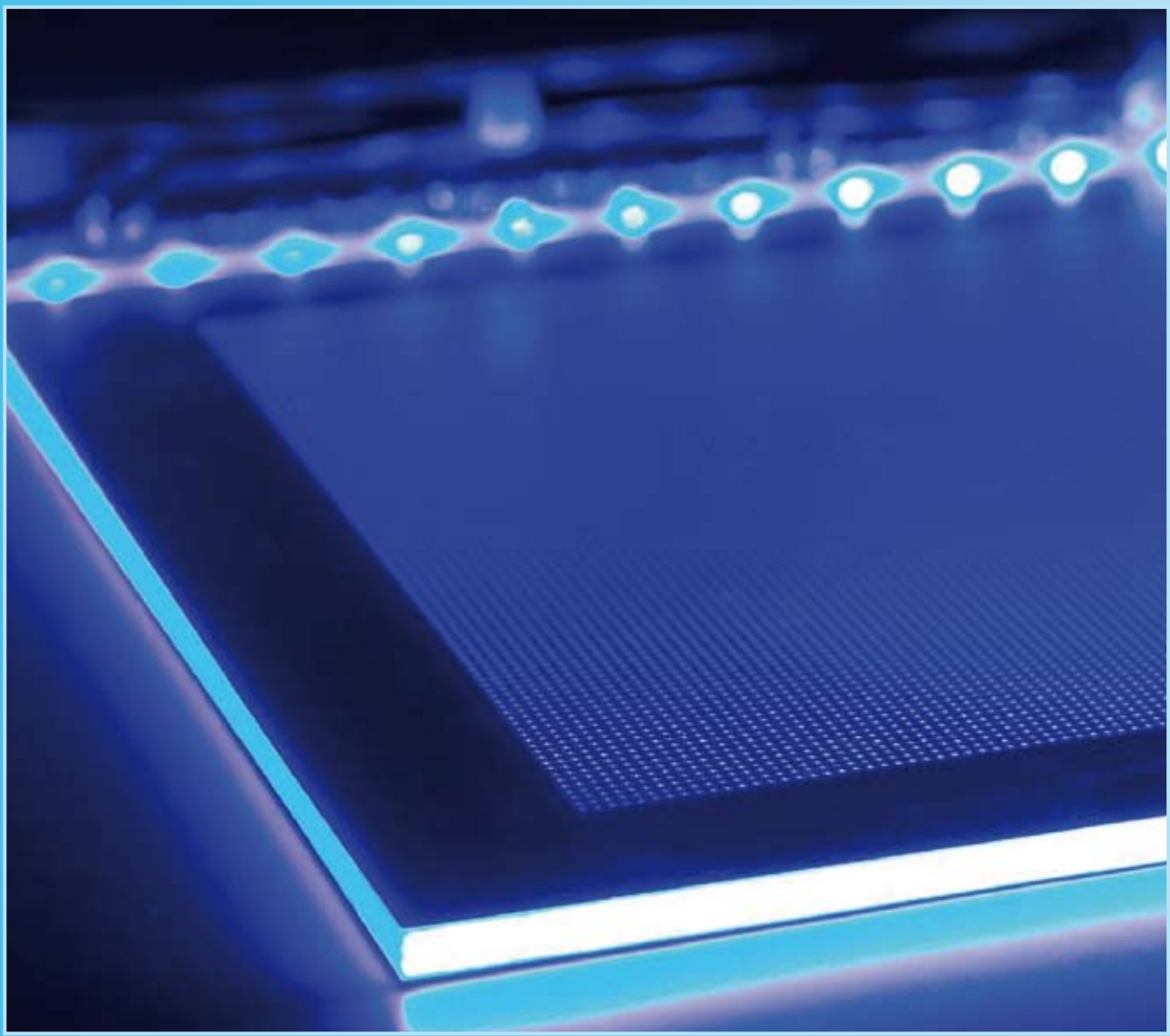

Scanning angles with nanoradial precision • Adaptive embossing technology
Optimal control with Dynamic Error Budgeting • Philips Innovation Services
Common sense in precision engineering • Motion control for micromachining
Keep your cool in precision design • Motion in the optical fiber industry

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TNO innovation for life

Demand for knowledge-intensive, high-tech products continue to increase. TNO responds to this trend by developing high-quality instruments and production equipment that enable work to be carried out at micro, nano and even pico scale, and in increasingly difficult environments.

TNO mobilises consortia in this innovation area, putting its multidisciplinary competencies, domain and system knowledge to use for the players in the value chains and other knowledge institutions.

We offer the following eight core competencies:

- System architecture
- Optronics & contamination control
- Nano/micro/organic electronics
- Flowtronics
- Mechatronics & precision engineering
- Infotronics from sensor-electronic dataflows
- Devices, especially RF/nano sensors
- Materials, for example nano or biomaterials

In this issue

Publication information

Objective
Professional journal on precision engineering and the official organ of DSPE, the Dutch Society for Precision Engineering. Mikroniek provides current information about scientific, technical and business developments in the fields of precision engineering, mechatronics and optics.
The journal is read by researchers and professionals in charge of the development and realisation of advanced precision machinery.

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The cover photo (a light-guide plate) is courtesy Fraunhofer IPT.

editorial

A world without content is nothing

In a world of complex innovation and complex technology, there are almost no questions that can be properly answered without involving technology professionals – people who truly understand and have experienced what it entails to innovate and to create. Being a non-technician with a background in management science and organisational psychology, I have learned this the hard way in my own company. Every day I am surprised to see that many decisions within the most fantastic high-tech enterprises are taken without involving technology professionals.

Several years ago we added training and education of technology professionals to our company's business roadmap. Things started off excellently, but in the years of crisis in our world economy, the training business evaporated. Many educational enterprises and institutes had to close their doors. This triggered us and challenged me personally to seek an answer to the question "How can we create a new educational platform for post-Bachelor and post-academic education of technology professionals at a top level that can and will survive in the long term?"

This has resulted in The High Tech Institute, focused on:

- Our platform can only survive in the long run if the best experts in technology are invited and motivated to work together, and share their energies to create a single excellent platform; avoid creating two or three at a mediocre level, go for the one that is best.
- Professionals who are capable of creating content, maintaining content and educating content at top level are entitled to and thus should be allowed a share in business profits.
- Major high-tech enterprises, universities and institutes have to be motivated to support this platform and allow and encourage their top experts to contribute to it on an ongoing basis.
- Key institutes that are commercially active in our market should be invited and motivated to join forces in exploring this platform.

Recently, I had an inspiring meeting with DSPE representatives. We generated ideas that could strengthen the future of DSPE and at the same time strengthen the educational platform we are building. Working together and creating synergy is fun. Today, more than 25 courses are up and running in The High Tech Institute and several of them have international status and are generating (inter)national interest from small and large high-tech enterprises. Several DSPE members excel as trainers within this setting.
Without content there simply is nothing.

John Settels
Director of The High Tech Institute
Director and Principal Consultant of Settels Savenije Van Amelsvoort

Scanning angles with nanoradial precision

TNO Science and Industry in Delft, the Netherlands, participates in ESA's Cosmic Vision programme by designing several instruments for the GAIA Mission, including BAM OMA, the Basic Angle Monitoring Opto-Mechanical Assembly [1]. In space the GAIA instrument will measure physical properties of objects with high precision. This precision has to be verified on ground before launch. For that purpose the team of system engineer Ellart Meijer from TNO recently designed AFMA, an Autocollimating Flat Mirror Assembly, which simulates GAIA's spinning behaviour in space by highly accurate variation of three angular degrees of freedom. AFMA illustrates how the principal application of generally accepted design rules helps to realise a sophisticated calibration instrument.

• *Frans Zuurveen* •

The GAIA instrument in space rotates every six hours one time around its axis, which coincides with the line between sun and earth, and thus keeps pace with earth as it orbits around the sun in one year. So the two telescope mirrors of GAIA are able to monitor every object in space. The two mirrors of the GAIA instrument are mounted under a relative angle of 106.5° and have a – folded – focal distance of 35 m, see Figure 1. Each mirror measures the angular position of each object against fixed reference objects, quasars extremely distant in the universe. Parallax between the two angle measurements makes it possible to determine the distance of each object, just like the two human eyes estimate distances. Analysis of spectra delivers other physical properties like speed, temperature and gravity.

Figure 1. The optical system of the GAIA satellite with two telescope mirrors with a focal distance of 35 m, made from silicon carbide. (Courtesy ESA)

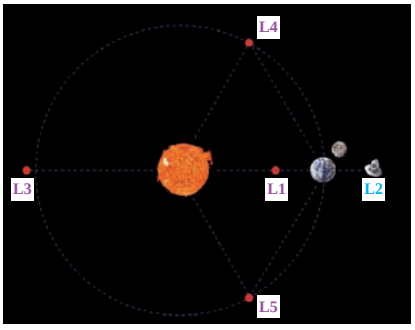

Figure 2. The five Lagrange points L1 up to L5 with respect to sun and earth (Courtesy Neil J. Cornish, NASA).

The GAIA instrument stabilises in a fixed position with respect to earth and sun in Lagrange point L2, 1.5 million km from earth. In the Lagrange points L1 up to L5 the combined gravitational pull of the two masses of earth and sun is in equilibrium with the centripetal force required to rotate with them. As Figure 2 illustrates, L2 lies on the line through the centres of earth and sun beyond the earth. To prevent the earth obscuring the sun – with unwanted cooling down of the instrument as a consequence – GAIA moves in a relatively small Lissajous-formed orbit around L2. The satellite operates at -100 °C, in vacuum of course.

Function of AFMA

AFMA has been designed to simulate the spinning of GAIA in space around its vertical axis. The difference with in-orbit operation is that in an on-ground thermal-vacuum testing set-up the satellite remains stationary and AFMA moves; see Figure 3. In fact, there are two AFMAs, each provided with an accurately machined flat mirror, positioned at right angles to the optical axis of each GAIA mirror.

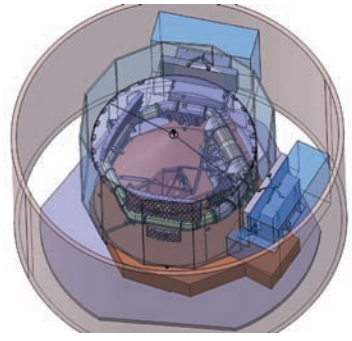

Figure 3. The GAIA satellite together with two AFMA units under an angle of 106.5° in a thermal vacuum testing vessel with a diameter of 6 m. (Courtesy TNO, like all figures hereafter)

AFMA is, as said, an acronym for Autocollimating Flat Mirror Assembly, which means that a point source in the plane of the CCD array (Charge-Coupled Device) for image forming in GAIA emits a parallel beam via the curved telescope mirror. The AFMA flat mirror reflects this parallel beam. After this back reflection the telescope mirror collimates the beam to a point image in the focal

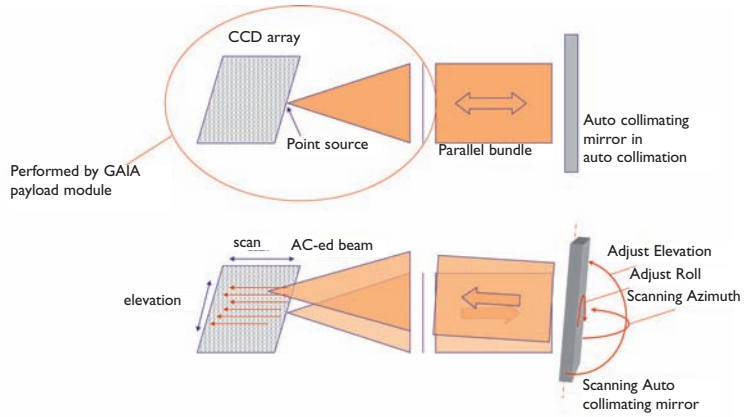

Figure 4. The autocollimation principle in the GAIA testing set-up with the AFMA flat mirror.

plane of GAIA, autocollimation; see Figure 4. When the AFMA mirror changes its angular position, the point image moves in the GAIA focal plane. The distance between point source and moving point image is a measure for the angular displacement of the AFMA mirror.

The AFMA mechanism has been designed to control the angular position of the flat mirror for three degrees of freedom (DoFs) separately: azimuth, elevation and roll; see Figure 5. The azimuth scanning movement is the angular position change around a vertical axis X in the test set-up, the elevation movement is a change around a horizontal axis Y, and the rolling movement is a change around an axis Z perpendicular to the flat mirror.

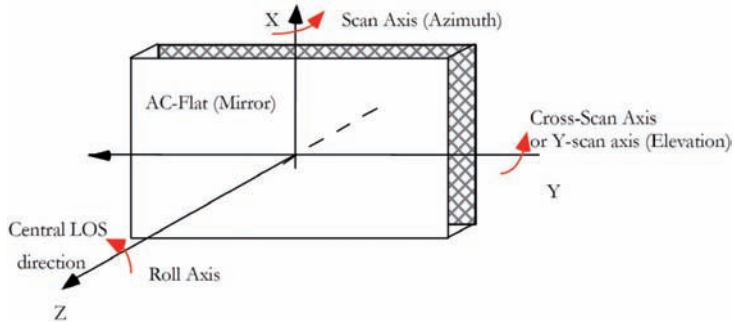

Figure 5. The three angular DoFs for the AFMA flat mirror: azimuth, elevation and roll.

The accuracy demand imposed upon the control of the azimuth scan is extremely severe. Within the operational angle of 20 mrad for the azimuth control around the X-axis, the mean velocity error should be lower than 3.2 nrad per 4.4 s. At a speed of 145 µrad/s this means an arc deviation of ± 100 nm over a span of 20 mrad at a radius of 1 m. Later on it will be shown that Heidenhain measuring scales help to fulfil these stringent accuracy demands. These demands are a logical consequence of the specified ability of GAIA to distinguish objects in space with an accuracy of better than 24 µarcsec, comparable with the unbelievable spotting of a human hair at a distance of 1,000 km!

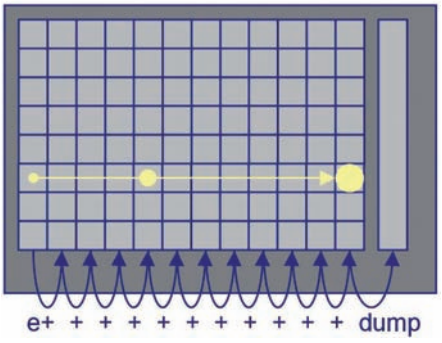

Figure 6. Energy transfer in the GAIA CCD-chip when AFMA autocollimates the point source over the GAIA focal plane on this chip.

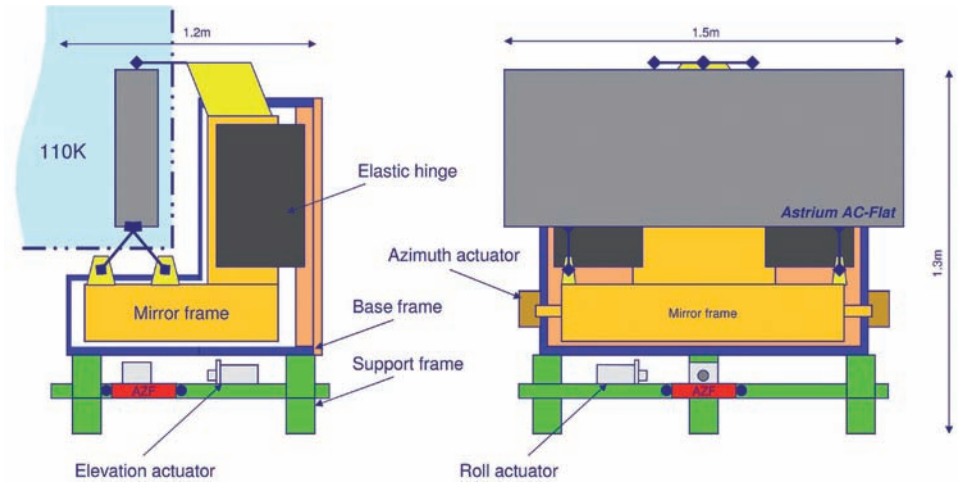

Figure 7. The box-in-a-box principle of mirror frame within the base frame. The base frame rests in spherical bearings on the support frame. The fixation points for the flat mirror are indicated in yellow.

For the control of each of the three DoFs the accuracy should be high enough to acquire a positional error lower than 2 µm for the autocollimated spot on each CCD chip in the GAIA focal plane; see Figure 6.

Application of design rules

The AFMA testing mechanism is a fine example of the application of some of the many design rules laid down in the well-known design handbook for accurate moving and positioning, written by Rien Koster [2], and re-edited, updated, translated and summarised by Herman Soemers [3].

One of the applied design principles is the realisation of high torsion and bending stiffnesses in a light-weight thin-walled box. Another principle is creating a virtual play-free pivot point with the aid of leaf springs. The last principle to mention is milling a reliable play-free linear guide with four leaf springs out of a solid block of aluminium. Not to mention the application of *n* well-defined support points to constrain (6 – *n*) DoFs of an object.

In fact, TNO's Ellart Meijer used a box-in-a-box design with three principle assemblies: mirror frame, base frame and support frame; see Figure 7. The mirror frame is a box that accommodates the flat mirror and accomplishes the azimuth rotation within the box-like base frame. The base frame is being supported by three spherical bearings on the support frame. These bearings together with two straight rods allow the elevation and roll DoFs. Figure 7 also illustrates the fixation of the flat mirror onto the mirror frame with supports that take the difference in thermal expansion coefficients of mirror and frame into account.

Azimuth design details

In the first prototype the flat mirror with a width of 1.5 m and a mass of 80 kg is simulated by a steel dummy mirror with about the same (mechanical) properties, except for the optical properties. The latter ultimately amounts to some tens of nanometers, which asks for special measures to avoid stress and thus deformation of the definitive mirror material, which is silicon carbide. That is why the mirror is supported by three bipods from invar, one at the upper and two at the lower side of the mirror; see Figure 7. Figure 8 shows how the dummy mirror is supported by one of the lower bipods, provisionally made from aluminium.

Figure 8. Design detail of one of the lower bipods for supporting the dummy flat mirror on the mirror frame.

Figure 9 illustrates the creation of two virtual pivot points above each other for the azimuth control with two sets of two leaf springs each. The elastic hinges are situated between mirror frame and base frame and allow the mirror frame to rotate around the X-axis. The 2x2 springs, made from titanium alloy Ti6Al4V, are stiffened in their middle, see Figure 10, to avoid local vibration modes. The blades are pre-loaded to avoid the instable – unwanted – behaviour called "oil canning", also known from the – wanted – behaviour of the contact spring in microswitches.

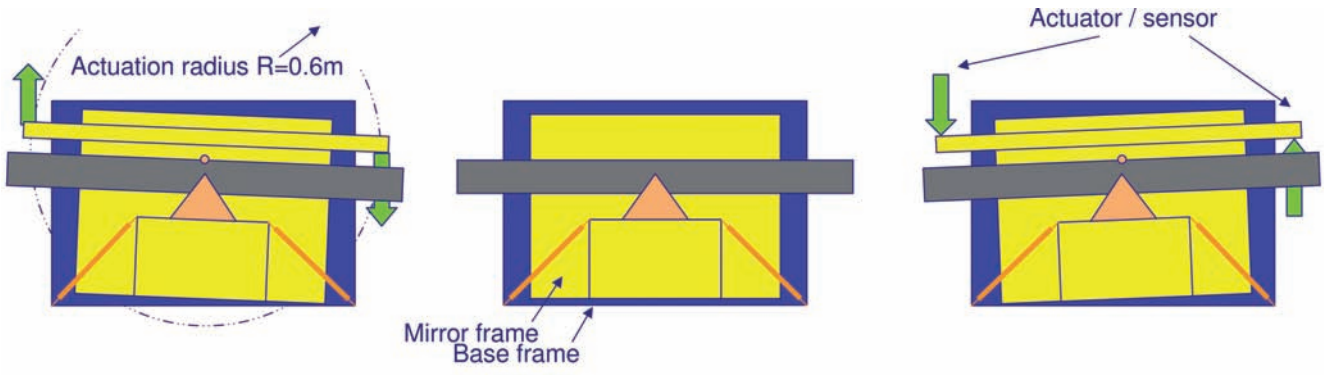

Figure 9. Creating virtual pivot points between mirror frame and base frame with two elastic hinges above each other, each with two leaf springs.

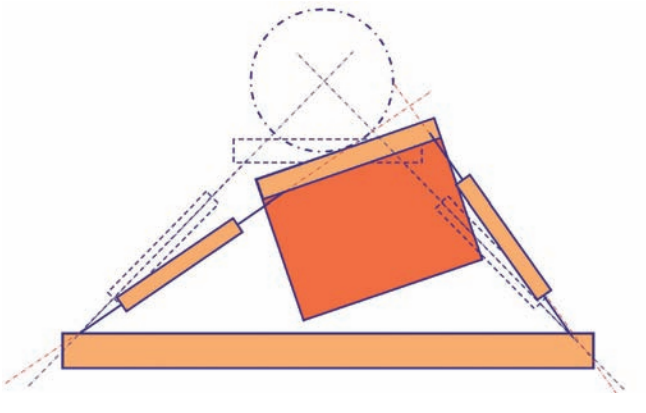

Figure 10. Principle of the virtual pivot mechanism.

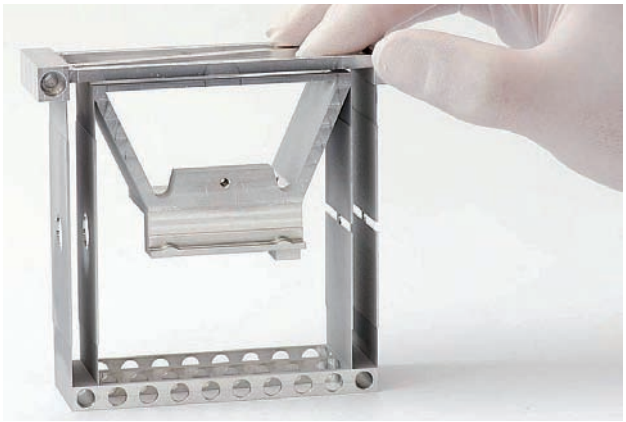

Figure 12. Parallel guide with four leaf springs, milled from one solid aluminium block.

Two voice-coil actuators provide a pure driving moment for the azimuth control. Heidenhain LIP 481V vacuum-resistant ruler grids with 2 µm scale division and 1000x electronic interpolation measure the displacement along the arc, see Figure 11. The ruler is mounted on a parallel guide with four leaf springs, milled from solid aluminium, see Figure 12.

Elevation and roll

Whereas the azimuth control with 20 mrad span is an essential GAIA calibration property of the AFMA mechanism, elevation and roll control only are fine adjustments of AFMA in relation to the GAIA satellite in the final testing set-up in vacuum. Nevertheless, these controls also have to meet stringent demands regarding reproducibility, position stability and freedom of play and stick-slip.

For the elevation and roll movement around respectively Y and Z axis, the base frame rests upon the support frame in three spherical sliding bearings with a radius of about 1 m and the centre point in the X-axis; see Figure 13. To reduce

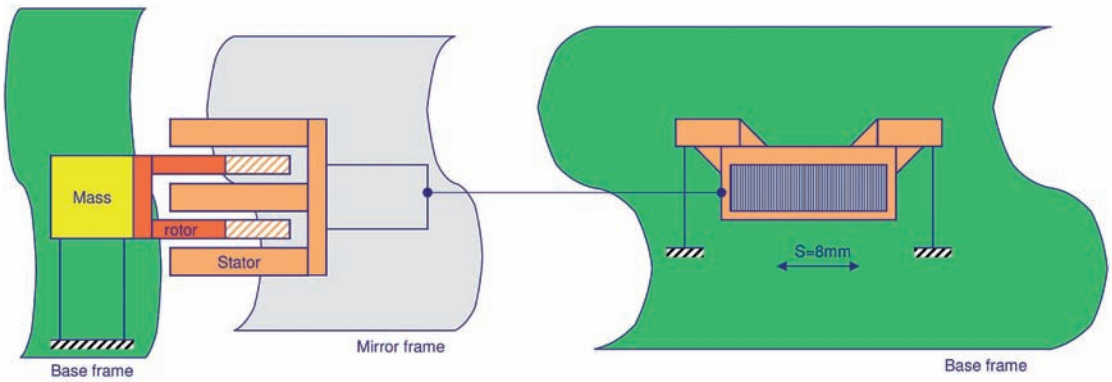

Figure 11. Azimuth control mechanism with voice coil (left) and ruler with 2 nm resolution (right) mounted on the parallel guide of Figure 12.

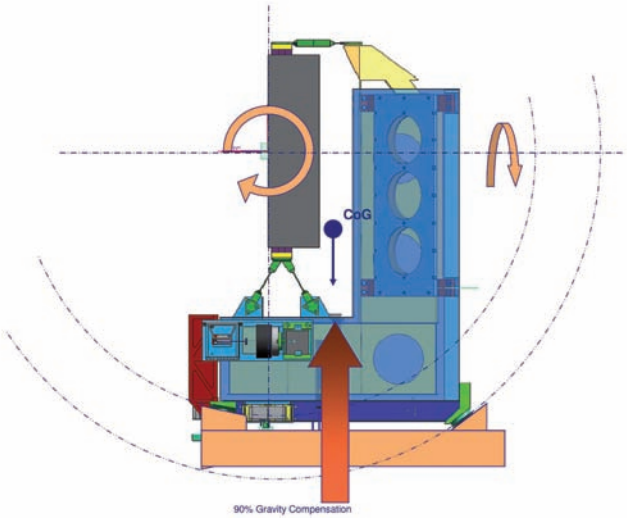

Figure 13. Support of the base frame on the support frame in three spherical bearings to allow elevation and roll movement, see arrows.

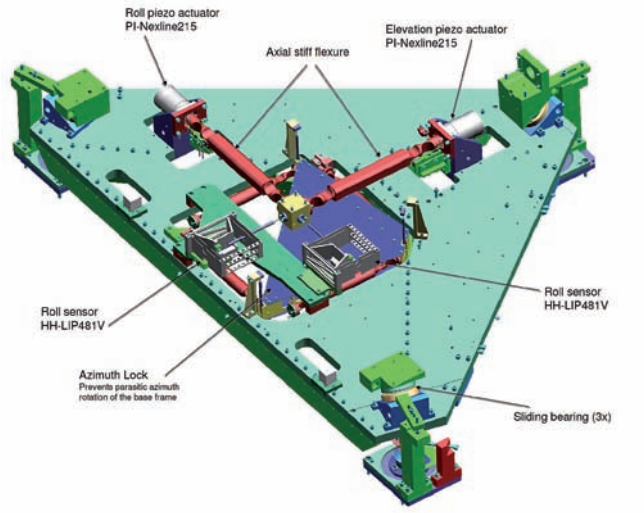

Figure 14. Elevation and roll control mechanism mounted on the support frame with piezo actuators and measuring scales. The central cubic block is connected to the base frame.

friction in those bearings, the surfaces are provided with a thin sheet of MoST™ coating (molybdenum disulphide / metal coating; by Teer Coatings) for application in air as well as in vacuum. Moreover, the normal contact forces are reduced by a gravity compensation spring, which gives an upward force somewhat smaller than the total actuated mass of frames and mirror; see Figure 13.
Figure 14 illustrates the drive and measuring arrangement for elevation and roll. A central square block mounted under the base frame is able to move in Y- (elevation) and Z- (roll) direction by coupling via long rods to piezo-type linear actuators. The rods are axially very stiff, of course, and the actuators have nanometer resolution. The Heidenhain measuring scales are of the same type as the azimuth ones and each are mounted on a parallel guide as shown in Figure 12. After calibration they indicate the roll and elevation angles.

Figure 15 shows the final AFMA realisation.

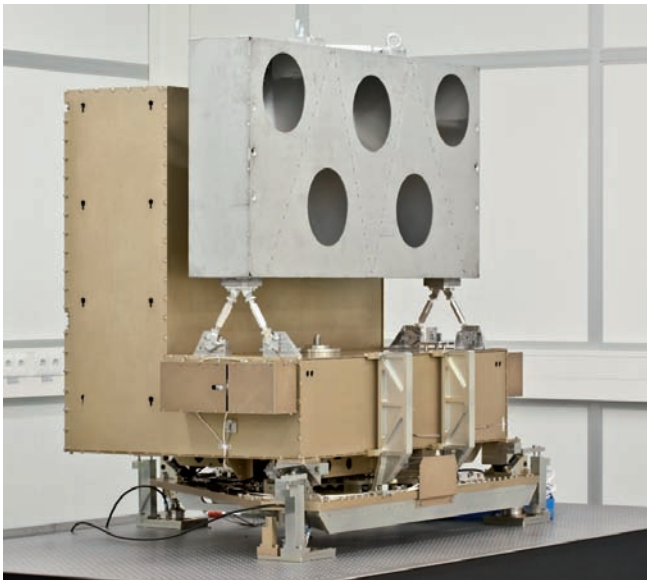

Figure 15. TNO's realisation of AFMA.

To conclude

Today's precision technology, together with well-known intelligently applied "old" design principles, form the hidden secret of the sophisticated AFMA calibrating instrument. Of course, the design details described before are – without doubt – the end stage of a series of brainstorming sessions and testing detail set-ups of Ellart Meijer's team. It is not unrealistic to think that they frequently riffled through the pages of Rien Koster's and Herman Soemers' design handbooks, which definitely should be far from hidden secrets.

Author's note

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

References

[1] Ellart Meijer and Fred Kamphues, "Picometre metrology in space", *Mikroniek* 46 (3), 2008.
[2] M.P. Koster, "Constructieprincipes voor het nauwkeurig bewegen en positioneren", ThiemeMeulenhoff, 2008, ISBN 978-90-5574-610-1.
[3] Herman Soemers, "Design principles for precision mechanisms", T-Pointprint, 2011, ISBN 978-90-365-3103-0.

Information

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Partner in product

Philips Applied Technologies no longer exists; one half of it has been absorbed by Philips Research, the other half has been merged with MiPlaza to form a new group called Philips Innovation Services. A new name, but customers who wonder what changes this will bring for them, don't need to worry: business will be as usual. Apptech's renowned mechatronics competence centre will be stronger than ever.

• *Jan Kees van der Veen* •

Philips Innovation Services on the High Tech Campus in Eindhoven.

The façade of the former Philips Applied Technologies building on the High Tech Campus in Eindhoven, the Netherlands, is already showing the new name, Philips Innovation Services. Well, that's the easy part of a reorganisation, but what has really changed, and why? To find out, Mikroniek interviewed Harry Vaes, Head of NPI Services and Mechatronics of Philips Innovation Services (NPI stands for New Product Introduction).

Harry Vaes, Head of NPI Services and Mechatronics of Philips Innovation Services.

Why this reorganisation?

"We had to adapt our organisation to a new reality. Since a couple of years, Philips Research is extending basic research to predevelopment and even development, entering an area that was hitherto covered by Philips Applied Technologies. Our activities started to overlap and

Author's note

Jan Kees van der Veen is a freelance technical journalist living in Son, the Netherlands.

development

we decided that it was more efficient to rearrange things. All product development within Applied Technologies done strictly for Philips – healthcare, lighting, lifestyle – has now been relocated to Research. This adds complementary expertise to Research in fields such as first-of-a-kind production and process development. All other activities – product development for third parties, innovation support groups and the mechatronics competence centre – have, together with MiPlaza's competences and facilities, been bundled in a new organisation, called Philips Innovation Services. The reorganisation increases transparency for our customers. It better separates activities for Philips and for external customers."

Does this make you more attractive for your customers?
"Yes. With Philips Innovation Services, our customers will have access to a package of services that is better and more comprehensive than before. Let me explain. Why do customers come to us? The main reason is they want products developed quickly. The pressure to shorten development times is high. Often, (starting) companies have just a product idea and lack the expertise to carry out simulations, build and test prototypes, estimate technology risks, make design decisions, in short: to develop the product. Philips Innovation Services can support them in all phases of the innovation process and even take over the development, up to and including the building of pilot-series or the selection of a manufacturer. The addition of the MiPlaza services makes our offerings even more

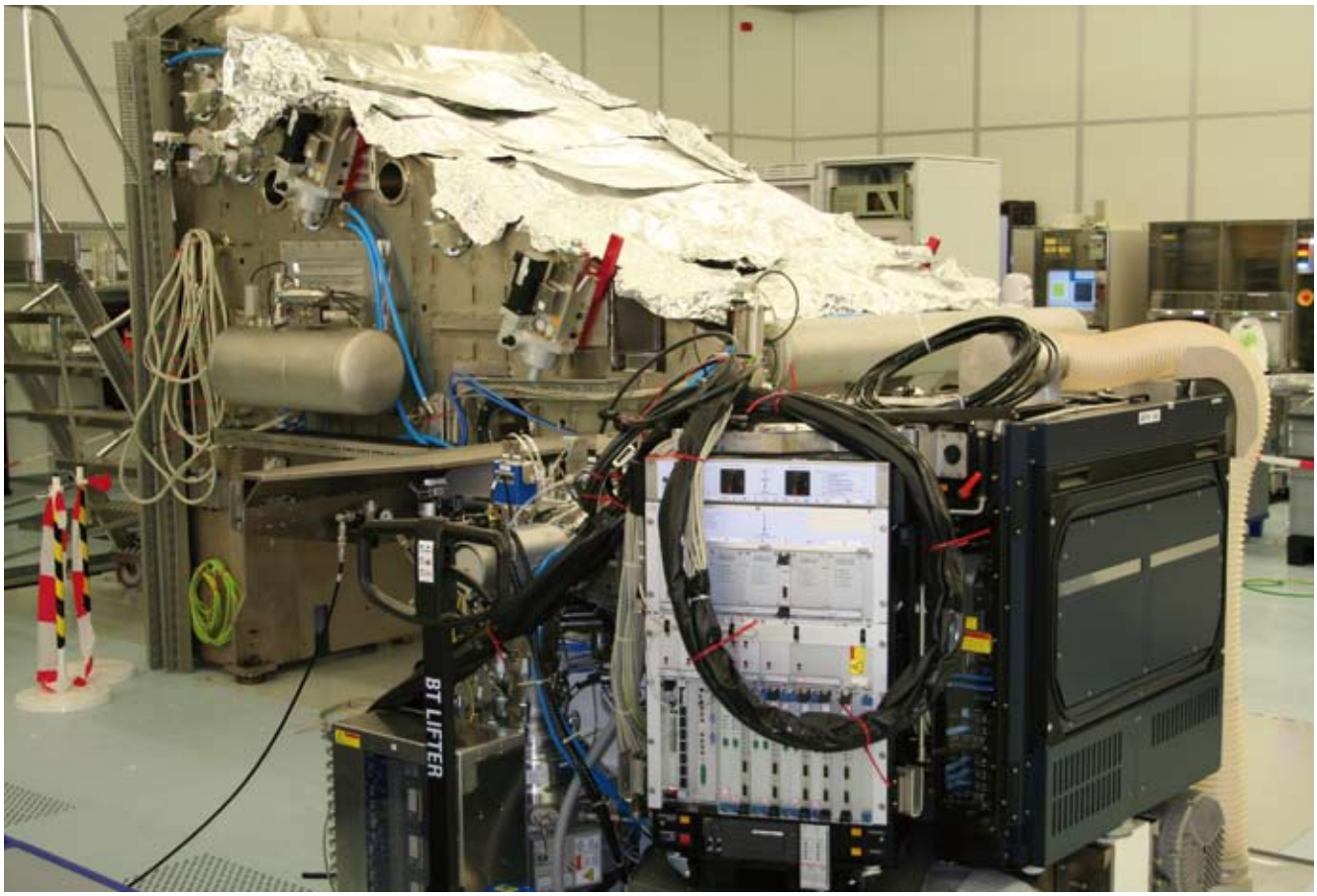
Some history

In the sixties of the previous century, when Philips ran hundreds of factories and employed more than 350,000 people, the development of production technology took place at several locations in the world. The company decided that this was inefficient and one could better concentrate these efforts in one place as much as possible. Therefore, in 1969 Philips founded the Centre for Manufacturing Technology ('Centrum voor Fabricage Technieken' or CFT, in Dutch) in Eindhoven as a knowledge and support centre for its factories.

In the first fifteen years of its existence, CFT worked exclusively for Philips, but gradually it started to offer its services to third parties. This was eased because of the fact that Philips departments that worked with CFT, but left the Philips organisation – being sold or privatised –, often remained CFT-customer even after the separation. The services offered by CFT also broadened in another way: CFT engineers assisted development groups in making products more 'production-friendly' and this extended to CFT building prototypes for customers, using the latest materials, technologies and tools.

In 2006 CFT merged with the Philips Digital Systems Lab (PDSL) and was renamed Philips Applied Technologies. Now, in 2011, Philips Applied Technologies has ceased to exist. Half of it has been brought together with MiPlaza to form Philips Innovation Services. MiPlaza (short for Micro-electronics Plaza) is a clustering of former technical support departments of Philips Research, offering facilities and expertise in electronic, mechanical and software design, prototyping and testing. Since 2004 it offers its services to third parties and it currently employs 350 people.

In the early eighties of the previous century, CFT started developing machines for mounting SMDs (Surface Mounted Devices) on printed circuit boards. In 1988-1989 the revolutionary FCM-II (Fast Component Mounter) was launched, featuring 16 placement robots working in parallel. More than 1,000 of these machines were produced. Later on, Philips privatised the business; it is now the Assembléon company.



The success of ASML once started at the NatLab. The first waferstepper, called PAS, for Philips Advanced Stepper, was built there in the early eighties. When ASML was founded in 1984, CFT was involved in the development of the first machines. In 1996, when development of the twin-scan machine for 300mm wafers started, CFT took responsibility for the development of the wafer stage and, later, for the reticle stage. For the next generation, EUV, CFT built extensive expertise in vacuum technology and in 2006 delivered two alpha demo tools, see the picture. (Courtesy IMEC)

complete and very strong. With their skills, prototypes can be developed and built even faster."

What happens to the mechatronics expertise?
"The Mechatronics Competence Centre is a stronghold within Philips Innovation Services and the only group that has the capability to run big development projects on its own. The list of mechatronics competencies that we can offer is long: system architecture, project management, electronics, mechanics, software, sensors, optics, vision, electromechanics (e.g. linear motors, MagLev), vacuum (increasingly important), dynamics, thermal analysis and design, motion control, and so on. All in all we have some 60 competencies under one roof, which is unique in Western Europe. In addition, we can call in colleagues or use facilities from our other groups: Greenhouse, located at Strijp (Eindhoven), for electronics prototyping; Electronic Design Services for a.o. PCB layout and EMC testing; MiPlaza with its technology labs, clean rooms, test and analysis facilities, support in electronics and software creation; and Industry Consulting for non-technical, process-improvement issues. No competitor can offer such a broad range of competencies and such experience."

So, the future is bright for Philips Innovation Services?
"Absolutely. In the past, outsourcing product development was unthinkable for a beginning company. Now, we see a new type of entrepreneurs emerging. They have a good product idea, have found financiers for it, but don't want to occupy themselves with development or manufacturing tasks. Instead, they contract a partner such as Philips Innovation Services, with its wealth of expertise and experience, to take over development of product and production processes, and another partner, say in the Far East, to do the manufacturing. These 'head-tail enterprises' concentrate on the marketing and sales. The approach has great advantages: utilisation of experience that would take ages to build on your own, lower risk, avoidance of rookie mistakes, short development times. We have opened a special desk for SMEs (small and medium-sized enterprises) to remove any barriers that might exist."

CFT and, later on, Philips Applied Technologies, did many projects for Philips Medical Systems, now Philips Healthcare, to make patient tables cheaper, lighter and more reproducible. This picture is from 2009.

Do you expect growth?
"The number of employees has been pretty constant around 800 over the years. We withstood the financial crisis without a scratch and, currently, all our groups are doing very well indeed; our order portfolio is filled to the brim. There is room for expansion and we are searching for qualified personnel. At this moment, Philips Innovation Services has between 50 and 60 vacancies for jobs in a technical field, 35 of which at the Mechatronics Competence Centre. It is hard to find good technicians, of all levels, even though we have intensive contacts with universities and technical colleges in the Netherlands and abroad (Aachen, Leuven), attend conferences and participate in Dutch programmes for adolescents, like JetNet, to promote technical careers. We can offer people interesting, varied and challenging jobs amid experienced colleagues they can learn from, and I am happy to say that most candidates who apply for a job and get an offer from us, invariably take it."

Where do your customers come from?
"Customers come from many countries and industries. Let's take mechatronics as an example. The traditional focus for our expertise is the semiconductor industry and we serve customers such as ASML (wafersteppers), KLA-Tencor (process control and inspection equipment) and IMS (e-beam writing, see next page). But mechatronics can be applied in many other areas. Aquaver (water desalination) and Biocartis (fast medical diagnostics through DNA-string detection) are also our customers. Areas that we are increasingly active in are solar and cleantech, and we are 'sniffing' at automotive. Apart from that, we support Philips Research and the businesses with their mechatronic problems."

Interesting for prospective customers: how much do your services cost?
"We have different models, ranging from 'time & materials' to co-entrepreneurship. Customers don't need to be afraid that, via us, IP or confidential information leaks to other parties, we are very careful about that. At the first discussions, we can draw up a Non-Disclosure Agreement (NDA), if requested, in which it is agreed what information is free – thus can be reused by Philips Innovation Services in other projects – and what information should stay within the project."

Information

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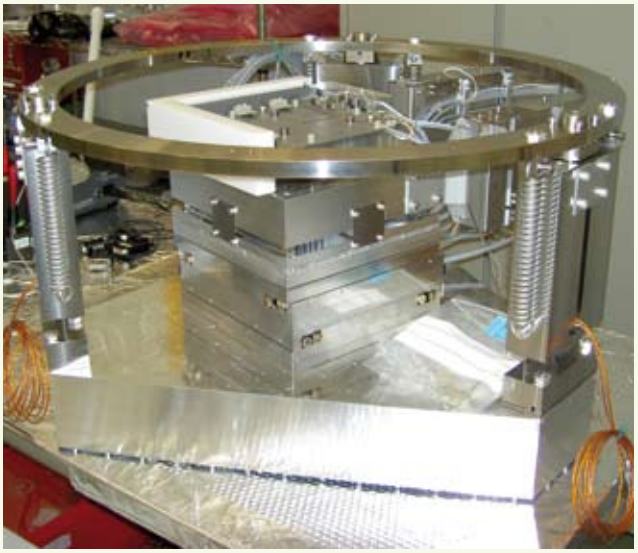
"It was worth the investment"

The Austria-based company IMS Nanofabrication chose Philips Innovation Services as partner to build a proof-of-concept system for their electron multi-beam Mask Exposure Tool (eMET). The project was completed in ten months, in a very good atmosphere and within budget.

IMS, founded in 2006, develops nanolithography technologies, e.g. for producing masks required for IC production. The technology is based on electron multi-beam writing, using 256 thousand beams in parallel. Current technologies for mask-writing are reaching their limits of accuracy and speed. Dimensions of ICs keep going down and although the patterns on the masks are a factor of four larger than the patterns on the wafer, the accuracy requirements are almost as high. Reason is that, with optical lithography, features on the chip are far below the wavelength of the light used (193 nm) and that clever optical tricks are necessary to obtain nanometer resolution. As for speed, IMS has set as target that the writing time of a mask must be less than ten hours. The company claims it will meet this requirement with its parallel beam writing. The IC industry is heavily interested in IMS's concept, as currently there is no other viable technology for the next generation mask-writing with comparable resolution and speed. eMET is also suitable for mask-writing for EUV lithography, the successor of 193nm optical lithography.

Philips was approached by IMS in 2009 to realise the high-precision stage in the eMET proof-of-concept system. The system was to be a mask-writer with full functionality, but with relaxed specs on throughput, uptime and thermal stability. According to IMS spokesman Christof Klein, Philips was an obvious choice. "We already had contact with them in 2008 and we were impressed by their expertise and skills in a.o. control engineering, thermal modeling and system dynamics. At that time we didn't have the money yet to build the system, but we came back a year later when we had the funding. We agreed with Philips that the stage would be realised within strict budget and time constraints." In spite of the stringent requirements – x-, y-position feedback with subnanometer resolution, position accuracy of 1 nm (1σ) – and technical challenges like vibration isolation and temperature management, the stage was delivered, as agreed, in ten months time and slightly below budget.

Christof Klein was happy with the collaboration. "The working atmosphere was very positive during our weekly progress meetings. Philips has not been a cheap partner, but it was worth the investment."



The high-precision stage in IMS's eMET proof-of-concept system as delivered by Philips Innovation Services.

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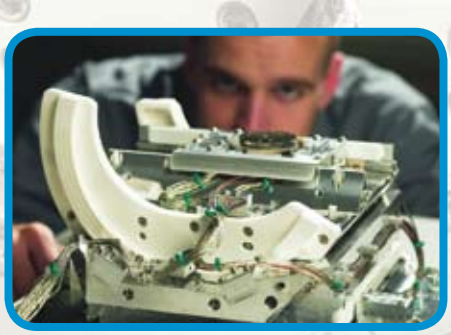
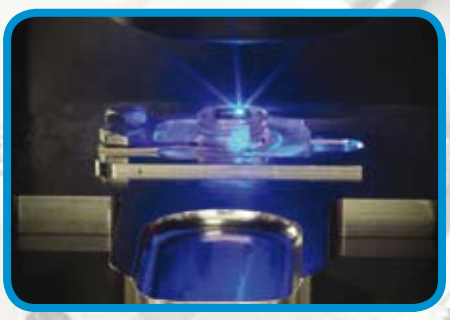

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Quantifying the of a closed-

The performance of a closed-loop system is determined by the design of the plant, the disturbances acting on it and the controller design. Dynamic Error Budgeting (DEB) allows to compare the contributions of various stochastic disturbances acting on the closed-loop system to the performance channel. This way, the design can be judged to see whether it can meet the requirements under the modeled disturbance environment. This article describes how optimal control can be used in the DEB framework. With optimal control the performance of a designed controller can be quantified, and it can provide clues on how to improve the design. It also allows to objectively compare different designs of mechatronic systems.

• *Leon Jabben and Jan van Eijk* •

Introduction

A large class of mechatronic machines have specifications based on their standstill (or constant-velocity) performance, e.g. step (or scan) machines for lithography, positioning stages for microscopes and other applications, active vibration isolation and many more. Here, the term mechatronic refers to closed-loop control systems with mechanical position as measured output. The standstill performance of such a system is limited by the noise sources (disturbances) acting on the closed-loop system, resulting in a performance measure with stochastic properties.

In the design of precision machines, error budgeting is often used to allocate how much each component is allowed to contribute to the total error, see e.g. [1, p.61]. For the design and analysis of mechatronic systems one would like to error budget the disturbances acting on the

Authors' note

After having worked in Switzerland, Leon Jabben obtained his Ph.D. at Delft University of Technology, the Netherlands, in 2007. He worked three years at TNO, primarily on space projects. In 2008 he started his own company, Jabius Innovations, for control and design of mechatronic machines. Jan van Eijk is part-time professor of Advanced Mechatronics at Delft University of Technology, and a consultant through his own company MICE (Mechatronic Innovation and Concept Engineering), based in Eindhoven, the Netherlands.

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performance
-loop system

closed-loop system. This can be done by realising that many disturbances in such a system are stochastic of nature and can often be modeled with their Power Spectral Densities (PSDs). This allows frequency-dependent error budgeting, which is why this approach is referred to as Dynamic Error Budgeting (DEB).

In [2] the DEB approach was applied to tune the controller of a hypothetical mechanical system, schematically depicted in Figure 1. In the system a tool tip is to be positioned with respect to a stator with a positioning error smaller than 50 nm (RMS). The tool tip is attached to a rotor of which the remaining five degrees of freedom (DoFs) are restrained by flexures, resulting in a resonance frequency of 150 Hz. The position of the rotor is measured with a sensor and is fed back to a digital controller. The controller commands the actuator, which acts between the rotor and the stator.

The disturbances that are considered are sensor noise, force disturbances and ground vibrations. The sensor noise stems from quantisation and electronic noise of the analogue-to-digital converter (ADC) and from the electronic noise of the sensor itself. The total sensor noise is 39 nm and has a uniform, “white”, distribution up to the Nyquist frequency.

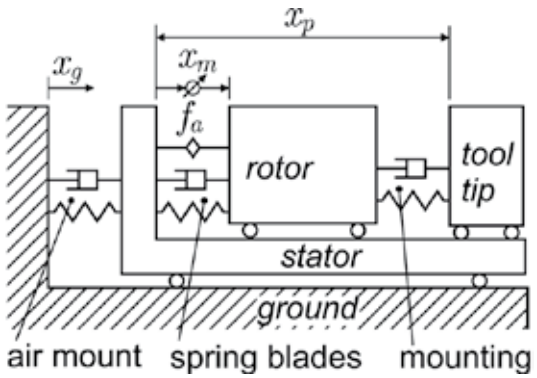

Figure 1. Lumped-mass model representation of the positioning problem example. The tool tip is to be positioned with an error smaller than 50 nm (RMS) with respect to the stator.

The force disturbances are from quantisation noise of the digital-to-analogue converter (DAC), resulting in white noise of 7.0 mN (RMS). Due to electronic noise of the amplifier, a $1/f^2$ component is dominant up to 5 Hz, resulting in a noise of 15.6 mN (RMS).
The floor acceleration is assumed to have a PSD of 10^{-5} $[(m/s^2)^2/Hz]$ from 1 up to 200 Hz with fourth-order roll-up and roll-off before 1 Hz and after 200 Hz. The integral of this PSD results in an RMS value of the acceleration of 47 mm/s^2. The vibration of the table is calculated by taking the PSD of the floor multiplied by the bode magnitude of the table transfer function squared, which gives a standard deviation of 12 mm/s^2.

In [2] it is described how the RMS performance achieved by a PID-type controller was tuned from initially 107 nm, to 66 nm, and finally 46 nm using clues provided by DEB. The performance of the final tuned controller predicted by DEB is summarised by the Cumulative Power Spectrum (CPS) depicted in Figure 2. The power of DEB is that it shows the achieved performance, as well as the

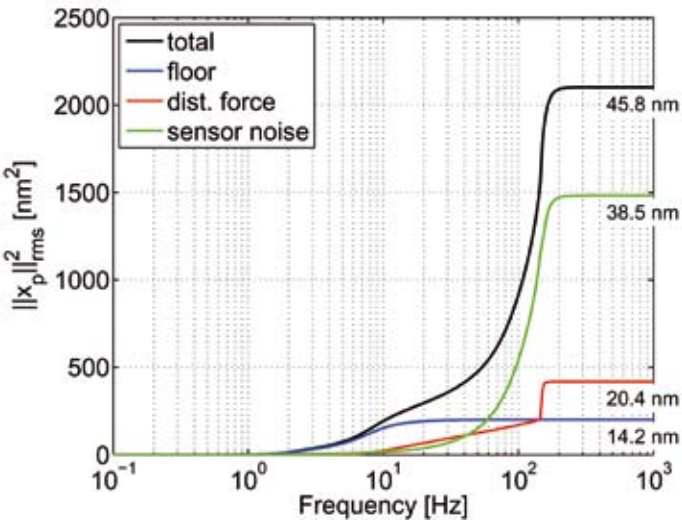

Figure 2. Cumulative Power Spectrum (CPS), showing the performance of the system with a tuned PID-type controller as well as the contributions of the different disturbance sources.

contributions from the various disturbances sources in one figure.
This example raises the following questions, which will be addressed in this article:

1) How good is the tuned controller? How much performance can still be gained through further tuning?
2) If, apparently, the controller design has such a big influence on the performance, how can different system designs be compared objectively?

Optimal control

Background of optimal control

Dynamic Error Budgeting models the disturbance as stochastic variables. The framework is par excellence suitable for optimal stochastic control. The theory on optimal control has been extensively studied in the 1960s and 1970s. Optimality was based on minimising an integral quadratic cost function in the time domain, assuming white noise disturbances. This method is called Linear Quadratic Gaussian (LQG) control, see [4], and is closely related to H_2-optimal control; any LQG control problem can be formulated as an H_2-control problem. The main limitation of H_2-optimal control, namely that it lacks the formal treatment of uncertainty in the plant, caused a shift of research effort towards H_∞-control and μ-synthesis in the 1980s and 1990s. For a good introduction in the subject, refer to [5]. An advanced and thorough coverage of H_∞- (as well as H_2-) control can be found in [6]. With the availability of solvers for so-called Linear Matrix Inequalities (LMIs), multi-objective control, which allows the use of mixed H_2- and H_∞-norms on a system, has recently received a lot of attention, see e.g. [7] and the references therein. The main difficulty with μ-synthesis and LMI-solvers is the numerical conditioning for large systems (e.g. state dimension > 50). This paper only considers H_2-optimal control.

Generalised plant setting

In Figure 3 the closed-loop block diagram of the system from Figure 2 is drawn in a so-called generalised plant setting. The generalised plant maps the disturbances and plant input to the performance channels and error signal. By minimising the H_2-system norm of the generalised plant, the variance of the performance channels is minimised. The performance channel should also include the controller output, in order to get sensible results.

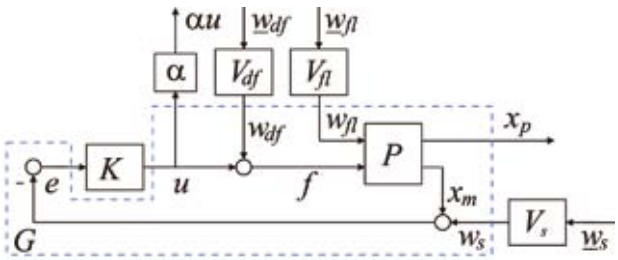

Figure 3. Block diagram of the control system. The dashed line indicates the generalised plant, with stacked inputs [w_{fl} w_{df} w_s u] and stacked outputs [x_p u e]. The symbols w_{fl} w_{df} w_s represent the floor, force and sensor disturbances, respectively. The filters V color the white-noise inputs $\underline{W}$ such that the outputs have the desired PSDs of the disturbances.

The H_2-controller synthesis requires white-noise inputs, hence the generalised plant should be augmented with weighting filters in order to account for the frequency content of the actual disturbances, as shown in Figure 3. The weighting filters *V(s)* should be designed such that the output has the desired PSD. In other words:

$$|V(j2\pi f)|^2 = \tfrac{1}{2} PSD(f) \qquad (1)$$

where *V(s)* should be a stable transfer function, otherwise the generalised plant cannot be stabilised. Finding such a stable transfer function is called spectral factorisation; see [8] for an overview of methods for factorisation. The factor ½ comes from the fact that single-sided PSDs (only defined for positive frequencies) are considered.

Performance vs controller effort

In general, controller effort can be traded for performance. For example, a higher gain of the controller usually yields better force disturbance rejection, at the cost of a higher control effort due to the increased gain of the sensor noise. The performance and controller effort can be balanced systematically with optimal control. In Figure 3 it can be seen that the controller output is weighted with a scalar α. Varying this scalar and calculating the optimal controller for each value results in a trade-off curve such as illustrated in Figure 4. Specifications below this curve cannot be achieved, while specifications on the curve are denoted Pareto optimal specifications, [9]. This trade-off curve is referred to as the Pareto curve.

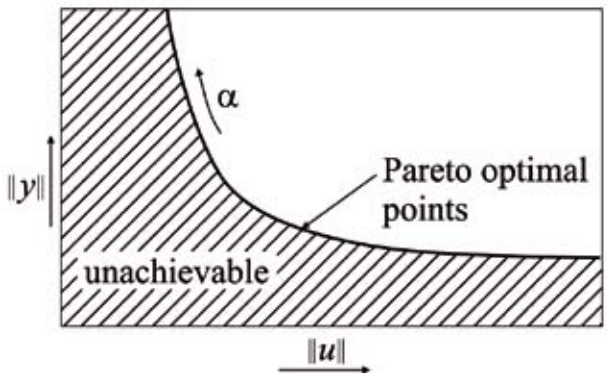

Figure 4. An illustration of a trade-off or Pareto curve. Each point on the curve represents the performance obtained with an optimal controller. The hatched area is not achievable and the area above the curve is not optimal. The curve is obtained by varying the scaling parameter α of Figure 3 and calculating an H_2-optimal controller for each α.

Optimal control results for example case

Calculating the optimal controller for the example described above, yields the CPS as depicted in Figure 5. The positioning accuracy has increased to 38 nm (RMS). For the synthesis of the controller a certain value for α, the weighting scalar of the controller output, must be chosen. In Figure 6 the Pareto curve for the example is given. The

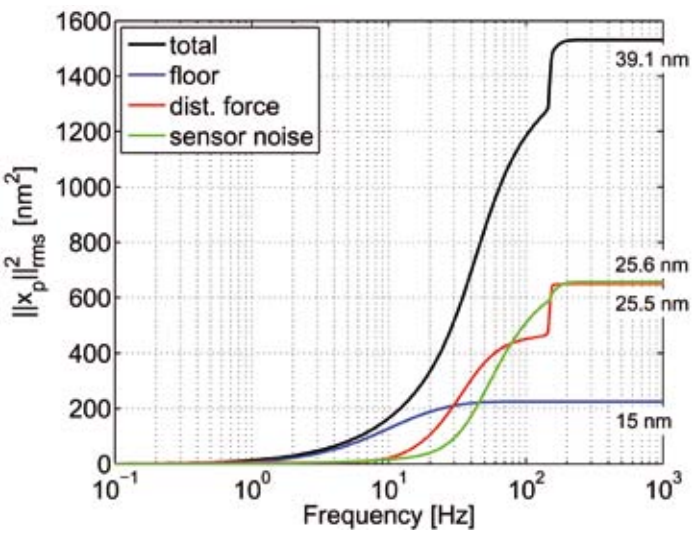

Figure 5. Cumulative Power Spectrum showing the performance of the system with an optimal controller. The contributions of the different disturbance sources are also shown.

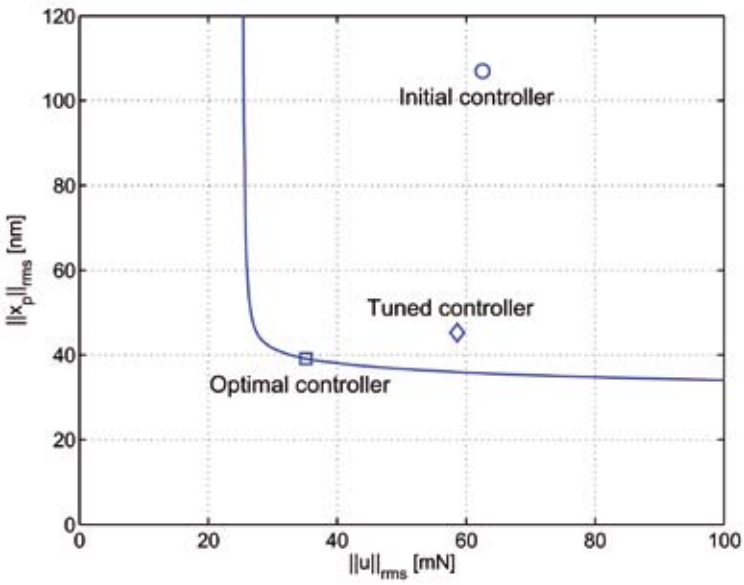

Figure 6. Pareto curve for the example case. Indicated are the initial controller from [2], the tuned controller and the optimal controller. The optimal controller achieves 13% performance increase with 40% less controller effort as compared to the tuned PID controller.

curve shows a rather sharp knee. It seems logical to choose α such that the performance is close to the knee. The chosen optimal controller is indicated in Figure 6, together with the initial controller and tuned controller from [2]. The optimal controller achieves 13% performance increase with 40% less controller effort as compared to the tuned PID controller.

Multiple Input, Single Output controller

To further demonstrate the power of optimal control to objectively compare different designs, a second sensor will be added to the system of Figure 1. With this sensor the position between the tool tip and the stator will be measured. The added sensor is the same as the one measuring between rotor and stator, having the same noise properties. With the additional information the controller should be able to achieve a better performance; however, this extra sensor will also introduce additional noise. Although the system is quite different than before, with a controller with two inputs and one output, the Pareto curve can be calculated in the same manner as before. In Figure 7 the resulting Pareto curve is given and compared with the

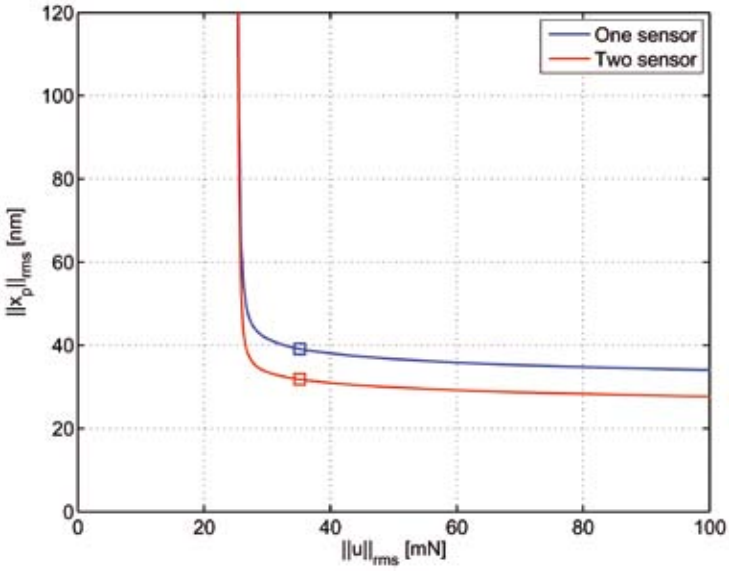

Figure 7. Pareto curve for the system with two sensors (red) compared to the Pareto curve of the system with one sensor. With the use of the Pareto curve two different designs can be easily compared. In this case, the additional sensor gives about 7 nm (RMS) performance improvement.

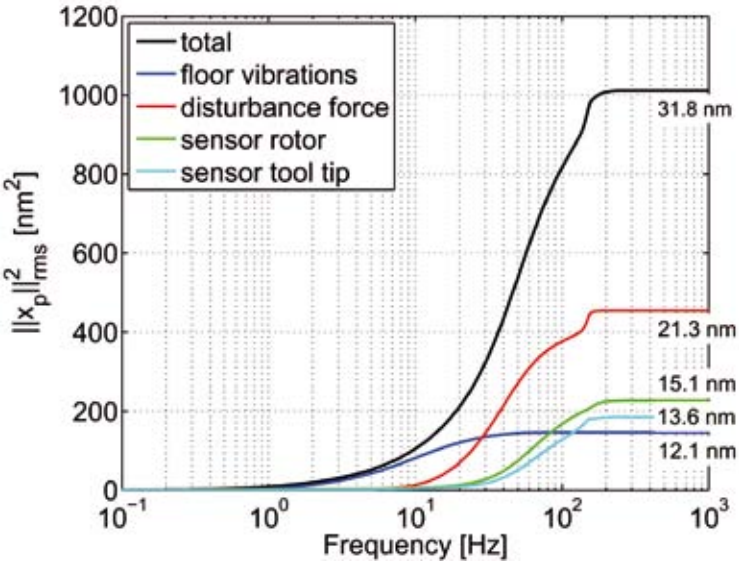

Figure 8. Cumulative Power Spectrum showing the performance of the system with two sensors. The contributions of the different disturbance sources are also shown.

curve for the system with one sensor. It can be seen that with the additional sensor a performance increase of about 7 nm (RMS) can be achieved.

Choosing a controller, as indicated in Figure 7, with the same controller effort as the system with one sensor, the CPS can be calculated. This is shown in Figure 8. In the system with two sensors all disturbance sources have less impact than in the system with one sensor (compare with Figure 5). The two sensors combined ($\sqrt{(15.1^2 + 13.6^2)}$ = 20.3 nm) contribute less than the single sensor. It can also be seen that the resonance at 150 Hz of the tool tip is less excited by the disturbance force.

Discussion

The examples above demonstrate the use of H_2-controller design in the DEB framework. First, it helps to evaluate the controller design. Especially the performance of a certain obtained controller with respect to the knee of the Pareto curve gives valuable information on the quality of the controller design. Second, the Pareto curve is an excellent tool to compare different designs in an objective and systematic manner. Each design has its own unique Pareto curve, which will tell exactly which set of requirements can and which cannot be achieved.

It is not advocated here to actually use the generated controller for implementation on real systems. Firstly, the optimal controller will have an order equal to the order of generalised plant, i.e. the order of the system model to which the orders of the various weighting filters are added. Hence, the order of the controller will be considerably higher than that of a tuned PID-type controller, which might not be desirable. Secondly, there may be other considerations at hand, such as a desired robustness for changes in dynamics and/or unmodeled dynamics and stability of the controller itself. These considerations are not taken into account with the H_2-controller design.

In addition to providing a systematic way to compare the different designs, the use of H_2-controller design with DEB could give the designer valuable clues on how to improve the controller design. Especially in case multiple sensors and/or multiple actuators are used and the manner of how to combine the various signals is not so straightforward.

References

[1] A. Slocum, “Precision Machine Design”, Prentice-Hall, Inc., New Jersey, USA, 1992.

[2] L. Jabben, “Mechatronic Design a Magnetically Suspended Rotating Platform”, Ph.D. thesis, Mechanical Engineering, Delft University of Technology, Delft, The Netherlands, 2007.

[3] L. Jabben, J. van Eijk, “Performance Analysis and Design of Mechatronic Systems”, *Mikroniek* 51(2): 5-12, 2011

[4] H. Kwakernaak and R. Sivan, “Linear Optimal Control Systems”, Wiley Interscience, New York, 1972.

[5] S. Skogestad and I. Postlethwaite, “Multivariable Feedback Control – Analysis and Design”, John Wiley & Sons, West Sussex, England, 1998.

[6] K. Zhou, J.C. Doyle, and K. Glover, “Robust and Optimal Control”, Prentice Hall, Upper Saddle River, New Jersey, 1996.

[7] C. Scherer, P. Gahinet, and M. Chilali, “Multiobjective Output-Feedback Control via LMI Optimization”, *IEEE Transactions on Automatic Control* 42(7):896-911, July 1997.

[8] A.H. Sayed and T. Kailath, “A Survey of Spectral Factorization Methods”, *Numerical Linear Algebra With Applications* 8:467-496, 2001.

[9] S. Boyd and C. Barrat, “Linear Controller Design – Limits of Performance”, Prentice Hall, 1991.

Using com

During the 2010 Precision Fair, I was pleasantly surprised to hear that I would receive the Prof. M.P. Koster Award, a biennial award for designers of precision/mechatronic systems in the Netherlands. As it is an award for lifetime achievements, I will try to describe my background so that the reader can better understand what, in my opinion, engineering is all about. Finally, I will outline some of the typical projects handled by the Janssen Precision Engineering team.

• *Huub Janssen* •

Figure 1. Winner of the 2010 Prof. M.P. Koster Award Huub Janssen flanked by the two doyens of Dutch precision engineering: Rien Koster, after whom the award was named (left), and Janssen's graduate professor, Wim van der Hoek. (Photo: Marisya Janssen)

mon sense

Childhood

I am the eldest son of a fruit-growing farmer and my father instilled in me the utmost confidence. I had an incredibly free childhood where creativity was concerned, and some examples of my early projects testify to this. At primary school up until the age of 12, I was very busy building 4-wheel push carts. Imagine taking wheels from a child's buggy, fixing them to timber boards, creating swivel points for steering and, last but not least, designing and creating the necessary brakes. I was lucky to have four younger brothers and sometimes one of them would act as an outboard engine. I also remember introducing a new steering concept, not with a single rope, but with two separate ropes connecting each front wheel to its own steering handle. Knowing what I know now, I would have preferred two push-pull rods (punches), but we'll come to that later.

Designing a boat was another adventure; this also included building it, but to me this was obvious and part of the game, so I won't mention it anymore. This was a very interesting project because I'd probably never even seen a real boat before. The boat turned out to be a bit strange in size. As far as I remember, it was 1.5 m long, 0.5 m wide and 1 m tall! So, I'd clearly never heard of Archimedes at that time, but I found out when putting the boat into the water that 90% stayed above water and the boat was far from stable...
I immediately understood that loading it with a few hundred kilograms was not an option and I had to make new plans. Of course, the 'boat' had see-through windows on the bottom to be able to view all the creatures in the water and this gave me the idea of turning it upside down and attaching four wheels to fashion my first weather-proof car.

Author's note

Huub Janssen is the founder and director of Janssen Precision Engineering (JPE) at Maastricht-Airport, the Netherlands. In December 2010, he received the Prof. M.P. Koster Award for his work as developer of precision/mechatronic systems.

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Apart from these building attempts, I have to say that I was also very fond of dismantling every mechanical or electro-mechanical toy I was ever given. While most of you were probably taking care of your electric train, your electric race car, your tower crane, etc., I was much more interested in the mechanisms inside, and within two weeks I would have taken apart the electric motor and used it for drilling holes or would have attached a homemade fan.

Secondary school

So building push carts, constructing complete houses out of fruit crates, dismantling batteries, melting down lead from plumber pipes to produce rings (I would never allow my children to do that now), I went to secondary school. During this period, I became more and more interested in electronics. This was at a time when transistors and integrated circuits became available and affordable. As you can imagine, my interest in what was behind the transistor radio case was piqued. What was frustrating, however, was the fact that, in contrast to the electro-mechanical parts of the electric train, you couldn't re-use the parts in the transistor radio. This meant that I had to understand the functionality of the components before they could be of any use to me.

In this way, I learned to regard components (transistors, resistors, capacitors, etc.) as black boxes with their own functionality. Using these black boxes, I managed to build various systems, resulting in my 'Automatic Bird Tracing and In-Flight Photographing System' (ABTFPS). In practice, this meant that when a bird in flight crossed a light beam, an enormous capacitor was unloaded. A solenoid then created a magnetic field and accelerated the iron core in such a way that it was able to push the shutter release of a camera fast enough to capture a picture of the bird in view. This enabled spectacular pictures to be taken without having to sit and wait for hours.

University

After secondary school, I went to Eindhoven University of Technology to study Electrical Engineering, switching to Mechanical Engineering after a year because it was more practical. After four to five years of basic study, I serendipitously met Professor Wim van der Hoek, who was coaching a small group of students in the field of dynamic response and precision engineering. To understand how

Figure 2. Janssen Precision Engineering at Maastricht-Airport.

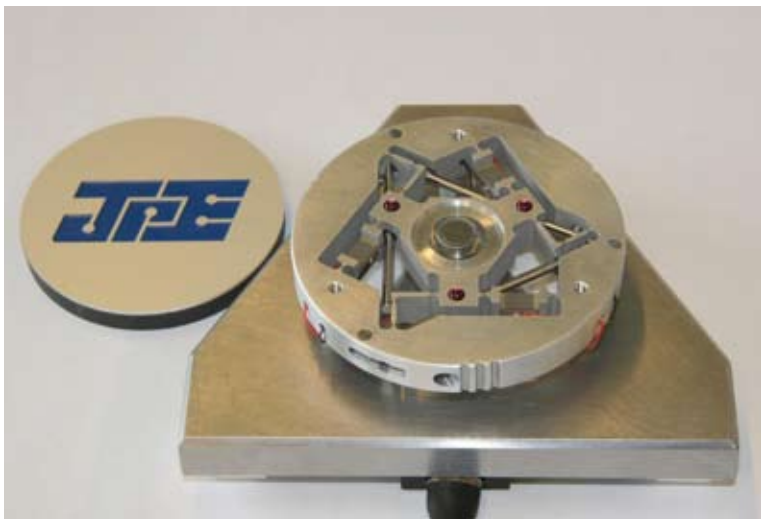


Figure 3. SetPack, 3-DoF piezo stage with nanometer stability.

this was done, you should imagine a large table with a large piece of yellow paper on it, at which the professor sat surrounded by five to ten students. All the students working on particular projects could bring up technical problems they were having, which would be discussed in the group.
Every technical aspect was written down on a part of this yellow paper and at the end of the session the professor tore your part off, so you could take this home. I was immediately convinced that this was it!

My master thesis was about the design and construction of an optomechanical instrument to image Moiré patterns on dental imprints. This involved light-weight thin sheet constructions, elastic hinges, laser interferometers and 6-DoF (degrees of freedom) sub-micrometer manipulation stages. During this project, I learned what it was like to be in the middle of a project bearing responsibility for constructing the instrument as well as handling discussions with the client. My entrepreneurial spirit was born.

Career development

Nevertheless, I was persuaded to join ASML, which was just starting out with their challenging activities in the design and construction of wafer steppers. At this high-tech company, I learned about the combination of complex mechatronic designs and project management – two disciplines which are completely connected, at least in the real world. From a technical point of view, it was interesting to see that although you would have learned to implement elastic, hysteresis-free constructions taking care of all six DoFs, it is sometimes better to opt for over-constrained design. As an example, I always mention opting for a table with four legs instead of three. This implies that in your designs you always have to make decisions; sometimes three legs are preferable and sometimes it's four legs. Luckily, the arguments can be understood and explained. Coming back to the table with four legs, you have to see that it works by virtue of the low torsion stiffness of the top plane of the table.

After three years at ASML, I joined Philips LCD Development and Production, where I was responsible for the development and construction of process equipment. In this environment, I learned that project lead time and costs were key and that project management is of utmost importance. This starts by defining the requirements in consultation with the client, followed by a phased approach to minimise development risks.

Own company

It was 1991 when Philips decided on a major reorganisation, which resulted in several factories closing and my decision to start my own company, Janssen Precision Engineering or JPE in short; see Figure 2. I had already stumbled upon the name Precision Engineering in 1986, when I attended a congress being held in Switzerland by the American Society for Precision Engineering. Now, almost twenty years later, we are a team of about twelve engineers and we are deeply involved in developing and constructing complex high-tech machines and instruments for the semiconductor industry, astronomy & space, and scientific research. Our company successfully combines various disciplines such as mechanics, electronics and physics.

Our challenging projects start with a brainstorming session where we discuss possible solutions for the project – something similar to my experience with Professor Wim van der Hoek, although we have run out of yellow paper. In my opinion, it's very important to discuss things freely and not follow certain elimination schedules, but to try and think creatively outside of the box. Creativity is key in these sessions. This is the essential 10% inspiration needed

Figure 4. Monolithic tip/tilt mirror.

to give direction to the development, followed by the 90% perspiration!

Common sense

As our projects always include accurate and stable positioning demands, often down to the nanometer, fundamental precision engineering design rules combined with practical experience are required for implementation and construction.
The first step in a project is to understand what the client wants. We believe it's very important to explore this together with the client, and so define the requirements. The JPE team tries to resolve the client's problems in such a way as though we were the client. This requires an efficient approach, where risks are to be eliminated as early as possible. We also stick to the rule: good is good enough. Specifications need to be achieved without the client incurring unnecessary costs and without wasting valuable time. In short, we use our common sense!

Examples of JPE projects

Figure 3 shows the SetPack construction with three (kinematic) spheres carrying the round 'JPE' plate. Three piezo stacks are integrated to create relative motion between the spheres and the round plate. Note the use of standard punches as elastic pretension rods.

Figure 5. HiPack 'soft' actuator for telescope mirrors.

Figure 4 shows an example of a tip/tilt mirror for astronomy to be operated in a cryogenic environment. Note the strain relief of the integrated mirror on the top. Since flatness is of utmost importance, the mirror is only connected in the middle and therefore not affected by forces from the elastic hinges.

To be able to position mirror segments from large primary telescope mirrors, we developed an electro/pneumatic actuator called HiPack for loads of up to 1,000 N and positioning resolution in the nanometer range; see Figure 5.

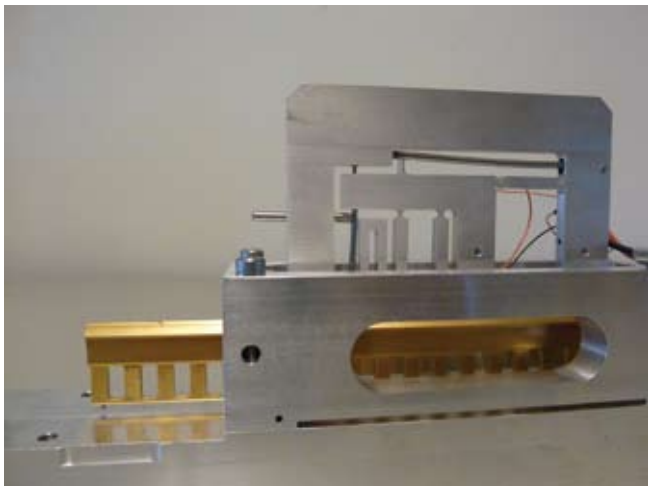


Figure 6. Configurable slit unit.

One of our most complex projects was developing a configurable slit unit (CSU), a kind of masking device with 110 individually addressable gold-coated bars to be positioned with micrometer accuracy under cryogenic conditions; see Figure 6. It meant developing dedicated actuators and sensors for a cryogenic environment. Note the use of punches for the pretension.

For cryogenic environments down to a few Kelvin above absolute zero, we developed a motor and dedicated electronics called PiezoKnob, achieving a millimeter stroke and a resolution of a few nanometers; see Figure 7. Note: you won't see the punches although they are somewhere in there….

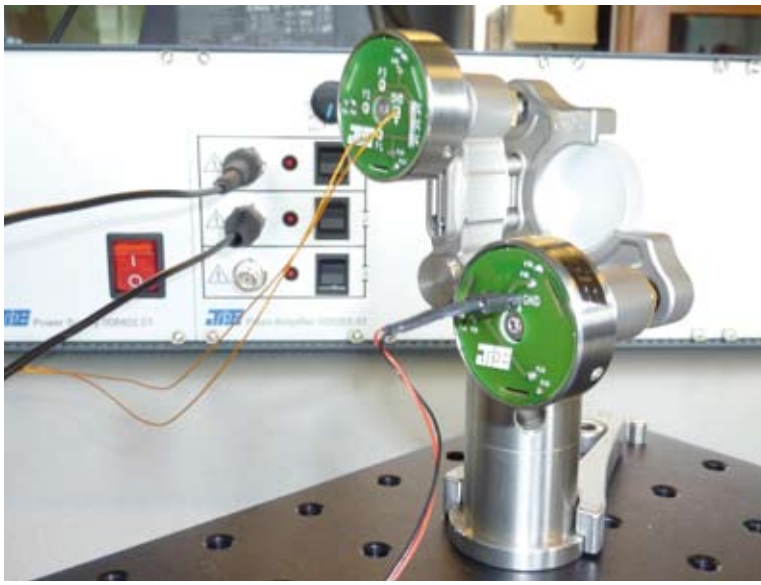
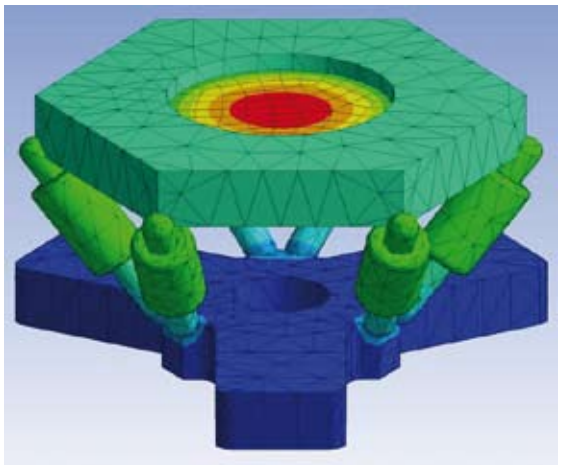


Figure 7. PiezoKnob, motor and dedicated electronics for cryogenic environments.

Keep your cool in precision machine design

Thermomechanical analysis plays an important role in the design process of precision machines, where specifications on position accuracy and stability in general are leading in the design process. Precision machines can also have tight specifications concerning maximum allowed temperature or material stress. Extreme conditions like a vacuum and/or cryogenic environment in combination with high heat loads make the design process even more challenging. Thermomechanical analysis shows the effects of design choices in an early stage, and therefore provides directions for determining the machine or component design.



• *Ronald Lamers* •

Precision machines have to achieve high position accuracy, be repeatable and remain stable over time. As described in [1], the required accuracy is disturbed by external and internal heat loads; see Figure 1. External heat loads e.g. are a process on a machine (cutting, printing, lithography, et cetera) or the environment in which the machine operates (vacuum and/or cryogenic, but also a workshop, cleanroom, et cetera). Internal heat loads can be dissipating components, such as the drive system, sensors or other electronic components, but also other sources such as friction.

Author's note

Ronald Lamers works as a senior mechanical designer for MI-Partners in Eindhoven, the Netherlands. He has a special interest in thermal effects in precision systems.

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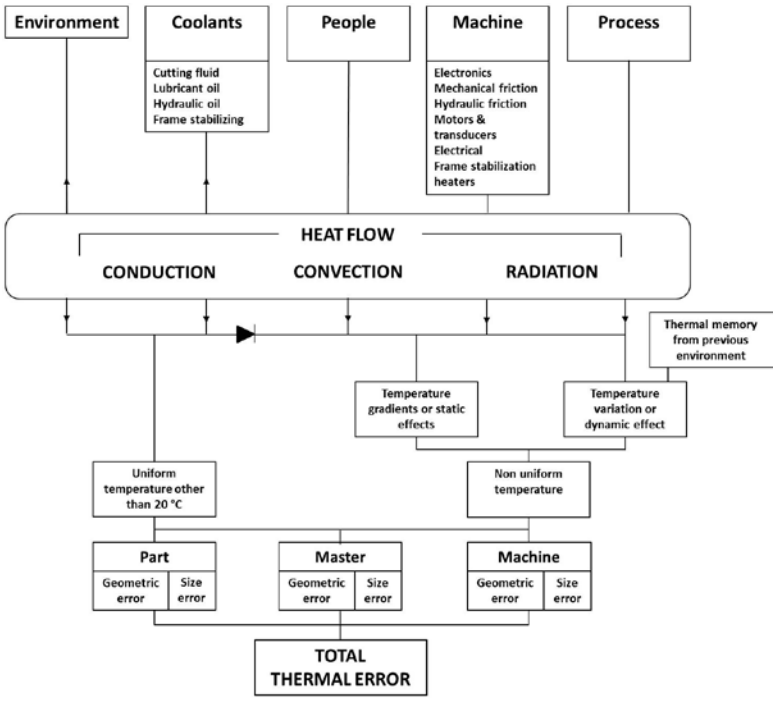


Figure 1. Thermal effects in manufacturing and metrology.

Thermal effects

According to [2], the overall thermal problem can be divided into two major categories: the effects of uniform temperatures other than 20 °C; and the effects of non-uniform temperatures. Every measuring and machining operation unavoidably comprises a three-element system made up of the part, the machine frame, and the master (or metrology system). Six sources of thermal influence can be discerned: heat generated from the (cutting) process, heat generated by the machine, heating or cooling effects provided by the various cooling systems, heating or cooling effects provided by the room, the effect of people, and thermal memory from any previous environment. All sources affect the three-element system through the three possible modes of heat transfer: conduction, convection and radiation.
The errors can be either in geometry or in size. Room environment and coolant systems are the only influences that can create uniform temperatures. The remaining heat sources will cause either steady-state temperature gradients or temperature variations, or both.

The change in temperature as a result of external and internal heat loads results in a (transient) temperature distribution over the machine and its critical components, which leads to thermal deformations and thus loss of position accuracy and stability. The (transient) temperature distribution can be influenced by e.g. the application of proper materials or conditioning techniques such as thermal shielding and gas or liquid cooling, as described in [3].

A thermomechanical analysis consists of a thermal calculation, in which the temperature distribution is computed. This is followed by a mechanical calculation to determine the thermally induced deformations. These calculations will provide an estimate of the effects on the performance of the machine in terms of e.g. temperature and on position accuracy and stability, which must be evaluated with respect to the machine requirements.

In general, there are three types of thermomechanical analysis:
- Hand calculations.
- Thermal system models, if possible combined with a kinematics model.
- FEM simulations.

Hand calculations

Hand calculations can be simple calculations to determine the temperature distribution or temperature change over time of a machine component and the corresponding thermal deformations. Hand calculations are used for doing fast estimations to determine whether a concept or idea will work.

Thermal analysis

There are three modes of heat transfer, which determine the temperature distribution of the machine: conduction, convection and radiation, as described in [4]. Conduction is the transfer of thermal energy between regions of matter due to a temperature gradient. Heat spontaneously flows from a region of higher temperature to a region of lower temperature: $Q = (\lambda/l)A\Delta T$. Where Q is the transferred heat [W], λ and l are the material's thermal conductivity [W/mK] and thickness [m], A is the conductive area [m^2] and ΔT is the temperature difference [K].

Convection is the transfer of heat from one place to another by the movement of fluids or gases. The heat transfer coefficient h_{conv} is used in calculating the heat transfer by convection or phase change between a fluid (or gas) and a solid: $Q = h_{conv} A\Delta T$. Where A is the convective area [m^2] and h_{conv} is the convective heat transfer coefficient [W/m^{2}K].

Radiation is energy carried by electromagnetic waves; all surfaces emit electromagnetic waves in proportion to the fourth power of their absolute temperature. If heat is

transferred by radiation between two gray surfaces of finite size, the rate of heat flow will depend on temperatures T_1 and T_2 and emissivities ε_1 and ε_2, as well as geometry. Part of the radiation leaving surface 1 will not be intercepted by surface 2, which is in general written as:
$Q_{1\to2} = A_1F_{1\to2}\,\sigma(T_1^4 - T_2^4)$.
Where $Q_{1\to2}$ [W] is the heat transfer from surface 1 to surface 2, and $F_{1\to2}$ [-] is a transfer factor, which depends on emissivities and geometry. For the special case of surface 1 surrounded by surface 2, where either area A_1 is small compared to area A_2, or surface 2 is nearly black, the heat transfer becomes: $Q_{1\to2} = \varepsilon_1A_1\sigma(T_1^4 - T_2^4)$. Where ε_1 is the material's emissivity, A_1 is the radiative area [m^2] and σ is the Stefan-Boltzmann constant ($5.67\cdot10^{-8}$ [W/m^{2}K^4]). The T^4 dependence of radiant heat transfer complicates engineering calculations. When T_1 and T_2 are not too different, it is convenient to linearise the equation, so radiation can be modeled as a radiation heat transfer coefficient h_{rad}: $Q = h_{rad}A\Delta T$. In this equation, $h_{rad} = 4\varepsilon_1\sigma T_m^3$, where T_m (= $(T_1 + T_2)/2$) is the average temperature.

Thermal energy is not only conducted through matter, but also stored in matter. The ability of matter to store thermal energy makes the thermal design in many cases a transient problem, because temperatures change over time. Such problems are often encountered in precision engineering practice and it may be required to predict the temperature-time response of a system. The amount of thermal energy that can be stored inside a material is determined by its mass m [kg] and its specific heat c_p [J/kgK]: $Q = mc_p\,dT/dt$, where dT/dt is the temperature change over time [K/s].

Mechanical analysis

Thermal expansion is the tendency of matter to increase in volume when heated. For solids the amount of expansion normally will vary depending on the material's coefficient of thermal expansion α [µm/mK].

Three deformation principles can be distinguished, as shown in Figure 2:

- Longitudinal translation (Δl): in case of a uniform temperature change and/or gradient in x-direction (G_x), the beam will expand in axial (x) direction. The translation $\Delta l_x(x)$ then is the integrated sum of expansions of infinite small lengths dx:

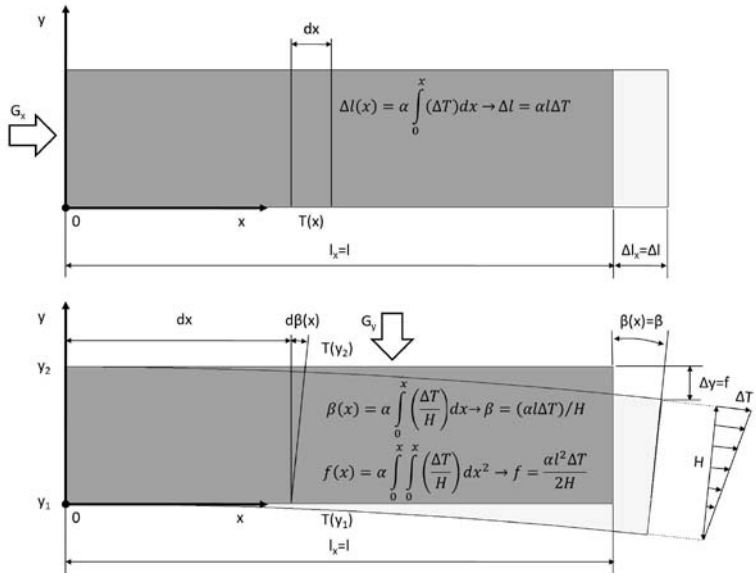


Figure 2. Three thermal deformation principles.

$$\Delta l(x) = \alpha \int_0^x (\Delta T)dx \to \Delta l = \alpha l \Delta T.$$

- Rotation (β): a temperature gradient in y-direction (G_y) introduces a local rotation $d\beta(x)$ around the z-axis caused by different expansions dl_x at different heights y_1 and y_2. The rotation $\beta(x)$ is obtained by integrating all local rotations $d\beta(x)$ over x:

$$\beta(x) = \alpha \int_0^x \left(\frac{\Delta T}{H}\right) dx \to \beta = (\alpha l \Delta T)/H.$$

- Transversal translation caused by rotation (f): a temperature gradient in y-direction (G_y) also causes a translation Δy in the (negative) y-direction. This transversal translation can be calculated by integration of rotation β over length l_x:

$$f(x) = \alpha \int_0^x \int_0^x \left(\frac{\Delta T}{H}\right) dx^2 \to f = (\alpha l^2 \Delta T)/2H.$$

It must be noted that material properties for most materials change as a function of temperature, which must be taken into account with e.g. cryogenic applications.

Example: sensor beam

In Figure 3, an optical sensor is shown mounted on a beam. The beam is subjected to a heat flux q'' ([W/m^2]) causing the beam to bend. For a proper functioning of the optical sensor, specifications are given for the values of β and f. With hand calculations, the temperature distribution over the beam and the corresponding deformation can be calculated. It can be determined whether the specification will be met with a passive solution (e.g. material choice (λ, α), insulation, shielding) or whether an active solution is required (e.g. water cooling).

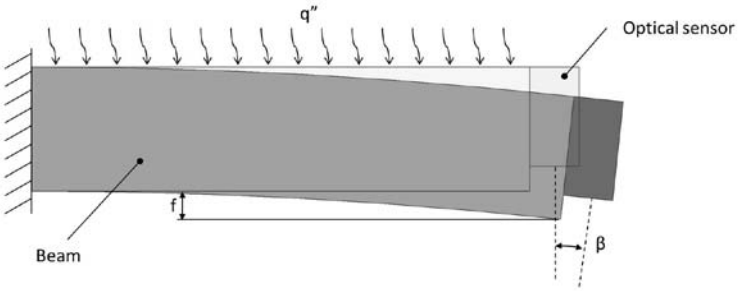


Figure 3. Beam holding optical sensor.

Hand calculations are a powerful tool for determining the feasibility of a concept or analysing certain problems, e.g. concerning measurement results. Also during verification of more advanced models, hand calculations are often used.

Thermal system model

In a thermal system model, the system is divided into subsystems, which are described as heat capacitances (also called lumped masses). Thermal resistances connect the heat capacitances with each other, and with the environment. A thermal system model enables fast system analyses. The development of a thermal system model, which must be done in the early stage of the design process where important conceptual choices have to be made, is essential from a system architectural perspective. A thermal system model gives insight in (average) temperature fluctuations, heat flows (between machine parts) and time constants. Temperatures and heat flows can be calculated steady-state and transient.

The main advantage of thermal system models is short calculation times (seconds, minutes), so that many cases can be evaluated in a short amount of time. This makes it possible to check many ideas in the act of determining the concept choice. A thermal system model can be made in software packages such as Matlab/Simulink or 20-sim, but also in Excel. With software packages such as Matlab/Simulink it is also possible to investigate the thermal system in the frequency domain, providing more insight in the transient behaviour and the dominant effects. Certain FEM packages also provide the possibility to simulate thermal system models.

Example: hexapod manipulator

An example of a commonly used precision system is shown in Figure 4. Here, a hexapod manipulator has to accurately position an optical component (e.g. a lens or a mirror) in six degrees of freedom and to keep the component stable in this position. The stability is disturbed by thermal effects such as changing environmental temperatures, heat dissipated in the linear actuators and heat-up of the optical component during operation.

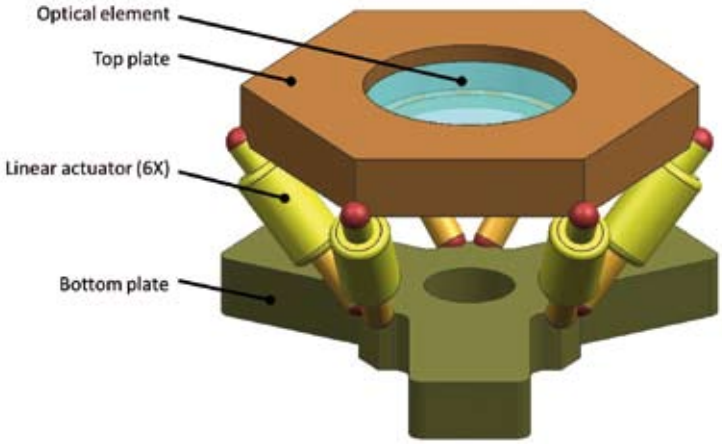


Figure 4. Hexapod manipulator.

A thermal system model can be made for determining the (transient) temperature distribution over the hexapod structure. Based upon these calculated temperatures, choices can be made regarding e.g. the material selection and the application of thermal conditioning techniques such as shielding or cooling. An example of such a model is shown in Figure 5. The main heat capacitances in this model are the base plate, the linear actuators, the top plate and the optical component. These heat capacitances are connected with each other by conductive resistances R_{cond} ($R_{cond} = l/(\lambda A)$; $\Delta T = R_{th}Q$; R_{th} is the thermal resistance [K/W]), which can also include the interface resistance (contact resistances). The heat capacitances are connected to the environment with convective resistances R_{conv} ($R_{conv} = 1/(h_{conv}A)$), which can also include (linearised) radiation R_{rad} ($R_{rad} = 1/(h_{rad}A)$).

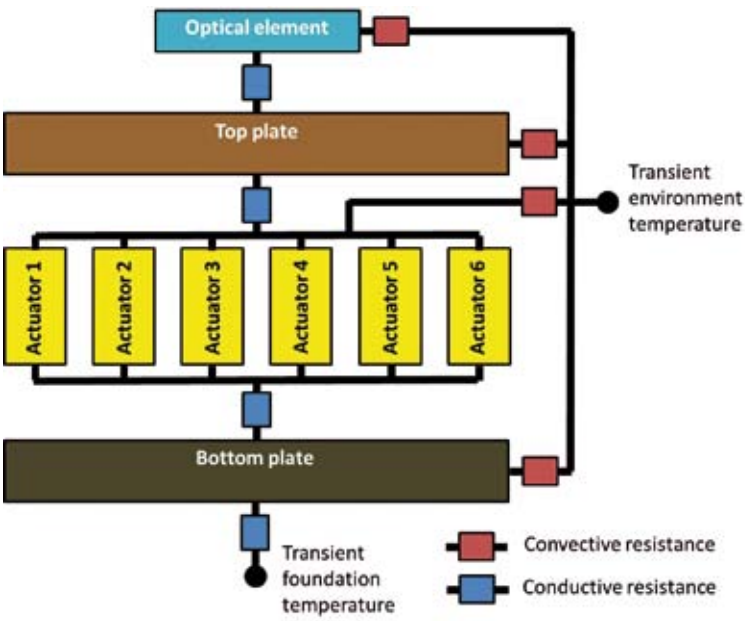
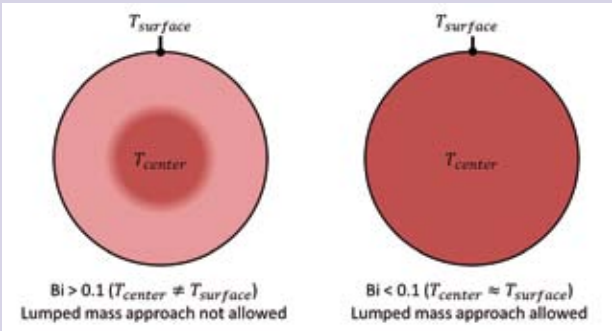


Figure 5. Thermal system model of the hexapod manipulator.

Biot number

To determine the number of heat capacitances in a thermal system model, the Biot number (*Bi*), a dimensionless system parameter, is used. *Bi* is defined as the ratio of the conductive heat resistance within the object to the convective heat transfer resistance across the object's boundary with a uniform environment of different temperature. The Biot number is defined as: $Bi = (hL_c)/\lambda$; where h is the heat transfer coefficient [W/m²K], L_c is the characteristic length [m], and λ is the thermal conductivity [W/mK]. The characteristic length L_c is commonly defined as the volume of the body divided by the surface area of the body, such that $L_c = V_{body}/A_{surface}$.

If the Biot number is less than 0.1 for a solid object, then the entire material will be at nearly the same temperature. The dominant temperature difference will be found at the surface. The Biot number must generally be less than 0.1 to allow an accurate approximation and a successful heat transfer analysis. This approach can be expanded to involve many resistive and capacitive elements, with $Bi < 0.1$ for each capacitance in the model. As the Biot number is calculated based upon a characteristic length of the system, the system can often be broken down into a sufficient number of capacitances, so that the Biot numbers of the different components can be kept acceptably small.



The effect of the Biot number on the temperature of a system.

Kinematics model

The main drawback of thermal system models is that no information is given on the system performance in terms of position accuracy. This drawback can be overcome to a certain extent when a (3D) kinematics model is coupled to the thermal system model.

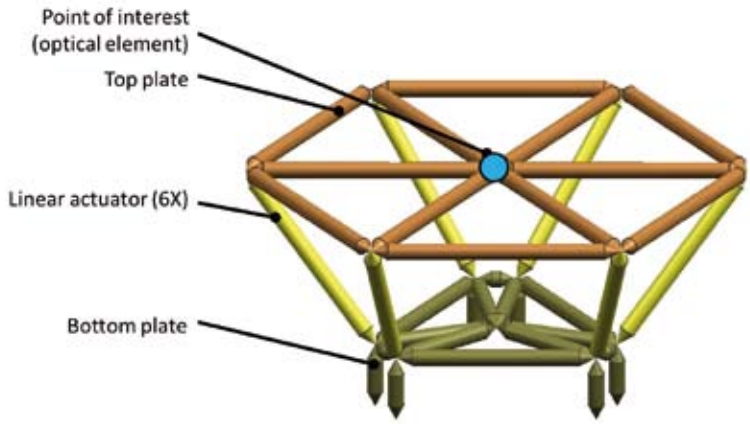


Figure 6. Truss model of the hexapod manipulator.

3D CAD packages often are used in an early stage of the concept design of precision machines to visualise the different mechanical concepts. With the aid of these 3D CAD packages, a (3D) kinematics model can be easily determined, linking system temperatures to displacements of the point of interest due to component deformations. This can be done by replacing the mechanical CAD model with a (statically determined) truss structure, as shown in Figure 6. Each bar in the truss structure has a certain thermomechanical sensitivity [µm/K], determined by the length of the bar l [m] and the coefficient of thermal expansion α [µm/mK]. The temperature change of a complete set of bars (the set corresponds to a "lumped mass" in the system model) leads to a displacement of the point of interest.

The transformation matrix, linking the displacement of a certain point of interest to changing component temperatures, can be determined with the CAD package by changing the lengths of the bars in the structure according to their thermomechanical sensitivity. The result will be a transformation matrix $\boldsymbol{S}$, which links component temperatures $\overline{\boldsymbol{T}}$ to displacements of the point of interest $\overline{\boldsymbol{p}}$: $\overline{\boldsymbol{p}} = \boldsymbol{S}\overline{\boldsymbol{T}}$

The thermomechanical transformation matrix for the hexapod structure for the point of interest is given below:

$$\begin{bmatrix} x \\ y \\ z \\ rx \\ ry \\ rz \end{bmatrix}_{6x1} = \begin{bmatrix} S_{x.top} & \cdots & S_{x.bottom} \\ \vdots & \ddots & \vdots \\ S_{rz.top} & \cdots & S_{rz.bottom} \end{bmatrix}_{6x8} \begin{bmatrix} T_{top\ plate} \\ T_{spindle\ 1} \\ T_{spindle\ 2} \\ T_{spindle\ 3} \\ T_{spindle\ 4} \\ T_{spindle\ 5} \\ T_{spindle\ 6} \\ T_{bottom\ plate} \end{bmatrix}_{8x1}$$

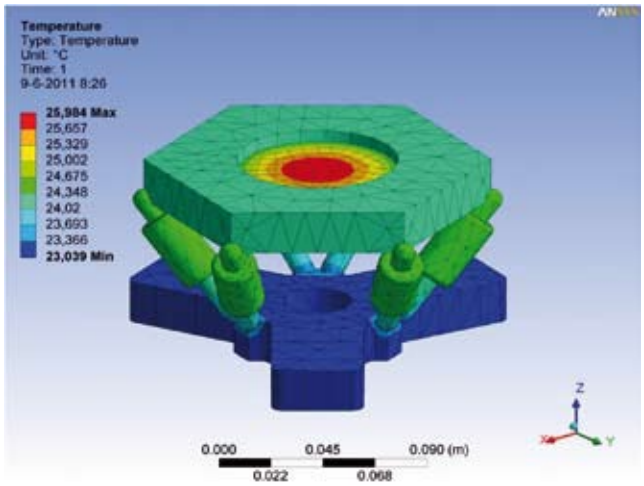


Figure 7. Full FEM model of the hexapod manipulator.

This transformation matrix can be easily added to the thermal system model, so it is possible to gain information on system performance in terms of position accuracy and stability.

FEM Model

In [5], the application of FEM models has been summarised. In finite element models, the assumption is that real matter consists of an infinite number of infinitely small heat capacitances interconnected by heat resistors, and that reality can be closely approximated using a fine-grained grid of partial differential equations. This can be done in one, two or three dimensions, depending on the modeling needs. FEM models are well suited to determine the temperature distribution of an object or system of objects, as well as the corresponding thermal deformations, and to predict the actual thermal characteristics of these objects. FEM models are commonly used to optimise the shape of individual components.

In a FEM model, the geometry and boundary conditions are known to calculate detailed temperature distributions and deformations. Typical of FEM models are long calculation times, in the order of minutes to hours. Especially thermal and thermomechanical transient calculations are very time-consuming. This makes FEM models less efficient for evaluating a large number of cases or analysing large systems. The detailed results can be compared with the specifications. Figure 7 shows a full FEM model of the hexapod manipulator.

Advanced system models

A thermal system model is often used in the early design stage of precision machines because such a model is flexible and has short calculation times, so many different scenarios can be evaluated. FEM modeling in most cases is only efficient if the design has progressed to a more mature state, in which the important concept choices already have

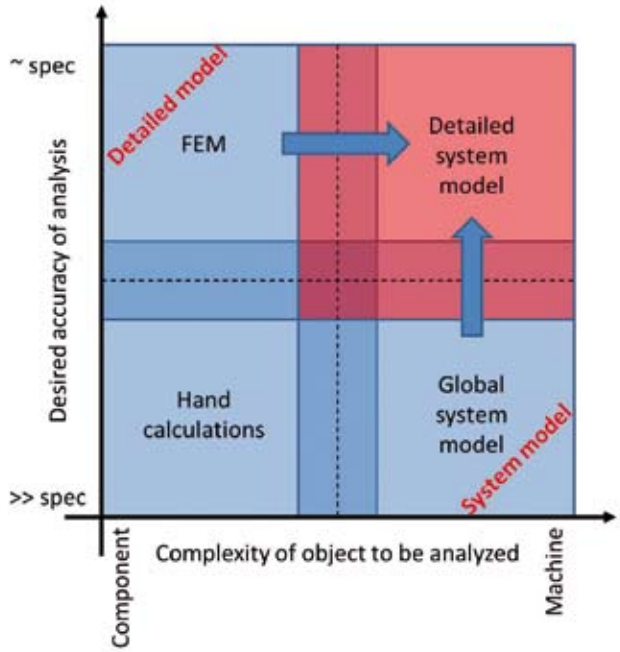
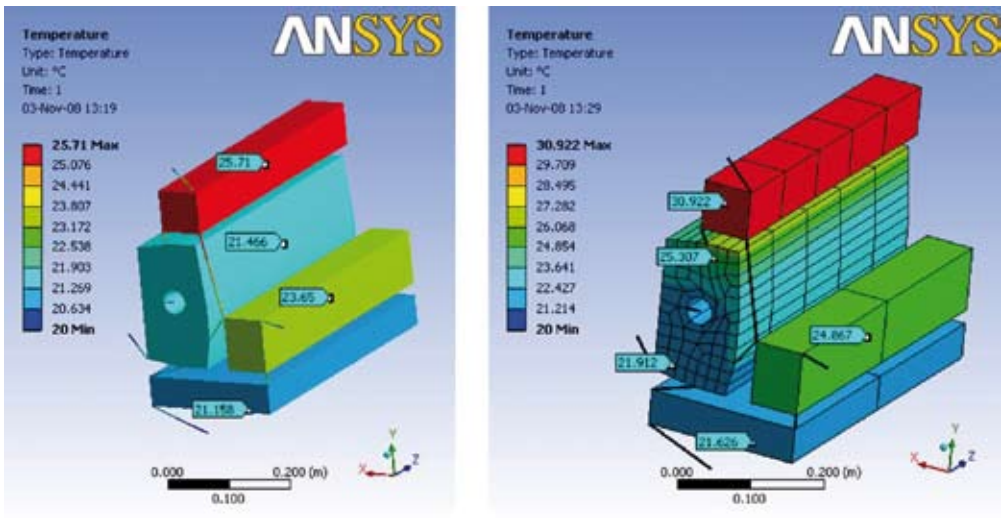


Figure 8. The different types of analysis and their applications.

been made. Figure 8 shows the different types of analysis and their applications, as described in [6]. Hand calculations are typically used on a component level with relatively low accuracy. System models are typically used on a machine level with relatively low accuracy. FEM models are used on a component level with high accuracy. No direct method is available to build a system model with high accuracy. During the design process, the thermal system model evolves as the design evolves. If at a certain stage (detailed) FEM modeling would become interesting for e.g. critical components, it would be beneficial to incorporate these detailed models into the system model.

This has been investigated in [6], where the basic idea is to use the FEM package ANSYS Workbench as a “lumped mass” modeler to build thermal system models. The main advantage is the strong interaction between ANSYS Workbench and CAD packages, such as Unigraphics NX. Since most mechanical designs are set-up in CAD in an early phase of the design process, this method allows for the system model to evolve as the design evolves, incorporating more detail as required during the design process. Because a FEM package is used to build the thermal system model, the components in the system model can also be replaced by a full FEM model. The post-processing capabilities of ANSYS Workbench allow for easy evaluation of the design problem. An example of the approach proposed in [6] is shown in Figure 9.

Another approach was investigated in [7], based on the way of working frequently used in the analysis of mechanical dynamic systems. The basic idea is to build a



a b

Figure 9. Example of the advanced system modeling approach proposed in [6].
(a) A CAD geometry loaded into ANSYS Workbench. With a special meshing technique, this system is approached as a "lumped mass" system.
(b) The cooling block in the center is replaced by a full FEM model in the system model.

FEM model of a critical component and incorporate this FEM model in the system model. The degrees of freedom of the FEM model can be reduced by applying model reduction techniques, which allows for fast analysis of the system with sufficient detail for the critical component. An example of the approach proposed in [7] is shown in Figure 10. By choosing the right simulation software for the system model (e.g. Matlab/Simulink) it is also possible, e.g., to investigate the thermal frequency response or to incorporate thermal controllers.

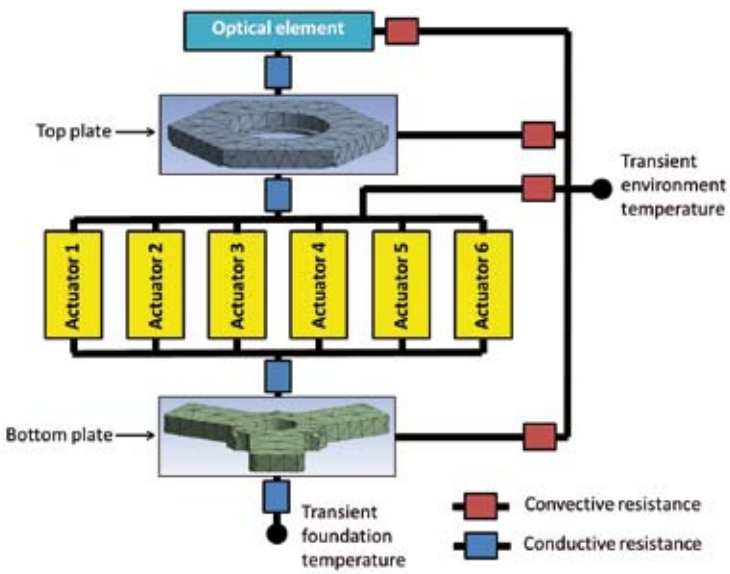


Figure 10: Example of the advanced system modeling approach proposed in [7]. In the "lumped mass" model, the top and bottom plate are replaced by (reduced) FEM models.

The development of a thermal or thermomechanical system model with sufficient detail for the critical components, however, is still not straightforward.

Conclusion

Thermomechanical analysis is a powerful tool in the design of precision machines. The type of analysis depends on the moment in the design process, the complexity of the system and the desired accuracy of the results. Thermomechanical system analysis in the conceptual phase is important to achieve optimal performance.

References

[1] J. Bryan, "International status of thermal error research", *CIRP Annals* 39/2, 1990.
[2] J. Bryan, "International status of thermal error research", *CIRP Annals* 16, 1968.
[3] R. Lamers, "When precision cannot stand the heat", *Mikroniek* 50(5), 2010.
[4] A.F. Mills, "Heat Transfer", University of California, Los Angeles, ISBN 0-256-07642-1, 1992.
[5] M. Heemels, "Boderc: model-based design of high-tech systems", ESI, 2007.
[6] M. Limpens, "Thermal system modeling using ANSYS Workbench", ANSYS Benelux user meeting, 2008.
[7] S. Box, "Towards thermomechanical system modeling", Topical meeting: thermal effects in precision systems, Maastricht, 2007.

Motion control for

Precise motion control is a key element in mechanical and laser micromachining. With some applications requiring submicron positioning accuracies in a 4- to 6-cubic-inch work envelope, motion control can be the difference between an operation's success and failure. Motion control supplier Aerotech presents solutions from its product portfolio.

• *Jim Johnston and Scott Schmidt* •

An advanced micromachining system must have either nanometer positioning capability or incorporate miniature machine tools with equivalent precision. Positioning subsystems must provide nanometer resolution and accuracy along with travels long enough and speeds high enough to permit machining campaigns that are of sufficiently short duration to make the application cost-effective. The magnitude of these speeds and travels are, obviously, dependent upon the application.

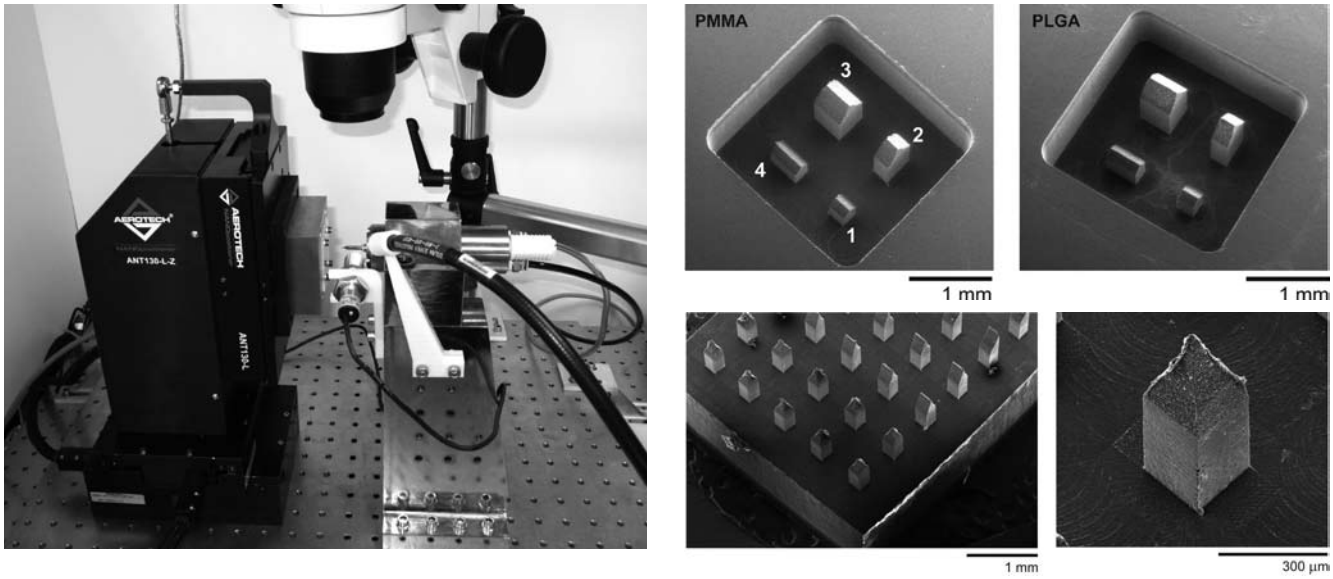


Figure 1. High-precision miniature micromachining using Aerotech stages. (Credit: Dr. Sinan Filiz and Dr. Erdrin Azemi, Mechanical Engineering Department, Bilkent University, Ankara, Turkey)
(a) Overview of the set-up.
(b) An example of microneedle fabrication on biocompatible (PMMA) and biodegradable (PLGA) polymers.
(c) An array of microneedles with different tip geometries fabricated from PLGA polymer.

advances micromachining

Figure 2. Aerotech's PRO165LM is an example of a linear stage that uses linear motion guide bearings.

Key motion requirements for mechanical and laser micromachining systems include high dynamic contour accuracy, repeatability, speed, and a flexible, advanced motion controller. These requirements cannot be achieved with a single technology. Rather, success depends on carefully integrating mechanical, electrical, control, and software elements. Common motion system components include bearings, motor and drive systems, feedback devices, amplifiers, and advanced control. Figure 1 presents an application example.

Bearing technologies

Stage selection starts with determining the desired bearing technology for a particular application. Options include linear motion guide bearings (see Figure 2), recirculating ball bearings, anti-creep crossed-roller bearings, and air bearings. Length of travel, dynamics, load, and friction considerations all influence the bearing selection.

Recirculating ball bearings offer the greatest flexibility among the options mentioned. Designs can range in travel from 25 mm to more than 3 m, with payloads varying from 2 kg to more than 1,000 kg. Applications are usually point-to-point motion or contouring, where contouring dynamics up to several microns are acceptable. Stages can be sealed with a hard cover and tensioned side-seals to help protect the internal components from machining-generated debris. However, the recirculating element of the bearing introduces disturbances to the system, as the individual balls enter and leave the recirculating path.

Crossed-roller bearings do not include a recirculating element, leading to smoother operation; see Figure 3. When coupled with an optimised control system these stages are capable of nanometer-level precision. Load capacities are generally from 0.5 kg to 50 kg, with practical travel ranges up to 300 mm. Longer travels are limited due to bearing cantilevering, which introduces pitch errors. Additionally, these stages are more difficult to seal against debris.

Figure 3. The ANT130-XY is an example of a dual-axis nanopositioning linear stage that uses crossed-roller bearings.

Air-bearing stages provide near-frictionless motion, and bearing geometric performance (pitch, roll, and yaw error motion) is superior to other bearing types; see Figure 4. Practical travels are from 25 mm to more than 3 m with

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Figure 4. The ABL1500WB-B is an example of an air-bearing linear stage with bellows.

payloads ranging from 1 kg to 250 kg. Bearing surfaces are large compared to other bearing types, allowing comparatively larger stages.

The frictionless nature of these bearings enables high accuracy and dynamic performance compared to stages that use mechanical elements. Also, their outstanding angular characteristics can yield submicron and sub-arcsecond off-axis errors such as straightness, flatness, pitch, roll, and yaw. The biggest disadvantage of using air bearings is that machining debris can damage the bearing surface. Bellows and other protective covers may be employed, but they add friction to the system, partially negating the advantage of air bearings.

Recirculating ball bearings are most commonly used in micromachining systems due to their flexibility and the ease with which they can be sealed. When higher-precision systems are required, crossed-roller bearings or air bearings are often employed, assuming debris generation and removal can be controlled.

Direct drive vs. screw-based motion

Motion in linear and rotary axes is commonly achieved either with screw-based stages (coupling a rotary motor to a ball screw or worm gear) or with direct-drive solutions. When considering the requirements of most micromachining applications, direct-drive stages offer numerous advantages over screw-based systems.

For example, in high-duty-cycle applications, the screw can wear over time, reducing accuracy and repeatability. Also, backlash in the screw's drivetrain limits its ability to achieve sharp direction reversals or to precisely track complex contours, which reduces system performance and throughput. Direct-drive systems do not exhibit backlash and windup and they can achieve much higher accelerations and system bandwidth than screw-based systems, thereby increasing part quality. Additionally, the non-contact design of direct-drive systems eliminates wear and requires no maintenance; see Figure 5. These advantages make direct-drive motors the obvious choice for micromachining.

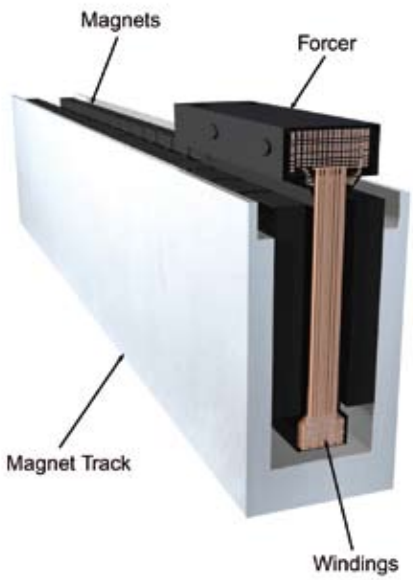


Figure 5. Schematic of an Aerotech linear motor. The non-contact design of such a direct-drive system eliminates wear and requires no maintenance.

Feedback devices

Micromachining requires feedback devices capable of submicron resolution, which allows the controller to close the servo loop. Common high-resolution feedback devices include linear encoders, laser interferometers, capacitance probes, LVDTs (linear variable differential transformers), and strain gauges. While each device has advantages and disadvantages, laser interferometers are prohibitively expensive for most micromachining applications, whereas capacitive probes, LVDTs, and strain gauges are limited to extremely short travels, making them impractical for most applications. Therefore, in most laser or mechanical micromachining applications, a linear encoder is the clear choice due to its accuracy, speed, range of travel, and ease of integration.

Linear encoders employ a scale with a grating period (distance between graduations on an encoder) and a read head. The optical read head measures the gratings and generates an analog signal whose period is the same as the grating on the scale. Typical encoder periods range from 200 nm to 20 µm, but advanced controller features can interpolate these fundamental period signals to subnanometer resolution, which is required for the control system to maintain the necessary accuracy when micromachining.

The effects of thermal expansion on the encoder scale also must be considered. Linear motors generate heat during operation, which dissipates into the stage and internal components. Stages are typically made from aluminum, which has a thermal expansion coefficient of 24 µm/m/ºC.

Figure 6. The Ndrive CP is an example of a PWM amplifier.

For example, a 100 mm aluminum stage will expand 2.4 µm when temperature increases 1 ºC. While alternative materials with lower thermal expansion coefficients can be considered, manufacturing the entire stage from such materials is often prohibitively expensive and can compromise system stiffness. One technique to maintain performance while minimising cost is to mount only the encoder scale on a low-coefficient-of-expansion material, isolating it from the thermal expansion experienced by the rest of the stage.

Amplifiers and drives

When operating at micron and submicron levels any disturbance can lead to positional errors that affect part quality. In addition to external disturbances, such as ground vibration or acoustical noise, internal disturbances from electrical noise or power electronics that emit electromagnetic noise can cause instabilities and jitter in the motion system. High-precision systems require advanced amplifier designs to achieve desired results. Amplifiers commonly used for micromachining include the pulse-width-modulated (PWM) amplifier (see Figure 6) and the linear amplifier.

PWM amplifiers modulate the “on-off” time of the power transistors to control the motor output. PWM amplifiers are efficient because resistance across the transistors is low when in the “on” mode, minimising power loss across the transistors. This allows high-power amplifiers to be housed in relatively small packages.
Despite their efficiency, PWM amplifiers produce ripple current and electrical noise, making them less suitable for high-precision applications. For example, when controlling systems with resolutions to 50 nm, the effect of this ripple current is negligible, but on systems with resolutions below 50 nm and, more specifically, lower than 5 nm, the ripple can cause system disturbances. This produces poor in-position stability. In other words, the unintended noise current issued to the motors will cause the stage to jitter. This positional jitter can be of the same order of magnitude as the features being machined, and therefore is very detrimental to system performance.
Also, PWM amplifiers exhibit non-zero “dead time” at direction reversals in contours produced by the motion program. When the commanded motion trajectory changes direction, the amplifier requires a small amount of time during which no current is output, reducing the stage’s tracking capability.

Linear amplifiers operate the power transistors in the linear region, where the device acts as a current amplifier. Linear amplifier voltage and current waveforms have no ripple current, leading to better in-position stability. Linear amplifiers also maintain much better control during motion direction reversals, allowing greater tracking ability.
Linear amplifiers are not without drawbacks. They are large and generate a significant amount of heat. They are also more expensive than PWM drives. As a result, PWM amplifiers are appropriate for some micromachining applications, whereas linear amplifiers are recommended when micron and submicron accuracy are desired.

Advanced control

Micromachining requires an advanced motion controller with algorithms and hardware that minimise disturbance errors, increase tracking capabilities, and provide superior in-position stability. Motion errors tend to be the greatest during acceleration or deceleration of an axis. In addition to changing velocities, axes accelerate and decelerate when following curvilinear paths – a frequent occurrence because of the complex contours found in micromachining.

Common motion control features that reduce these errors include acceleration limiting and multiple-block look-ahead. Acceleration limiting compares linear and centripetal acceleration commands against predefined thresholds, and if the command exceeds the threshold, the controller decreases tangential velocity to maintain part quality. To optimise this feature the controller must analyse future motion commands.

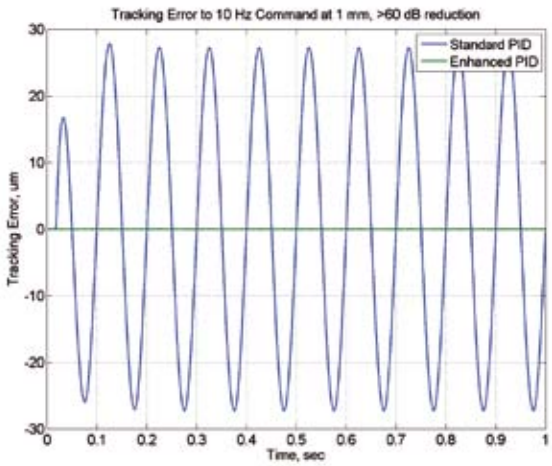


Figure 7. Screenshot showing the benefits of the harmonic cancellation feature.

Figure 8. Screenshot showing the benefits of the iterative learning control feature.

Multi-block look-ahead enables the controller to compare future commands against those currently being executed, compensating when necessary to reduce motion errors. For example, if the controller analyses a future curved path, it calculates the centripetal acceleration and can decelerate over multiple commands so it enters the curve at the correct speed, within the predefined acceleration threshold. This feature is particularly useful for the short toolpath segments and direction reversals common in micromachining, where the length of a segment may not be sufficient to allow the axes to decelerate at a static, programmed rate without overshooting. Multi-block look-ahead and acceleration limiting also allow the user to maximise throughput by programming higher feed rates, which enables the controller to process at the highest possible feed rate without violating acceleration parameters.

More advanced algorithms can help further reduce motion errors, and increase part quality and throughput. For example, Aerotech has developed an algorithm called "harmonic cancellation" that rejects periodic error motions, such as position-dependent wobble in a spindle, by cancelling the frequency of the error with a cross-axis correction; see Figure 7.

And Aerotech's "enhanced throughput module" increases machine throughput by measuring base motion and appropriately combining this with the servo loop. Another feature, iterative learning control, reduces following error and increases dynamic accuracy by learning and optimising repetitive move sequences; see Figure 8.

System approach needed

Successful mechanical and laser-based micromachining operations require a holistic approach to ensure that desired performance and quality specifications are met. One or two components cannot produce precise motion by themselves, but a complete mechatronic system can. Selecting and integrating the appropriate bearing technology, feedback device, amplifier type, and control technology helps ensure efficient and successful micromachining.

Using PSO for precise laser positioning

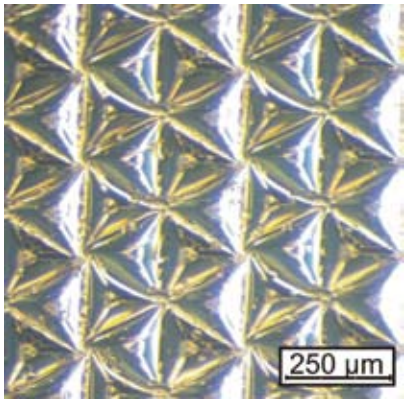
In laser-based micromachining, proper laser pulse spacing must be maintained in a highly dynamic system. When processing with a fixed-frequency laser, maintaining constant vector velocity is required for consistent pulse spacing and process quality. This is often made difficult by the complex contours of laser micromachining, and significant speed and throughput are sacrificed to maintain consistent velocity through the profile.

An option available with Aerotech motion controls is "position synchronised output" (PSO). It removes the speed and throughput limitations by triggering a high-speed output at predefined distances in real time, based on the actual encoder positions during motion, even while accelerating. This eliminates the need for velocity regulation to maintain consistent processing quality. In addition to fixed-distance firing, array-based triggering allows the user to specify trigger points that are unequally spaced along the travel.

This style of PSO firing can be used to trigger the laser at precise positions along irregular contour operations. PSO can be configured for up to three axes of motion so that the triggering output pulse can be dependent on a vector position in 3D space, and not simply tied to one moving axis. Additionally, the trigger is based on calibrated encoder positions – not simply the raw data – which further enhances system accuracy.

Thermal step-and-repeat embossing of complex micro-optics

The constant further development of light-emitting diodes (LEDs) has led to efficient, resource-saving light sources during the last years. However, the use of such light sources has so far been limited to few applications, although the advantages with regard to energy-efficiency and durability are well known. Within the context of the European research project FlexPAET, the Fraunhofer Institute for Production Technology IPT is developing a process for producing cost-effective flat optics, which will enable a widespread use of LED-lighting engineering in the future.



• *Christian Brecher, Christoph Baum and Christian Wenzel* •

Structured and planar light guides possess ideal properties as optics for lighting engineering. Based on these light guides, complex and 3-dimensional microstructures make an optical functionality possible. The production of large-area components with microstructured surfaces confronts industrial process technology with so far irresolvable problems. Flexible microstructuring with step-and-repeat hot embossing processes provides the opportunity to eliminate the production-related deficits of previous processes.

Within the context of FlexPAET (Flexible Patterning of Complex Micro Structures using Adaptive Embossing Technology), the Fraunhofer IPT is developing an adaptive hot embossing process and is integrating the technology in a process chain of cost-effective production of planar lighting optics. The main focus of this European research project is on the development of a machine system that systematically imprints the structure of complex microtools into a thermoplastic component.

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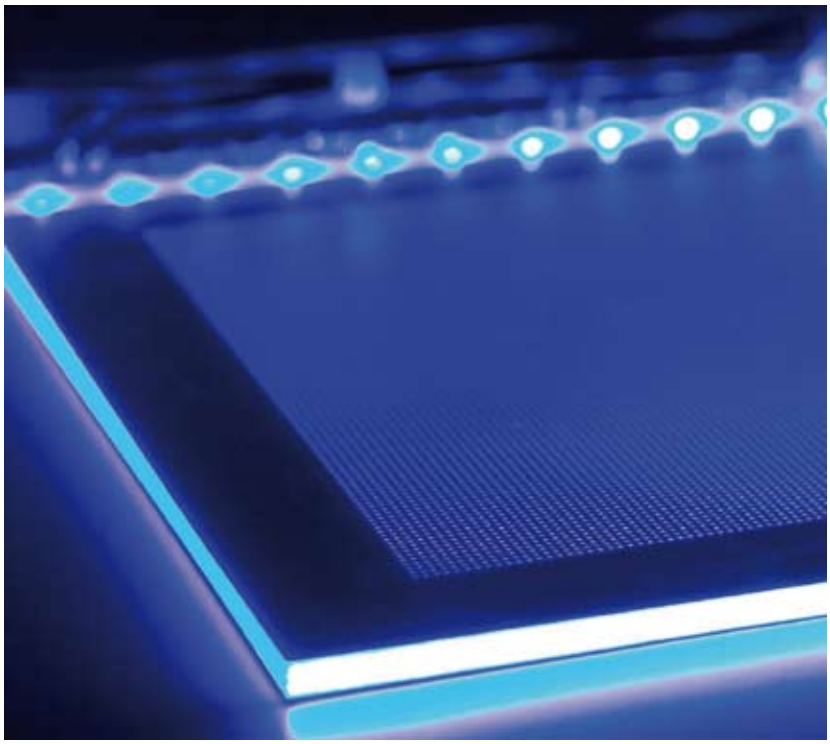

Figure 1. Example of a light-guide plate.

The process is part of a replication process chain fitted for mass production. Similar to the approach of CD and DVD production, mould inserts will be produced out of the embossed component by means of galvanic electroforming processes, enabling the cost-efficient production of high-quality optics by injection moulding or by continuous roll-to-roll processing of optical films.

Light-guide plates and light-guide films

Structured light-guide plates and films are elements that can transform the light of point light sources like LEDs into an area light. Figure 1 shows an example of a light-guide plate. LCD backlights are the most important application for area lights, but for many other applications – like general lighting, signal lighting and advertisement – area-light sources are needed as well. In contrast to conventional flat lights, where light of light bulbs or fluorescence tubes passes a strong diffuser plate in order to achieve a homogeneous lighting area, light-guide plates can provide higher energy efficiency and thinner mechanical setups.

For the transformation of point light into area light, light-guide plates make use of total internal reflection; see Figure 2. Total internal reflection occurs when a ray of light propagating in a medium with a certain refractive index hits the boundary to a medium with a lower refractive index, as long as the angle with respect to the surface normal is below the critical value. The critical angle depends on the ratio of the refractive indices of the materials. For a plate of PMMA surrounded by air the critical angle is approximately 42.2°. Light that is coupled into a PMMA plate consequently propagates in the plate as long as the incident angle is smaller than this critical angle.

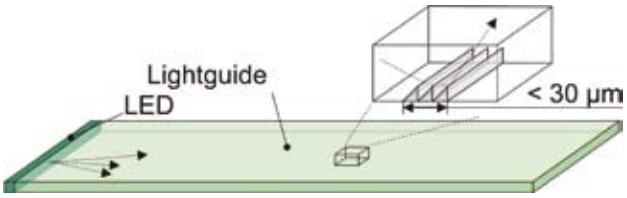

Figure 2. Principle function of a light-guide plate.

For the production of light-guide plates, elements that locally inhibit the total internal reflection are distributed on defined positions. By optimised distribution of the elements, homogeneous lighting of the whole area of the light-guide plate can be achieved. Elements that inhibit the total internal reflection can be screen-printed lacquers or 3D patterns that change the light-guiding behaviour. By means of complex micro-optics the most efficient redirection of the light can be achieved. Those micro-optical elements typically have dimensions in the range between 5 and 30 µm. The surface roughness R_a needs to be as low as 20 nm, and often sharp edges and slanted surfaces are required. Available production technologies for manufacturing complex optical micostructures with such characteristics are limited to structuring small areas only. Large areas can not be directly machined.

In order to produce complex microstructures on large surfaces, a recombination of micro-optical features by step-

Figure 3. Example of an embossing sequence.

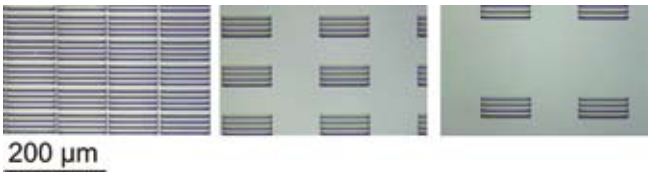

Figure 4. Seamless recombination of microstructures.

and-repeat embossing was developed. In the past years, several approaches for step-and-repeat processes were presented. Step-and-repeat forming processes make use of selected tools that repeatedly form/stamp the features into a substrate; see Figure 3. All common processes have a lack of quality at the positions where the tools of a single process step need to be fitted side by side. At those positions the formed geometry differs from the specifications due to the stitching effect.

In contrast to the existing step-and-repeat methods, solid substrate material is used for the hot embossing replication. Conventional hot micro replication processes start with the production of a master, which functions as a mould. A thermoplastic polymer as well as this master then is heated just above the glass transition temperature T_g of the substrate material. Subsequently, the mould is pressed into the material, applying a certain pressure. After a defined dwell time, the mould cools down and is removed out of the polymer material. The process is suitable to replicate with high precision microstructures, even if they have high aspect ratios. The process time for each embossing operation strongly depends on the type of mould. The greater part of the cycle time is used to heat up the mould to the desired temperature above T_g and to cool it down before removing it out of the material. Typical cycle times for one embossing movement are in the range of a few minutes.
For the microstructuring by means of the step-and-repeat hot embossing method, a tool is repeatedly positioned, heated and pressed into a solid thermoplastic substrate. Analoguous to the conventional process, the heated thermoplastic material is deformed and even very precise geometrical structures can be formed in the substrate surface. By means of this process the flexible recombination of micro-optical features without any defects between adjacent embossing positions is possible; see Figure 4.

Machine development

Within the FlexPAETresearch project, the development of a machine system that systematically imprints the structure of complex microtools into a thermoplastic component was realised. In contrast to the conventional process of hot embossing, singular structural elements are put together piece by piece on one surface. In surfaces up to 1x2 m² the machine can imprint microstructures with a positioning accuracy of 2 µm. Concerning flexibility and speed, unknown opportunities with regard to the production of optically functionalised surfaces result. The optical function of the embossed component is measured directly in the machine system by means of integrated metrology. Thus errors in the optical design can be detected directly on the machine. An algorithm compares the optical function of the embossed component with the required value. In this manner, the system identifies those positions on the surface where the structure has to be improved. The optimisation process will be continued until the measured optical properties correspond to the required specifications.

An ultra-precise machine system was built that positions a specially designed embossing unit relative to a thermoplastic substrate. The system was designed in a cooperation between Fraunhofer IPT, Eitzenberger Luftlagertechnik, and Johann Fischer Aschaffenburg. The machine is fully equipped with air bearings and driven by direct linear drives. The structural components are made out of granite material. In addition to an axis for positioning of the embossing head there are axes for positioning of a confocal microscope and a fly-cutting unit for diamond machining of large areas.

Online inspection and optimisation algorithm

An innovative optimisation algorithm was designed, based on the specifically developed metrology system for monitoring the light density and illumination performance of the substrate during production. The algorithm determines structures, positions and orientations for

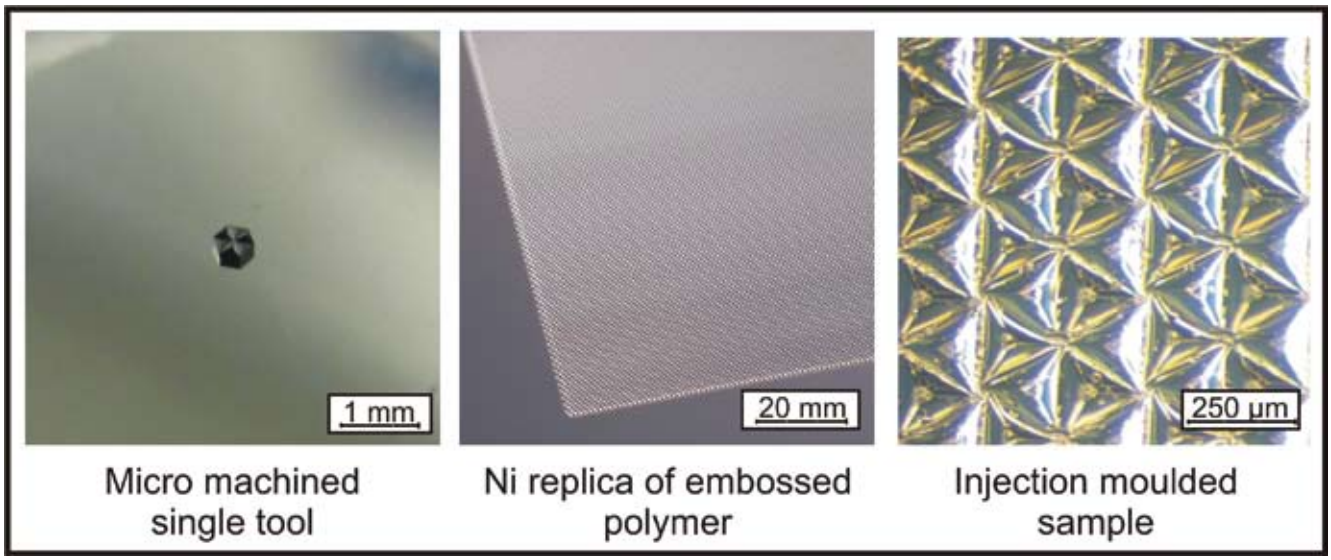

Figure 5. Production sequence.

required rework in order to achieve the desired substrate performance, thus constituting a truly self-optimising manufacturing system. A software programme is being developed that can autonomously determine necessary rework on the substrate surfaces, calculate the required stamping positions including tool geometry and orientation, and communicate the results with the system control in order to start the iteration cycle. After every finished iteration cycle the performance will be re-measured and potential further rework will be determined by the optimisation algorithm. This process will continue until the element performance matches all design requirements.

Utilising the actual optical performance of the workpiece as an evaluation criterion, as opposed to measuring the geometry of the structure, constitutes a breakthrough in optically-functionalised element production, eliminating deviations between the theoretical and practical structure performance.

Mould making

After the mastering process has been finished, a mould is formed of the fully embossed master structure. This mould will be used to replicate the master structure for high-volume production. Using advanced electroforming processes for the replication of microstructures, the mould will be produced by building a nickel shim consisting of multiple functional layers. Figure 5 shows the production sequence. In the final step of the FlexPAET process sequence, high-volume replication processes by injection moulding and injection compression moulding were tested; see Figure 6. Several replication technologies were optimised and evaluated with respect to their qualification for the production of the optically-functionalised elements.

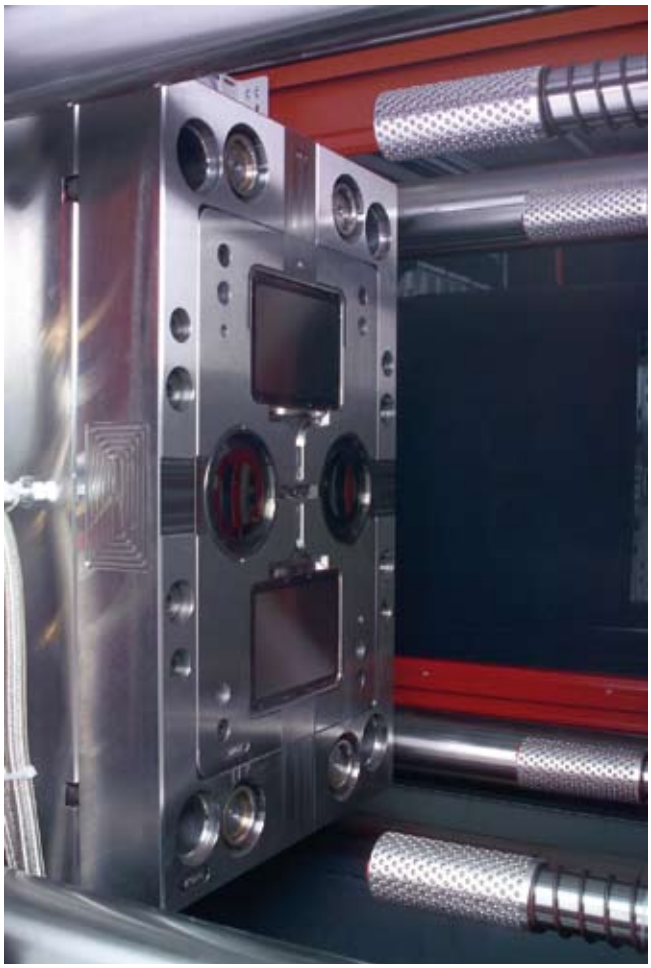

Figure 6. Injection moulding tool with structured mould inserts.

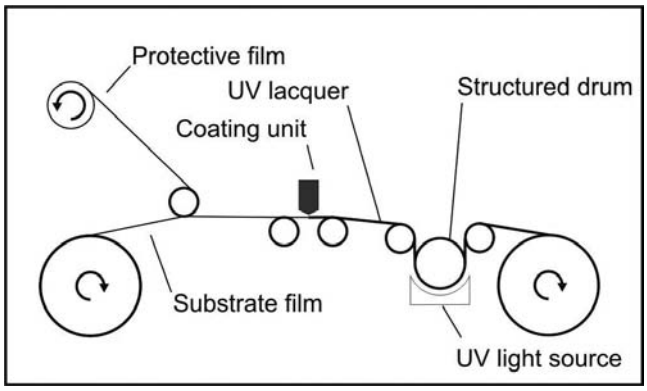

Figure 7. Schematic of the roll-to-roll process.

Mass replication by roll-to-roll processes

In addition to replication by injection moulding, roll-to-roll processes allow for a cost-efficient production of structured light-guide films. At Fraunhofer IPT a system is being installed that structures films by means of UV-curable lacquers; Figure 7 shows a schematic of the roll-to-roll process. A substrate film is first coated with a lacquer. A structured embossing drum transfers the structures of the nickel shim produced by step-and-repeat embossing into the lacquer while UV light cures the lacquer. As result, high-performance replication of microstructures in a continuous process is possible.

Summary

Fraunhofer IPT has developed a machine system that is able to produce complex micro-optics on areas up to 2 m^2. The system principle is based on step-and-repeat hot embossing. A thermoplastic master substrate can be patterned and the optical behaviour can be directly analysed on the machine system. Subsequent to the mastering process, electroforming of the thermoplastic master enables replication into nickel shims for the production of mould inserts for injection moulding and drum production for continuous production of structured optical films.

Information

FlexPAET (Flexible Patterning of Complex Micro Structures using Adaptive Embossing Technology) is funded by the European Commission through the 7th Framework Programme.

www.flexpaet.com

Applications of the optical

Pushed by the ever increasing demand for data bandwidth, the telecom industry is embracing the target of 100 Gbps as the new data rate standard. To that end, companies are embarking on new research into optical fiber devices. This research includes optical waveguide patterning, optical switches and investigations into production methods to increase efficiency and throughput of manufactured components. Three examples of research being conducted to improve the current technology will be presented.

• *Beda Espinoza* •

In the march to deliver higher data bandwidth, telecommunications companies must look to expanding technology that can accommodate the data demands of an increasingly networked society. One of the issues is the choice between optical fiber and electrical (or copper) data transmission, based on a number of trade-offs. Optical fiber is generally required for transmission systems demanding higher bandwidth or for spanning longer distances, that electrical cabling cannot accommodate.

As wireless technology enables the push of data to mobile devices, the section between the cellular network and the IP backbone, known as the cell site backhaul is becoming the data bottleneck. According to AT&T, upgrades to cell site backhauls in the United States are now happening with optical fiber technology. At present, AT&T estimates that about 24 petabytes of data moves through its cellular network per day. This amazing amount of data is estimated to be three times as much more, when including all other US cellular carriers.

Another technological advance is taking place around the rate of communication achievable through fibers. About a decade ago, achieving a reliable 10Gbps optical communication was considered state of the art. R&D labs were hard at work to develop a 40Gbps solution in the early to mid 2000s, when the telecom bubble collapsed. Pushed by the ever increasing demand, the telecom industry is now embracing a new target of 100 Gbps as the new data rate standard. To that end, companies are embarking on new research into optical fiber devices.

Author's note

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www.newport.com

motion in fiber industry

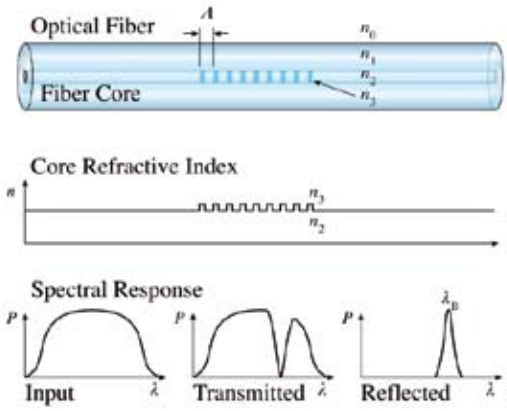

Figure 1. Image of a fiber Bragg grating.

The research includes optical waveguide patterning, optical switches and investigations into production methods to increase efficiency and throughput of manufactured components. In this article, three examples of research being conducted to improve the current technology will be presented: fiber grating fabrication, waveguide alignment and fiber winding. In these application examples, a common thread is the selection of Newport motion products, which turned out to be vital in the successful completion of this research.

Fiber grating applications

The first application is centered on the manufacture of fiber gratings using phase mask inscription techniques. A fiber grating is an optical device that enables the systematic variation of refractive index in the core of an optical fiber; see Figure 1. Optical communications systems use fiber gratings to allow optical signals of various wavelengths to be combined, transmitted and then decoded. This is the key to achieving the increased efficiency and capacity of fiber optic networks.

Fiber gratings for the most part, have a broad range of applications in optical fiber networks, like optical filtering, dispersion compensation and fiber sensing. The broad range of application of fiber gratings has motivated a new wave of researchers to develop new techniques and materials in producing fiber optic gratings.

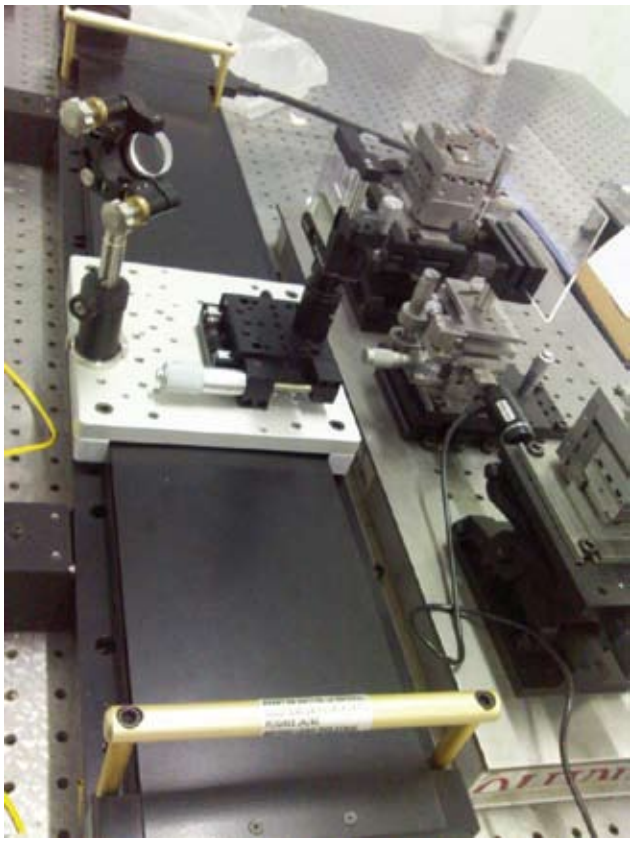

Figure 2. Phase inscription system.

Figure 2 shows the phase inscription system. This system consists of a UV laser (not shown), a cylindrical lens, a phase mask and high-precision motorised stages.

In this set-up, the mask is mounted on a 600mm travel linear stage, with a Minimum Incremental Motion (MIM) of just over 1 µm and a uni-directional repeatability of 1.25 µm. The stage enabled continuous patterning of long sections of fiber, while the XPS Universal Controller's excellent speed control helped achieve a smooth grating spectrum with a high lobe-suppression ratio. In addition, a pair of XYZ stages, upgraded with ultra-high resolution

Figure 3. Two-station optical fiber measurement system.
(a) Design.
(b) Realisation.

piezo actuators, was used to ensure proper orientation and location of the fiber relative to the mask. The XYZ pair was also critical for adjusting the strain applied to the fiber during processing.

Silicon photonics application

In another application, this time at a much smaller scale, silicon is used as a novel optical medium to confine light into waveguides. By using silicon, advantage is taken of established semiconductor processing techniques for the fabrication of complex optical circuits. Silicon photonics technology, the application of silicon to manipulate light, can be applied to optical communications, sensors, medical diagnostics and signal processing. The development effort behind silicon photonics research relies on a large amount of optical measurement data taken under various conditions. To fabricate and test complex microelectronic circuits at the wafer level, both high speed and high positioning accuracy are critical to achieving large amounts of highly reliable results.

In this silicon photonics application, design and realisation of which are shown in Figure 3, Newport supplied the entire test station comprised of the main positioning platform with an XYZ and ThetaZ assembly to position the Device Under Test (DUT) and two independent optical fiber measurement stations each with an XYZ stage platform plus an integrated goniometer. The main platform's XY was based on a long-travel stage, while vertical and rotation stages provided the Z and ThetaZ,

Figure 4. Typical fiber alignment set-up.

Figure 5. 5-Axis fiber winding system.

respectively. All these stages are driven by the XPS Universal Controller.

Fiber alignment application

Another popular motion application is in the automatic alignment of waveguides or fibers. A typical automated alignment system consists of a motorised XYZ stage system with an integrated tilt stage and a controller that is programmed to utilise one or a number of search and optimisation algorithms. This three-dimensional optical alignment of 500nm core diameter optical fibers required MIM accuracy and repeatability. Speed was also important, as this system was used not only as an engineering unit, but was also planned for production. The XMS linear motor stage family was chosen in part for its very precise positioning capability of 10nm MIM, better than 1µm accuracy (after error mapping) and 200mm/s maximum speed. The gap between the two devices had to be controlled within 1 µm. The stage having a travel range of 50 mm was selected to allow alignment of future larger and longer optical devices. For angular adjustments of the devices, a tilt platform incorporating a compact motorised actuator proved to be a cost-effective solution that met the less stringent positioning requirements. Shown in Figure 4 is a traditional fiber alignment set-up used in many production centers around the world. This system is built with a combination of other Newport technologies such as laser diode controller, power meter, manual alignment stages and a motorised XYZ stacked-stage system.

Fiber winding application

The last application example covers the winding of optical fiber into coils that are eventually used in fiber optic gyroscopes. Knowing that fiber optic cables are delicate, the winding or packaging into spools requires sub-micron MIM and velocity control to prevent twisting, breakage or introducing mechanical stresses on the fiber. Mechanical stresses induced in the fiber results in transmission losses due to micro-bending.

As shown in Figure 5, Newport supplied a 5-axis motion system wherein a kilometer-long fiber from a standard spool is re-wound into a compact spool device. A linear stage was selected as the loading carriage to move an empty compact fiber spool to the winding position. Linear stages, a vertical stage and a rotation stage adjust the final position of the device relative to the main spool, at which point winding commences. A motor in the spool device is controlled to start winding once the motion system is in place. At the same time, the controller synchronises the motion of the 5-axis system with the winding process. Upon completion, the system moves the device to the unload position and the cycle repeats.

Conclusion

As demonstrated in these varied optical fiber related applications, the stages and controllers that were provided enabled swift progress in research and development, while also improving throughput and yield of device manufacturing in the optical fiber industry.

27 June - 1 July 2011, Eindhoven (NL)
International Summer school Opto-Mechatronics 2011

Organised by DSPE, and hosted by TU/e, TNO Science and Industry, TUD, ESO and ASML, the event 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 and venue is TNO at the university campus in Eindhoven.

www.summer-school.nl

Summer school Opto-Mechatronics
Precision Technology

26-28 July 2011, Cambridge (UK)
Euspen Challenge 2011

An international competition to identify outstanding young engineers and scientists across Europe with potential to be future leaders in the field of precision engineering and nanotechnology. The challenge is organised by the European society for precision engineering and nanotechnology, euspen.

www.studentchallenge2011.euspen.eu

euspen challenge 2011

31 August 2011, Best (NL)
DSPE networking event on Certification

Information and discussion session on the DSPE certification initiative aimed at creating a register for Certified Precision Engineers, complemented with a mini exhibition of training institutes. The event at Best Golf also offers plenty of opportunities (golf clinic and dinner) for networking in the Dutch high-tech systems and precision industry ecosystem. Entrance is free, but capacity is limited. Therefore, timely registration is advised.

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CPE
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lucienne.bots@dspe.nl (information and registration)
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28-29 September 2011, Veldhoven (NL)
High-Tech Product Lines

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

www.bits-chips.nl/events/hpl

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

The seventh edition of the Netherlands MicroNanoConference, organised by NanoNextNL and MinacNed, provides an overview of the latest developments in micro- and nanotechnology, both from the academic and industrial point of view.

www.micronanoconference.nl

Networking during the Netherlands MicroNanoConference '10.

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

Tenth edition of the conference on embedded systems and software, organised by Bits&Chips publisher Techwatch. The lecture programme is made up in collaboration with the Eindhoven-based Embedded Systems Institute and features contributions from academia and industrie. Keynote speaker will be the ASML CEO, Eric Meurice.

www.embedded-systemen.nl

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

Eleventh edition of the Benelux premier trade fair on precision engineering. Some 200 specialised companies and knowledge institutions from the Netherlands, Belgium, Germany and other countries will be exhibiting in a wide array of fields, including optics, photonics, calibration, linear technology, materials, measuring equipment, micro-assembly, micro-connection, motion control, surface treatment, packaging, piezo technology, precision tools, precision processing, sensor technology, software and vision systems. The lecture programme comprises more than forty contributions from academia, knowledge institutes and industry.
The Precision Fair is organised by Mikrocentrum, with the support of DSPE, NL Agency and media partner Mikroniek.

www.precisiebeurs.nl

Impression of the Precision Fair 2010.
(Photo: Mikrocentrum)

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

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

www.rapidpro.nl

System Architect Conference

Nowadays, high-tech systems are constructed in a modular fashion in close collaboration between OEMs and OMMs (Original Module Manufacturers). The OEM system architect decides on the technical vision, develops the outline of the integral design, maintains the overall picture and controls the interfaces between modules. It is of upmost importance that the OMM master this vision of systems thinking.

The System Architect Conference will provide delegates with a greater insight into the practical aspects of system architecture and show them how to deal with the multidisciplinary approach between OEMs and OMMs. The focus will be on the collaborative aspects of a project, which range from system requirements to a properly functioning system. The main objectives of this event will be to strengthen the ecosystem, to network and to share knowledge.

The conference is the fruit of the close collaboration between Mikrocentrum and DSPE and it aims to strengthen the ecosystem of the high-tech systems industry. It can be considered the successor to PACT (Philips Conference on Applications of Control Technology), albeit a slightly modified one.

The conference target group comprises trained (future) system architects, group leaders, senior designers and project leaders from OEMs and OMMs with several years of experience in the product development of high-tech systems. Participation is by invitation only and delegate numbers are limited to 100. The event will be held in the winter of 2011/2012 in the Southern Netherlands, and the programme is still being finalised.

r.gommers@mikrocentrum.nl (Ruud Gommers)

The Dutch photonics website

This spring saw the launch of www.dutchphotonics.nl, which intends to distribute photonics-related information, to present the activities of the IOP Photonic Devices research programme – funded by NL Agency – and to offer Dutch photonics companies and institutions a platform for presentation (an online version of the Dutch Photonics Company Guide). The website is an initiative of and will be maintained by Mikrocentrum, with the support of the Dutch Ministry of Economic Affairs, Agriculture and Innovation and PCN (Photonics Cluster Netherlands).

www.dutchphotonics.nl

Successful plasma technology theme day

In the plastics industry, surface activation is a crucial process step, and not just for attaching glues and topcoats to plastic surfaces. The rise of hybrid products and multi-material constructions requires flawless connections between metals, plastics and rubber. Atmospheric plasma technology provides an innovative solution.
On 12 May, Mikrocentrum organised a theme day on this subject at VITO in Mol, Belgium. With over 110 participants, it was a successful event, comprising lectures, practical examples, a small table-top trade fair with some fifteen exhibitors and live demonstrations in VITO's plasma laboratory, which included a robot applying low-friction coatings to rubber, the application of superhydrophobic nano-coatings and the functionalisation of micro- and nano-powders.

Picture of the lab tour.

New training platform for the high-tech industry

Settels Savenije Van Amelsvoort, a leading high-tech R&D and consultancy firm located in Eindhoven, the Netherlands, and Nijmegen-based Techwatch, which publishes Bits&Chips and Mechatronica Magazine, are combining their current activities in the field of training and setting up The High Tech Institute. The new institute's programme is for highly-trained professionals working in electronics, mechatronics, optics, software technology or system architecture.

Many of the training courses in the programme for post-HBO (Dutch higher professional educational qualification) and post-academic levels enjoy international fame, including those for mechatronics, precision technology, design principles, system architecture and optics. Some of these training courses were part of the programme offered by the Philips Centre for Technical Training. On 1 January 2010, Philips stopped its training activities and handed over parts of its portfolio to Settels Savenije Van Amelsvoort (mechatronics and precision technology), Sioux (information technology and system architecture) and T2Prof (electronics and optics). Techwatch is responsible for marketing the training courses for which Sioux and T2Prof will now be providing content.

In the meantime, the implementation of the mechatronics courses has been assigned to a separate limited company specialising in mechatronic content, where Dr. Adrian Rankers, Prof. Jan van Eijk and Prof. Maarten Steinbuch will be in charge of the content. These three were involved in the mechatronics courses that were developed within Philips and organised by CTT.

www.hightechinstitute.nl

New Carl Zeiss Measuring House

Carl Zeiss in Best, the Netherlands, opened its new Measuring House in mid-June. Here, Carl Zeiss offers a wide range of services including programming measuring assignments, contract measurements, calculation of measurement inaccuracies, analysis using computer tomography, MSA (R&R) studies (Measurement Systems Analysis, Reproducibility & Repeatability), training courses and workshops. The Measuring House has been fitted out with, among other things, the Zeiss 3D measuring machines, Accura II, Contura G2 and DuraMax.

www.zeiss.nl

New Applied Optics course

On 8 September, Mikrocentrum will start a new, advanced course, Applied Optics. The course was designed for the junior specialist and for those already experienced in working with optics. On completion of the course, the participant will be aware of modern optical principles and will be able to apply them in various practical situations. The course deals with a wide range of "ancient" and modern optical phenomena. The theory is illustrated by practical examples ("how does a wafer stepper actually work?") and hands-on demonstrations with optical equipment ("build your own interferometer"). The target group includes technicians working with optical instruments (e.g. in production, test or laboratory environments) and engineeers involved in the development of systems applying optical principles.

www.mikrocentrum.nl

NTS-Group takes over GMZ Precision

The Dutch firm NTS-Group, with headquarters in Eindhoven, has taken over GMZ Precision in Schaijk. This firm employs 14 staff and produces high-quality components using rotary and milling cutter tools. CEO of the NTS-Group Marc Hendrikse: “NTS-Group clients are increasingly asking us to develop modules and machines from start to finish and by taking over GMZ Precision we are also underlining our role as manufacturer of modules and components.”

The NTS-Group develops and produces optomechatronic systems and mechanical modules, an indispensible part of which is the production of critical components. In addition to its development and assembly businesses, the NTS-Group, therefore, also includes businesses that concentrate on manufacturing parts from sheet metal work and machining, such as NTS Mans in Bergeijk. The GMZ Precision takeover will strengthen NTS’s position in this sector. NTS Mans and GMZ Precision activities will be brought together at one site in the course of 2011.

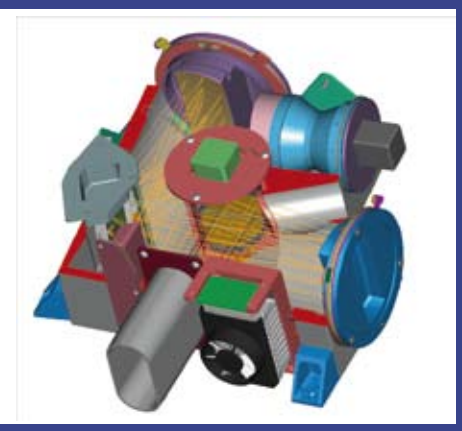
www.nts-group.nl

Lencon engineering agency: knowledge and flexibility

The challenges precision engineers are facing continue to grow. The pressure on projects is increasing because of the need for an ever shorter time-to-market. Furthermore, the technical developments required to stay ahead of the competition are emerging at an ever more rapid pace. Engineering agency Lencon provides the solution to address these challenges.

Located in Koudekerk aan den Rijn, the Netherlands, Lencon can support the development and production of high-tech products by providing flexible engineering services and high-quality technical knowledge. Together with its clients, Lencon will tackle the increasing challenges by supplementing client teams with experienced design engineers or carrying out projects entirely in-house. Lencon provides clients, which include multinationals, scientific institutions and SMEs, with the knowledge and flexibility they need to stay ahead of the curve.
Lencon is made up of a number of business units – Precision & Optics, Mechanical, Products and Defence – that exchange a great deal of knowledge. Lencon Products for instance boasts expertise in ergonomics, design and plastic injection moulding. This means that Lencon can develop instruments from start to finish – from the precision engineering of optical components to the design and final development of the housing.

Precision & Optics
Lencon Precision & Optics works on projects for such sectors as space research, semiconductor industry and defence. Technical developments and new materials continue to push the boundaries in these markets, and clients expect the same knowledge and passion from external engineers that they expect from their own staff – or maybe even more, because "the devil is in the detail", especially in the precision industry. In-house expertise is available in the fields of optomechanics, glass fibres (fibre Bragg grating), thermal compensation mechanisms and statically determined structures. Lencon engineers also have ample experience with light and stiff construction, strength and stiffness calculations and product optimisation using various FEM packages.



Design of the MIBS spectrometer.

Lencon engineers have worked on optical observation tools for space research, medical instruments and precision motion systems. A prime example is the MIBS spectrometer, a 2-D infra-red spectrometer for recording the thermal radiation of the earth and its atmosphere. Using the optical CAE model, Lencon's optomechanical engineers completed the mechanical design, provided the tolerance analysis and drafted all of the detail drawings for production.

Defence
Given the wide experience gained from the specific requirements set within defence-related projects, Defence has grown into a separate area within Lencon. It combines various fields of expertise and handles a range of very diverse projects. Examples include armoured vehicles, communication equipment, night-vision scopes and helmet-mounted displays for fighter pilots. Lencon is one of the few engineering agencies in the Netherlands that is certified to handle confidential defence-related information.

A helmet-mounted display.

Information

www.lencon.nl

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

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

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

Mikroniek guide

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

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