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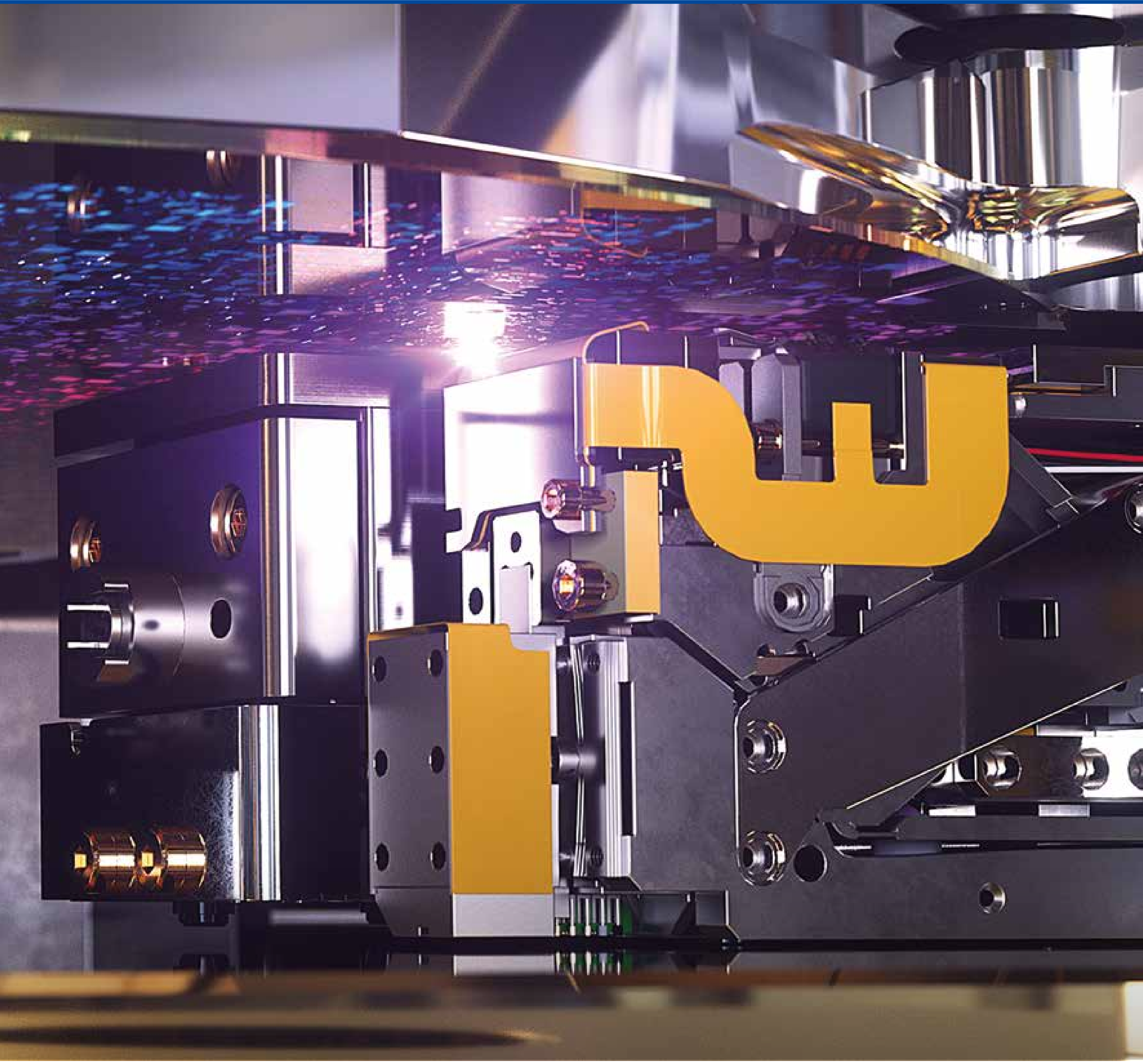

- **THEME: HIGH-TECH SYSTEMS**
- **SILICON CARBIDE OPTICS FOR HIGH-ENERGY LASERS**
- **IMPROVING HEXAPOD POSITIONING PERFORMANCE**
- **CONTINUOUS EVOLUTION OF 60-YEAR-OLD LASER TECHNOLOGY**

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DSPE
YOUR PRECISION PORTAL

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The cover image by Tim van der Steen (featuring the Quadra high-throughput scanning probe metrology system) is courtesy of Nearfield Instruments. Read the article on page 5 ff.

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FEATURES

"TOGETHER WE PROUDLY PUT ENERGY IN **MAKING FRIENDS** AND **CREATING SYNERGY**"

The above slogan was conceived during a training weekend at my first employer. I was 20 years old when, during an offsite retreat, my colleagues and I were tasked with thinking about what this commercial company, which provided staff to the hotel and catering industry, stood for. After several brainstorming sessions, we unanimously decided that this should be the slogan. And it has remained so to this day. At that age, I may not have realised that this is a maxim which ultimately encompasses everything I, and I think very many people too, stand for.

Over the years, I quickly learned the importance of networking. After holding a number of commercial positions in the FMCG sector, I encountered DSPE. Something entirely different. Does this slogan also hold true in this world and can I also apply my way of working here? These questions shot through my mind. But that is precisely why this seemed to be such an interesting opportunity. My back garden borders on the smartest region in the world, so it was about time I gained some insight into why it amply deserves this title.

I soon discovered that the world of precision is continuous and everywhere in our everyday lives. What is so normal for you readers, was quite a discovery for me. I realised that without this world we cannot function nowadays and then I'm not just referring to phones or computers. This precision is involved in every device we use, both at home and at work. I think that like me, many people fail to see how important, indispensable and all-encompassing this precision world actually is.

Having discovered this, I wondered how approachable people in this field are and how they work. As it turns out, these creative people don't actually work very differently than I was used to. They talk about their profession, full of passion and knowledge. And yes, they also want to get to know as many people as possible with whom they can share their knowledge. It goes even further, as I discovered after organising the first lunch lectures for DSPE. These professionals are eager to share their findings with other professionals so that together they can produce an even more impressive product. I did not encounter the slightest feeling of competition.

Of course, the pandemic made 2020 completely different to other years for everyone. Unfortunately, all events, such as the Martin van de Brink Award ceremony and the Precision Fair, were cancelled. All physical contacts ceased and had to make way for digital meetings via Teams. What a change. But the members of DSPE are not standing still. As a matter of urgency, they are developing machinery that contributes solutions to problems caused by the current crisis. We noticed that there was soon a need to share knowledge again, so we started to organise digital events. The monthly lunch lectures have been a great success and the first online knowledge days are scheduled as break lectures for 2 and 9 March. So DSPE is changing with the times.

Although it was a completely different year, I was able to gain a clear picture of what precision engineering is all about. Should I now again be asked what this industry stands for, I can again say only one thing: "Together we proudly put energy in making friends and creating synergy". Here's to a great year together!

I hope you enjoy reading the first Mikroniek issue of the new year.

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DEVELOPING A MINIMUM VIABLE PRODUCT THROUGH AGILE SYSTEMS ENGINEERING

In the semiconductor industry, Moore's law comes with increasing and complex demands and the need for advanced process control metrology. Nearfield Instruments fulfils these needs with their high-throughput scanning probe metrology (HT-SPM) systems. January 2018, they started working on their first product, QUADRA.
By rigorously adhering to an agile systems engineering methodology and promoting the concept of a minimum viable product, Nearfield Instruments was able to develop, integrate, test, and subsequently ship their first QUADRA to a major semiconductor fab in December 2020.

ARJEN VAN ELTEREN, MARK BOEREMA, JAN DO LIVRAMENTO, ROLAND VAN VLIET AND HAMED SADEGHIAN

Metrology challenges in semiconductor industry

As in every manufacturing process, and as well in semiconductor manufacturing, the adagio "if you cannot measure it, you cannot make it" holds firmly. In order to accommodate new manufacturing paradigms (as described below; see also the roadmap in Figure 2) in a technologically and economically viable way, breakthroughs in metrology processes and equipment for IC device development and manufacturing are required. Critical dimensions (CDs) of the features and wafer surface roughness need to be measured

AUTHORS' NOTE

Arjen van Elteren (lead software architect), Mark Boerema (system engineer), Jan do Livramento (strategic supply chain manager), Roland van Vliet (co-founder & COO), and Hamed Sadeghian (president & CTO) are all associated with Nearfield Instruments (NFI).

NFI, headquartered in Rotterdam (NL) with a mechatronics & control-focused location in Eindhoven (NL), was founded in January 2016 as a spin-off from TNO. Since then, NFI has grown into a semiconductor metrology equipment company developing and delivering ground-breaking process control metrology solutions for the worldwide advanced semiconductor IC manufacturing industry.

NFI successfully closed two financing rounds, engaged in close interaction with some top-tier IC manufacturers, established state-of-the-art development and integration & test facilities, and grew to 90 fte.

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First shipment

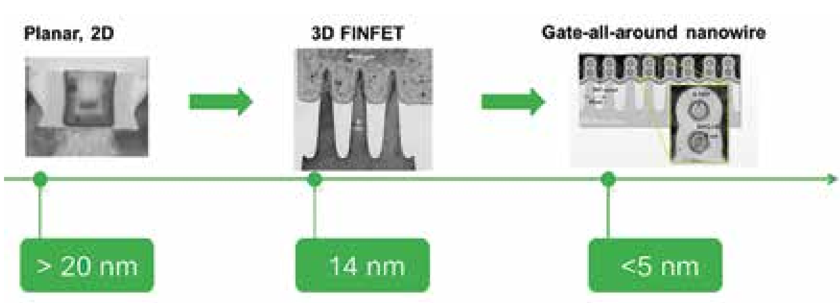
Following Moore's law, chip manufacturers face an increasing complexity of their integrated circuits (ICs), as new, sensitive materials, 3D structures, and buried features are introduced. This also leads to increasing and complex demands and the need for advanced process control metrology. Nearfield Instruments (NFI) fulfils these needs by developing and delivering a high-throughput scanning probe metrology (HT-SPM) system. It is the only metrology system that can provide a 3D-capable, non-destructive, inline atom-scale metrology and wafer defect review instrument at industry-level throughput.

NFI has realised its first product, QUADRA, and shipped the first system to a major semiconductor fab in December 2020 (Figure 1). QUADRA enables the industry to obtain better insights into the chip's manufacturing process variations in the nanometer-sized features. These insights allow the industry better control of its manufacturing process, leading to an increased production yield.


1a

1b

NFI's Quadra.
(a) Metrology core
(b) First system shipped to a customer.



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Roadmap of logic devices. Some fabs will adopt gate-all-around for 3 nm and beyond, and TSMC for 2 nm.

down to sub-nanometer level. Critical defects need to be imaged and measured in three dimensions to trace back their origin. With the full switch to 3D features, the alignment of different IC layers requires atomic-scale precision.

However, the current industry state-of-the-art metrology systems run into physical limits: classical optical metrology equipment, for so-called in-device-metrology, does not provide an acceptable resolution at the required feature sizes, while electron-beam metrology equipment faces challenges in the depth of field, accurate 3D information, and sensitive materials. Therefore, to enable the application of the current and next-node disruptive semiconductor scaling technologies, novel atom-scale metrology solutions at industry-level throughput are needed.

NFI approaches these process control challenges based on scanning probe metrology (SPM), featuring a cantilever with a sharp tip (probe) at its end that is used to scan the specimen surface. When the tip is brought into proximity of a sample surface, forces between the tip and the sample lead to the cantilever's deflection. In a sense, the information is gathered by 'feeling' the surface with a mechanical probe. Piezoelectric elements that facilitate tiny but accurate and precise movements on (electronic) commands enable very precise scanning.

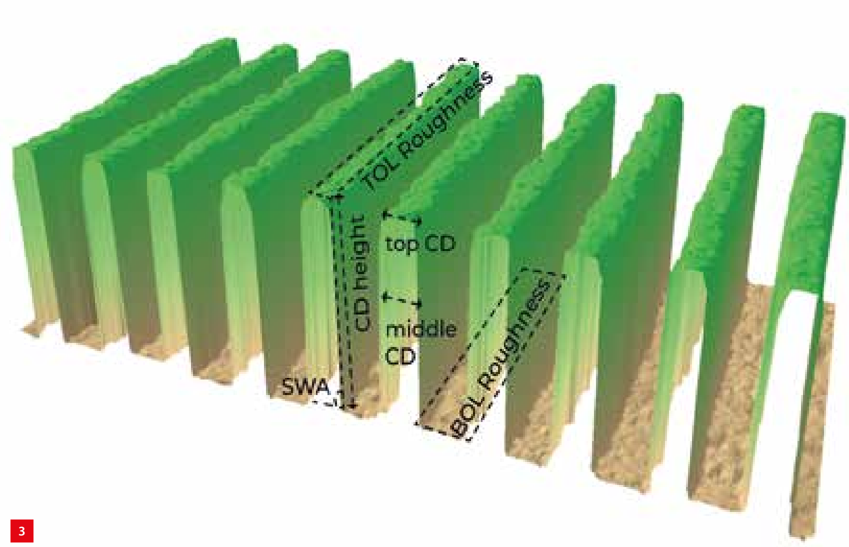
SPM, therefore, has the potential to fulfil the current and future requirements of the semiconductor industry. It has the advantage of providing a three-dimensional surface profile (3D capabilities). Additionally, samples viewed by SPM do not require any special treatments or sample preparation (unlike transmission electron microscopy) that would irreversibly change or damage the sample. They do not typically suffer from charging artifacts in the final image. SPM also has soft materials sampling capabilities as it produces a very high atomic resolution.

QUADRA: high-throughput metrology equipment

Atomic force microscopy (AFM) is an established SPM technique for analysing profile and surface properties with (sub-)nanometer precision. In AFM, a cantilever with a sharp tip attached to its free end is excited at a frequency near its fundamental resonance frequency to reach a specified free-air amplitude. Then, using a piezoelectric actuator, it is brought into proximity of the sample surface. Due to the tip and sample surface interactions, the vibration amplitude reduces, which indicates the distance between the sample surface and the tip. By scanning the sample surface while adjusting the overall distance to keep the amplitude constant, a 3D topographic profile of the sample is recorded.

Although AFM is a three-dimensional technique in principle, regular AFM cannot be used to provide images of 3D structures containing deep and narrow trenches, as widely used in the semiconductor industry. Therefore, a new scanning mode, called Feedforward Trajectory Planner (FFTP) mode, is currently being developed by NFI (Figure 3). This scanning mode enables non-destructive nanoimaging of high-aspect-ratio, narrow trenches, such as those common in the semiconductor industry.

Moreover, a single AFM instrument is known for its very low speed and not suitable for scanning large areas, resulting in very-low-throughput measurement. QUADRA addresses these challenges by parallelising AFM instruments. The parallelisation is achieved by miniaturising the AFM instrument and operating many of them simultaneously. This concept has the advantage that each miniaturised AFM can be operated independently. We have developed an architecture that enables operating many miniaturised scanning heads in parallel, increasing the throughput to an industry-acceptable level. The first



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3D metrology of high-aspect-ratio GAA FET structures with FFTP mode.

product out of this FFTP architecture is based on four scanning heads, the so-called QUADRA.

While modern foundries produce from 20.000 to over 100.000 wafers per month, semiconductor manufacturers have automated their factories to a high degree. Foundries are built by integrating tools provided by different suppliers, each tool performing one or more steps in the chip manufacturing process. To be able to deliver a tool to the semiconductor manufacturers, the tool must be fully automated and compatible with the manufacturing execution systems of each factory.

In QUADRA, all subsystems have their automation software, and the machine is managed with a machine control system. We have automated every step in measuring a wafer, from loading and unloading the wafer, exchanging probes, determining the measurements' location on the wafer, and finally, to the actual measurement. As QUADRA will not be used to provide measurements but to provide actionable information to our customers, the interpretation of the 3D data from each measurement is also automated.

Minimum viable product approach

Early customer engagement

To develop and deliver a product to market in a very short period of time while still satisfying the customer needs, NFI has adopted the minimum viable product methodology. A minimum viable product (MVP) is a version of a product with just enough features to be usable by early customers who can then provide feedback for future product development.

Adhering to a rigorous approach in developing an MVP does not equal delivering an unfinished product. An MVP is a product that is to be accepted and used by the customer satisfying all necessary industry and customer requirements, but only the necessary requirements. From this follows that early customer engagement is of great importance to learn what it really is what a customer needs and expects from a first-in-fab product. As it is a new product with new technology this deep engagement works both ways: together with the customer NFI went through a journey of exploration and creating mutual understanding.

One can distinguish four steps we went through:

1. A good understanding of the general market trends and developing a decent proof-of-concept set-up to be able to demonstrate the viability of the technological solution.
2. Deep understanding of specific customer needs. This can only be achieved by regular personal interaction, not with the customer but with the users, the persons that feel the pain in the factory. Listen, learn, experiment, and show the results, whether good or bad. This builds the trust to get into a dialogue on applications and to have the customer release samples to directly show customer application solutions.
3. Showing the viability and reliability of the solution; in dialogue we can get clarity and agree upon the key performance indicators (kpi's) on which a first product would be evaluated and, equally important, which kpi's are less or not important.
4. Discuss and engage with more customers, to ensure the product will be able to serve a broader customer base and add value to the whole industry.

Obviously, steps 1, 2 and 3 are a constant iterative process that requires the system architecting and development to take place in an agile manner, as with growing insights on both NFI and customers side, the priorities often change, certainly in the beginning. Having a solid system architecture with a flexible design process allows to absorb those changes. The challenge lies in dampening out the changes to an ultimately frozen set of parameters. This can only be done through a deep and trustworthy engagement with the customer. NFI has done this by 'getting out of the building' as early as possible. Engaging with the users on-site, experiencing their pain and needs and getting feedback on our ideas immediately and directly, constantly helped us to stay focused towards the end goal: a system that satisfies the customer needs while minimising development risks, time, and resources.

The customer is not seeking the perfect system, a jack of all trades. Ultimately, a customer wants an ultimate tool, but principally a customer wants a solution to their pain as soon as possible, satisfying as minimal as possible boundary conditions, which can be challenging enough already. By distinguishing between and agreeing on what parameters are need-to-have and what are nice-to-have (and providing a clear path towards those), an MVP can be defined that at the same time satisfies the customer needs while minimising the design parameter space. This leads to a swifter, less complex development and integration process.

Agile systems engineering

Developing a highly complex system requires a structured and phased approach, with clear milestones and decision points to go to the next phase. At NFI, we apply proven systems engineering methodologies to structure system definition and product development. Following the well-known V-model (Figure 4), the QUADRA product requirement specifications were agreed with the customer, then the system performance specifications were defined from high-level system requirements on functionality,

Realisation of QUADRA via V-model systems engineering and an adapted V-model for project management.

performance, reliability, and serviceability, down to specifications on the part level, taking into account the interfaces between all constituent elements in the system. Key is that the interfaces are chosen such that the subsystems are disentangled as much as possible to enable swift integration, easy repair and recovery, and scalability for future products based on the QUADRA architecture.

To have a factual basis for subsequent development, intimate contact with our development partners on the clarity and feasibility of specifications has proven invaluable. With extensive FMEAs (failure modes and effects analyses) to capture risks and include countermeasures, this ensured that specified parts, modules, and subsystems were developed, designed, and manufactured successfully, with full understanding, commitment, and support of all parties involved. Qualifying the system was done in reverse order, from part level to modules, subsystems, to finally system functions and performance.

Projects for all significant subsystems and system functions were organised and managed in close cooperation with our development partners. Specifications and timelines were translated to detailed work breakdowns, a master planning for the entire system, and more detailed plans for its subsystems and modules. To ensure quality and time-to-market within budget constraints, a significant part of the work in developing and realising the system consisted of managing uncertainty and risk. NFI adopted a strong, agile way of working to make this happen. All teams conduct daily and weekly reviews based on the available facts and the projection on the goals to be met. These were used in fast and efficient decision loops and priority setting at different organisational levels to mitigate risks and keep track. Motto: manage the unavoidable and avoid the unmanageable.

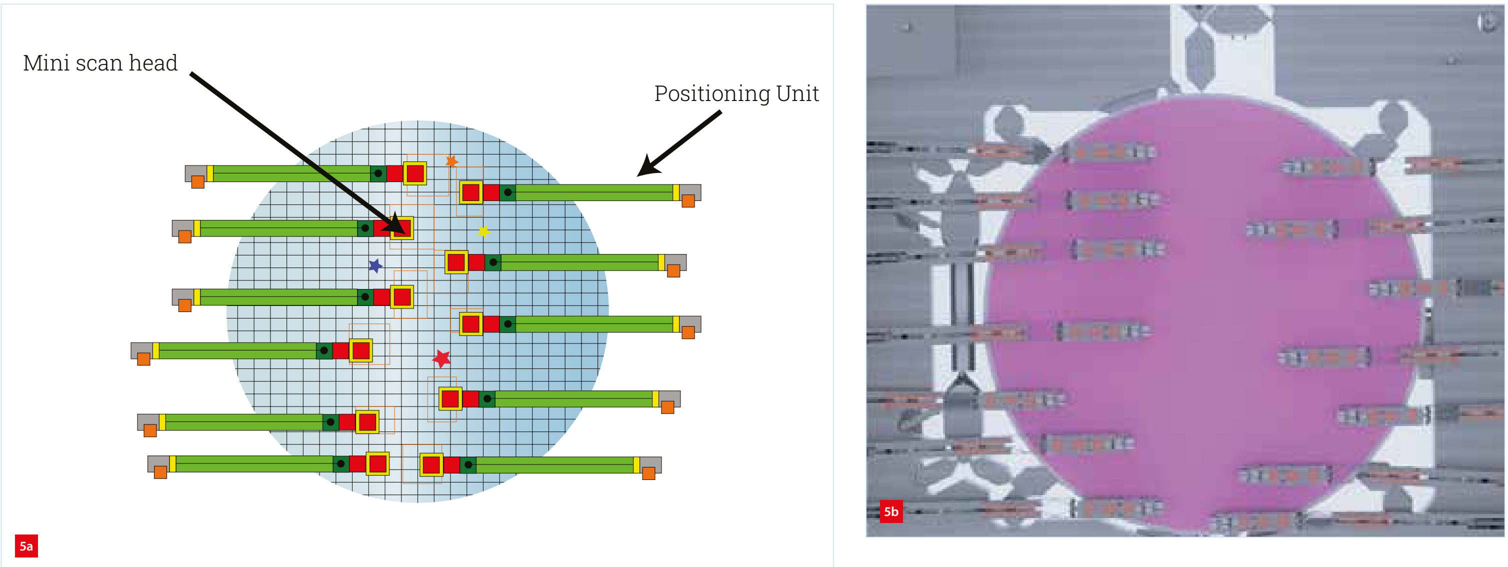
This agile way of working was deployed to all parties involved, internally and externally. Timely early integrations for parts and modules were conducted to quantify technical risks and correct them before full system integration requires them to function properly in an even more complex setting. Alternatives for time-consuming and/or costly solutions were discussed and decided on. Additionally, project organisation was adapted wherever necessary to match the phase's needs in the project.

This structured way of working, deeply involving all parties, has proven its value, and has resulted in a well-defined, well-developed, well-built, and well-performing system. Following the principles described, NFI has succeeded in realising and shipping its first high-throughput scanning probe metrology tool with unprecedented performance in the shortest possible time – right first time.

Architecture

The mechatronics architecture of QUADRA has been designed to fulfil three high-level requirements:

1. developing an imaging mode suitable for high-aspect-ratio, dense 3D structures in the semiconductor industry (Logic, DRAM, and 3DNAND);
2. increasing the throughput of SPM to a level that can be leveraged in the semiconductor production line, and;
3. full automation of the system with interface to the factory control software or MES (manufacturing execution system).



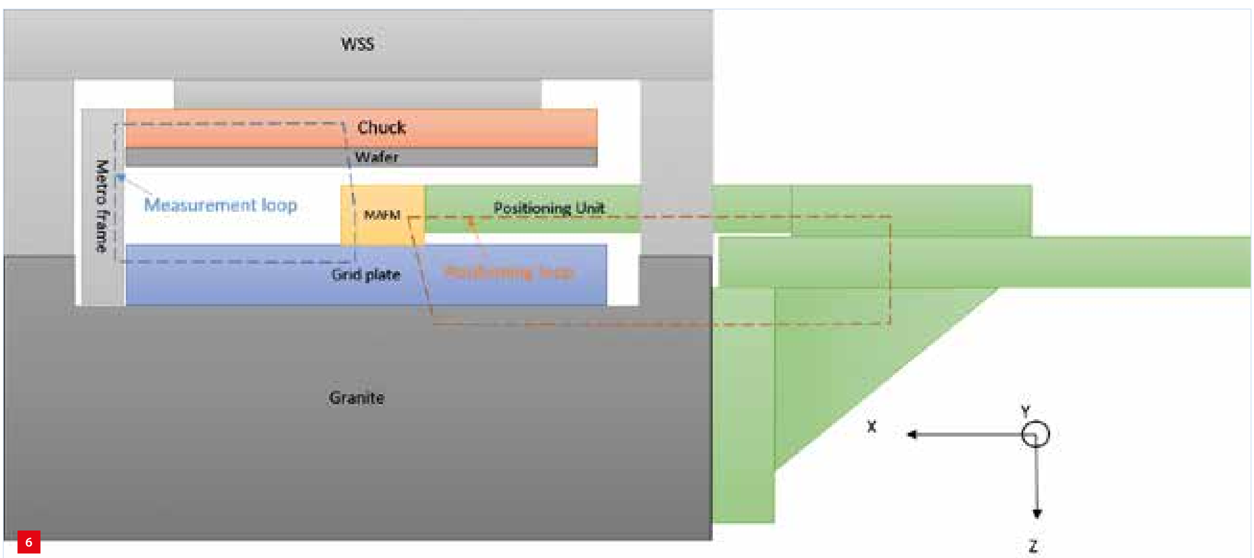
The original concept of the high-throughput metrology: miniaturised scan heads or miniature AFMs (MAFMs) being positioned to the target of interest via miniaturised, fast and accurate positioning units and parallel metrology of several locations on a wafer.
(a) Schematic.
(b) Realisation.

We have achieved a very high throughput in AFM via three developments: by increasing the speed in MAFM (miniature AFM); by increasing the bandwidth of the AFM's sub-modules, i.e., the mechanical stages (*x*, *y*, *z*), optical read-out, controller bandwidth, approach speed, and speed of positioning; and by a fast and automated probe exchange.

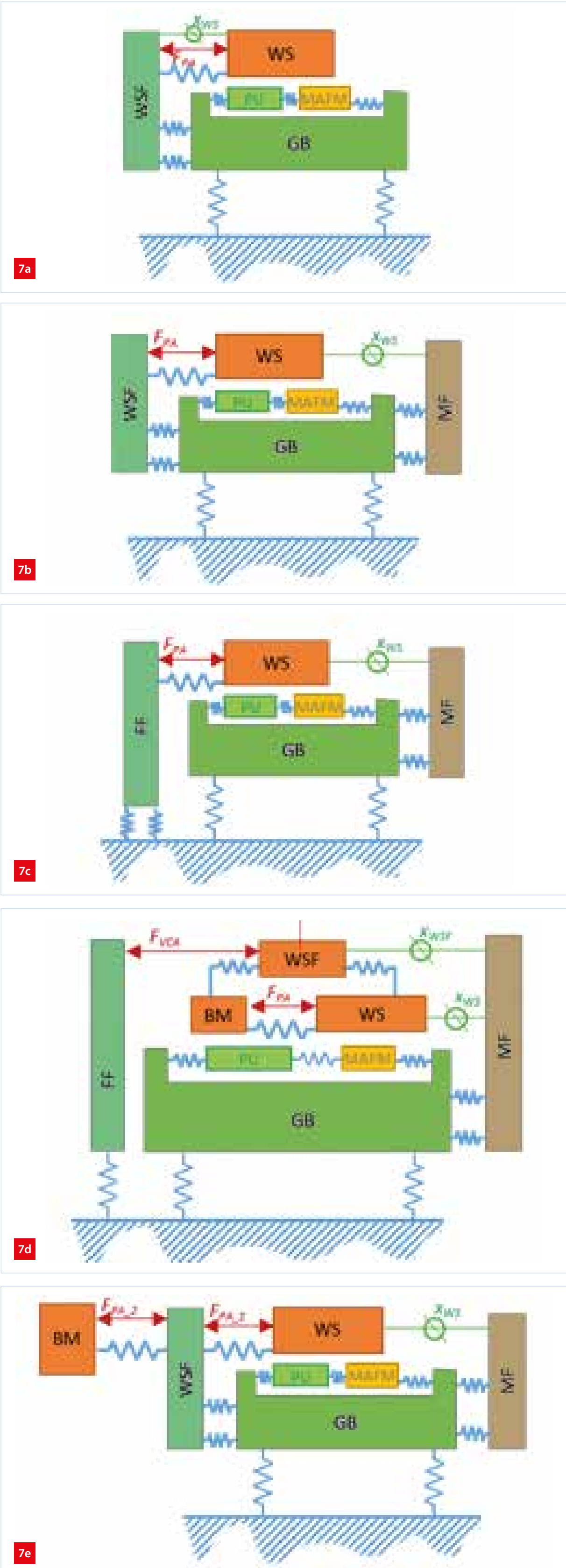
Completely fixed *x,y*-positions of the MAFMs would significantly limit the flexibility. Therefore, the MAFMs can individually be positioned relative to the wafer prior to scanning the wafer. To keep the design simple, each MAFM is positioned on a wafer by its own fast and accurate positioning unit. In this way, a set of parallel MAFMs can cover the full wafer, and they can be moved onto and off the wafer to enable loading and unloading of the wafer.

To significantly increase the measurement bandwidth while maintaining the high accuracy of metrology, it is crucial to keep the metrology loop short. Since the MAFMs are connected to a long positioning arm, the metrology loop is large and external disturbances and wafer stage reaction forces at high speeds limit the measurement performance.

We opted for an architecture to overcome this, in which the MAFMs are mechanically detached from the positioning arms during the measurement. In this way, the metrology loop becomes much shorter. But it requires the system to be upside-down such that by detaching the MAFMs from the positioning arm, the MAFM can land on the frame of the system. The two loops, for positioning and metrology, in the upside-down system are depicted in Figure 6.



The positioning loop vs. the metrology loop in the upside-down architecture.



Different dynamics architectures considered during the concept phase.
(a) Combined (single) frames.
(b) Separate metroframe.
(c) Separate metroframe & force frame.
(d) Balance mass & force frame.
(e) Balance mass.

Dynamics architecture

QUADRA dynamics architecture has been chosen to enable sub-nm metrology performance while maintaining high throughput for today and future products. The architecture must fulfil the measurement performance in the presence of external disturbances (floor vibrations, electronics noise, acoustics, thermal effects, etc.) and reaction forces due to motion stage accelerations. Five different concepts have been considered (Figure 7) and analysed, and a trade-off has been made to choose the baseline.

Our study showed that a metroframe or balance mass is likely to be required to reduce the measurement's sensitivity to vibrations introduced by "wafer scanning stage motion reversals". As a balance mass was considered more complicated than a metroframe, and a metroframe could also be beneficial for long-term machine stability measurement to improve possible future overlay measurement, the second concept (separate metroframe) was selected. The study also pointed out that the metroframe could be helpful in the vertical degree of freedom (z) as well.

Once QUADRA metrology performance and accompanying budgets were defined, a quantitative study on system dynamics was conducted. Consequently, the requirements and budgets were determined for different parts of the system, as shown in Figure 5. Next, the budgets were divided over various contributors. Figure 8 illustrates the dynamics layout of QUADRA.

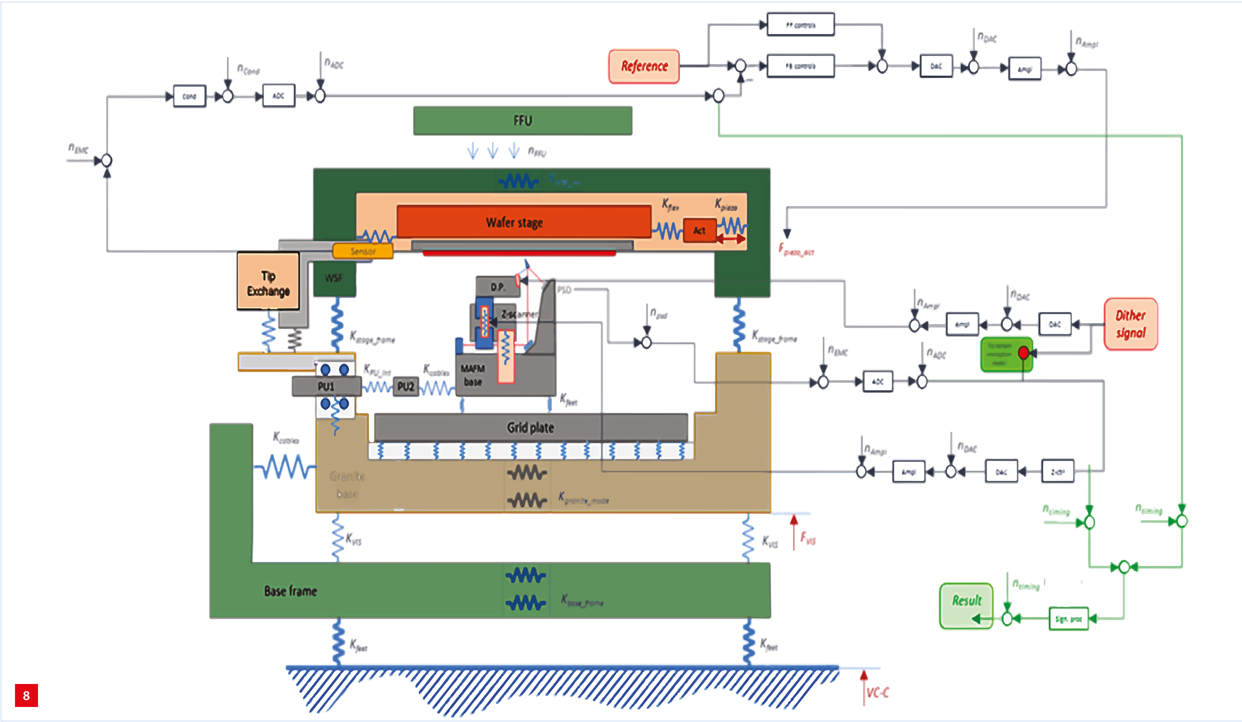
It is vital to experimentally test and validate the mechatronics design. Testing the full system at the end means that when problems occur, it is difficult to pinpoint the cause. Therefore, it is important to be able to isolate each risk/function and test it separately and slowly increase the complexity, e.g. by combining more functions. We call this early integration.

With the use of early integrations, we have experimentally validated the following:

- positioning units capable of positioning each MAFM instrument quickly and accurately on a 300-mm wafer;
- performance of the MAFMs for customer wafers, especially high-aspect-ratio structures;
- operation of four MAFMs in parallel;
- performance of active vibration isolation and the metrology loop to reduce floor vibrations, reaction forces, and acoustic and thermal disturbances.

Architecture impacts

Other vital criteria could influence the modules and overall systems considered, including required volume for mechanical layout, which determined required fab floor



The dynamics layout of QUADRA.

at the customer (affecting the cost of ownership), the volume of service and access paths needed, thermal and contamination constraints, and human and machine safety.

We considered the number of interfaces in the system. This number determines the balance between the system's performance, manufacturability, and serviceability. We also considered the complexity of modularity of the concept. This was also essential for spare parts strategy and parallel development, scalability to be used as a platform for future products, the ability to be tested (as it is vital that suppliers are able to test modules), industrialisation, and readiness (whether it is an off-the-shelf solution and has been already proven to work in the semiconductor industry).

Early software integration

The development of the software started simultaneously as the whole system's design and played an essential role in the choices we made. Automation was an essential requirement, and we foresaw that we needed to develop all systems in a close corporation. In this way, the software could shape part of the hardware development and vice versa. Also, as both hardware and software systems were developed in parallel, we could align expectations faster than if we had waited for software development and integration until the very end. By investing in early integration moments, we could find problems in our design when these were still small and could be managed. Not every system function could be thoroughly tested with the hardware then available. For these functions, we developed simulators. These simulators helped us design the functions of the subsystems.

Software architecture

We designed our software's architecture to support our overall machine development and to be aligned with the hardware architecture. This architecture resulted in a system divided over three layers of control. In the lowest layer, all real-time control of the hardware is implemented. In this layer, the 'what' of an actuator-controlled movement is translated to the 'how' of a movement (for example, with PID control loops) and high-frequency sensor readings are translated to lower-frequency quantitative measurements. On top of this layer, we implemented a non-real-time subsystem layer. In this layer, the 'what' of a subsystem is translated to the 'how' in terms of actuators and sensors.

Finally, in the top layer (machine control layer), we coordinate all functions of subsystems to be able to provide the system functions. These system functions combine different ways to realise the various functions that the QUADRA performs in a factory. This work division helped us develop subsystems in parallel and decouples the machine control layer from the actual hardware. As during QUADRA's development, we changed the subsystem's hardware design but not their function, no change to the QUADRA machine control layer was needed.

Software frameworks

At the start of the project, we realised that we could not develop a machine control software system for a new system that would also be immediately fully capable of integrating with the existing customer MES. In the semiconductor industry, the machine's communication and control has been standardised over the past 25 years by the industry-wide standards body SEMI (*www.semi.org*). This is of great benefit to our development, as we do not have to develop a custom integration system for each customer.

It also poses a challenge as the standard has grown to become big and complex. Proven solutions for factory integration and tool management are available in the market, and we based our development on a pre-existing framework. We did what we always do faced with an important choice, and we made an extensive trade-off.

The framework we have chosen has allowed us to focus on automation that is specific to QUADRA. The framework handles all common patterns for tools in semiconductor foundries (like loading wafers, interfacing with factory systems, starting recipes). One of our criteria was the implementation platform; the framework runs on .net, and we can use the high-level language C# as our systems' language.

A significant development in the high-tech machine-building industry is the use of model-driven technologies. The execution of one or more system functions can be modelled with state machines. As the complexity of a machine grows, so does the complexity of the state machines and the interaction between state machines.

Validation of a machine's correct function is hampered by the fact that hardware and software need to interact. We use a commercially available system that allows us to verify our models' correctness and to manage the complexity and move a lot of the validation from testing to proving.

Agile way of working

Above, we already described the importance of defining a minimal viable product. This concept is also closely related to the agile way of working. We developed QUADRA using the scrum methodology, with 2-week sprints. This allowed us to have predictable integration moments and be flexible on the direction of development but still deliver a working system. It also allowed the different software development teams to focus on a fixed set of deliverables per two weeks and finish these. We found that a 2-week reaction time did not fit with the day-to-day problems encountered during the final full system integration stage. We went through an adaptation period and are now partially developing using scrum and partially using Kanban methods.

QUADRA was built within a growing company. We started with a small team, relying on expert suppliers, and grew to the almost grown-up team we have now. From the start, we looked for expertise, teamwork, and good communicative skills in our candidates. We found this in people worldwide and currently have more than 25 nationalities working at NFI. In the software team, we first organised daily meetings with the whole team, but we split up teams and their meetings according to the architectural layers as we grew. We keep full team meetings on a regular schedule to stay connected and share knowledge. In 2020, we also moved from a local team in one room to a distributed remote team. We found that it is especially important to provide a safe and open working environment in such a situation as communication is more fragile in a remote setting.

Innovation ecosystem

To successfully develop and introduce a highly complex system like QUADRA, careful consideration of where to focus on as a company was necessary. This consideration was even more critical for a start-up. Where should NFI have unique added technological value? Can we include strong technological competencies available in the existing high-tech industrial landscape from other companies? As the primary strategy, NFI has a preference to do only what we are good at: the elements that form the heart of the machine and architecture and that no one else can do. All technology to make this heart tick in a complete industrial machine is outsourced to competent development partners.

We work at the limit of what is physically and technologically possible. Therefore, the network of development partners formed needs to satisfy several criteria: partners must have the right technological competences to begin with, but also a thorough knowledge of systems engineering principles, what it means to have interfaces with many subsystems developed by various parties and being capable of handling that, understanding the technical challenges the other partners have.

Furthermore, experience in the semiconductor industry with its specific requirements is essential. And last but not least, an understanding and the willingness to work in a very flexible – agile – way with a start-up like NFI, where not all processes are already in a mature state, is paramount for success. The intimate cooperation with all partners in this highly innovative ecosystem has been a key factor in enabling NFI to introduce QUADRA.

The current innovation ecosystem will keep evolving over time to keep pace with the ramp-up to series production of the existing product and new products to be developed and introduced. The next steps with the currently involved partners are to establish, consolidate and maintain long-term strategic partnerships to ensure and secure the next nodes in the NFI product-technology roadmap, volume flexibility and lifecycle management of QUADRA and subsequent platforms, and excellence in the supply chain performance areas Technology, Quality, Logistics, and Cost.

What's next?

NFI is preparing for the series production of QUADRA, to meet the market demands that have been communicated by its customers. Moreover, NFI continuously works on R&D for the next products of its roadmap. The throughput of the NFI metrology systems will be further increased on the one hand while introducing new metrology functionalities on the other hand. The next product that is currently under development at NFI is a non-destructive, nanoscale subsurface scanning probe metrology system (SSPM), targeting applications of buried void and on-product overlay metrology.

Current and future semiconductor devices have features that are buried under several layers (so-called subsurface features). Most of these layers are metal or carbon layers that are fully optically non-transparent (or opaque). Moreover, semiconductor fabs require to perform metrology on the product itself, rather than traditionally measuring on targets in the scribe-lines. NFI, together with TNO, has developed a new measurement concept by combining ultrasound excitation and SPM. In this concept, an acoustic wave (frequency in the order of several MHz to even above several GHz) is launched through the SPM tip.

The ultrasound wave interacts with the subsurface features, and the tip of the SPM can measure the effect. NFI will use the same approach used in QUADRA's development to bring SSPM to its launching customer soon.

IMPROVING HEXAPOD POSITIONING PERFORMANCE

In hexapods using six length-adjustable struts for positioning an end-effector, the compliance (or inversely, the stiffness) of individual components or structures, such as these struts, is an important performance determining factor. With increasing load of the hexapod, increasing position deviations are observed for the end-effector. A control engineering approach has been developed and tested, using a model-based calculation method (stiffness model) to compensate for the compliance and thus reduce the position deviation. Improvements by a factor of 10 to 20 have been demonstrated.

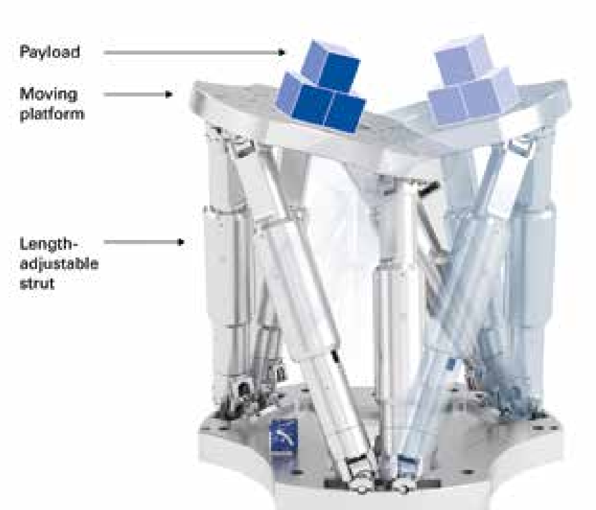
CHRISTIAN SANDER, JENS MATITSCHKA AND CHRISTIAN MUELLERLEILE

Introduction

Parallel-kinematic machines are structures with closed kinematic chains. The hexapod is a specialised version of a parallel-kinematic machine. In such a hexapod system, six length-adjustable struts enable the end-effector (moving platform) to be positioned in space along six degrees of freedom (Figure 1). Depending on the drive concept and the size of the hexapod, the range of motion extends from a few micrometers to several hundreds of millimeters and several tens of degrees. Due to their accuracy, load capacity and stiffness when moving along six axes, hexapods are used in numerous applications, such as semiconductor manufacturing, medical technology and industrial automation, and are thus an integral part of the technologies used by modern companies. [1-3]

For positioning any load in space while maintaining positional accuracy and repeatability, the compliance (or inversely, the stiffness) of individual components or structures is an important determining factor for the performance of hexapods. Figure 2 shows the stiffness distribution in one plane of a hexapod's workspace. It can be seen that the system stiffness is position-dependent and thus the position deviation due to compliance (in this case in the range of 0.127-0.106 μm/N) also depends on the position and orientation of the system. [4]

In addition to optimising the individual actuator stiffness (strut stiffness) by means of individual components with higher stiffness, and optimising the stiffness of the support structure to increase the overall stiffness, control engineering methods to compensate for position deviations are being developed and tested. These methods have been adapted for parallel-kinematic structures and validated on PI standard hexapods. The goal here is to make



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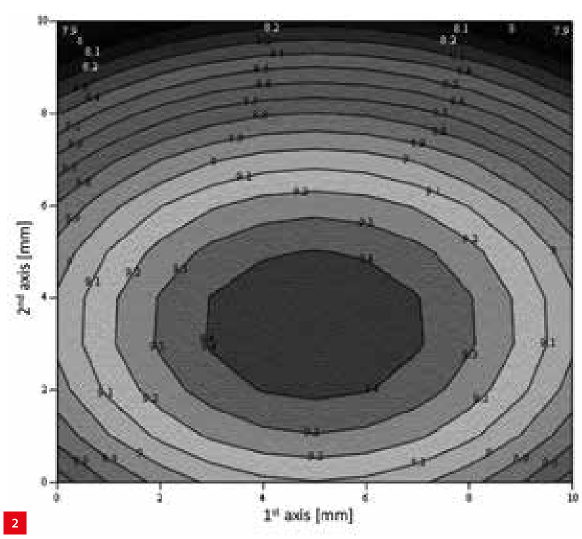
Hexapod, showing workspace and main elements.



2

Stiffness distribution (10^6 N/m) in one plane of a hexapod's workspace. [4]

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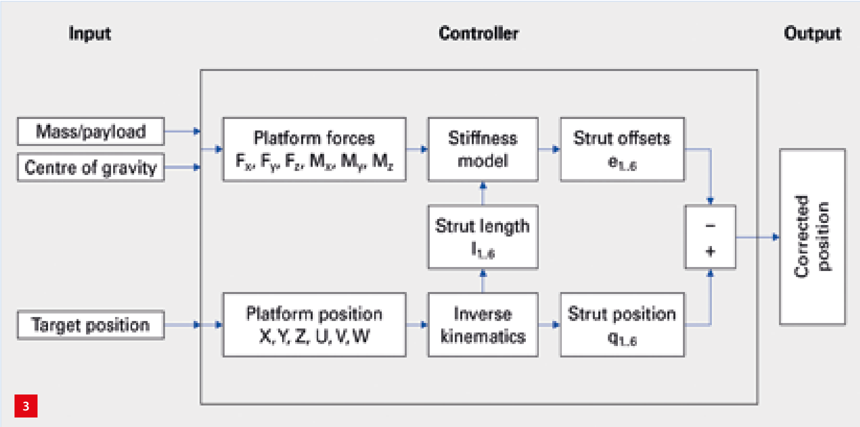


3

Model-based calculation method (stiffness model).

compensation for compliance available to customers for all PI hexapods. A reduction in the compliance of the overall system leads to an increase in the system stiffness.

The relevant influencing factors are analysed and, on this basis, a method is developed to compensate for the resulting static position deviations of the end-effector for each pose. The method presented here is based on a mathematical model and can be clearly distinguished from the increase in the geometric physical stiffness of the mechanical structure or the individual components – it should be regarded as an extension.

Concept

In the concept presented here, a model-based calculation method (stiffness model) is used to compensate for the compliance and thus reduce the position deviation. One major advantage of this approach is that no additional sensors are required. In parallel with the model-based method, approaches based on an active evaluation of measurement data are also being pursued; these are not described here.

The kinematics model and stiffness model are calculated in parallel. The latter allows the calculation of the deformation of the hexapod struts for an arbitrary pose. The compliance compensation is based on the compensation for the changes to the overall strut length, which can be calculated depending on the respective strut deflection (tension/compression resulting from its associated spring constant) and respective (scalar) strut force. For the model, the load mass, its centre-of-gravity coordinates as well as the direction of the gravity vector must be known and stored as parameters in the hexapod controller. Figure 3 shows the schematic approach on which the model is based.

The correction values are directly taken into account in the strut coordinate system and the individual actuators move to the corrected position. This also results in a corrected pose of the end-effector. The compliance is compensated for in this way and the system stiffness is virtually increased.

Implementation

In general, a hexapod can be described in terms of overall stiffness as a system of six spatially arranged bars (struts) with a finite stiffness. Bars in a framework can only be loaded in tension and compression (normal force) and cannot be loaded by shear forces or bending moments like beams. Assuming the absence of transverse connections in the strut coordinates *S*, the following relationship can be formulated:

$$F_S = K_S * \Delta S = \mathrm{diag}(k_{Sn}) * \Delta S$$

Here, k_{Sn} describes the strut stiffness in the *n* x *n* matrix of the total stiffness and F_S and ΔS are the vectors of the corresponding dimension. The absence of the transverse connections means that K_S is a diagonal matrix.

The relation between force and deformation in Cartesian space is of interest. With the help of the kinematic Jacobian matrix J_{kin} for the transformation of the forces and the oriented Jacobian matrix J_{or} in Cartesian space for the transformation of the displacements ΔS, this equation can be transformed into a relationship based on Cartesian coordinates:

$$F_x = J_{\mathrm{kin}}^{\mathrm{T}} * K_S * J_{\mathrm{or}} * \Delta X$$

Thus, the stiffness value in Cartesian space resulting from the translation of the stiffness values from the strut space K_S is:

$$K_x = J_{\mathrm{kin}}^{\mathrm{T}} * K_S * J_{\mathrm{or}}$$

However, a key component of the approach used in this concept is a stiffness model that determines the deformation per strut and offsets this value against the target position as a correction value. All rigid bodies mounted on the moving platform of the hexapod, together with the platform, are treated as one single rigid body. (The compliance of the platform is negligible compared to the strut compliance.) For the static force calculation, the rigid body is described by the position vector of its centre of gravity and by its mass. The calculation is based on the one-time input of the customer load, the centre-of-gravity coordinates of this load, as well as the gravity vector in relation to the orientation of the whole system. Via extended calculations, the forces and the compliance due to the acceleration of the rigid body can also be calculated. In this case, the inertia tensor of the rigid body must be defined.

The stiffness model transforms this vector into the strut space using the Jacobian matrix of inverse kinematics, resulting in the following relationship for the strut forces. Using the strut forces as a basis, and knowing the strut stiffness, the deformation per strut is calculated according to the equation for a linear spring:

$$\vec{F_S} = J^{\mathrm{T}} * \vec{F_x} = (f_n)_{n=1..6}{}^{\mathrm{T}}$$

$$\overrightarrow{F_S} = K_S * \overrightarrow{\Delta s}$$

The stiffness matrix K_S contains the strut stiffness on the main diagonal. If the hexapod struts are in a rotationally symmetric position, the entries for the individual strut stiffness are identical. If there is a subsequent deflection of the end-effector, the values deviate. The assumption is therefore made that a change in the strut stiffness only occurs via a change in the length of the strut. The amount of this change lies within the mean variation for the stiffness values of the struts considered here and is therefore ignored.

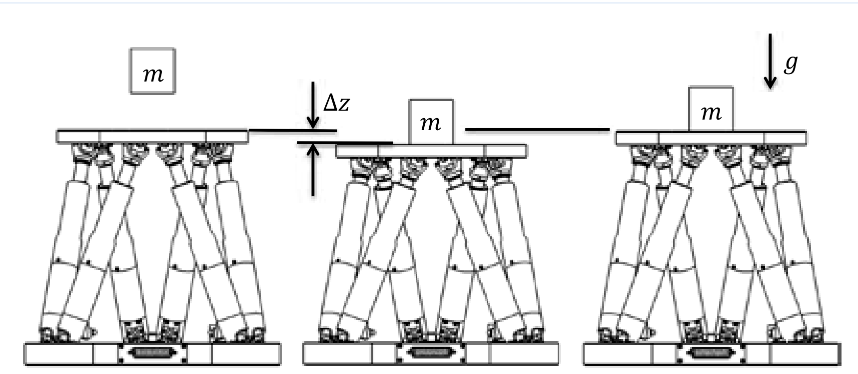
The deformation of the struts can be determined at any time via the stiffness matrix K_S and the load vector F_x. The individual deformations due to the compliance of the struts are calculated directly as compensation values on the basis of the actual strut positions.

Adopting this quasi-static compensation approach for a positioning hexapod by means of the stiffness model means that no additional parts or design changes are necessary. This approach can be directly applied and implemented via a one-time extension of the kinematics calculation to include the stiffness model.

Experimental validation

Validation on a horizontally standing system

For the experimental validation of the concept described above, a load test was performed on a hexapod with known strut stiffness. This hexapod stood horizontally on a flat surface in such a way that the moving platform was also aligned horizontally. The gravity vector and the *z*-axis were parallel to one another. Defined masses of 10 kg, 20 kg and 30 kg were applied to the hexapod and the position deviation of the end-effector was recorded at three measuring points using dial gauges. The three states during the load test are shown in Figure 4.



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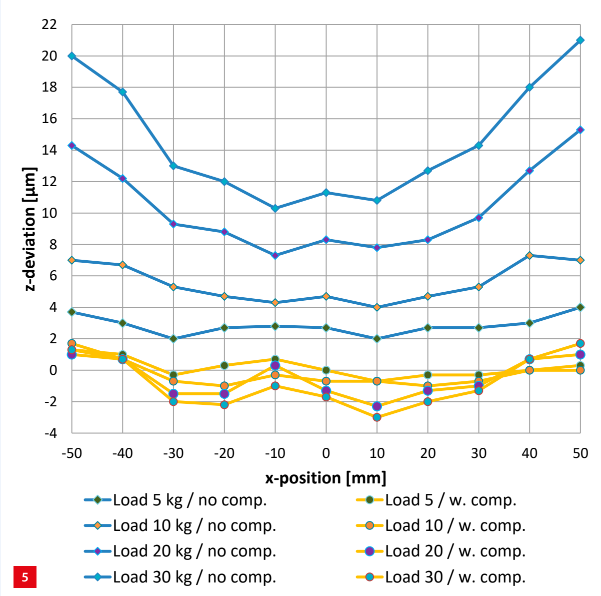
Load test with and without compensation

The hexapod was referenced in the unloaded state and the position value was zeroed in the INI position. In the next step, one of the masses described above was placed centrally on the cover plate and the change in position Δ*z* due to the compliance was measured. The stiffness model was then configured and enabled in the hexapod controller, and a second measurement of the position change was taken. This measurement procedure was repeated for different positions in the hexapod's workspace (defined in terms of deflection in the *x*-direction), whereby poses were approached along the Cartesian main axes in sections, each with 10 mm intervals.

This procedure was carried out for different masses. In order to reduce thermal influences and minimise settling behaviour, measured values were acquired for the uncorrected and corrected state within a short time window. Furthermore, the system was referenced after each measurement run to provide a consistent initial situation for each measurement. The results allowed a direct comparison of the corrected and uncorrected state.

In Figure 5, typical position deviations as a result of different loads are plotted as averaged error values over a wide range of *x*- (deflection) positions.



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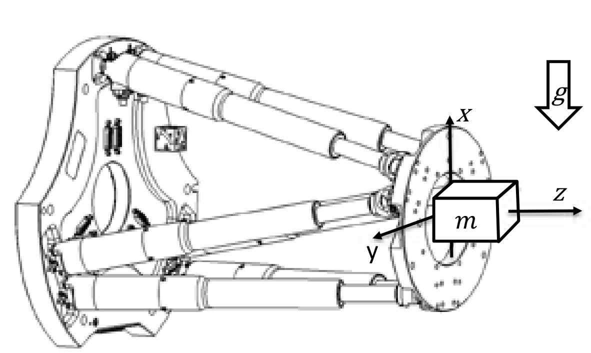
Compensation for compliance using a stiffness model; the horizontally standing system case. Comparison of the uncorrected (no comp.) and corrected (w. comp.) position deviation of the end-effector for different loads over a range of x- (deflection) positions.

It can be seen that the deviations in the z-direction systematically increase with higher mass and a greater x-deflection. The maximum position error in the uncorrected case is 21 µm and occurs at a maximum load of 30 kg at the edges of the workspace. If the corrected values are considered, the position errors are at a constant level of ±2.5 µm around the zero position. The measurement with the dial gauges used here (having micrometer resolution) reaches its limits in this range, resulting in a measurement error of a similar size; use of an interferometer (see below) could have yielded even more precise results. The experimental validation of the compensation concept shows very good results. The position deviation due to compliance can be reduced by a factor of 10 in this set-up for this exemplary movement.

The fluctuations in the compensated positions around the zero position are noticeable. A significant cause of this might be the deviation in the centre of gravity between the model and the load actually applied. Manual application of the load weights on top of the platform can cause deviations with respect to the expected centre of gravity, causing the actual forces to deviate from the expected theoretical forces and ultimately resulting in fluctuations in the corrected level. This hypothesis needs to be proven in additional experiments. Furthermore, there is a variation in the stiffness of the six real struts, which was not taken into account. Manufacturing and assembly-related influences, such as backlash as a result of manufacturing tolerances or preload of angular contact ball bearings, will have an effect on the individual strut stiffness.

Validation on a suspended system

As an additional experimental validation of the concept, a load test was performed on a hexapod with known strut stiffness mounted on a wall and the x-axis pointing in the negative gravity vector direction (x_{up}, Figure 6). The hexapod was loaded with a mass of 2.46 kg and the position deviation of the end-effector was recorded with an interferometer. One measurement consisted of three steps:



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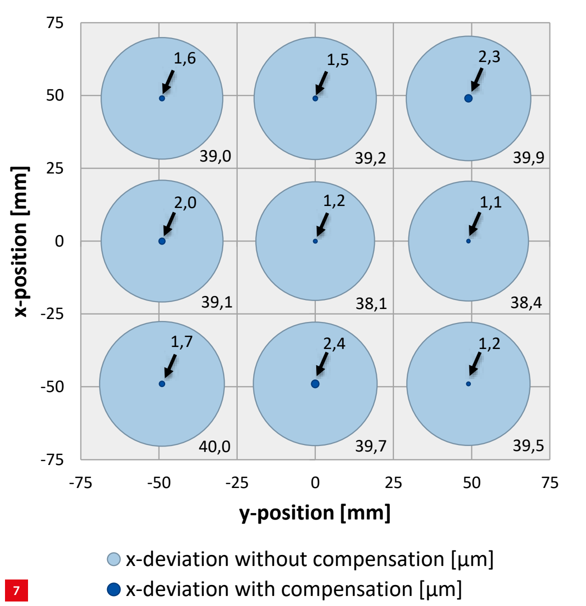
Hexapod x_{up} load test.

1) the hexapod was referenced in the unloaded state;
2) the mass described above was placed on the top plate and the position change due to the compliance Δx was recorded;
3) compensation was enabled in the hexapod controller and the position change was again recorded. This measurement was repeated for different edge positions in the workspace.

Figure 7 shows the position errors for a fixed z-position as a function of the x- and y-position (as an example). The centres of the circles correspond to the xy-position, the diameter of the circle represents the position error in the x-direction. The maximum deviation in the x-direction in this example is 39.5 µm (light blue circle). Activating the compensation reduces this value by a factor of 20 to below 2 µm, the circle being reduced to a dark blue point in the display with the same scaling in Figure 7. The comparable diameters of the two circles over the workspace show that the stiffness has been significantly improved over the entire workspace on this scale.

Feasibility and limitations of the method

The approach using the theoretical model is very successful. Maximum position deviations of 21 to 40 µm are corrected to a level of 2 to 5 µm, which corresponds to an improvement by a factor of 10 to 20. Furthermore, the expenditure in terms of integration and costs is low. One disadvantage is the required additional effort for the user. It is necessary to specify the magnitude of the masses as well as their centre-of-gravity coordinates, since this data is required input information for the stiffness model. This can usually be derived from a CAD model; otherwise it must be determined experimentally. The centre-of-gravity



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Compensation for compliance using a stiffness model; the hexapod x_{up} load test with 2.46 kg, z = 0. Comparison of the uncorrected and corrected position deviation of the end-effector over a range of x- and y- (deflection) positions.

coordinates in combination with the position on the end-effector are identified as a source of error.

In order to optimise the model in a way that excludes errors and additional costs, additional investigations are carried out to determine the strut forces directly. However, this requires additional components, which ultimately increases the manufacturing costs for the system. Therefore, it is necessary to check for each individual case which concept is best suited to the application in question.

The approach described here was designed for hexapods used for positioning tasks. Approaches to compensate dynamic effects are being elaborated. Additional external forces and moments have not yet been considered, but can be implemented in the future as needed. These include, for example (in increasing order of modelling complexity):

- A force that is constant with respect to its point of application and orientation.
- A constant moment of inertia.
- A force with a constant direction, but a wandering point of application.
- A force with its point of application at the TCP (tool centre point) and the orientation of the TCP.
- Influence of milling and cutting operations as a function of machining speed.

REFERENCES
[1] Gloess, R., "Hexapod Strukturen mit Mikrometer-Genauigkeit", *Chemnitzer Parallelstruktur Konferenz*, pp. 63-69, 1998.
[2] Gloess, R., and Lula, B., "Challenges of extreme load hexapod design and modularization for large ground-based telescopes", *Proc. SPIE Int. Soc. Opt. Eng.*, 7739, pp. 327-330, 2010.
[3] Rudolf, C., Haase, Th., Gloess, R., Klein, S., and Huber, S., "Directly Driven Hexapods for Highly Dynamic 6 DoF Applications", *Proc. euspen's 15th International Conference & Exhibition*, pp. 217-218, 2015.
[4] Neugebauer, R., in Neugebauer, R. (ed.), *Parallelkinematische Maschinen*, VDI-Buch, Berlin/Heidelberg: Springer-Verlag, 2006.

SiC IN HEL

Silicon carbide (SiC) optics are becoming more and more prevalent in high-energy laser (HEL) designs, so it is important that manufacturers are aware of the potential risks when using these materials early in the product development process, thereby avoiding what could be costly and time-consuming problems if discovered too late. Exactly what is possible, and what solutions (and traps) are out there?

MIKE ALBRECHT AND JOE SALEMI

The key to success in SiC optics development is to be well informed when it comes to partner selection and material selection, as this will help mitigate project risks especially early on in the design phase. This is vital as SiC is not a standard "buy, grind, and polish" material. There are many nuances when designing and manufacturing a SiC optic, so the sooner customers access expert feedback from an experienced optical manufacturer, the lower the risk to their projects. The chosen optics partner should employ a multi-faceted approach ensuring that design, fabrication, coding, and metrology issues are all navigated successfully.

Why choose SiC?

SiC excels in HEL applications, space-based telescope applications, and applications in high-acceleration and thermally variable environments. This is because it exhibits high specific stiffness with a low coefficient of thermal expansion (CTE), excellent thermal stability (desirable so that heat absorption does not affect the beam path), resonant frequency advantages over materials like Zerodur (a key attribute for HEL applications undergoing acceleration), and it can be formed into complex shapes. In addition, it is non-toxic, unlike a key material with similar attributes, beryllium.

The anatomy of a SiC optic

The mirror face of the SiC optic is made up of the face sheet with a cladding material deposited on top prior to polishing (Figure 1). Bare SiC usually doesn't meet the surface quality or roughness requirement needed for a laser-quality surface, and this is why the cladding is added.

1 The mirror face of a SiC optic.

Cladding should uniformly extend to the edge of the substrate, and during the design phase it should be considered whether an incidental overcladding on the edge is permissible, and the implications of this in terms of manufacturability, cost, and lead time should be included in the analysis. Cladding thickness must also be taken into account from the perspective of potential reworking and finishing processes required.

The substrate

When choosing the substrate material it is important to realise not all SiC is the same. There are many different 'flavours' as there are many different ways of manufacturing SiC substrates, each having different parameters in terms of strength, stress, and other design considerations. Different flavours have different cost structures and lead times, and there are several general processes used to create SiC substrates with proprietary technology used by individual substrate manufacturers.

So, the primary concern of the end user should be the specific properties of a particular SiC, and whether the manufacturing technique is compatible with the type of optic required. The pre-clad surface quality of the chosen substrate is also a huge consideration. Substrate flatness concerns and subsurface damage of the pre-clad mirror face can lead to extra optical fabrication down the line.

Cladding

The two most common claddings are chemical vapour deposited (CVD) SiC and silicon. Silicon cladding produces a lower surface roughness and better surface quality, but it introduces a CTE mismatch. Silicon cladding also tends to be thin (less than 30 microns), so it conforms to the base substrate very well, which, however, does not leave much room for potential rework in the event that a defect is picked up during the manufacturing process.
CVD SiC can yield a good surface figure, but it is limited in roughness and surface quality due to the porosity of the cladding. It does tend to be thicker (over 100 microns), so it conforms a little less to the shape of the base substrate, but may give some leeway in the event that there is some rework needed. Voids, pits, and inclusions in CVD SiC cladding can also affect quality.

AUTHORS' NOTE

Michael Albrecht (optics product line director) and Joe Salemi (OEM sales manager) are both associated with Zygo Corporation, headquartered in Middlefield, CT, USA. ZYGO, part of the Ultra Precision Technologies Division of Ametek, is a worldwide supplier of optical metrology instruments, high-precision optical components and complex electro-optical systems.

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Mechanical features and mirror geometry

For an optical manufacturing partner to quote realistically, required mechanical features and mirror geometry must be clear. As such, it is always best to include up front not just drawings showing optical and mechanical requirements, but also the 3D CAD solid model which helps in evaluating the manufacturability of the specific application.

When evaluating manufacturability, the face sheet thickness and the lightweighting rib structure need to be assessed. Designers tend to always want to keep face sheet thicknesses as low as possible in order to keep the mirror as light as possible, but there is a fine line here because a very thin face sheet can cause lightweighting ribs from the backside to print through to the optical surface.

In terms of the lightweighting rib structure (see Figure 2), the wall thickness of the ribs is limited by certain substrate manufacturers, so if there is a tolerance that is a "must have", then that might steer towards one manufacturer over another. Different suppliers have different parameters for the cross-section thickness, volume, etc.

Other factors to consider are centre of gravity and mass moment of inertia; how the mirror will be held, using either threaded holes or inserts; whether additional machining will be necessary after the substrate is formed. Finally, with dimensional tolerances it is better to try not to overspecify non-critical features when working with SiC. Sometimes one can get away with this with other ceramics, but with SiC it is better to keep it simple.

Optical and coating requirements

In optical manufacturing, it is crucial to translate a customer's system level requirements into an optical tolerance for the mirror. As an example, the closer the aperture is to the edge of the optic the higher the cost, and there are several other considerations such as slope or surface roughness that need to be evaluated based on beam size and laser power.
When looking at thin-film coatings (Figure 3), the basic coating considerations include required spectral performance, critical wavebands, angle(s) of incidence,

2

The back of a SiC optic.

3

A coating chamber at ZYGO.

polarisation, laser damage, durability, quantity of deliverable witness samples, and environmental factors. It goes without saying that it requires experience to marry all these considerations together.

Also, HEL applications typically require low-loss coatings, which can be stressful on an optic with CTE differences between the substrate and thin-film coating. The reflected wavefront may be distorted after the coating has been applied. Engaging the optics partner early in the design process will help mitigate the effects of coating stress, for example by using his capability to measure and compensate for that stress. Post-coating metrology may be problematic if there is no metrology equipment available at the wavelengths needed. Without it, it may not be possible to know if the optic meets required performance criteria until it is integrated into the system, and this is the wrong time to find out that there is a problem.

Such issues are best mitigated during the design phase. Compensation techniques that can be used include finite-element analysis, sample surrogate coating tests, polishing a bias into the cladding, stress compensation, and coating on the backside.

Summary

When embarking on an HEL optics application, optical manufacturer selection is key to success. Suitable candidates should be viewed as a design partner, not a job-shop supplier, and must have extensive knowledge of the material properties and design parameters for the different flavours of SiC; no vested interest in promoting one specific type of material over another; attention to detail on cladding type and cladding requirements; metrology capabilities; the engineering resources to predict and mitigate common issues such as coating stress and print-through; the project management expertise for these types of applications; and also the thin-film coating expertise, all under one roof. Vertical integration is key.

LEADING THE WAY INTO A BRIGHT FUTURE

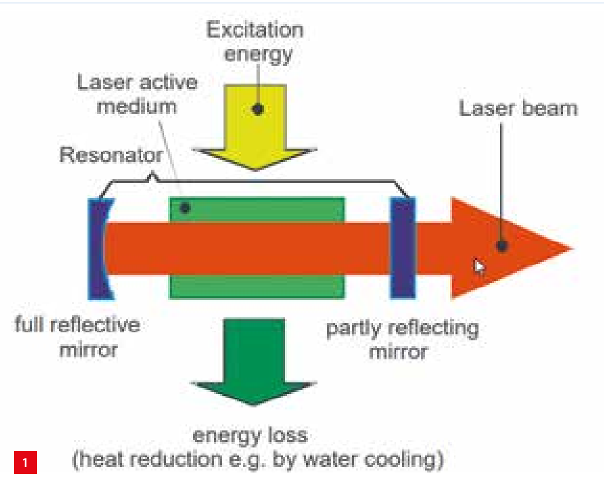
Sixty years after its inception, laser technology is still steadily evolving and a large number of industrial applications have been developed over this period. In recent years, institutes and manufacturers have presented a tsunami of innovations around this powerful source of light, regarding knowhow, technology and practices. For laser-based materials processing, the continuous evolution towards shorter wavelengths stands out, as opening up a wide 'supply' of dedicated wavelengths fitting major contemporary practical purposes. Furthermore, laser quality has increased, efficiency has surpassed 50% and performance has improved spectacularly even with a decreasing laser footprint, while functionality expanded considerably in micro- as well as macro-applications.

JAN WIJERS

A bit of history

After World War II, quite a number of researchers worldwide invested their energy in inventing a laser technology – building on Einstein's discovery of the phenomenon of stimulated emission in 1917 – and they actually made a lot of progress. Nevertheless, it was 1960 before Theodore Maiman of the then famous Hughes Aircraft Corporation Labs made the very first active laser a reality and lit it for mankind. It was classified as a glass-type laser with a ruby crystal as the lasing medium.

In its early days, this unique invention (Figure 1) was qualified as sort of a 'solution to a non-existent problem'. At first, research into medical applications boomed. Five to ten years later, high-powered specimens of the new laser light source hit the market in professional configurations, with sheet metal cutting being the first industrial task for this new, advanced tool.



1 *General laser principle showing the main components. (Source: SLT)*

AUTHOR'S NOTE

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Machining drive

At that time, conventional machining or chipping was already at a respectable level, while worldwide R&D was running for further improvement. New non-traditional technologies, such as EDM (electrical discharge machining), ECM (electro-chemical machining), WJM (water jet machining) and USM (ultrasonic machining), also came out in the open. They were applied, for example, to master in particular those jobs where intrinsic blank hardness and miniaturised dimensions became a critical problem – concerning tool wear, process forces and quality – with materials such as tungsten carbide and hardened and cold-drawn steel.

However, the long, slender, 'sharp' and in itself weightless laser beam proved to be able to execute all these demanding tasks, while also reaching further down – with a larger aspect ratio – without being bent or displaced, as compared to a solid cutting tool that produces chips. A typical example is the profiling and drilling of diamond, which could be done using spark erosion preceded by the graphitisation of a thin layer. It is extraordinary that a 'soft tool' such as the intense radiation of a Nd:YAG or an excimer laser could also execute the job, without pre-treatment and leaving no traces of converted graphite.

In the machining industry, new base materials were introduced over the years, including titanium, tungsten carbide and hybrid materials such as fibre-reinforced aluminium composites. Many of these materials are brittle and hard to machine; they require specials tools and cause considerable tool wear, thereby reducing flexibility while increasing processing time and costs. As a flexible, no-wear technology, laser machining became the preferred option for these materials.

It is striking that currently an increasing selection of conventional high-end machine tool producers – e.g. Kern or KLM, Makino, Elb, Mazak, GF and Vollmer – are (on the way to) integrating some kind of advanced laser technology into or onto their 3- and 5-axis machining centres, for processes such as engraving, welding, deburring, hardening, structuring and additive manufacturing (AM).

Exploiting the full availability of different laser implementations over time initiated an increasing number of applications in machining, (tele)communication and Internet-of-Things data technology, medical technology and metrology. The laser proved to be a perfect tool – both technically and economically – for delivering energy in the demanded format to exactly the one or more spots where it is needed. Light as a ground-breaking, powerful energy source will continue to push frontiers in many key enabling technologies during the 21st century.

Conventional versus laser light

LASER is an acronym for 'Light Amplification by Stimulated Emission of Radiation', covering part of the electromagnetic spectrum. The main difference between a laser and a conventional light source is that a laser intrinsically emits highly directional, monochromatic light (i.e. at one wavelength only). A laser beam has a very small divergence, its light is coherent in time and space – regarding direction, phase and wavelength – and the beam has a high intensity, whether it is produced in continuous wave (CW) or in pulsed mode. Its good focusability onto a small focal spot is another highly valued merit.

Design for laser manufacturing

By comparison, energy density (W/m^2) is 10^3 for sun rays, 10^{10} for EDM pulses and 10^{12} for an electron beam, while a laser beam is able to deliver 10^{12} up to 10^{20} W/m^2, representing an incredible amount of power. Wavelengths used by the various lasers cover the visible light range – approximately between 380 and 750 nm – as well as the infrared (IR) and ultraviolet (UV) range of the electromagnetic spectrum (Figure 2).

In the end, it is the – mainly thermally based – application that dictates the particular choice of laser, in terms of sufficient quality at an acceptable price. Making the selection for a particular laser beam to fit an application is certainly not easy. The benefits of laser applications, such as the larger range of materials available for machining and the increased flexibility, have a strong positive influence on engineering and designing new goals with fewer constraints for both actual as well as new products, apparatus and machines. To exploit these advantages, a dedicated design-for-laser-manufacturing approach and matching mindset is required.

Basic physics

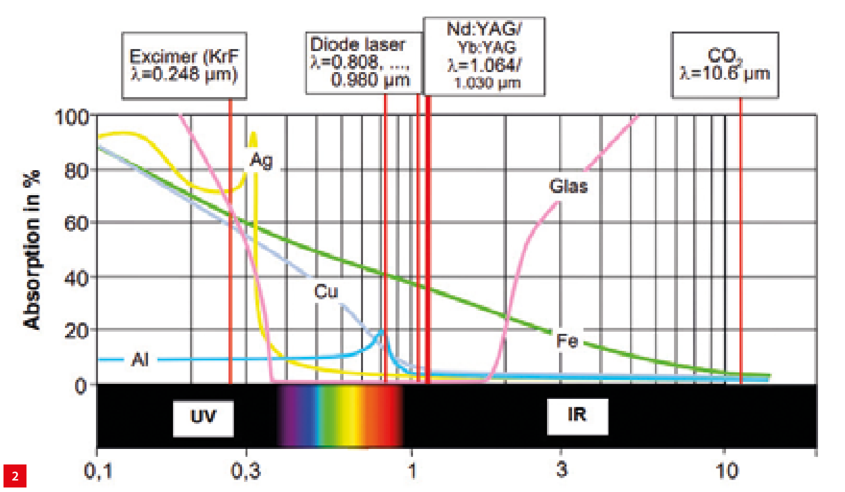
The LASER acronym explains that a laser produces light through stimulated emission of radiation, by means of an active gas or a solid-state medium confined inside a so-called resonator (Figure 1). This consists of two in-line mirrors, one fully reflecting (the rear mirror) and opposite it one partly transparent (the output mirror), which determines the amount of laser power that becomes available. By way of transmitting or 'feeding' energy from the outside into the medium – 'pumping' in jargon – a (stimulated) emission of light at one specific wavelength is brought about. The photons thus produced are reflected back and forth between the two mirrors, while each time part of them passes the output mirror and exits the laser.

In practice, the majority of applications in material removal (machining) are based on efficiently converting as much as possible of the energy projected onto the workpiece into just sufficient heat to do the required job properly, while preventing any possible harm; quite a delicate balance. Even more so because of the effect that the incident beam at the surface is spent – to a material-specific degree – on reflection, absorption and transmission, respectively. All imaginable physical effects do occur during the interaction of the laser with the workpiece surface, ranging from heating (the main aspect in hardening) and melting (in drilling) to evaporation through ionisation (in ablation), sublimation and immediate dissociation (in structuring).

Advantages

Advantages of laser technology include:

- Universality in practical use.
- Short switch-over.
- Contactlessness, independent of mechanical properties.
- 'Cold' as well as 'hot' applicability.
- No-wear 'tool'.
- High reproducibility.



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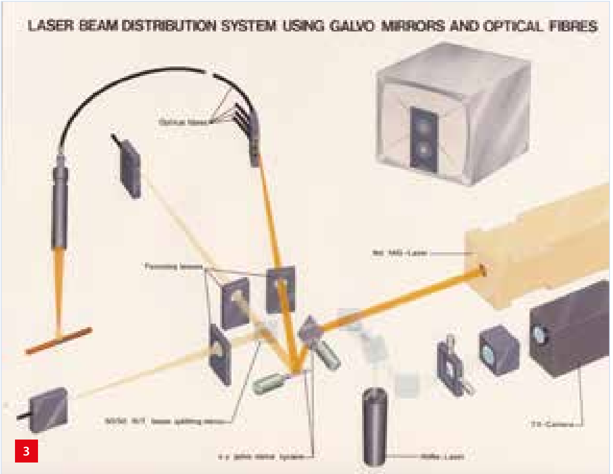
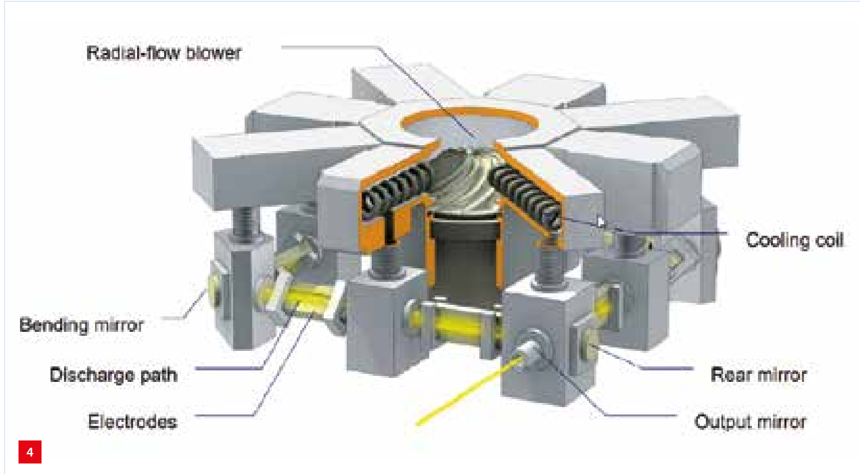
The relevant part of the electromagnetic spectrum, showing emission lines of lasers and absorption curves of various materials.



Optical beam splitting, with one single power source feeding several 'output stations.' (Source: WISE 2000)



Cross-section of a fast-flow CO_2 gas laser; fast-flow refers to the internal fan-induced gas flow for optimal mixing and cooling. (Source: Trumpf)

- Low weight, making accurate, ultrafast and dynamic 3D manipulation feasible.
- Direct deployability, without (time- and energy-consuming) warm-up.
- High flexibility (regarding power, position, spot, geometry and speed).
- Easy optical beam splitting, with one single power source feeding several 'output stations' (Figure 3).
- Digital fit for Industry 4.0 (integration in the digitalisation and big data trend).

Gas lasers

As the different types of laser configurations are rather numerous – CO_2, HeNe, Nd:glass, Argon-ion, ruby, etc. – only those that are dominant in industry and research are worked out briefly below; see Table 1 for an overview. A standard high-power CO_2 gas laser with 2-20 kilowatt power, DC- or RF-excited, like the one in Figure 4, with the robust and folded resonator (folded for minimising length and footprint) and an integrated and shielding beam guide, is a top-quality, high-tech machine, operating reliably with good beam quality in the IR spectrum at a wavelength of 10,640 nm (see Figure 2). Its efficiency η varies in line with its specific configuration from 10-15%, whether operating in continuous wave (CW) or pulsed mode.

It is still without doubt the go-to, relatively low-priced flat-bed workhorse in the sheet metal industry, producing products of an excellent cutting quality in a wide diversity of materials and thicknesses. Guiding the IR beam to the work spot and compensating for the varying beam length for obtaining a stable spot can only be effectuated by means of a not-so-flexible, bulky combination of flying optics and protection measures. In the infrared, guidance with a far more flexible fibre cable comes with too much intensity loss and, therefore, is unsuitable. Another drawback is that the laser gas – being a mixture of helium, nitrogen and CO_2 – requires frequent handling; this includes sampling the composition and refilling, and is a quite cumbersome necessity. Currently, the CO_2 types are gradually being overtaken by younger alternatives, except in specific (high-power, pulsed) applications such as ASML's EUV generator.

The excimer laser (excited dimer) also belongs to the gas-laser division, operating with an efficiency that runs around 1-3%. They operate at various UV wavelengths – solely in

Table 1
Overview of high-power laser configurations with their main industrial applications.

Medium*	Efficiency (%)	Power (kW)	Wavelength (nm)	Applications
Gas / CO_2	10-15	0.05-100	IR: 10,640	Micro/macro 2D/3D cutting, welding, surface treatment, EUV-generation (lithography)
Gas / excimer	≤ 2	1	UV: 157 (F_2), 193 (ArF), 248 (KrF), 308 (XeCl), 351 (XeF)	Micro/precision fabrication, drilling (inkjet nozzles), perforation/ablation
Solid-state / crystal/glass, Nd:YAG**	1-20	< 10	Near IR: 1,064	Micro-welding, -cutting and -drilling
Solid-state / active fibre (diode-pumped)	~30	1-20	Near IR: 1,030-1,070	Cutting, drilling, welding and marking
Semiconductor / diode	30-50	≤ 20	Near IR: 800-980	Precision machining
		1.5-3	Visible (blue): 450	Welding of copper and dissimilar metal combinations
		> 1.5***	Visible (green): 515	AM of copper

* All laser types can be used in CW as well as pulsed mode (ultrashort pulsed mode with fibre and diode lasers); excimers are mainly operated in pulsed mode.
** Three versions: rod, slab, disk.
Pulsating mode: Q-switched (1,064 nm), frequency-doubled (532 nm) or -tripled (355 nm).
*** Disk version.

Elaborated complete fibre beam delivery system. (Source: HIGHYAG)

pulsed mode in microlithography as an application field, amongst others – with a high-pressure gas mixture inside, consisting of a halogen gas and a rare gas (i.e., the dimer), for example XeF (xenon fluoride) at 351 nm, KrF (krypton fluoride) at 248 nm and ArF (argon fluoride) at 193 nm.

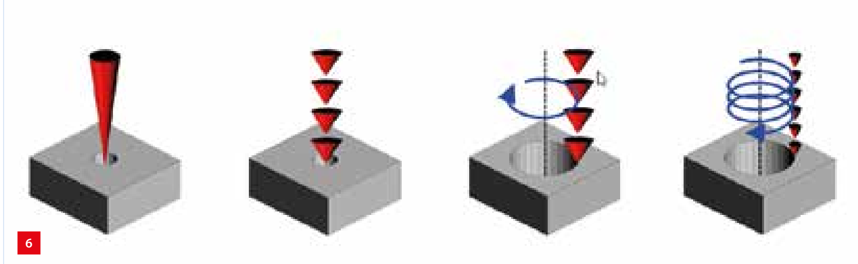
Solid-state, fibre or diode

The more costly Nd:YAG solid-state laser uses a flash lamp or diode to pump a neodymium-doped transparent substance (yttrium aluminium garnet) as its medium. At lower operational costs, as compared to the aforementioned gas lasers, in general it uses a rod as a resonator and will transmit at the 1,064 µm wavelength at a mean 4-5 kW power, with η = 3-15 %. Being in a so-called frequency-doubled or -tripled state, this laser transmits at 532 or 355 nm, respectively – aside from the originally often-used Q-switching mode. Two alternative versions of this solid-state laser, both offering good beam quality, are identified by the names 'slab' and 'disk', reflecting the polished outline of the specific resonator: a rectangular bar and a thin disc, respectively. Use of a flexible, totally internally reflective glass-core fibre for beam delivery to the actual work spot over a considerable distance is normal practice with this kind of industrial light source (Figure 5).

Recently, two mainly electronics-based, easily controllable, high-efficient power sources with high potential and low service costs came out of the labs. These are the far more compact, robust and efficient cladding-pumped fibre lasers (η = 30%; natural cooling, reduced spot size) and the upcoming diode (or semiconductor) types (η up to 50%; fluid cooling through integrated microchannels). They can be assembled from existing, easy-to-handle and easy-to-scale-up electronic modules. These newcomers leave behind the initial barriers of laser technology, such as large dimensions, inflexible and massive free-standing components, separate cooling units, semi-mechanical-electrical controls and service sensitivity.

Applications

State-of-the-art and next-generation industrial fabrication

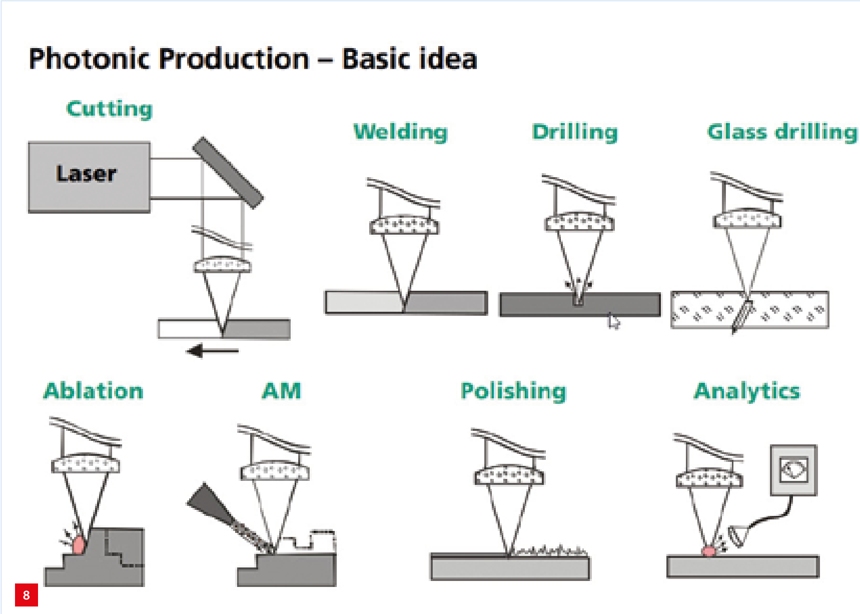


Four laser drilling modes: single-pulse, percussion, trepanning and helical. (Source: SLT)

applications of laser technology, from the macro- and micro- down to the nanoscale, include:

- 2D and 3D cutting.
- Drilling (Figure 6) and perforating.
- (Laser-assisted) turning.
- Joining: welding (including micro- and hybrid), soldering and high-temperature brazing.
- Deburring.
- Ablating (surface micromachining, Figure 7).
- Marking, by means of masks.
- Engraving (free-moving laser beam using mirrors or galvo-scanner motion).
- Etching, by way of a reactive gas or fluid.
- Polishing.
- Surface microfunctionalisation (e.g. texturing and graining: visually, haptically and in a tribological sense [1]).
- Balancing.
- Dressing (profiling and re-sharpening grinding wheels).
- Scribing (wafers).
- Wire stripping.
- Cleaning (even under water).
- Cladding (applying wear-resistant, hardness-enhanced or tribologically improved layers, or re-engineering).
- Heat treatment (hardening, annealing, ...) and other material transformations.
- Substrate surface modification (alloying, diffusion, ...).
- Glazing (rapid self-quenching of a laser-molten layer).

Ablated revolution counter in 'day-night' design.



Some of the major industrial fabrication applications of laser technology. (Source: ILT/AKL)

- 3D printing (AM) of metals, plastics, amorphous matter and so on, in various formats:
  - PBF: powder bed fusion;
  - SLS: selective laser sintering;
  - LMD: laser metal depositioning.

From these, major applications are visualised in Figure 8.

Developments

A number of major advances in the field of laser technology are certainly worth highlighting here. It can be noted that the operational pulse-to-pulse stability has increased significantly, in combination with improved laser beam quality – as every user knows, reproducibility is an absolute requirement in most production chains.

These days, quite a line-up of high-energy, (ultra)short-pulsed laser types are at hand, with pulse duration ranging from milli- (ms: 10^{-3} s), micro- (µs: 10^{-6} s) and nano- (ns: 10^{-9} s) down to pico- (ps: 10^{-12} s) and femtoseconds (fs: 10^{-15} s). The latter (ps and fs pulses) are bringing 'cold' machining within reach, even when using a principally 'thermal tool', for example in micromachining application such as ablation and surface microstructuring. The interaction time is so short that the energy beamed in does not get time to penetrate deeper than into a thin top layer of the material.

Copper

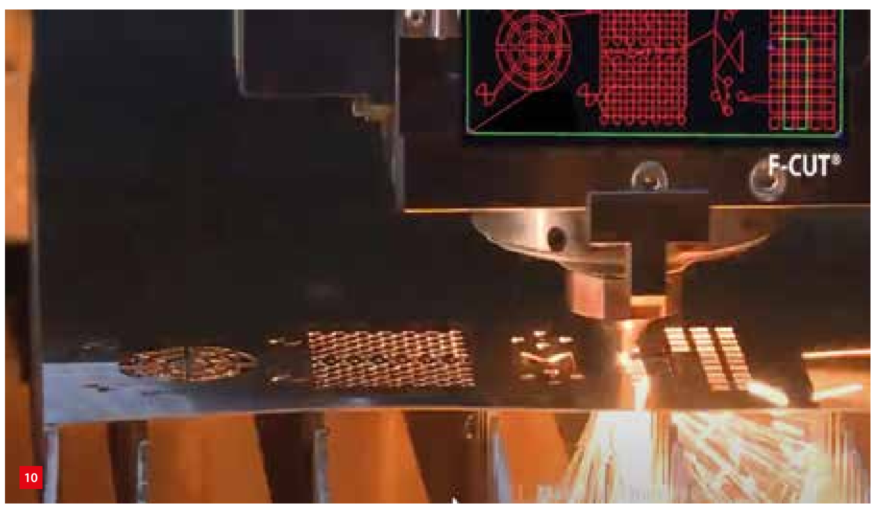
As a base material in the periodic system, the chemical element 29 (copper, Cu) stands out for its optimal, low-loss conductivity of both electricity and heat. For example, new types of high-efficiency heat exchangers made from copper are on the road to mass production, in some cases using laser welding, while the more complex configurations can at last be 3D printed, also using a laser.

Also relevant is the e-mobility trend away from fossil fuels. This boosts especially the manufacturing of automotive e-drives – which use a very different type of coil windings requiring an advanced joining technique involving the 'shooting' of copper wires with a square cross-section into the iron packet and laser welding the so-called 'hairpins' (Figure 9) [2] – and brake systems, as well as potentially more powerful solid-state battery packs and charging and energy-storage stations. Their production features a lot of laser welding of copper, for example of cyclic loading-resistant copper microjoints (5 to 15 µm thick) for battery cells, modules and packs both on the anode and cathode side, and in the necessary power electronics. The specification of the required quality of all those welds in sheet, strip and foil material has also boosted laser engineering in the blue and green wavelength range.

Cutting needs welding

This has brought welding as well as sheet metal cutting (Figure 10) back into the spotlight for lightweight car body

BMW e-motor manufacturing line recently opened in Dingolfing (Germany), at the top of each motor showing the protruding ends of hairpin-like windings that are laser-welded together.



Laser cutting using a modern flat-bed laser cutter. (Source: Mitsubishi).

Production of newest 19"-generation 2 kW fibre-coupled blue diode LDM 2000 lasers. (Source: Laserline)

and platform solutions, with strict specifications regarding speed and quality. Normally, each of these techniques requires a different laser configuration. However, in this case what is cut must generally be joined afterwards as the next operation in the product chain to obtain a ready-to-use part. Therefore, one-of-a-kind combination heads for welding and cutting have been introduced that increase productivity and quality. There is even work currently being undertaken to add 3D-printing functionality.

Shorter wavelengths

So, copper has boosted laser innovation, while simultaneously constituting a processing horror: laser-matter interaction is hampered by copper's exceptionally high specific reflection – up to 90% at wavelengths of 1 µm and higher, as proven, for example, in the CO_2-laser optical guidance systems fitted with copper mirrors – and correspondingly low absorption (and transmission). When using infrared radiation, it is therefore necessary to start with a high-energy setting, to get some energy into the material. In the very split second after melting occurs, the absorption exhibits a peak, so it is an absolute must to switch back the energy within an extremely short time lap and settle at a considerably lower level, to prevent large-scale melting.

One (marginal) solution to increase absorption for an improved processing effect is to roughen the copper surface slightly or provide it with a special coating. A more fundamental solution is to go to shorter wavelengths, where copper's specific absorption is higher (Figure 2). For this, laser solutions have become available, in pulsed mode in a robust power pack size. Especially, blue (450 nm, Figure 11) and green (515 nm) lasers, both in the visible spectrum, have been launched as very promising precision tools that are perfectly tuned to copper and other high-reflective materials. In addition, ultrashort pulsing brings more stability in conduction welding, even under highly varying conditions for a variety of materials.

'Cold' precision alternative

The shorter the laser pulse, the less energy is inserted into the material with each pulse. Hence, short-pulsed fs-laser machining is called 'cold' machining. A remarkable example is the possibility – developed by Trumpf – of cutting and welding hard and brittle stock, such as glass, using lasers with adjustable beam quality, instead of sawing or grinding and gluing with all their disadvantages. Lasers are also called upon for delicate cleaning jobs, as well as – at the other extreme – for removing, in a coarser marine style, biological fouling from ships.

Another remarkable achievement comes from companies such as Avonisys, Sitec and Synova [3], who produce advanced, automated CNC laser systems based on a fine-tuned, small-diameter pressurised waterjet as an innovative

Waterjet-guided laser technology.
(a) Straight diamond cut.
(b) Synova's Laser MicroJet in action.

High-speed copper AM production.
(a) Intricate heat-exchanger design.
(b) Induction coils.

means to guide a laser beam in a controlled way.
This extraordinary laser technology (Figure 12) adds unprecedented material processing capabilities – away from local heating, up to the 'cold' machining of almost any material – without any negative effects such as heat-affected zones, micro-cracks and burrs. Aside from a clear, sharp cut and the large aspect-ratio precision bores that can be achieved in drilling, proven advantages include an increased working distance and range, as well as controlled surface cooling and flushing (Figure 12).

3D printing copper

Until recently, it was inconceivable that AM could master copper in 3D printing. However, several companies have now demonstrated the possibility of producing complex AM parts (Figure 13), such as Trumpf with its high-performance 515-nm green disk lasers, while Nuburu, Shimadzu and Laserline used their proprietary blue 450-nm diode versions.
In the quest for more speed in AM, multi-beam configurations have been introduced in modern printers fit for small batch or small-scale series production of AM metal monoparts, which have no vulnerable weld seams.

Perspective

The latest innovation, by GLOphotonics (Fr), is the so-called hollow-core fibre concept, following up on the traditional glass core build-up of fibres. This provides a simpler interface using a new micro-structured cladding, for completely confining the laser beam, and has proven to deliver high-power ultrashort pulses in a reliable way, opening up future application potential in dedicated laser communication networks.
Still missing – if ever conceivable in future – is one single universal type of laser that will handle all imaginable tasks in materials processing and manufacturing.

REFERENCES
[1] "High precision, low energy, no heat – Ultrashort-pulsed laser machining of hard materials", *Mikroniek*, Vol. 60 (5), pp. 37-38, 2020.
[2] F. Zuurveen, "Lasering e-cars – Facilitating mass production of electric vehicles", *Mikroniek*, Vol. 58 (5), pp. 36-37, 2018.
[3] J. Wijers, "The hybrid Laser MicroJet is cool and precise – 'Wet' laser machining technology picking up speed", *Mikroniek*, Vol 55 (4), pp. 29-35, 2015.

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PERFECTLY PRINTING PORSCHE PISTONS

Usually, pistons for combustion engines are forged or cast. Porsche, however, has succeeded in making improved pistons for their 911 GT2 RS by applying 3D-printing technology, in collaboration with two German industrial household names. Mahle Engine Components contributed its piston fabrication disciplines and Trumpf its precision laser technology. This successful cooperation has resulted in pistons with an effective cooling channel and a considerably lower piston mass, produced in a printing production cycle of twelve hours.

FRANS ZUURVEEN

Improving engine performance

One might discuss the usefulness of a continuous increase in engine performance, but we cannot ignore the joy many people derive from driving or watching fast cars. Although Porsche did develop a highly advanced electrically driven car called Taycan, most precision mechanical engineers will be more interested in learning how Porsche succeeded in extracting more power from its combustion engines.

Several roads led to the enhancement of the 515 kW of the Porsche 911 GT2 RS engine with double turbo charging (Figure 1). One straightforward method was to increase the rotational engine speed, but this required a lower mass for the moving engine components, especially the pistons, as well as a better heat distribution in thermally higher-loaded pistons. This also made the integration of an extra piston cooling channel behind the piston rings mandatory. These considerations led to another piston fabrication technology: additive manufacturing (AM, or 3D printing). This enabled the rules of 'bionic' design to be followed: only adding material in places where it contributes to force transmission.

One principal advantage of AM is that it shortens the development time for prototype engine parts. That's because there is no need for expensive tooling for new cast or forged components that has to be designed and manufactured. Printing directly from CAD files reduces development time by about 30 per cent. On the other hand, printing requires some redesign of an object because AM has to follow its own rules, such as avoiding 'overhangs' of 45° or more.

Partners

Mahle Engine Components delivers pistons to every second vehicle worldwide. The preferred manufacturing technology used for this is forging, because it provides a finer microstructure than casting. Following its motto, "We shape future mobility", Mahle was eager to work together with Porsche to improve the performance of the pistons for their famous vehicles. Mahle is also aiming to develop further applications for AM technology independent of the combustion engine, such as thermal management components or parts for electric drivetrains.

AUTHOR'S NOTE

Frans Zuurveen, former editor of Philips Technical Review, is a freelance writer who lives in Vlissingen (NL). All pictures are courtesy of F. Porsche AG.

1 *The Porsche 911 GT2 RS and its six-cylinder engine, a so-called boxer engine with three times two cylinders arranged opposite each other for near-perfect balancing of dynamic mass forces.*


2

Two Porsche 911 GT2 RS pistons, the conventionally forged one at the left, the innovative 3D-printed version with extra cooling channel at the right.


4

Five printed pistons.

For the printing of the Porsche piston, Mahle contributed metal powder consisting of its aluminium alloy M174+ for casting pistons. This is a eutectic Al alloy, secret to Mahle, with 12% silicon and about 1% each of Cu, Ni and Mg. This alloy has been developed for improved piston strength at high temperatures. To achieve ultimate accuracy, low porosity and high strength, Mahle delivered an ultrafine powder with a maximum grain size of 30 to 40 µm.

Trumpf started as a supplier of sheet metal forming and cutting equipment and turned into a precision laser technology specialist. In recent years, it has developed 3D-printing machines, suitable for printing products such as the Porsche pistons. It contributed its TruPrint 3000 precision-printing machine with a build volume of Ø 300 mm x 400 mm, which can accommodate five printed pistons with an outside diameter of 104 mm each. The next-generation TruPrint 5000 with three lasers is able to print components much more quickly.

Pistons

Thanks to printing, Porsche, in collaboration with Mahle and Trumpf, achieved a piston mass reduction of 10 per cent, ultimately yielding a potential 22 kW power increase for the 515-kW engine. This power increase is not intended for serially produced Porsche cars, but only for special editions, for example GT cars. Figure 2 shows the conventionally forged piston besides the innovative 3D-printed one. The outer wall of the extra cooling channel behind the piston ring grooves is clearly visible.

Figure 3 shows three lasers in action when printing a thin sheet of Al powder by heating and melting the powder exactly at the position where material is required. CAD software helps to accurately drive the three laser focusing points. This printing process is called LPBF: Laser Powder Bed Fusion. Within 12 hours, 1,200 layers with a minimum thickness of 20 µm provide five printed pistons, see Figure 4.

It will be clear that despite the relative accuracy of the printing machines, the ‘rough’ printed parts need extremely accurate finishing by precision grinding. Figure 5 shows a printed piston, before and after finishing with an ultimate accuracy in the µm-area. Regarding the finishing of the piston skirt, it has to be remarked that the ultimate form to be aimed at is not an ideal cylinder. Every Porsche piston has a slightly elliptical cross-section, based on Porsche’s long and extensive experience and simulations.


3

Heating and melting Al powder in a TruPrint machine.


5a


5b

A printed piston before and after finishing.
(a) The initial, ‘rough’ product.
(b) The final, ‘polished’ product.

The printed twin-mound forked spray injector, showing some finishing on the left, for the connection to the oil pump.

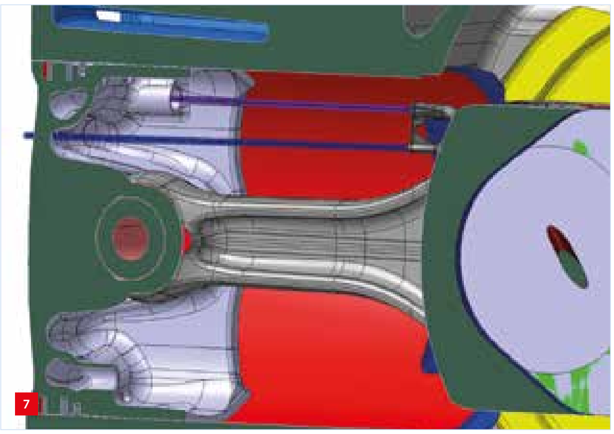
A disassembled piston and connecting rod after many testing cycles.

Another example: spray injectors

The standard 911 GT2 RS engines are provided with six spray injectors in the crank case. Each injection mound sprays a jet of oil into the crankshaft side of a piston, aiming at better cooling for higher engine performance. The integration of an extra cooling channel in each printed piston inspired Porsche engineers to redesign the spray injectors, by adding a second spray mound for directing a piston cooling jet right into the cooling channel. Figure 6 shows the new twin-mound forked spray injector, made from stainless steel particles. It is clear to see that such a complicated part is extremely difficult to fabricate with conventional cutting and welding technology, so AM was used here as well. Figure 7 shows the functioning of the double spray injector.

Testing

Firstly, the finished 3D-printed pistons were tested geometrically with Zeiss precision measuring equipment by comparing measurement results with CAD data. Differences proved to be within tolerance values. Metallographic samples were investigated using light microscopy, X-ray spectroscopy and computer tomography. Also, the cooling channels were inspected for remaining powder or grinding particles. These tests showed no fundamental errors and the porosity was found to be below 0.5 per cent.



The double spray injector (upper right) in action in the cilinder, comprising from left to right: piston with piston pin, connecting rod, and crank case with crankshaft. The upper jet (purple) sprays directly into the entrance opening of the piston cooling channel, the lower jet (blue) cools the piston from below.

Subsequently, the pistons were mounted in a 911 GT2 RS engine and subjected to heavy loading in an engine testing station. After a large number of loading cycles, the heavily tested moving parts were disassembled and inspected; see the piston and connecting rod in Figure 8. No ruptures or cracks were discovered.

To conclude

The successful collaboration of Porsche, Mahle and Trumpf has once again demonstrated the design freedom provided by 3D printing. Complicated internal cavities can be integrated more easily in a product with AM than by using conventional cutting technology. Unfortunately, this freedom has to be paid for with longer fabrication throughput times. AM machine builders are working hard to reduce printing time.

Literature

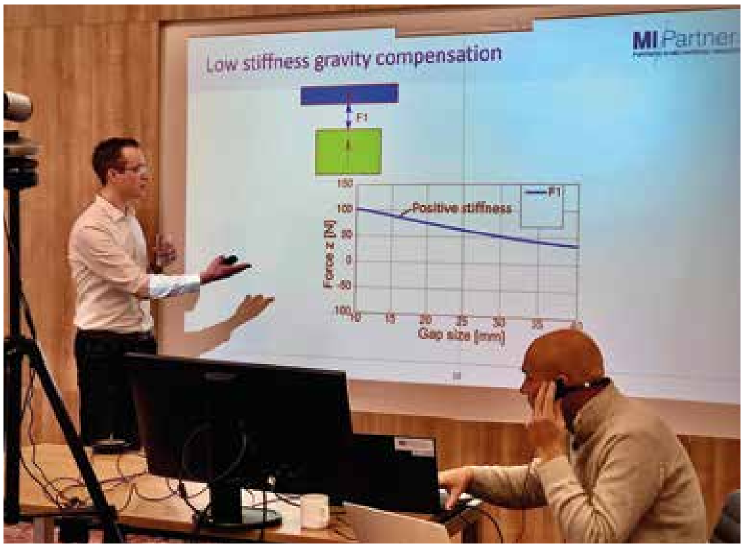
D. Abele, F. Ickinger, V. Shall, and M. Klampfl, "Additive Fertigung von hochbelasteten Antriebsbauteilen", *MTZ (Motortechnische Zeitschrift)*, vol. 82, pp. 14-21, 2021.

INFORMATION
WWW.PORSCHE.COM
WWW.MAHLE.COM
WWW.TRUMPF.COM

PRECISION BRAIN FOOD FOR LUNCH

In order to keep the precision engineering community connected during the Covid-19 lockdown period, DSPE in collaboration with MI-Partners has taken the initiative to organise a series of online (Teams) lunch lectures, with the aim of sharing knowledge for and by DSPE members. These lunchtime lectures, on technical topics, take place on the first Monday of every month just after 12:00 pm (once the monthly air-raid siren test has stopped). Afterwards there is the possibility to ask questions or to chat.

The first online lunch lecture was given in December by Elwin Boots, senior mechatronic system designer at MI-Partners, located in Veldhoven (NL). He introduced the magnetically levitated 'through-wall' stage that he designed as part of his graduation work at Delft University of Technology, and discussed the redesign of the stage chuck. This redesign was part of the Imsys-3D project (Integrated 3D Motion System Synthesis for High-Performance Semiconductor Equipment). In this project, the topology of the chuck was optimised with the aim of maximising the first three natural frequencies, and the resulting design was realised by 3D printing. Boots discussed the design process and showed the final results.



Impression of the presentation room for the first lunch lecture, with presenter Elwin Boots (left) and Ronald Schneider, managing director of co-initiator MI-Partners. (Photo: Julie van Stiphout)

The premiere session attracted over 70 participants and went very well, says moderator Björn Bukkems, also senior mechatronic system designer at MI-Partners. "Beforehand we had practised and found out that just sharing the Powerpoint slides was too static, so we opted for a combination of direct slides presentation and live video of the presenter in front of a large screen. Obtaining a good exposure of this setting required some fine-tuning. The interaction with the participants in the Q&A afterwards also went quite well."

The new year opened with the second lunch lecture, which involved more than 80 participants. Hünkar Kemal Yurt, mechatronics system design engineer at VDL ETG in Eindhoven (NL), talked about flexible multi-body dynamic simulations for a 3-DoF scara robot with an integrated controller. Such robots are part of the precise mechatronic handler systems for lithography machines that VDL ETG develops. The robots are mainly responsible for moving the payload between the modules with the desired accuracy under high environmental vibration loads. Hünkar discussed the calculation of the position accuracy of the payload for different scenarios, using a validated Computer Aided Engineering (CAE) model for both frequency- and time-domain accuracy calculations.

The February lunch lecture (with 45 participants) was delivered by Gerben van Oosterhout, senior project manager medical systems at Demcon in Best (NL). The title of his lecture was "DemcAir – Project under Pressure". At the very start of the Covid-19 pandemic, Demcon was asked by the Dutch government to develop, realise and deliver a complete IC (intensive care) respirator within one month. The biggest challenges were to create a design that was as simple as possible, with parts that were sufficiently available, that was also a safe, life-saving system which could be used by IC doctors and nurses. Van Oosterhout explained how Demcon succeeded, with the commitment of over 40 partners, including companies, hospitals and test & certification company DEKRA.

The lecture on 1 March will be by Alexander Eigenraam, senior mechanical design engineer at SRON. His topic is the development of the SPEXone spectropolarimeter instrument, the Dutch contribution to the NASA PACE satellite observatory. For more lunch lecture topics, check the DSPE site.

WWW.DSPE.NL/EVENTS

WITH ECP2 BRONZE FROM SOFTWARE TO SYSTEM ARCHITECT

Martijn Wijns, software architect at Sioux Technologies in Eindhoven (NL), has been awarded the Bronze certificate from ECP2, the European precision engineering course certification programme that is a collaboration between euspen and DSPE. He is the sixth person to receive this certificate since the first was presented in 2015. The Bronze certificate requires 25 points (one point equals roughly one course day); Silver requires 35 points and Gold 45 points, which qualify a participant for the title 'Certified Precision Engineer'. Unfortunately, due to the pandemic measures, there was no "flowers and cake" ceremony to officially present the Bronze certificate to Wijns.

Euspen's ECP2 programme grew out of DSPE's Certified Precision Engineer (CPE) programme, which was developed in the Netherlands in 2008 as a commercially available series of training courses. In 2015, euspen, DSPE's

European counterpart, decided to take certification to a European level. The resulting ECP2 programme reflects industry demand for multi-disciplinary system thinking and an in-depth knowledge of the relevant disciplines.

Martijn Wijns studied Computer Science at Eindhoven University of Technology and did an internship at Sioux. As he and the company proved a good match, he started working there as a software engineer after graduating in 2007. He successfully pursued a typical software career and became a software architect four years ago. In 2019, he switched to the mechatronics department within the company. "We have our own culture of building systems, based on a holistic system engineering vision. My ambition is to become a system architect and that is what I can learn from my colleagues here."

The courses that Wijns has taken in recent years are geared towards that ambition. "It started with a course in the field of vision: Machine Vision for Mechatronic Systems. The vision architect presenting that course gave me a complete overview of the subject. That made me want more, because you also meet people from other companies during the courses and you can learn from their approach. So I decided to follow the basic courses Mechatronics System Design, Part 1 and 2. For mechanical engineers that was easier to deal with than it was for me, with my software background, but I enjoyed really going into study mode and thinking more broadly than bits and bytes."

After a course-free intermezzo, Wijns then followed Motion Control Tuning. "That was because of the experimental set-up with which we had to work; this really gave me a feel for the subject, while the Dynamics and Modelling course enabled me to understand the theoretical background. Next, I followed Actuation and Power Electronics. I like to understand the various disciplines, so that I can communicate with colleagues, for example when we're in the integration phase of a system development project." It helps that Sioux is very encouraging when it comes to personal development.

Martijn Wijns, sixth recipient of the ECP2 Bronze certificate.

Last year, Wijns took the Design Principles course. "It was nice to dive into mechanics and at the end of the course to consider bringing all the disciplines together in one system in a balanced way. The ultimate question: how can you make use of the strengths of the different disciplines?" Now, he is planning to take a course on soft skills development, which will also help to bring that 'dot on the horizon' closer: becoming a system architect. "Ultimately, I want to work towards the Silver and Gold ECP2 certificates."

WWW.SIOUX.EU
WWW.ECP2.EU

INTERNATIONAL SPEAKERS FOR **SPECIAL EDITION OF DSPE CONFERENCE**

The DSPE Conference on Precision Mechatronics 2021 will combine two elements:

1. Inspirational presentations from multiple invited international speakers from adjacent application areas like bio-inspired mechatronics, robot assisted surgery, virtual reality, artificial intelligence and more.
2. An opportunity for the community to meet/network and exchange ideas in a pleasant atmosphere, including a BBQ.

One of the confirmed speakers is Auke Ijspeert, professor at EPFL since 2002 and head of the Biorobotics Laboratory. His research interests are at the intersection between robotics, computational neuroscience, nonlinear dynamical systems and applied machine learning. He will talk about investigating animal locomotion using biorobots and assisting humans with bio-inspired robotics technology. The ability to move

Auke Ijspeert, professor of biorobotics at EPFL in Lausanne (CH), is a confirmed speaker at the DSPE Conference on Precision Mechatronics 2021.

efficiently in complex environments is a fundamental property for both animals and robots, and the problem of locomotion and movement control is an area in which neuroscience, biomechanics and robotics can interact fruitfully.
We expect to have all the international speakers confirmed by 1 May and registration will then open.

INFO@DSPE-CONFERENCE.NL
WWW.DSPE-CONFERENCE.NL

Please check for any rescheduling, online reformatting or cancellation of events due to the coronavirus crisis.

Virtual event

2 and 9 March 2021

DSPE Break lecture: Topology Optimization part 1 and 2

The goal of these online DSPE Knowledge Days is to familiarise participants with the subject of Topology Optimisation: the state of the art, the possibilities and limitations, and examples of practical cases from industry where optimisation has already been successfully applied to solve precision engineering problems. Registration: *info@dspe.nl*.

WWW.DSPE.NL/EVENTS

Virtual event

10-11 March 2021

Lamdamap 2021

Fourteenth edition of this event, focused on laser metrology, coordinate measuring machine and machine tool performance.

WWW.EUSPEN.EU

Virtual event

16 March 2021

Bits&Chips System Architecting Conference

The fourth edition of this conference will be an online event series of four afternoon sessions on 16 March, 13 April, 18 May and 15 June 2021.

WWW.SYSARCH.NL

7-11 June 2021, Copenhagen (DK)

Euspen's 21th International Conference & Exhibition

The event features latest advances in traditional precision engineering fields such as metrology, ultra-precision machining, additive and replication processes, precision mechatronic systems & control and precision cutting processes.

DTU, the Technical University of Denmark, will provide the venue for euspen's 21th International Conference & Exhibition, if the Covid-19 pandemic situation permits.

WWW.EUSPEN.EU

16-17 June 2021, Den Bosch (NL)

Vision, Robotics & Motion

This trade fair & congress presents the future of human-robot collaboration within the manufacturing industry.

WWW.VISION-ROBOTICS.NL

16-17 June 2021, Den Bosch (NL)

Food Technology 2021

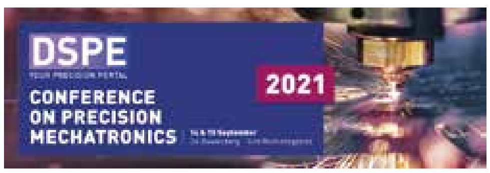
Knowledge and network event about high-tech innovations in the food industry.

WWW.FOOD-TECHNOLOGY.NL

14-15 September 2021, Eindhoven (NL)

DSPE Conference on Precision Mechatronics 2021

The fifth DSPE conference on precision mechatronics, organised by DSPE, will be a special edition, in view of the uncertain pandemic situation. It will combine two elements: (1) inspirational presentations from multiple invited international speakers from adjacent applications areas like bio-inspired mechatronics, robot assisted surgery, virtual reality, artificial intelligence and more; (2) the opportunity of the community to meet/network and exchange ideas in a pleasant atmosphere including a BBQ. For more information, see page 34.



WWW.DSPE-CONFERENCE.NL

15-16 September 2021, Den Bosch (NL)

Materials+Eurofinish+Surface

At this event, a combination of three trade fairs, product developers, product designers, engineers, R&D professionals, production staff, materials specialists and researchers can meet the entire materials value chain.

WWW.MATERIALS-EUROFINISH-SURFACE.COM

w/c 20 September 2021, St. Gallen (CH)

SIG Meeting Advancing Precision in Additive Manufacturing

Special Interest Group Meeting hosted by euspen and ASPE, focusing on, a.o., dimensional accuracy and surface finish from AM, design for precision, standardisation, metrology, and integration of AM into an overall holistic manufacturing process.

WWW.EUSPEN.EU

10-11 November 2021, Den Bosch (NL)

Precision Fair 2021

The Benelux premier trade fair and conference on precision engineering, organised by Mikrocentrum.

WWW.PRECISIEBEURS.NL

15 November 2021, Düsseldorf (GE)

Gas Bearing Workshop 2021

Fourth edition of the initiative of VDE/VDI GMM, DSPE and the Dutch Consulate-General in Düsseldorf (Germany), focused on gas bearings as important components or integral technology of most advanced precision instruments and machines.

WWW.GAS-BEARING-WORKSHOP.COM

24 November 2021, Utrecht (NL)

Dutch Industrial Suppliers & Customer Awards 2021

Event organised by Link Magazine, with awards for best knowledge supplier and best parts & process supplier, and the Best Customer Award.

WWW.LINKMAGAZINE.NL

8-9 december 2021, Eindhoven (NL)

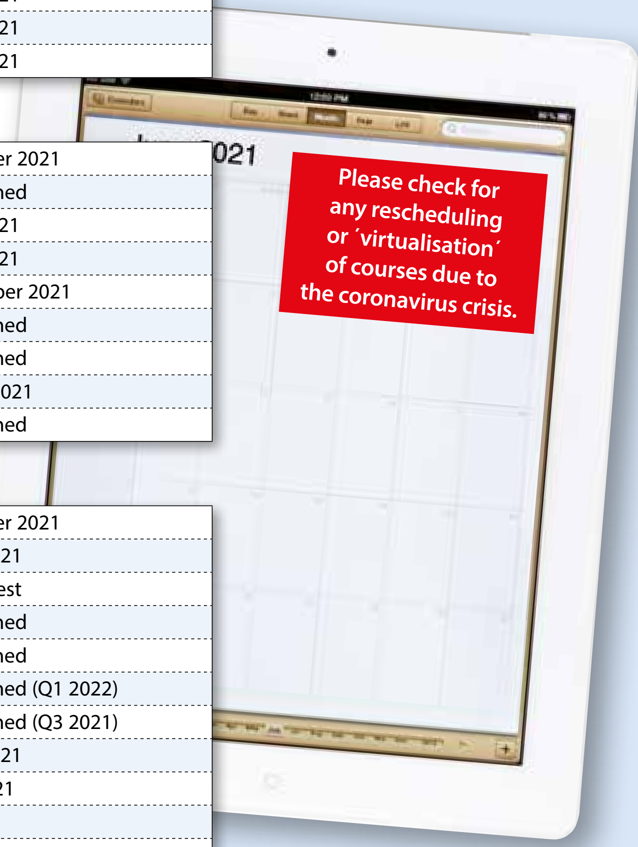
RapidPro 2021

The annual event, this time at the Brainport Industries Campus, showcasing solutions for prototyping, product development, customisation and rapid, low-volume & on-demand production.

WWW.RAPIDPRO.NL

ECP² COURSE CALENDAR

COURSE (content partner)	ECP² points	Provider	Starting date
FOUNDATION			
Mechatronics System Design - part 1 (MA)	5	HTI	12 April 2021
Mechatronics System Design - part 2 (MA)	5	HTI	8 November 2021
Fundamentals of Metrology	4	NPL	to be planned
Design Principles	3	MC	10 March 2021
System Architecting (S&SA)	5	HTI	12 April 2021
Design Principles for Precision Engineering (MA)	5	HTI	21 June 2021
Motion Control Tuning (MA)	6	HTI	14 June 2021
ADVANCED			
Metrology and Calibration of Mechatronic Systems (MA)	3	HTI	2 November 2021
Surface Metrology; Instrumentation and Characterisation	3	HUD	to be planned
Actuation and Power Electronics (MA)	3	HTI	29 June 2021
Thermal Effects in Mechatronic Systems (MA)	3	HTI	15 June 2021
Dynamics and Modelling (MA)	3	HTI	30 November 2021
Manufacturability	5	LiS	to be planned
Green Belt Design for Six Sigma	4	HI	to be planned
RF1 Life Data Analysis and Reliability Testing	3	HI	15 March 2021
Ultra-Precision Manufacturing and Metrology	5	CRANF	to be planned
SPECIFIC			
Applied Optics (T2Prof)	6.5	HTI	1 November 2021
Advanced Optics	6.5	MC	4 March 2021
Machine Vision for Mechatronic Systems (MA)	2	HTI	upon request
Electronics for Non-Electronic Engineers – Analog (T2Prof)	6	HTI	to be planned
Electronics for Non-Electronic Engineers – Digital (T2Prof)	4	HTI	to be planned
Modern Optics for Optical Designers (T2Prof) - part 1	7.5	HTI	to be planned (Q1 2022)
Modern Optics for Optical Designers (T2Prof) - part 2	7.5	HTI	to be planned (Q3 2021)
Tribology	4	MC	9 March 2021
Basics & Design Principles for Ultra-Clean Vacuum (MA)	4	HTI	31 May 2021
Experimental Techniques in Mechatronics (MA)	3	HTI	5 July 2021
Advanced Motion Control (MA)	5	HTI	11 October 2021
Advanced Feedforward & Learning Control (MA)	2	HTI	23 June 2021
Advanced Mechatronic System Design (MA)	6	HTI	to be planned (2021)
Passive Damping for High Tech Systems (MA)	3	HTI	to be planned (Q2 2021)
Finite Element Method	2	MC	to be planned
Design for Manufacturing (Schout DfM)	3	HTI	8 April 2021



ECP² program powered by euspen

The European Certified Precision Engineering Course Program (ECP²) has been developed to meet the demands in the market for continuous professional development and training of post-academic engineers (B.Sc. or M.Sc. with 2-10 years of work experience) within the fields of precision engineering and nanotechnology. They can earn certification points by following selected courses. Once participants have earned a total of 45 points, they will be certified. The ECP² certificate is an industrial standard for professional recognition and acknowledgement of precision engineering-related knowledge and skills, and allows the use of the ECP² title.

WWW.ECP2.EU

Course providers

- High Tech Institute (HTI)
  WWW.HIGHTECHINSTITUTE.NL
- Mikrocentrum (MC)
  WWW.MIKROCENTRUM.NL
- LiS Academy (LiS)
  WWW.LISACADEMY.NL
- Holland Innovative (HI)
  WWW.HOLLANDINNOVATIVE.NL
- Cranfield University (CRANF)
  WWW.CRANFIELD.AC.UK
- Univ. of Huddersfield (HUD)
  WWW.HUD.AC.UK
- National Physical Lab. (NPL)
  WWW.NPL.CO.UK

Content partners

- DSPE
  WWW.DSPE.NL
- Mechatronics Academy (MA)
  WWW.MECHATRONICS-ACADEMY.NL
- Technical Training for Prof. (T2Prof)
  WWW.T2PROF.NL
- Schout DfM
  WWW.SCHOUT.EU
- Systems & Software Academy (S&SA)

Lifelong Optics Learning

The Dutch Optics Centre (DOC), a joint venture of TNO and Delft University of Technology (TUD), has launched the Lifelong Optics Learning initiative. The aim is to set up an optics and photonics training platform, and design a practical, testable and modular curriculum that can be widely used for all companies within the optics/photonics domain. The project is subsidised by the Dutch Ministry of Social Affairs, under the SLIM incentive scheme for learning and development in SMEs. The official kick-off is scheduled for next month.
In a collaboration between the optical groups of TUD, The Hague University of Applied Sciences, the Leidse instrumentmakers School (LiS) and TNO, the Lifelong Optics Learning platform will offer optical training at different levels to professionals from Dutch industry. The companies supporting the project are Hyperion, DJM, Admesy and Optics11.
The curriculum will include modules (lectures and training courses with self-study) at the intermediate and higher vocational education and the academic level, practicals and an assignment based on a case from the participant's own company. A team of experts will test the acquired knowledge and skills.
Interested companies can contact DOC for an assessment of their need for optical training. DOC can define a tailormade curriculum matching the optical technologies applied and the corresponding knowledge and skills base required today and in the future.

(Photo courtesy of TNO)

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BART.SNIJDERS@TNO.NL (DOC)
WWW.DUTCHOPTICSCENTRE.COM

Detailed accuracy spec

The accuracy class of Heidenhain's high-precision linear encoders is normally defined by means of an interval of one meter, the international length standard. In many applications, however, it is the accuracy over shorter distances that matters. Therefore, Heidenhain now specifies two numbers for the accuracy of its open length measuring systems: the accuracy class and the interval accuracy. The accuracy defined on the basis of shorter intervals shows much better how the measuring system performs over shorter movements and better error compensation can be implemented in the machine ('mapping'). In addition, the actual interpolation error is now presented, whereas previously this was specified as a maximum of 1% of the signal period.

WWW.HEIDENHAIN.NL

Wide variety of anti-friction linear guide cages

PM has announced the release of a variety of cages for use in precision linear guides. The cages are enclosed between two rails and filled with rolling elements to offer smooth and precise motion. With a wider range of cage types, PM offers the engineer more choice in materials and designs. As a result, a suitable cage can be found for almost any application, starting with the use in general machinery and extending to ultra-high vacuum applications.
Cages are supplied with retained rolling elements for easier handling. The main function of the cage is to separate the rolling elements at a fixed distance and to prevent them from coming into contact with one another, which would affect the running performance, resulting in oscillations.

Precision linear guides are used in high-tech systems. These include microscopes, manipulators and scanning systems in the medical industry. The linear guides distinguish themselves by their compact dimensions, unsurpassed smooth-running properties and high load capacity. With the brass- and plastic-type ball cages and the plastic-, steel- and aluminium-type crossed-roller cages, PM today offers the widest range of cages, meeting all demands for high-tech industries. For example, in situations where a shorter slide moves over a longer rail, the use of protruding cages is recommended. The aluminium-type cages are suitable for these applications as they are strong and lightweight.

Precision linear guides fitted with roller cages particularly excel in terms of stiffness and load capacity. This allows them to be used in both high-precision and dynamic applications. Ball cages are used in low- and medium-load applications, as they offer very low friction resistance. They are also the favourite in dust-contaminated environments as they swipe the particles away from the point of contact.
Depending on the type and size of the cage, different cage types are available. The smallest cages are suitable for roller bodies with a diameter of 1.5 mm. They are ground to the highest possible precision for high run-out accuracy and the best running properties. The sets with the smallest cage have an installation dimension of only 8.5 mm in width and 4.0 mm in height. The largest cages in the standard range are suitable for roller bodies with a diameter of 9 mm.

Precision linear guides are available as a standard set, which include four rails, two cages and endpieces, but the components are also available as a single piece. PM also manufactures cages with customised non-standard lengths. The linear guide rails start with a length of 20 mm, while the longest one is 1,400 mm in one piece. For longer lengths, multi-section pieces are available that are ground to an equal size. For cleanroom and vacuum applications there are also many stainless-steel solutions available. As an option, the anti-friction guides can be cleaned and bagged for vacuum or cleanroom use.

Crossed-roller steel cage linear guide from PM, with an application in a manipulator stage.

WWW.PM.NL

Rotary axes for nm-range surface measurements

Aerotech introduces the ABRX high-performance air-bearing stages, a new generation of air-bearing rotary tables.
To meet maximum payload and form factor requirements for use as a single-axis positioner, as part of an integrated system or even an integrated machine, ABRX rotary axes are available in diameters of 100, 150 and 250 mm. This makes them particularly suitable for exacting requirements in wafer inspection, high-precision metrology, optical inspection and precision manufacturing, MEMS/nanotechnology device production, and medical technology (X-ray or CT applications).

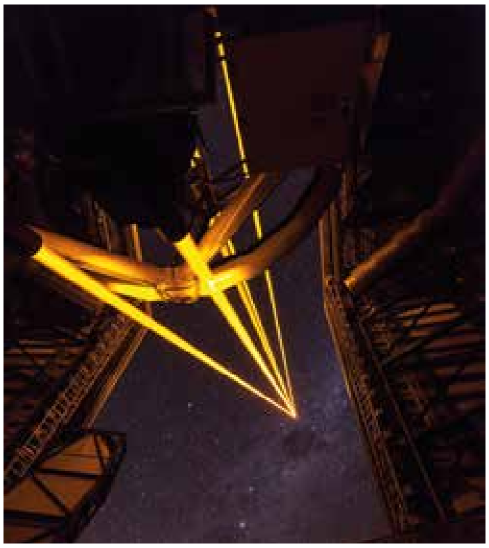
ABRX's large air-bearing surfaces provide significantly better running accuracy than a mechanical or other commonly available air-bearing turntable. The rotary tables are directly driven and can therefore achieve rotational speeds of up to 300 rpm. The air-bearing design minimises radial and axial errors, which are typically in the range of less than 25 nm. The error types can be divided into synchronous and asynchronous ('noise'). By compensating the synchronous errors, the errors can be reduced to well below 10 nm.

WWW.AEROTECH.COM

Artificial stars for the world's largest telescope

The European Southern Observatory (ESO) is creating the world's largest telescope. It has selected TNO to provide a key enabling technology that will allow the telescope to produce better views of the universe than have ever been possible. In the project, applied research organisation TNO will collaborate with Demcon Focal, a specialist in design, engineering and assembly of bespoke optomechatronic systems, as a major sub-contractor.

With the help of TNO's laser guide star launch telescope technology, the Extremely Large Telescope (ELT) will provide insight into some of the greatest astronomical questions of our time, from the birth of stars to the search for signs of life on exoplanets in other star systems. ELT's 39-meter primary mirror array has 15 times the light-collecting area of the largest existing telescopes. Together with corrective optics, this will allow the telescope to bring even the faintest objects into clearer view.
Ground-based telescopes have the power to see deep into the universe, but the Earth's atmosphere distorts the images. TNO's laser launch telescopes project artificial stars onto the edge of the atmosphere, which offer a point of reference for the telescope. By identifying the atmospheric distortion on the known qualities of the artificial stars, the overall level of distortion can be calculated. The ELT's adaptive mirrors can then 'correct' the telescope's vision in real time to produce the clearest images possible of the specific area being explored.
TNO's capabilities were already proven during ESO's development of the Very Large Telescope (VLT). For the VLT, TNO developed the state-of-the-art optical tube assemblies for the laser launch telescopes, among other contributions. Now, ESO is awarding a contract to TNO again to help make the ELT successful. TNO, in cooperation with Demcon Focal, will apply its expertise to design the overall laser launch system, including the optics and precision mechanics that help bring deep space into focus. Demcon Focal will develop the laser beam conditioning, electronics, control systems and housing for the laser launch telescope.



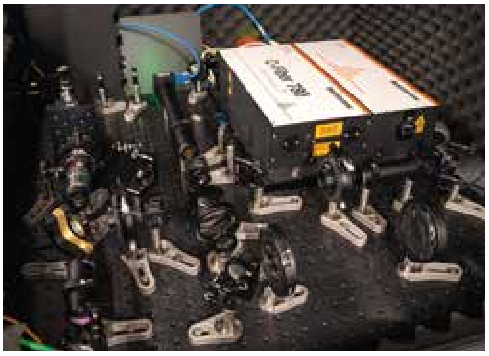
Laser beams projecting an artificial star. (Photo: Henri Werij)

WWW.TNO.NL
WWW.FOCAL.NL

Mapping non-visible materials at nanoscale with ultrasound

The increasing miniaturisation of electrical components in industry requires a new imaging technique at the nanometer scale. Delft University of Technology researcher Gerard Verbiest and lithography machine builder ASML have developed a first proof-of-concept method that they now plan to further develop. The method uses the same principle as ultrasound scanning in pregnancies, but on a much, much smaller scale.
Existing non-destructive imaging techniques for nanoelectronics, such as optical and electron microscopy, are not accurate enough or applicable to deeper structures. A well-known macroscale 3D technique is ultrasound, which works for every sample. Verbiest: "That makes ultrasound an excellent way of mapping the 3D structure of a non-transparent sample in a non-destructive way." But, ultrasound technology at the nanoscale did not exist yet. The resolution of ultrasound imaging is strongly determined by the wavelength of the sound used, and that is typically around a millimeter.
"To improve this, ultrasound has already been integrated into an atomic force microscope (AFM)", Verbiest continues. AFM is a technique that allows scanning and mapping out surfaces extremely accurately with a tiny needle. The advantage here is that not the wavelength but the size of the tip of the AFM determines the resolution. At the frequencies used so far (1-10 MHz), however, the response of the AFM is small and unclear. "So, the frequency of the sound used needed to be further increased, to the GHz range, and that's what we've done, through photoacoustics. Using the photo-acoustic effect allows you to generate extremely short sound pulses. We've managed to integrate this technique into an AFM. With the tip of the AFM, we can focus the signal. Our set-up is ready, and we've carried out the first tests."

Besides nanoelectronics, potential applications lie in cell biology, for example, to make a detailed 3D image of a single living cell, and in materials science, for research into heat transport in a novel material such as graphene. Verbiest has made rapid progress. "In about eight months we managed to make the first measurements with our set-up and we'll continue to develop this in the coming period. Eventually, ASML, which also owns the intellectual property, will take over the research and hopefully accelerate the industrial application of the new method."



Measurement set-up at Delft University of Technology.

WWW.TUDELFT.NL
WWW.ASML.COM

Multidimensional manufacturing

Automation company B&R , an ABB subsidiary, heralds a new era of manufacturing with its ACOPOS 6D magnetically levitated shuttle system. Magnetic levitation allows shuttles to move individual products freely through the machine, which is ideal for small-batch production with frequent changeover between products of different designs and dimensions.

Shuttles with integrated permanent magnets float over the surface of electromagnetic motor segments. The modular motor segments are 240 mm x 240 mm in size and can be arranged freely in any shape. A variety of shuttle sizes carry payloads of 0.6 to 14 kg and reach speeds of up to 2 m/s. They can move freely in two-dimensional space, rotate and tilt along three axes and offer precise control over the height of levitation. Altogether, that gives them six degrees of motion control freedom.
ACOPOS 6D offers up to four times the shuttle density of other systems on the market through the unique ability to control four shuttles on the same motor segment simultaneously. The shuttles can also be used as axes in processing stations. A shuttle carrying a workpiece could follow a CNC path, for example, allowing the processing tool to be mounted rigidly. Weighing stations can be eliminated entirely, since each shuttle can also serve as a high-precision scale. This makes it possible to design a more compact machine.

The shuttles levitate freely without any contact or friction. With no abrasive wear, there are no parts to be maintained. If a stainless-steel cover is placed over the motor segments, IP69K protection is offered – ideal for cleanrooms.

ACOPOS 6D is fully integrated in the B&R industrial automation ecosystem. Each shuttle is assigned a globally unique ID. At start-up, the controller immediately knows the location of each shuttle on the motor segments. The shuttles offer a positioning repeatability of ±5 µm, making the system perfectly suited for applications with strict positioning requirements, e.g. for precision assembly. Sophisticated algorithms ensure the shuttles follow an optimal path while avoiding collisions and minimising energy consumption.

WWW.BR-AUTOMATION.COM

ADVERTISERS INDEX

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Festo is a leading world-wide supplier of automation technology and the performance leader in industrial training and education programs.

member DSPE

Cleanrooms

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Brecon Group can attribute a large proportion of its fame as an international cleanroom builder to continuity in the delivery of quality products within the semiconductor industry, with ASML as the most important associate in the past decades.

Brecon is active with cleanrooms in a high number of sectors on:
* Industrial and pharmaceutical
* Healthcare and medical devices

member DSPE

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Developing the most appropriate cleanroom to transform your production is our passion. Our scalable and connected cleanrooms have been delivering regulatory compliance to our clients since 2002. We innovate to overcome your contamination control challenges – resulting in a new generation of scalable cleanrooms that set an unprecedented benchmark in the industry.

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Development

TNO
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TNO is an independent innovation organisation that connects people and knowledge in order to create the innovations that sustainably boosts the competitiveness of industry and wellbeing of society.

member DSPE

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W www.tbrm-es.nl

TBRM Engineering solutions (previously Segula Technologies Nederland B.V) is part of the TBRM Group. TBRM-ES is an engineering company which operates internationally and aims at supporting customers by providing services from consultancy to complete project solutions including delivery of hardware, which are carried out either at the customer’s location or at TBRM-ES.

TBRM-ES aims at providing innovative solutions for both existing OEM companies, as for small start-ups: Together we can create opportunities!
In addition, we aspire to be a company which distinguishes itself with a high degree of commitment, honesty, accessibility, professionalism, customer focus, quality, and an entrepreneurial spirit, where the team element is paramount in the working environment.

member DSPE

Education

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The LiS is a modern level 4 MBO school with a long history of training Research instrumentmakers. The school establishes projects in cooperation with industry and scientific institutes thus allowing for professional work experience for our students. LiS TOP accepts contract work and organizes courses and summer school programs for those interested in precision engineering.

member DSPE

Electrical Discharge Machining (EDM)

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W www.cvtbv.nl

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member DSPE

terhoek edm & precision solutions

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INNOVATION OF TOMORROW, INSPIRATION FOR TODAY
Staying ahead by always going the extra mile. Based on that philosophy, Ter Hoek produces precision components for the high-tech manufacturing industry.

We support customers in developing high-quality, custom solutions that can then be series-produced with unparalleled accuracy. That is what makes us one of a kind.
It is in that combination of innovative customization and repeated precision that we find our passion. Inspired by tomorrow's innovation, each and every day.

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Lasers, Light and Nanomotion

LASER 2000

Laser 2000 Benelux C.V.
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Laser 2000 Benelux considers it her mission to offer customers the latest photonics technologies available.
Our areas of expertise are:

- Piezo- and stepper motion products for nano- and micro positioning
- Lasers, scanners and laser machines for industry and research
- Light metrology instruments for LED and luminaire industries
- Light sources for scientific applications
- Laser safety certified products

TLS te lintelo systems bv photonics. our passion! 35 YEARS

Te Lintelo Systems B.V.
Mercurion 28A
6903 PZ Zevenaar
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Photonics is our passion!
Our experienced team is fully equipped to assist you with finding your best optical business solution.
For over 35 years TLS represent prominent suppliers in the photonics industry with well-educated engineers, experience and knowledge.
Over the years we became the specialist in the field of:

- Lasers
- Light metrology,
- Opto-electronic equipment,
- Positioning equipment
- Laser beam characterization and positioning,
- Interferometry,
- (Special) Optical components,
- Fiber optics,
- Laser safety

Together with our high end suppliers we have the answer for you!

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Mechatronics Development

SIOUX TECHNOLOGIES

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Sioux Technologies is a global technology partner that supports or acts as the R&D department for high-tech companies. We help leading companies with the development, industrialization and creation of their products, from concept stage to a prototype and/or delivery of series production. Commitment, motivation, education and skills of our employees are the solid basis for our business approach. Together with the customer, we bring high-tech to life.

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MTA creating mechatronics

MTA B.V.
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CHANGING THE GAME OF MECHATRONICS.
We develop mechatronic products in such a way that they can be produced in series, at a pre-defined price point, at a pre-defined quality level and with the shortest time-to market.
Our unique "V^2-way of working" enables viable business cases.
Product and production design run concurrently and are continuously coordinated and synchronized during the development process.
This is how we make a difference in the world of mechatronics.

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Mechatronics Development

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MI-Partners is active in R&D of high-end mechatronic products and systems. We are specialised in concept generation and validation for ultra-fast (>10g), extremely accurate (sub-nanometers) or complex positioning systems and breakthrough production equipment.

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Metal Precision Parts

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

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Micro Drive Systems

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maxon is a developer and manufacturer of brushed and brushless DC motors, as well as gearheads, encoders, controllers, and entire mechatronic systems. maxon drives are used wherever the requirements are particularly high: in NASA's Mars rovers, in surgical power tools, in humanoid robots, and in precision industrial applications, for example. To maintain its leadership in this demanding market, the company invests a considerable share of its annual revenue in research and development. Worldwide, maxon has more than 3000 employees at nine production sites and is represented by sales companies in more than 30 countries.

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Micro Drive Systems

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FAULHABER specializes in the development, production and deployment of high-precision small and miniaturized drive systems, servo components and drive electronics with output power of up to 200 watts. The product range includes brushless motors, DC micromotors, encoders and motion controllers. FAULHABER also provides customer-specific complete solutions for medical technology, automatic placement machines, precision optics, telecommunications, aerospace and robotics, among other things.

Physik Instrumente (PI)
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Stay ahead with drive components, positioners and systems by PI. In-depth knowledge, extensive experience and the broadest and deepest portfolio in high-end nanopositioning components and systems provide leading companies with infinite possibilities in motion control.

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Motion Control Systems

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Aerotech's motion control solutions cater a wide range of applications, including medical technology and life science applications, semiconductor and flat panel display production, photonics, automotive, data storage, laser processing, electronics manufacturing and testing.

Motion Control Systems

mks
Spectra-Physics®
Newport™
Ophir®

Newport Spectra-Physics B.V.
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Newport Spectra-Physics B.V. is a subsidiary of Newport, a leader in nano and micro positioning technologies with an extensive catalog of positioning and motion control products. Newport is part of MKS Instruments Inc., a global provider of instruments, subsystems and process control solutions that measure, control, power, monitor, and analyze critical parameters of advanced processes in manufacturing and research applications.

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Opt for state-of-the-art motion control systems from the world's leading provider PI. Developed, manufactured and qualified in-house by a dedicated and experienced team. Our portfolio includes a wide and deep range of components, drives, actuators and systems and offers infinite possibilities in motion control on a sub-micron and nanometer scale.

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Optical Components

molenaar optics

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Molenaar Optics is offering optical engineering solutions and advanced products from world leading companies OptoSigma, Sill Optics and Graticules Optics.

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Piezo Systems

HEINMADE
supplier piezo system solutions

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As partner for piezo system solutions, HEINMADE serves market leaders in the high tech industry. Modules and systems are developed, produced and qualified in-house.

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Piezo Systems

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High-precision piezo systems and applications that perform on a sub-micron and nanometer scale: world leader PI develops, manufactures and qualifies these in-house. With a broad and deep portfolio with infinite possibilities in components, drives, actuators and systems at hand, our experienced team is dedicated to find the best solution for any motion control challenge.

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Precision Electro Chemical Machining

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As Application Centre we possess the required knowledge to support our clients in every phase of development and process selection.
With our own PEM800 machine we can also use PECM in-house for the benefit of our clients.

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Ultra-Precision Metrology & Engineering

IBS Precision Engineering

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IBS Precision Engineering delivers world class measurement, positioning and motion systems where ultra-high precision is required. As a strategic engineering partner to the world's best manufacturing equipment and scientific instrument suppliers, IBS has a distinguished track record of proven and robust precision solutions. Leading edge metrology is at the core of all that IBS does. From complex carbon-fibre jet engine components to semiconductor chips accurate to tens of atoms; IBS has provided and engineered key enabling technologies.

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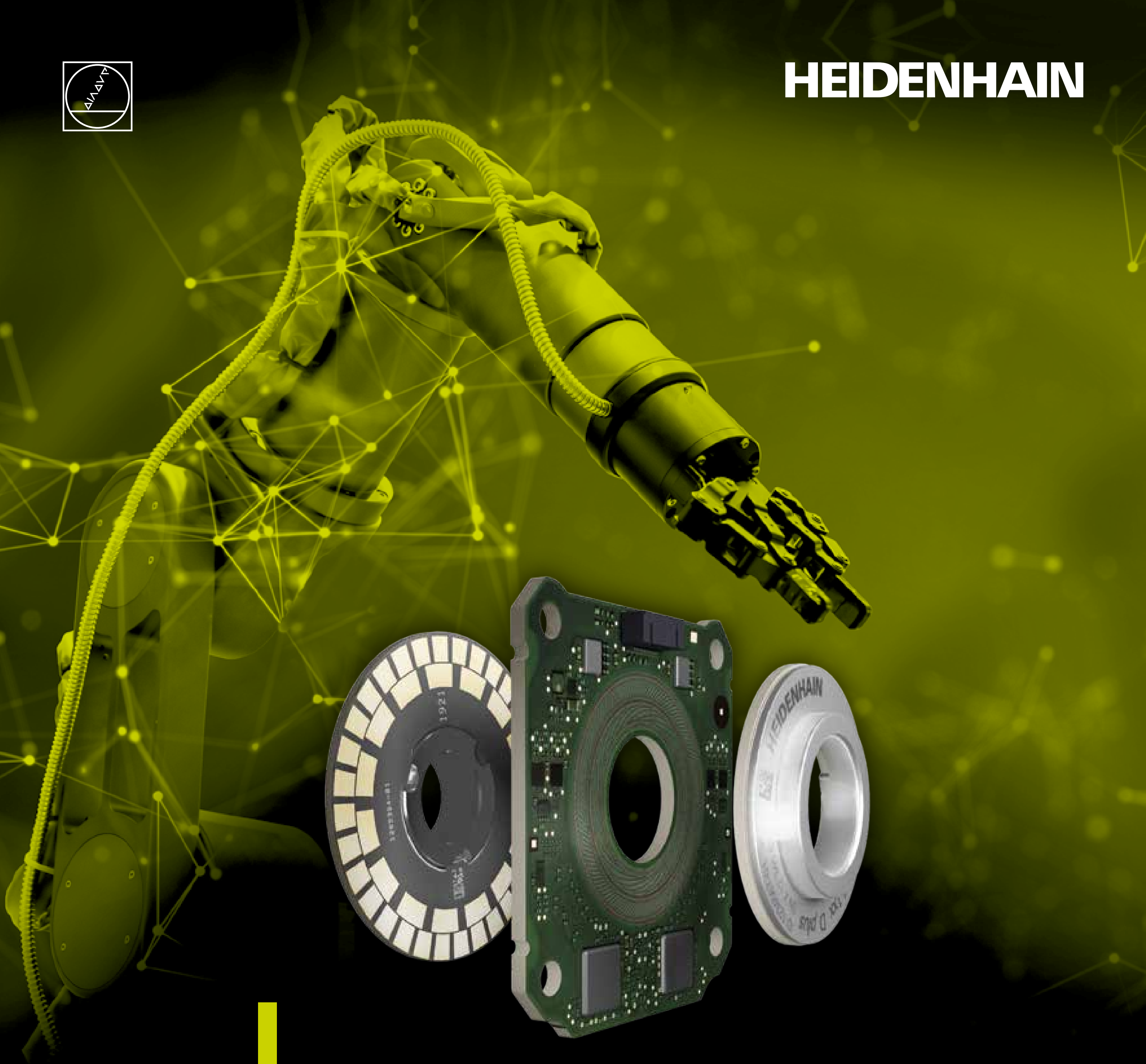
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