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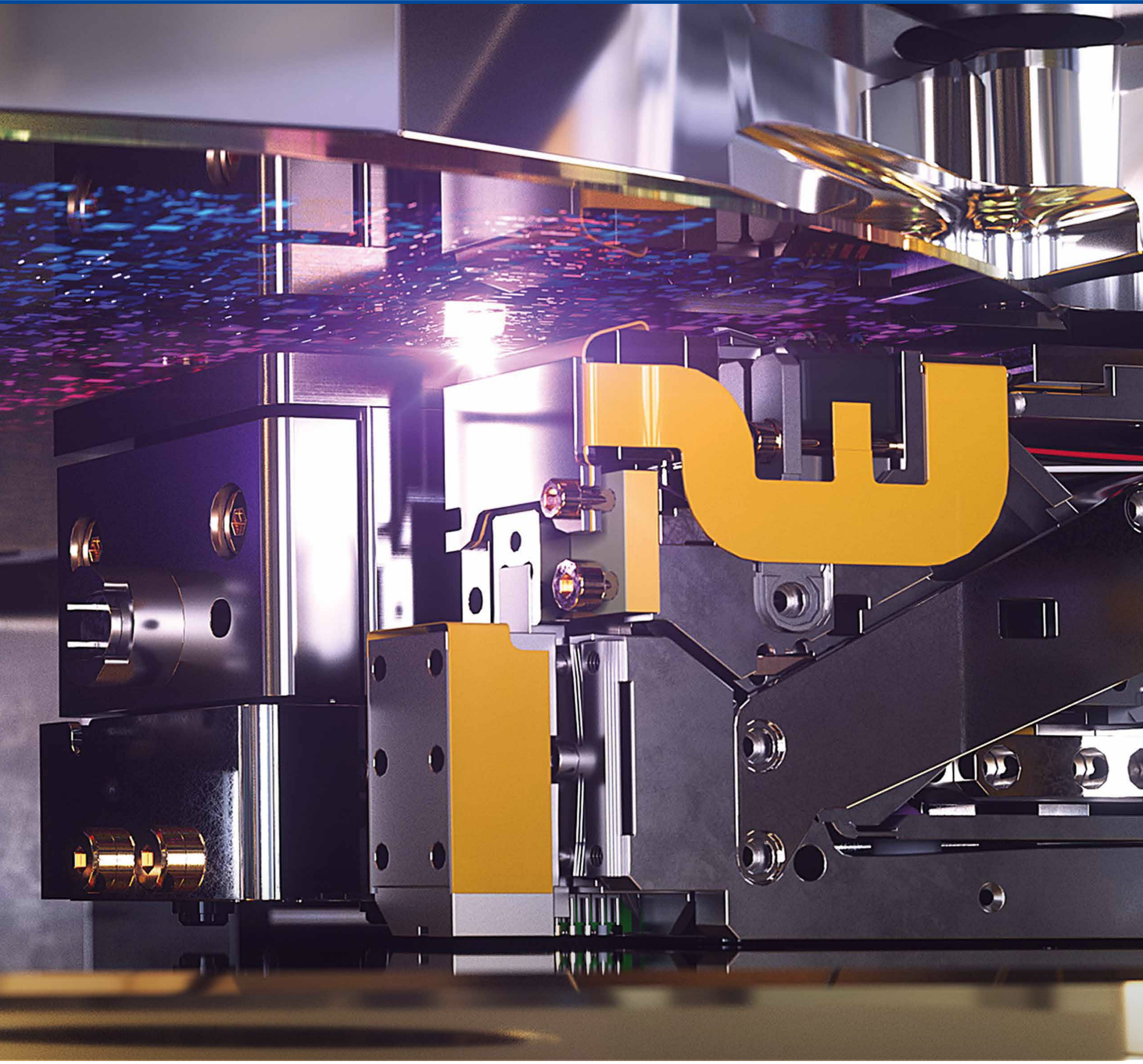

- THEME: HIGH-TECH SYSTEMS
- SILICON CARBIDE OPTICS FOR HIGH-ENERGY LASERS
- IMPROVING HEXAPOD POSITIONING PERFORMANCE
- CONTINUOUS EVOLUTION OF 60-YEAR-OLD LASER TECHNOLOGY

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DSPE
YOUR PRECISION PORTAL

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DSPE
Julie van Stiphout
High Tech Campus 1, 5656 AE Eindhoven
PO Box 80036, 5600 JW Eindhoven
info@dspe.nl, www.dspe.nl

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

Advertising canvasser
Gerrit Kulsdom, Sales & Services
+31 (0)229 – 211 211, gerrit@salesandservices.nl

Design and realisation
Drukkerij Snep, Eindhoven
+31 (0)40 – 251 99 29, info@snep.nl

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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.

Julie van Stiphout-Sassen
DSPE office manager
info@dspe.nl, www.dspe.nl

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

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.

medhat.othman@nearfieldinstruments.com
www.nearfieldinstruments.com

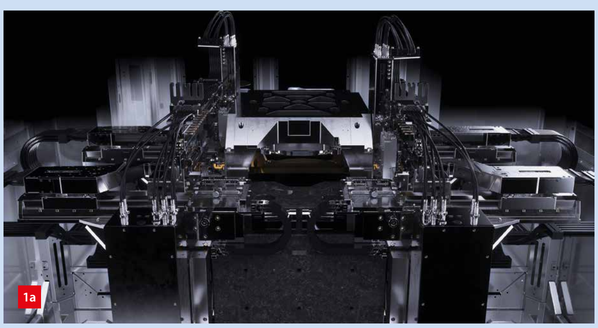
Metrology challenges in semiconductor industry

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

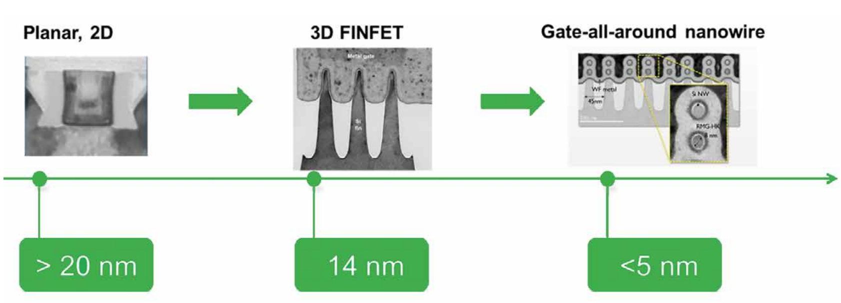
First shipment

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.



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.

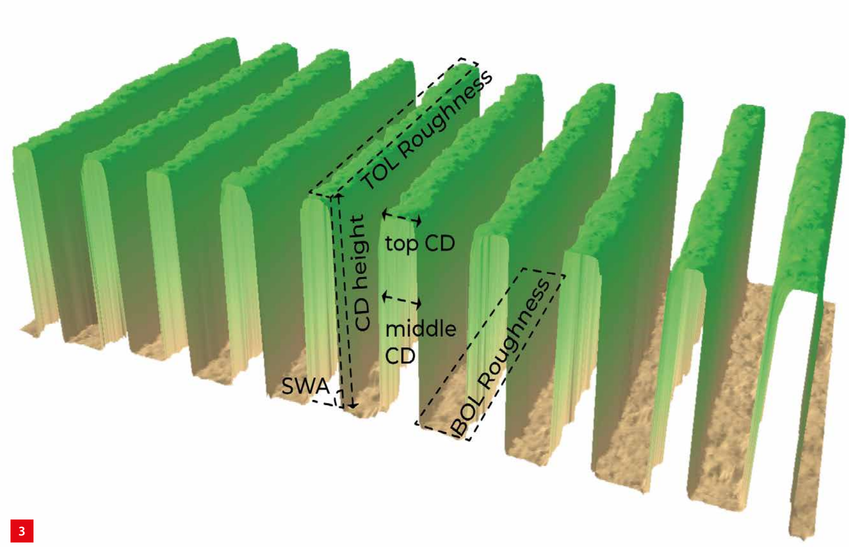
SPM, therefore, has the potential to fulfil the current and future requirements of the semiconductor industry. It has the advantage of providing a three-dimensional surface profile (3D capabilities). Additionally, samples viewed by SPM do not require any special treatments or sample preparation (unlike 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.

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.

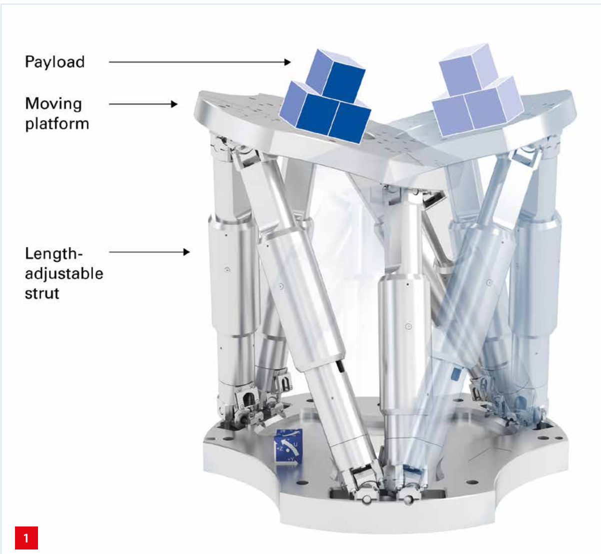
CHRISTIAN SANDER, JENS MATITSCHKA AND CHRISTIAN MUELLERLEILE

Introduction

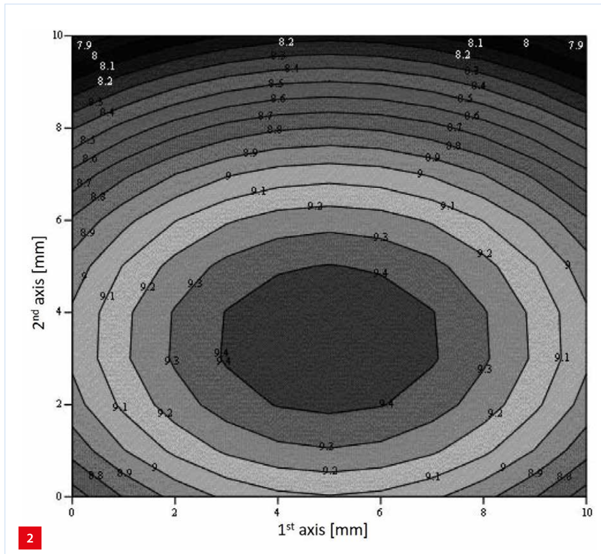
Parallel-kinematic machines are structures with closed kinematic chains. The hexapod is a specialised version of a parallel-kinematic machine. In such a hexapod system, six length-adjustable struts enable the end-effector (moving platform) to be positioned in space along six degrees of freedom (Figure 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



1 Hexapod, showing workspace and main elements.

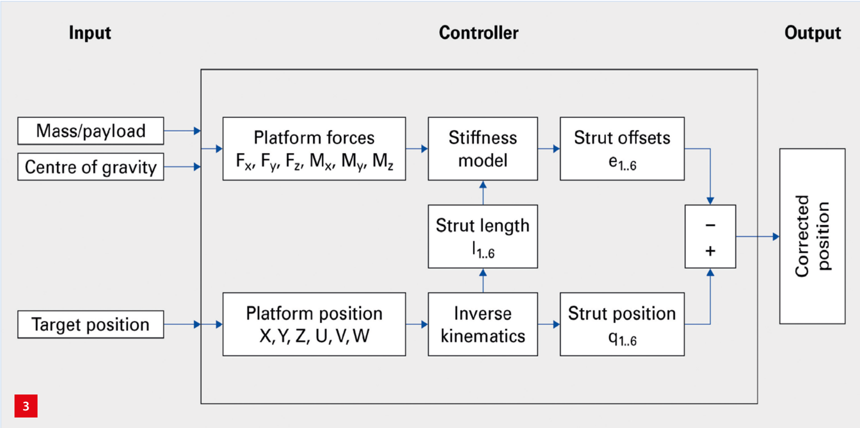


2 Stiffness distribution (10^5 N/m) in one plane of a hexapod's workspace. [4]

AUTHORS' NOTE

Christian Sander (senior expert), Jens Matitschka (design engineer), Christian Muellerleile (senior electronics engineer) all work at Physik Instrumente (PI), headquartered in Karlsruhe (Germany).

info@pi.ws
www.physikinstrumente.com



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,