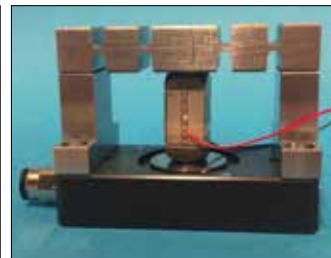
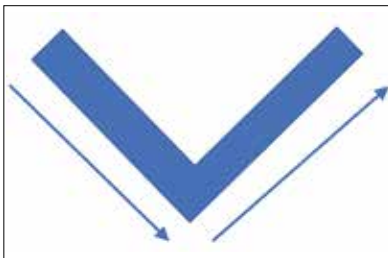
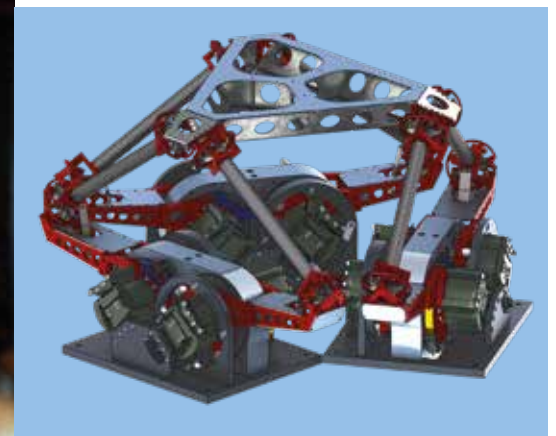
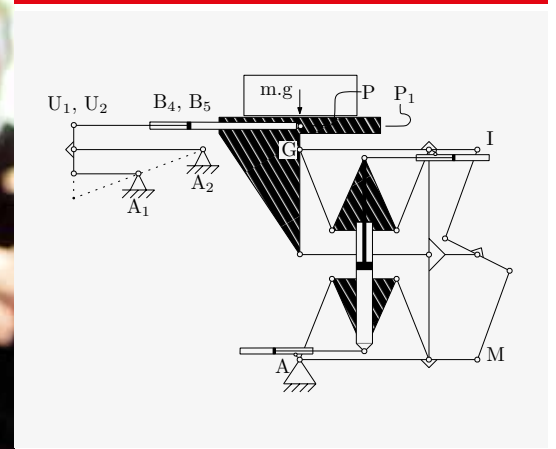
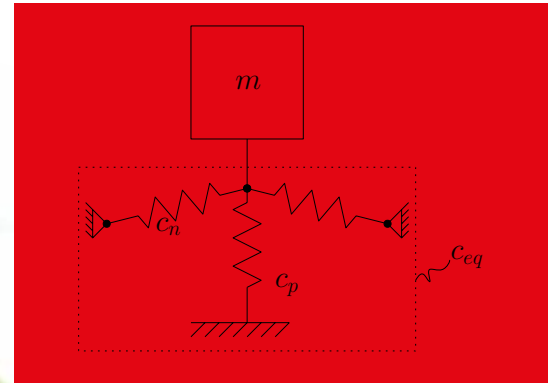


# MIKRONIEK

PROFESSIONAL JOURNAL ON PRECISION ENGINEERING

2019 (VOL. 59) ISSUE 3



- WIM VAN DER HOEK MEMORIAL ISSUE
- DIGITAL SKILLS FOR HIGH-TECH SYSTEM ENGINEERING
- ELECTRON MICROSCOPY WITH EXTREME RESOLUTION
- EUROPEAN SCOPE OF GAS BEARING WORKSHOP

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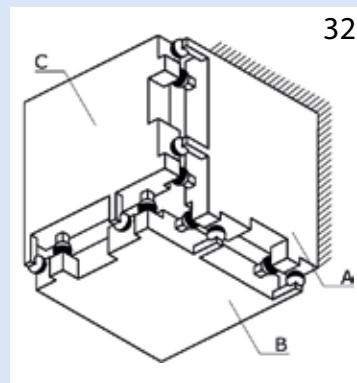
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## WIM VAN DER HOEK'S LEGACY

Professor Wim van der Hoek, honourable member of our community of precision engineers, passed away on 12 January 2019.

On many occasions Wim told with characteristic enthusiasm about his childhood and the endless hours he spent playing with Meccano; a popular toy in the 1920s and 1930s. There was no doubt that Wim would study mechanical engineering in Delft. In 1949, he graduated at Delft University of Technology and joined N.V. Philips Gloeilampenfabrieken in Eindhoven, as a mechanical engineer in Production Engineering. At that time, most high-speed mass-production machines were cam-operated; they had to achieve a high degree of repeatability in order to meet the product requirements. Engineers paid considerable attention to the accuracy of movement and positioning of mechanisms.

Wim van der Hoek was the first to emphasise the dynamics of cam mechanisms as a source of positional errors in high-speed production machinery. He developed a simple design tool by means of which the positional error – due to the dynamics of cams and the backlash – could be estimated in the drawing office. He also suggested improvements in the design of mechanisms from a dynamics point of view, involving lightweight, high stiffness and the avoidance of backlash. These suggestions, presented as design principles, turned out to be useful for a wider range of applications. More examples were added with relevancy for the generic issue of positional accuracy, which concerned topics such as flexures, micromanipulators, kinematic constraints, friction and hysteresis, rolling contact and energy management.

As a scientific advisor to the Philips board of directors, Wim was one of the founding fathers of the Philips Centre for Manufacturing Technology (*Centrum voor Fabricage Technologie*, CFT), the company's laboratory for the development of production processes and machinery. There he was appointed as manager of the Mechanics and Mechanisms section. In this role Wim developed to become an inspiring role model for many (starting and experienced) engineers.

From 1962 onwards Wim was a part-time professor at Eindhoven University of Technology in the chair of Design and Construction of Mechanisms. He started to collect design principles in his lecture notes called "The Devil's Picture Book" (*Des Duivels Prentenboek*, DDP). Although each individual picture was suitable for direct application, it was primarily intended as an invitation to the engineers to think about and – if possible – to make a better design. The DDP content was continuously updated with examples from the field throughout his professional life. New areas of application were added in order to keep up with the advancing technology of precision engineering. DDP became popular, amongst students and within industry. After Wim's retirement in 1994, the development of DDP continued, led by his successors at the three Dutch universities of technology and in the Netherlands' precision industry. It is hard to imagine what the high-tech precision industry in this country would currently look like without DDP.

Wim also paid attention to the design process itself. His inaugural lecture in 1962 was entitled "Constructing as Confrontation between Critique and Creation" (*Construeren als Confrontatie tussen Critiek en Creatie*). He considered creativity to be a unique property of humans and encouraged its use. In his view, the results of creativity needed to be criticised by the application of scientific tools. He liked to be a participant in the confrontation between the two approaches. Wim definitely was not the magician who presented solutions by heart; he welcomed every contribution of participants and tools to the innovation process. As he explained: "Designing is playing with Meccano and getting a salary on top of it." We will remember his inspiring enthusiasm, his scientific approach, his craftsmanship and his love of people.

We would like to extend our most sincere condolences to Mrs. Van der Hoek and the Van der Hoek family.

Rien Koster

*Emeritus professor in Mechatronic Design at the University of Twente and former group leader at Philips CFT*  
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# BETWEEN CRITIQUE AND CREATION

Wim van der Hoek died at the beginning of this year at the age of 94. He worked at Philips from 1949 to 1984 and during the period 1961-1984 was part-time professor at the Eindhoven University of Technology. In these positions, he laid the foundation for the critical and creative manner of mechanical engineering design that has driven the Dutch high-tech and manufacturing industries to great heights. This edition of Mikroniek aims to honour his memory with articles about designs in his vein and reflections that build on his ideas. At the end of this year a (Dutch) biography will be published, which will describe and analyse his life, his work and his legacy in detail.



Wim van der Hoek.

Wim van der Hoek gained an important formative experience, both in characterological and professional terms, during the Second World War, when he became involved in espionage for the Dutch resistance. On the basis of his secondary school knowledge, he had to interpret intelligence gathered about (the trajectory of) the V2 missiles which the Germans, not far from his then home town of Leiderdorp, fired at London. He thus contributed to the answer to the question whether the V2 was radio-controlled or ballistic; he found the latter to be the case.

## EDITOR'S NOTE

The input for this article came from Rien Koster, Jan van Eijk, Piet van Rens, Herman Soemers, Wouter Vogelesang, Frans Geerts, Jos Günsing, Piet Steeghs, Hein Reinders, Rouke van der Hoek, Lambert van Beukering and others.

It was possibly his first exercise in independent thinking about technical problems and thereby contributing to a greater goal. After the war he discovered that this knowledge had indeed been passed on to the British authorities. His early war experiences and the later awareness of the strategic value of production mechanisation for Philips and Dutch industry led to his decision to always publish in Dutch. This was to prevent the knowledge and ideas that he had generated together with colleagues and students from ending up in foreign hands and being used for military purposes. This sense of social responsibility was a common thread in the rest of his life.

Wim van der Hoek studied mechanical engineering at Delft University of Technology and joined a department of production mechanisation at the industrial giant Philips in Eindhoven in 1949 (Figure 2). There he became involved in Philips Internal Technical Education two years later. With him, the constructor/designer and the lecturer were inextricably in one person united.



After graduating from Delft University of Technology, Wim van der Hoek joined a department of production mechanisation at the industrial giant Philips in Eindhoven. (Source: Philips Museum)

He became scientific advisor to the Board of Directors at Philips and as such he was a co-founder of the Philips Centre of Manufacturing Technology (*Centrum voor Fabricage Technologie*, CFT), where he was heading the department of Mechanics and Mechanisms. He acted as a (technical and scientific) advisor for all sections of the Philips group, from the workshop to the board. Hierarchical thinking was alien to him. When a design engineer was 'promoted' to become a manager, Van der Hoek jested: "We have lost him to the management."

### Visual thinking

In 1961 he was appointed part-time professor in the chair of Design and Construction in the Department of Mechanical Engineering at Eindhoven University of Technology. He explained his programme in his inaugural speech, in which he answered the question he had raised himself, namely how to teach students to design. "Together with them, searching for inspiration, 'scanning the field for ideas', on one hand, and on the other hand, challenging them to apply their knowledge quickly and logically, and make it accessible. This will help them to start real designing in the sense that I have wanted to elucidate for you today: constructing as a confrontation between critique and creation."

Van der Hoek used this educational approach in his teaching and in his work at Philips. Entering into a confrontation with students or colleagues and staff and preferably letting them create the 'invention' themselves, or letting them formulate the answer to the problem at hand for themselves. He did this mainly by asking a lot of questions, giving positive feedback and acting as a 'visual thinker' *avant la lettre*.

He called on the (student) designers to visualise for themselves how a construction behaves, how a part of it moves and how it feels under the influence of the occurring forces. This to intuitively understand/feel what is happening and where the bottlenecks lie. For example, how a ball runs in a recirculating ball nut or how a cam mechanism behaves and where the wear or backlash occurs. Of course it was necessary to understand a piece of technology theoretically, but also to physically grasp it and 'get inside it'.

This visual thinking was reflected in his use of language, which was extraordinarily flowery and sometimes 'unparliamentary', even where design and technology were concerned. He was also careful not to use any secret language or too much jargon. He did everything in his power to demythologise his profession with understandable language and to make his reasoning imitable. He also insisted on the importance of words. Describing a design in words causes a designer to consider his own work with a critical distance and wonder whether it could be made smarter.

Illustrative for this approach are the renowned Monday sessions that Van der Hoek held with his students at Eindhoven University of Technology. Together they sat around a table on which a large sheet of yellow drawing paper invitingly lay for sketching and calculations, mutual remarks, spontaneous generation of ideas and everything that came to their minds.

On the one hand, Van der Hoek's approach was based on inventiveness in constructive insight, and on the other hand, on the confrontation of these ideas with descriptive calculations and, where necessary, thorough numerical analysis, drawing on disciplines such as theoretical mechanics, the theory of strength of materials, materials science and control technology, which Van der Hoek described as the 'indispensable auxiliary sciences'. He was in favour of every mechanical engineer building a 'royal household' around him by establishing personal relationships with a 'court physicist', 'court optician', 'court chemist', 'court electrical engineer', etc., in order to be able to quickly compare ideas with them.

### Production mechanisation

The construction of machines for production mechanisation was Van der Hoek's field of work at Philips and the source of inspiration for satisfying the duties of his professorship. This generally concerned machines for assembling discrete products, often with feeding, positioning and fixing processes. The production of electron tubes is a representative example in this respect. The tolerated inaccuracies were 1 micrometer or better at speeds of 2,000 to 3,000 products per hour. These machines were usually single pieces and their development always took more time than desired. After such a machine was put into service, development often continued.

To gain competitive advantage, accuracies had to improve and production speed had to increase. Better control of the accuracy of the movements and the positioning of the tools in the machine had to be obtained, combined with an increase of machine speed. This prompted Wim to focus on the dynamic behaviour of cam mechanisms.

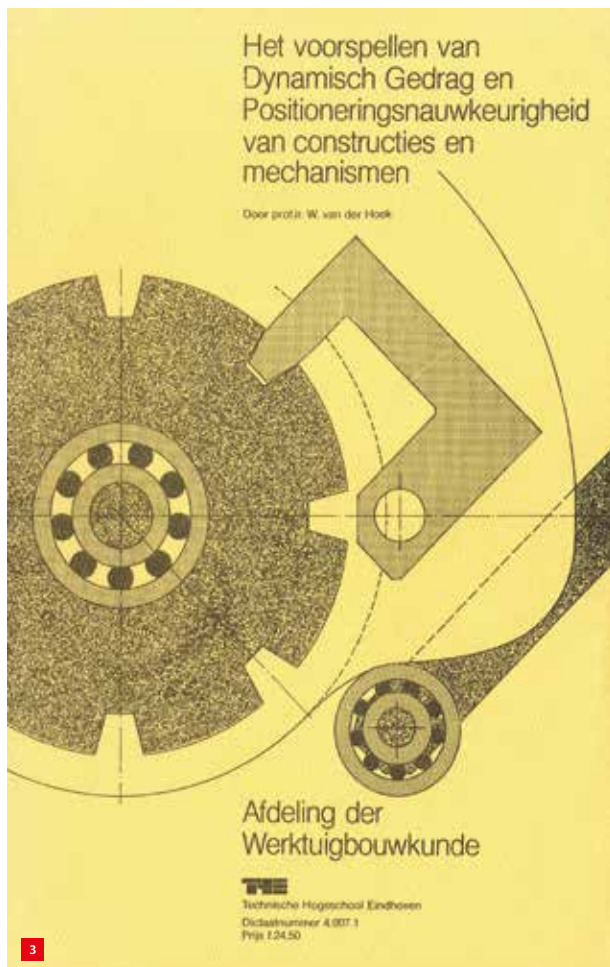
In the first edition of Van der Hoek's lecture notes, a start was made on modelling (cam) mechanisms. The responses of a mechanism based on a simple one-degree-of-freedom model to different incoming movements were evaluated. These responses were due to discontinuities in velocity, caused by backlash, or due to different cam shapes. This led to the insight for responsibly choosing a cam function (preferably without discontinuities in speed or acceleration) and the awareness of the disastrous effect of backlash in the machine on the accuracy of movement and positioning, all under the dominant limitation of the mechanism's natural frequency.



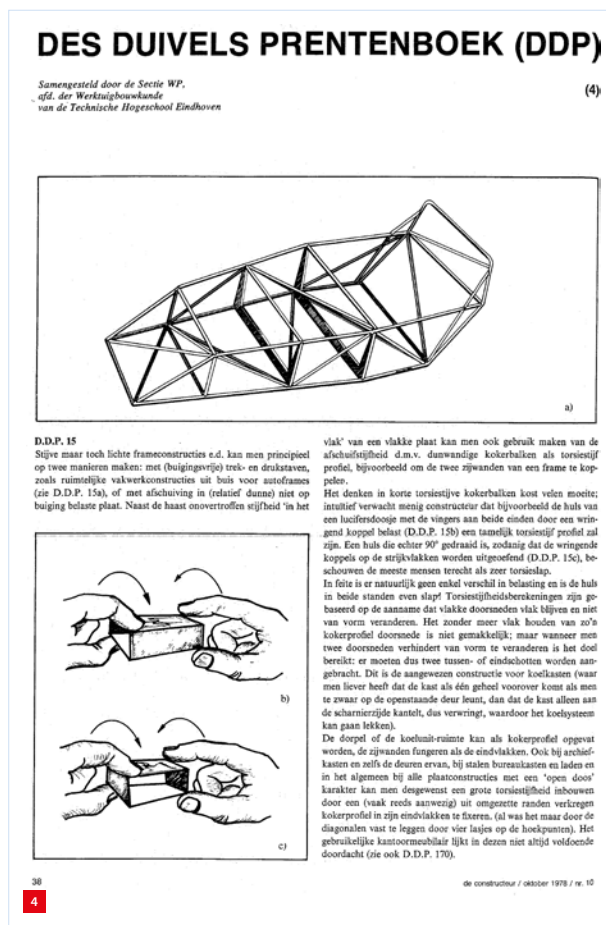
The newly acquired understanding helped in predicting the contribution of dynamics to positioning errors in a mechanism. It also resulted in qualitative and quantitative insight into the mechanical design measures that had to be taken to control these positioning errors. 'Stiffness' turned out to be the new design paradigm.

### The Devil's Picture Book

Van der Hoek included all this in his lecture notes (Figure 3), entitled "Predicting Dynamic Behaviour and Positioning Accuracy of constructions and mechanisms" (*Het voorspellen van Dynamisch Gedrag en Positioneringsnauwkeurigheid van constructies en mechanismen*). The first issue was: how do you realise a lightweight structure with high stiffness in order to raise the natural frequency of the mechanism in a fast-moving machine. And secondly: how do you eliminate the backlash? The idea was to show, by means of illustrations with a description, how a compliant mechanism or compliant (frame) structure could be redesigned to exhibit a higher stiffness, how the mass could be reduced in crucial places and how the backlash could be avoided.



Van der Hoek's lecture notes (in Dutch), entitled "Predicting Dynamic Behaviour and Positioning Accuracy of constructions and mechanisms".



A page from DDP (as published by the Dutch professional magazine Constructeur in 1978) describing the design of stiff yet lightweight constructions.

This description of mechanical design issues and ways of thinking in order to find good solutions was the beginning of "The Devil's Picture Book" (*Des Duivels Prentenboek*, or DDP), the collection of pictures that Van der Hoek amassed with the goal being to promote good designs from a dynamics and positioning point of view. Each picture, with a unique DDP number, was accompanied by a description of the corresponding design problem, the defects in the (initial) design and the experience gained in solving them. The central idea was: perhaps there are only a discrete number of problem types in the construction of precision machines and it is always a challenge to recognise the relevant problem type(s).

Lightweight and high stiffness was the first topic in DDP (Figure 4); avoiding backlash the second. The collection was soon extended to other topics: elastic elements, degrees of freedom, manipulation and adjustment, friction and hysteresis, the use of friction, guiding belts and wires, and energy management. Van der Hoek considered these subjects to be representative of 'cold mechanical engineering' and to be decisive for accuracy in movement and positioning.

The DDP was set up according to Van der Hoek's approach described above, the 'confrontation between critique and creation': not thinking in terms of solutions, but dissecting the design problem into parts with the topics of the DDP in mind, and checking whether solutions are possible with the aid of effective, estimating, quick calculations. Outsiders often had the impression that he was a 'devil's artist', who, taking note of the problem at hand, conjured up a solution by heart. This was by no means the case. In the mechanical engineering field, many unsuccessful attempts were made to convey the profession of design and construction. However, it was Wim van der Hoek who succeeded in synthesising criticism and creation in mechanical design, getting a good reception from the Dutch engineering community.

### Beyond mechanical engineering

With his education and DDP in particular, Van der Hoek has elevated thinking about precision to a discipline and laid the mechanical foundation for current precision technology, in which micrometers have now been replaced by nanometers where the order of magnitude of relevant (in)accuracies is concerned. He was a mechanical designer *pur sang*; the functionality and required precision of a construction were for him the result of the mechanical design.

Mechatronics – the collaboration between disciplines such as mechanics, electronics, software and physics to raise the performance of high-tech systems to even higher levels – really matured in the 1990s, after Van der Hoek's retirement. However, he was involved in the development of Philips products such as the CD player, which could be called 'mechatronical' *avant la lettre*. For him, control technology was primarily about the control of movements on the basis of mechanical principles, which he considered in the domain of time and position, rather than in the frequency/Laplace domain of the modern control engineer.

Not that Van der Hoek had no foresight. As early as 1970, he told his class for first-year students that it would be an enormous step forward if, in addition to turning and milling, a production technique were to be available that "would allow material to grow towards the light like plants". This is now called additive manufacturing and in recent years has developed into an accepted technology, not only for prototyping but also for series production in a wide range of materials, such as plastics, metals, ceramics and glass.

### Impact

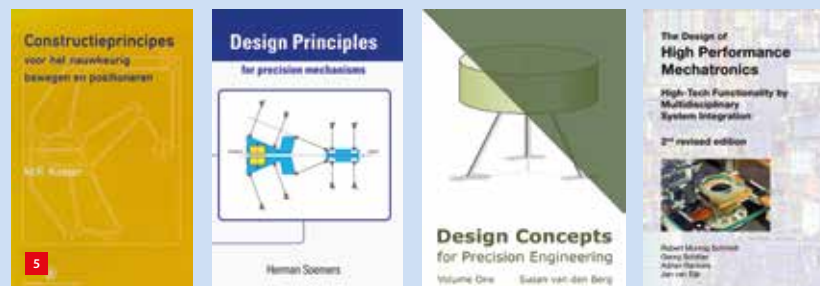
Directly and through his 'successors', Wim van der Hoek had and still has a lasting impact on the Dutch high-tech and manufacturing industries in various ways. In the first place, of course, at his employer Philips, where production mechanisation was his field of activity and

## Legacy

Wim van der Hoek's work was continued and further developed at Philips CFT, in the first place by Rien Koster and Jan van Eijk, and at the Eindhoven University of Technology, by people such as Rien Koster (his immediate successor as part-time professor), Nick Rosielle and Maarten Steinbuch. Rien Koster, who later became part-time professor of Mechatronic Design at the University of Twente (UT), has updated and restructured DDP. This resulted in the textbook (in Dutch) "Design principles for precise movement and positioning" (*Constructieprincipes voor het nauwkeurig bewegen en positioneren*), which was first published in 1996 and was reprinted several times (Figure 5a). This was later updated and translated into English by Koster's successor at the UT, Herman Soemers, also working for Philips CFT (now Philips Innovation Services); "Design principles for precision mechanisms" appeared in 2010 (Figure 5b).

The latest addition to the 'DDP line' is "Design Concepts for Precision Engineering" by Susan van den Berg, lecturer at Fontys University of Applied Sciences in Eindhoven. Her book was published this year as the first – successful – attempt at a didactically sound study book for students in higher professional education (Figure 5c). Appearing in 2011, parallel to the 'DDP line', was "The Design of High Performance Mechatronics" by Robert Munnig Schmidt, Georg Schitter, Jan van Eijk and (for the second edition in 2014) Adrian Rankers (Figure 5d).

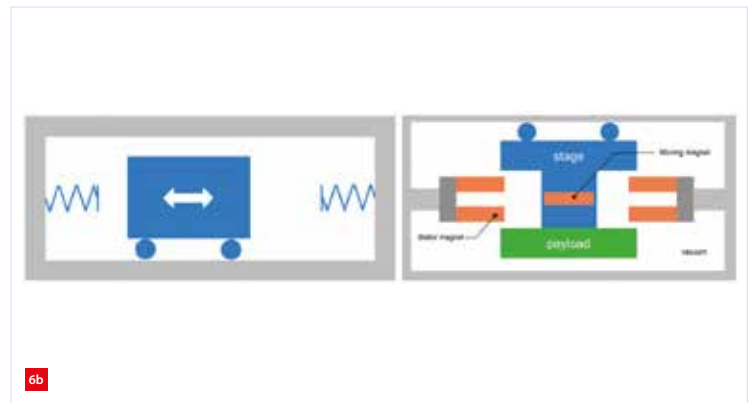
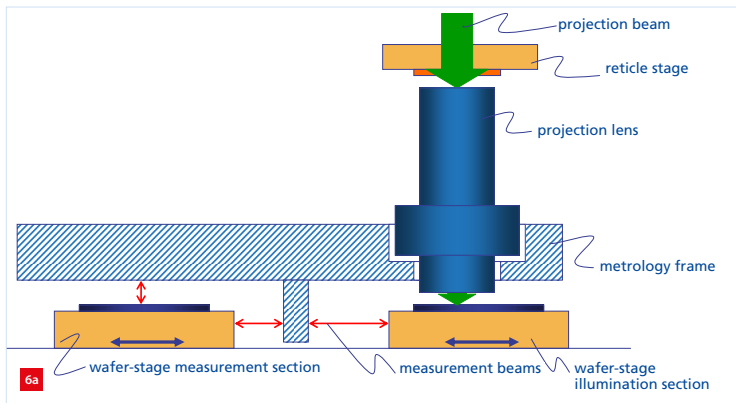
In addition, the DDP philosophy forms the basis for various courses. Thus, for example, Piet van Rens, a former student and employee of Van der Hoek who currently works at Settels Savenije, has been providing courses for more than thirty years, now also internationally.



Textbooks in the wake of DDP; see text for the titles.

he helped the various business units to reach a higher level in that area. His influence reached much further and much wider at Eindhoven University of Technology, where he worked for more than twenty years as an endowed professor and with his design approach and concepts reached many hundreds of students, about sixty of whom graduated with him.





Building on DDP; the designs for the ASML lithography machines.

(a) Schematic of the ASML Twinscan machine. (Sjef Box, *Mikroniek* vol. 46 (6), pp. 5-9, 2006)

(b) Concept for an in-vacuum linear stage with 30G acceleration capacity. (Jan Huang et al., *DSPE Conference on Precision Mechatronics*, 2018)

His alumni put this design knowledge and experience into practice in their professional lives at various companies. Naturally Philips (which is nowadays less of a production-oriented company, as evidenced by the transformation of Philips CFT into Philips Innovation Services; see the article on page 46 ff.) and spin-offs such as ASML, FEI (now part of Thermo Fisher Scientific), Assembléon (now part of Kulicke & Soffa) and VDL ETG (the former *Philips Machinefabrieken*).

In addition, development companies such as Settels, MI-Partners, CCM (now part of Sioux), Janssen Precision Engineering, Demcon and many others. Finally, original equipment manufacturers and systems suppliers such as Océ, Additive Industries, Cerescon, AAE and MTA, and numerous manufacturing companies. The fact that he held on to publishing in Dutch (except for an English translation of DDP for internal Philips usage) is the reason why the 'Van der Hoekean' thinking has been confined mainly to the Netherlands and has not been followed much, or at least only very late, in other countries.

Van der Hoek was directly involved, via Philips and/or the Eindhoven University of Technology, with various companies, in particular VDT and ASML. At VDT (Van Doorne's Transmissie, now Bosch Transmission Technology) in Tilburg, he helped to develop Hub van Doorne's invention, the continuously variable transmission in the form of an ingenious push/pull belt, into an easily producible mass-market product. At ASML, established in 1984, the year of Van der Hoek's retirement, he was involved as an advisor for a number of years. There he made important contributions to the further development of Philips' machine concept into the advanced lithography machines that have made ASML the world market leader. The designs for the ASML machines breathe 'DDP' (Figure 6).

## Technology and people

But during his career and after his retirement, Van der Hoek was also concerned with design challenges that were less technically advanced, but were at least as socially appealing. Examples include the 'humane' syringe, which does not 'punch' holes in the patient but only makes narrow incisions that heal quickly, and the tension-free clamping and tensioning of piano strings to prevent the need for retuning, or the patient-friendly compression stocking.

Compression stockings, which are intended to prevent fluid accumulation in the patient's leg, cause too much pressure – and therefore pain – in places where the radius of the leg is small, such as the heel. Challenged by a district nurse, Van der Hoek devised a concept for winding elastic tissue around the leg in such a way that the radius – and therefore the pressure – is everywhere the same and never becomes too high. Former colleague Riné Dona built a winding machine for this on the basis of his notes. This has not yet reached the conservative medical market, however.

This example shows that Wim van der Hoek always had an eye for people and believed that the technology he was working on should support them. As a person he was open, jovial and involved with the ups and downs of colleagues, students and mankind. In the inaugural speech for his professorship (1962), he referred to the Allied leaders who, at the end of the Second World War, pointed out that peace would only be won when all mankind would be assured of freedom from fear, hunger, and want. "In the first instance, in this struggle for peace, it is the personal will, conviction and inspiration of everyone that are at stake; but the technical means to be used for this purpose must also not to be underestimated. With our technical knowledge, (...) we can contribute a lot to this."

## Wim van der Hoek Award



Wim van der Hoek at the festive reunion on the occasion of his eightieth birthday. (Photo: Bart van Overbeeke)

The name of Wim van der Hoek lives on in the award named after him. This prize was an initiative of Wouter Vogelesang, Ad Weeber and Frans Geerts, members of the alumni association of Eindhoven mechanical engineers and former students of Van der Hoek. They organised a festive reunion on the occasion of his eightieth birthday (Figure 7) and decided to introduce a prize. Maarten Steinbuch, professor of Control Technology at the Faculty of Mechanical Engineering at Eindhoven University of Technology (TU/e), supported this initiative and gave it momentum.

The name of the prize, originally called Wim van der Hoek Constructors Prize, is a tribute to the inspiring and unique way in which Van der Hoek disseminated the profession of mechanical engineering design to his students. The prize was also intended as an incentive for students at the universities of technology to take up the subject of design and as support of the argument in favour of more room for the discipline of designing/constructing in the mechanical engineering curricula of the universities of technology.

In its current form, the Wim van der Hoek Award is awarded annually for the best graduation work in the field of design in mechanical engineering at the universities of technology and universities of applied sciences in the Netherlands and Belgium. The prize includes a certificate, a trophy made by the Leiden Instrument Makers School (Figure 8) and a sum of money (sponsored by HTSC, the TU/e High Tech Systems Center). The criteria for the jury assessment of the graduation reports are quality of design, substantiation and innovativeness, as well as suitability for use in education. There have been multiple nominations since 2017. Each year in November, the award ceremony takes place on the second day of the Precision Fair (*Precisiebeurs*) at the Koningshof in Veldhoven (NL).



The trophy belonging to the Wim van der Hoek Award is made every year by the Leiden Instrument Makers School. The illustration is taken from *The Devil's Picture Book*; a micrometer-accurate mechanical adjustment for an optical slit for a laser beam, conceived and implemented by student Hein Ruyten in 1968. As a cover image for Rien Koster's textbook, it symbolises the fact that 'accurate' and 'expensive' do not have to be synonyms.

As long as his health permitted, Wim van der Hoek was present to contribute to the annual presentation of the award. He then often had an animated conversation with the laureate and other people present. In 2006, the prize was awarded for the first time to Erik Manders (Figure 9), who graduated from the TU/e on the design of a robotic eye that reacts interactively – in a more human-like manner – to the person approaching the robot. Today he is senior architect mechatronics at Philips Innovation Services (the continuation of Philips CFT), which is featured in this memorial issue (see the article on page 46 ff.). Also, the Wim van der Hoek Award 2018 winner Martin Kristelijn and nominee Roy Jacobs, both TU/e graduates, each contributed an article, on pages 12 ff. and 22 ff., respectively.



The first ceremony for the Wim van der Hoek Award, in 2006. From left to right: Wim van der Hoek, laureate Erik Manders and two of the award initiators, Wouter Vogelesang and Ad Weeber.

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# ARRANGING THE DEGREES OF FREEDOM

Imagine that you would like to build an offshore windfarm in the harsh environment of the North Sea. At some point, this requires the transportation of wind turbine components to the offshore installation site, where they are installed. If, for a moment, you forget the wind and wave impact at the offshore installation site, this sounds quite doable. In practice, however, these two factors have considerable influence on the installation procedure through causing delays in lifting operations. This calls for a motion-compensation mechanism. Its design was founded on Wim van der Hoek's design principles.

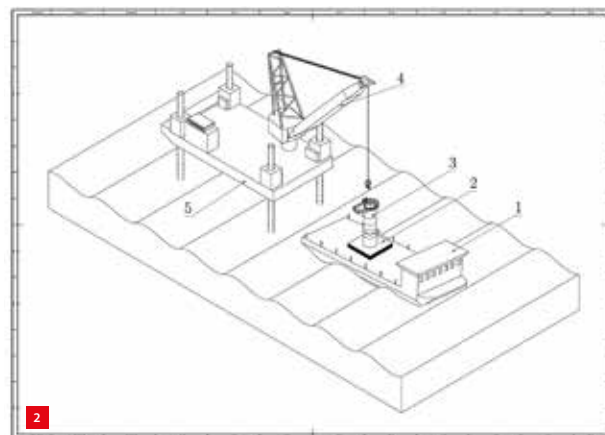
## AUTHOR'S NOTE

Martin Kristelijns graduated cum laude from Eindhoven University of Technology, Eindhoven (NL), in March 2018, in the study Mechanical Engineering, specialising in Design Principles. Currently he works at Bosch Rexroth (Boxtel, NL, [www.boschrexroth.com](http://www.boschrexroth.com)) as a mechanical design engineer and has several side activities related to mechanical design. He is the recipient of the Wim van der Hoek Award 2018.

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## MARTIN KRISTELIJNS

To minimise the influence of weather conditions, installing wind turbine components is commonly executed by a jack-up vessel, as shown in Figure 1, which can lift itself above the water line using its jack-up legs. In this jacked configuration, the deck crane (4) of the jack-up vessel, shown in Figure 2, stands stably on the sea floor and is therefore able to install the wind turbine components with high precision, minimally influenced by wind and waves. To streamline the installation sequence, the jack-up vessel is constantly fed with wind turbine components from a supply vessel (1).



Overview of installation configuration.

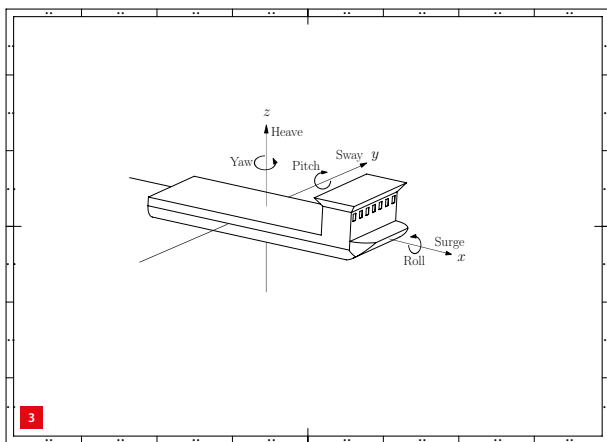
- (1) Supply vessel
- (2) Platform
- (3) Payload
- (4) Deck crane
- (5) Jack-up

The supply vessel has optimised sailing properties such as speed and manoeuvrability, which are convenient for long-distance transits and for positioning the floating supply vessel alongside the stationary jack-up vessel. The manoeuvrability of the supply vessel is provided by its dynamic positioning system, consisting of one thruster at each corner of the vessel's hull, which combined prescribe the horizontal motions of the vessel, i.e. surge, sway and yaw, as indicated in Figure 3.

However, the remaining wave-induced vessel motions, i.e. heave, roll and pitch, are uncontrolled vessel motions. When lifting payload (3) from the moving supply vessel, its uncontrolled heave, roll and pitch motions cause varying tension on the lifting cables that could damage the stationary jack-up crane and its lifting equipment; an example is given in this video [V1].



Offshore wind turbine installed by a jack-up vessel. (Source: Siemens [1])



Degrees of freedom (DoFs) of the supply vessel.

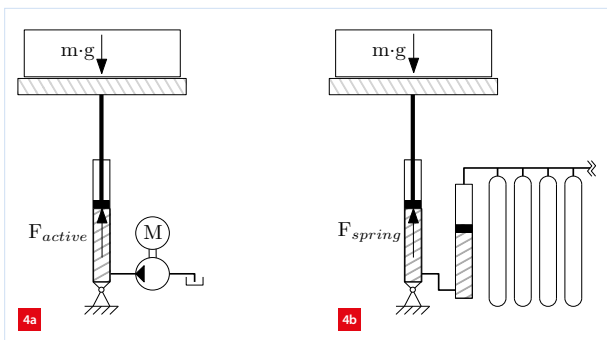
Placing the payload onto a motion-compensated platform (2) solves this challenge. Therefore, this article will describe the design of a motion-compensation mechanism that decouples the wave-induced vessel motions from its payload to facilitate safe offshore load transfer.

### Specifications

The following specifications have been established in collaboration with Bosch Rexroth. The motion-compensation mechanism has to support a payload, positioned on a platform, with a maximum mass of 1,000 metric tonnes while compensating for motion in three degrees of freedom (DoFs), namely vessel heave, roll and pitch. The payload has to be offloaded with a rate in excess of 5 metric tonnes per second for a heave stroke of 3 m.

### Passive heave compensation

Vessel heave motions can be compensated for by placing a vertically orientated hydraulic cylinder between the vessel's hull and the payload platform (see Figure 4a). The hydraulic cylinder is actuated to retract during upwards heave and to extend during downwards heave of the vessel. The payload therefore maintains its vertical position. The cylinder actuation is achieved using a hydraulic pump, powered by a diesel generator. To support a payload of



Heave compensation of the platform using a hydraulic cylinder.  
(a) Actuated by an active hydraulic pump.  
(b) Actuated by a passive gas spring.

1,000 metric tonnes over a heave stroke of 3 m, however, several megawatts of peak power are required.

A more energy-efficient solution is passive heave compensation. Instead of actively actuating the hydraulic cylinder over the vessel's heave stroke, the cylinder is connected to a large gas volume (see Figure 4b). Connecting a hydraulic cylinder to a gas volume yields the behaviour of a gas spring. Therefore, little active power is required to only compensate for the effect of the pressure-volume curve of the gas spring as induced by the volume variation of the hydraulic cylinder over the heave stroke.

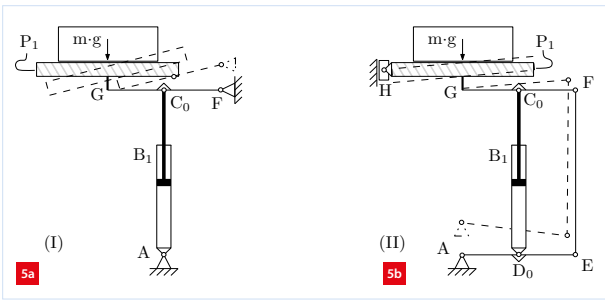
The force of the gas spring  $F_{\text{spring}}$  is in balance with the combined weight of the payload  $m \cdot g$ , the platform and the proposed mechanism. Load transfer off or onto the platform causes an imbalance between the gas spring force and the weight it has to support. This leads to the hydraulic cylinder being extended uncontrollably by the pressurised gas and the platform potentially hitting the payload. Prevention can be managed by actively countering the gas spring force, again using a hydraulic pump driven by a diesel generator. This leads us back to the required several megawatts of peak power.

### Load transfer mechanism

The imbalance between the gas spring force and the weight it has to support is prevented by introducing a lever between the platform and the gas spring. During offloading, the lever ratio increases gradually, after which the gas spring force is finally countered solely by the combined weight of the platform and the mechanism. Vice versa, during the loading of the payload onto the platform, the lever ratio reduces gradually such that the gas spring force remains balanced by the combined weight of the payload, the platform and the mechanism.

Figure 5a shows a payload with weight  $m \cdot g$  on platform  $P_1$ , which is supported by mechanism I. The platform is rigidly connected to linkage GF, acting as a lever. Joints F and A are rigidly connected to the vessel and are therefore referred to as vessel ground joints. Linkage GF is vertically supported at joint  $C_0$  by the gas spring's hydraulic cylinder  $B_1$ , whereas vessel ground joint A connects cylinder  $B_1$  to the vessel. The cylinder supports linkage GF at half its length in joint  $C_0$ , giving it a lever ratio of 1:2, such that a payload mass of  $1,000 \text{ tonnes} / 2 = 500 \text{ tonnes}$  is supported by the same gas spring as shown in Figure 4b, where it is supporting 1,000 tonnes. By translating joint  $C_0$  over linkage GF, the lever ratio alters to perform load transfer.

During heave motion of the vessel, joints A and F move upwards, which requires the retraction of cylinder  $B_1$  to maintain a stationary platform position. The resulting



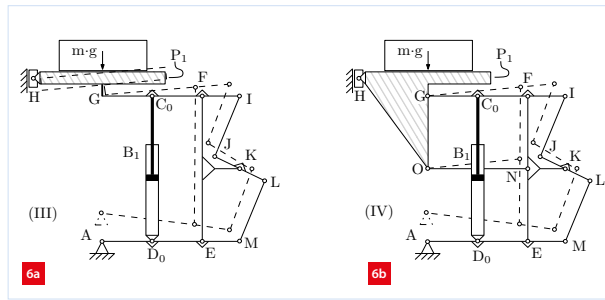
'Simple' load transfer mechanism designs.  
(a) I, with a horizontal lever, exhibiting multiple parasitic platform motions.  
(b) II, with the added linkages AE and EF, eliminating one parasitic motion.

rotation of linkage GF simultaneously rotates the platform and additionally translates it horizontally towards joint F as indicated by the dashed lines. These undesired parasitic platform motions are reduced in mechanism II, as shown in Figure 5b.

The configuration of mechanism II uses two levers, in the form of linkages GF and AE, interconnected by linkage EF. The two levers prevent the horizontal parasitic motion of the platform; instead, linkage EF performs the horizontal parasitic motion, which is acceptable. The rotating parasitic motion of the platform is still present, due to the rigid coupling of the platform to linkage GF. As an interim solution, a slider element is added at joint H, to prevent rotation of the platform and mechanism about vessel ground joint A. Mechanism II has now two DoFs, of which one is desired, namely the heave stroke. The second DoF is rotation of the platform about joint H. This DoF is eliminated by synchronising the rotation angle of linkages GF and AE, since a synchronisation of two linkages eliminates one DoF from the mechanism.

The synchronisation mechanism is added to mechanism III, displayed in Figure 6a, consisting of linkages LM, JL and JI. Linkage GF elongates to linkage GI, while linkage AE elongates to linkage AM. An additional joint is added to linkage EF, being joint K. The mirrored angle of linkage AM is coupled to linkage GI via linkages LM, JL and JI. The number of DoFs within mechanism III is one, namely the heave stroke as prescribed by cylinder  $B_1$ . However, during a heave stroke the rotating parasitic motion of the platform due to the rigid coupling to linkage GI is still present, as depicted by the dashed lines.

Mechanism IV, displayed in Figure 6b, eliminates the parasitic platform rotation by introducing joint G such that linkage GI can rotate with respect to the platform. By adding platform joint O and linkage ON, a parallelogram arises consisting of linkages GI and ON. This parallelogram prevents rotation of the platform, while it allows joint A



Load transfer mechanism designs with synchronised linkages GI and AM.  
(a) III, with one DoF eliminated, i.e. the rotation of the platform about joint H.  
(b) IV, with the parallelogram GI – ON, eliminating all parasitic platform motions.

to move up and down with the vessel's heave motion.

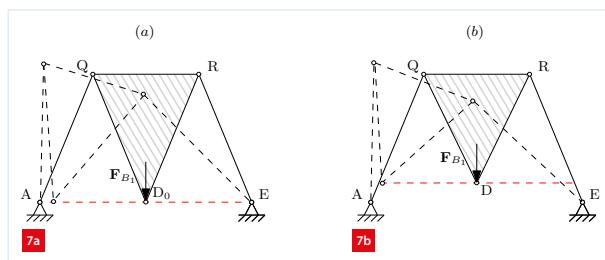
This mechanism has one DoF as prescribed by cylinder  $B_1$  and eliminates all parasitic platform motions.

## Gas spring lever-ratio change

In the previously discussed mechanisms I to IV, linkages AE and GF are loaded in bending by cylinder  $B_1$  to create the required lever effect. It is more favourable, however, to connect cylinder  $B_1$  to an axially loaded straight-guide mechanism, which additionally provides the translation of the cylinder during load transfer. The suitable mechanism for this is the Roberts approximate straight-guide mechanism [2]. The Roberts mechanism is a symmetrical four-bar linkage capable of providing an approximate straight-guided point by converting a rotational motion into an approximate straight motion. The mechanism is depicted in Figure 7a.

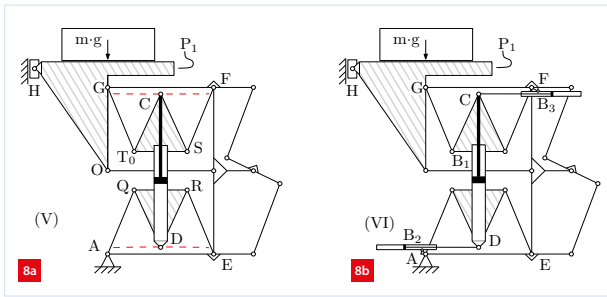
Joint  $D_0$  traces an approximate straight horizontal line between ground joints A and E, as indicated by the dashed line. This mechanism is suitable, since the ground joints and the approximate straight-guided joint are at the same line, which is required to translate the gas spring's hydraulic cylinder  $B_1$  over the levers GF and AE. The proportions of the individual linkages that give the most accurate straight line of joint  $D_0$  are:  $AQ = QD_0 = D_0R = RE$  and  $AE = 2QR$ .

Joint  $D_0$  is suitable as a point of application for the gas spring's hydraulic cylinder  $B_1$ . The compression force on the



Linkage ratios of the Roberts approximate straight-guide mechanism.  
(a) For the most accurate straight line.  
(b) For a convenient transition to a 3D design.





Load transfer mechanism designs with two Roberts mechanisms.  
(a) V, translating cylinder  $B_1$  as indicated by the dashed lines.  
(b) VI, with the positions of joints D and C prescribed by cylinders  $B_2$  and  $B_3$ , making the whole mechanism statically determined.

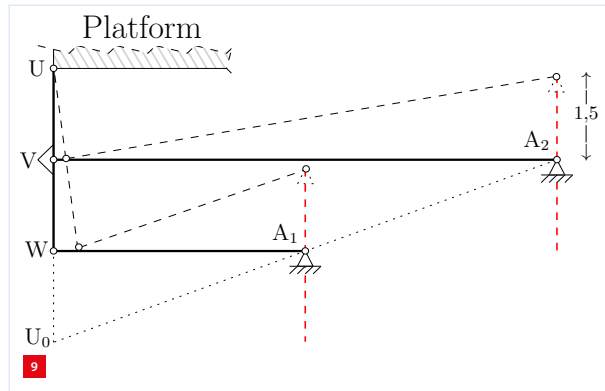
cylinder,  $F_{B1}$ , loads triangle  $D_0QR$  in tension, while linkages AQ and ER have a compression load. However, it is convenient for the transition of the planar design to a 3D design to move the path of  $D_0$  upwards, to prevent the coincidence of multiple hinge points. This modification is depicted in Figure 7b, where joint D replaces joint  $D_0$ . The maximum deviation of joint D with respect to a horizontal line in the proposed mechanism becomes 17 mm, which is acceptable.

Mechanism V has two Roberts mechanisms, as shown in Figure 8a. Next, the position of joints D and C is prescribed by two hydraulic cylinders,  $B_2$  and  $B_3$ , as shown in Figure 8b, required to execute load transfer. Mechanism VI has three DoFs, one being the heave motion as prescribed by cylinder  $B_1$ . The second and third DoF are the translation of joints D and C as prescribed by cylinders  $B_2$  and  $B_3$ , respectively. One DoF is then eliminated by synchronising cylinders  $B_2$  and  $B_3$ , using fluid-power synchronisation on the cylinder chambers with equal volume. If  $B_2$  extends,  $B_3$  retracts, and vice versa, leading to joints D and C remaining at the same vertical line and thereby preventing cylinder  $B_1$  from tilting within the mechanism. The remaining two prescribed DoFs are the heave motion and the translation of cylinder  $B_1$  for load transfer. Mechanism VI is therefore statically determined.

### Motion-compensation mechanism

To maintain the platform's stationary position and prevent it from rotating about vessel ground joint A, slider H was introduced. Since sliding contacts are undesirable within this application, the slider is replaced by a four-bar, quasi-straight-guide mechanism [3], as shown in Figure 9. The mechanism is constructed by intersecting  $A_2A_1$  and VW in  $U_0$ , giving length  $WU_0$ . By adding  $WU_0$  to VW, linkage UW is formed, with U the quasi-straight guided point. For U to have the least deviation, the following ratio is applied:

$$UV = WA_1 \cdot VW / (VA_2 - WA_1)$$

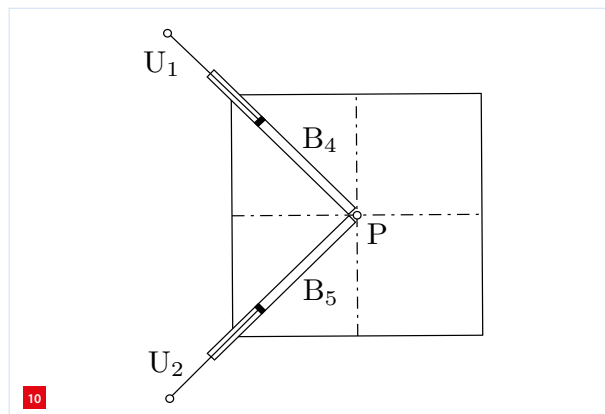


Quasi-straight-guide mechanism, with joint U motionless with respect to the platform and vessel-mounted joints  $A_1$  and  $A_2$  moving with the vessel's heave motion as indicated by the dashed lines.

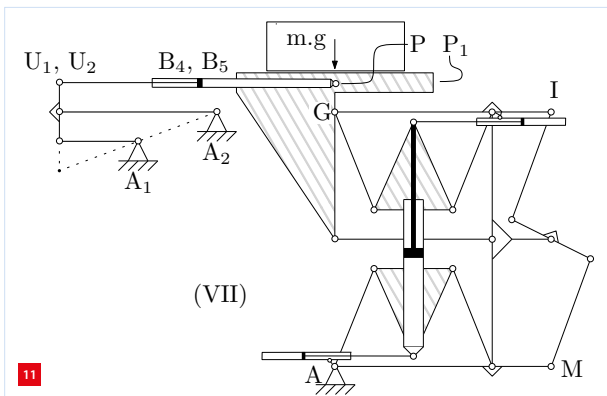
However, joint U is connected to the platform and therefore remains stationary. Instead, vessel ground joints  $A_1$  and  $A_2$  move vertically with the vessel's heave motion of +1.5 m and -1.5 m, as indicated by the dashed lines in Figure 9.

The remaining two vessel motions to be compensated for are roll and pitch. The previously described rigid connection between joint U and the platform couples the roll and pitch motions of the vessel directly to the platform. Instead, the rigid connection is replaced by two hydraulic cylinders. Figure 10 shows the top view of the platform with two perpendicular hydraulic cylinders  $B_4$  and  $B_5$  connected at the platform's central joint P. The two cylinders can rotate about joint P in the plane of the platform. At each joint  $U_i$  ( $i = 1, 2$ ), a quasi-straight-guide mechanism is attached, as shown in the side view of mechanism VII in Figure 11.

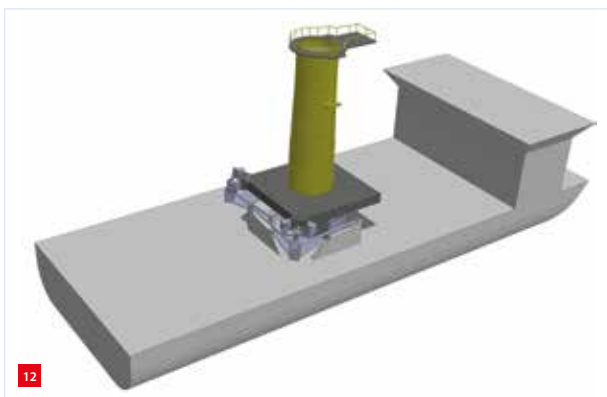
The vessel's roll and pitch motions are decoupled from the platform by actuating the cylinder pair accordingly. Incorporating cylinders  $B_4$  and  $B_5$  into the platform reduces the footprint of the mechanism. Mechanism VII compensates for the vessel motions of heave, roll and pitch, while performing a load transfer of 1,000 tonnes off and onto the platform.



Top view of the platform, with cylinders  $B_4$  and  $B_5$  compensating for the roll and pitch motions of the vessel.



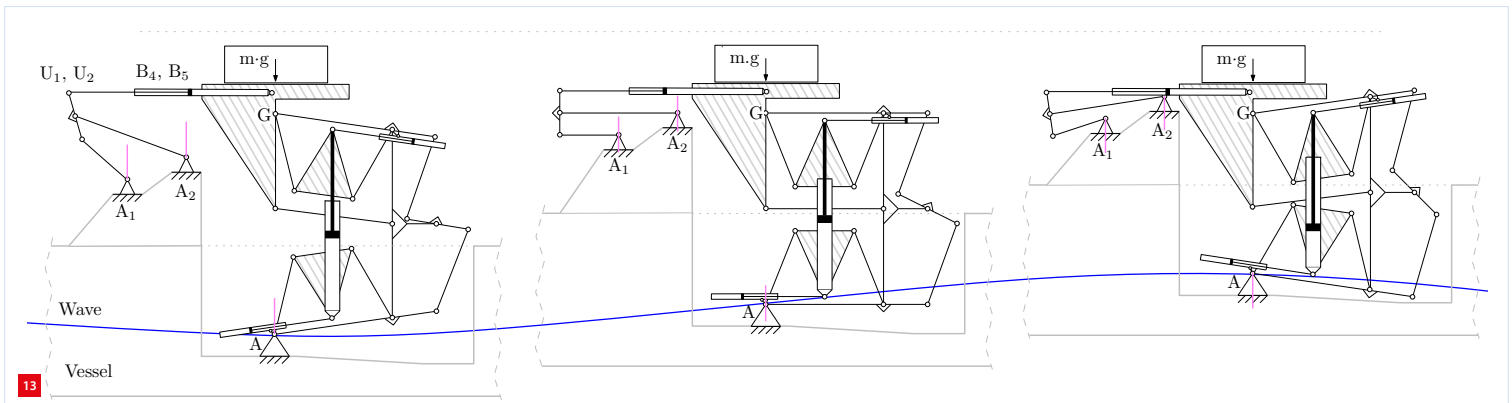
Load transfer mechanism design VII, with the quasi-straight guide to the vessel.



3D model of the motion-compensation mechanism with payload in the form of part of the turbine tower foundation.

Figure 12 shows the transition of the planar kinematic mechanism into the 3D spatial mechanism, supporting a payload in the form of part of the foundation for the turbine tower. Due to issues of confidentiality, only limited details can be provided on the spatial design.

Figure 13 displays the rotation and translation of each linkage during a heave motion of the vessel, such that the platform remains stationary.



The mechanism decoupling the heave motion of the vessel from the platform, which therefore stays stationary.

## Conclusion

The final motion-compensation mechanism meets the requirements of the project. Now that all the global aspects of the mechanism have been investigated, calculated and elaborated, it could become a game changer for the installation of future offshore wind farms.

## REFERENCES

- [1] [www.siemens.com/press/photo/PN201301-07e](http://www.siemens.com/press/photo/PN201301-07e)
- [2] H. Eckhardt, *Kinematic Design of Machines and Mechanisms*, McGraw-Hill, 1998.
- [3] K. Hunt, *Kinematic Geometry of Mechanisms*, Oxford University Press, 1978.

## VIDEO

- [V1] Bad crane lift offshore,  
[www.youtube.com/watch?v=Sd8junbzTrY](http://www.youtube.com/watch?v=Sd8junbzTrY)



## Wim van der Hoek's design principles

The principle 'control of degrees of freedom' has been incorporated in the planar kinematic design. To explain which motion each linkage has to make and which motion it has to constrain, several cardboard models were made, as inspired by the examples of Wim van der Hoek.

Furthermore, the transition of the planar kinematics to a 3D spatial mechanism was guided by the principle 'design for lightweight and stiffness'. For example, planar linkage EF (Figure 6a) becomes a 3D body loaded in torsion. According to Van der Hoek's design principles, a torsional stiff box is an excellent candidate to fulfil this function. And finally, to dimension the whole mechanism, simple 'back of an envelope' calculations have been made to get an idea of whether this could work in real life. The short answer: yes it can!

# MAINTAINING HIGH SUPPORT STIFFNESS

Spherical flexure joints with three degrees of freedom are typically limited to small deflections, because when deflected they lose a great deal of stiffness in support directions. To allow for a larger range of motion while maintaining high support stiffness, an advanced stacked folded-leafspring-based spherical joint has been developed. Optimisations of this design have led to a spherical joint with a 30° range of tilt motion in combination with a high support stiffness (> 200 N/mm) and load capacity (> 290 N).

MARK NAVES, RONALD AARTS AND DANNIS BROUWER

## Introduction

In high-precision applications, flexure-based mechanisms are used for their deterministic behaviour because of the absence of play and friction. Spherical flexure joints are often encountered in spatial precision manipulators with parallel kinematic arrangements and sub-micron repeatability, such as spatial (6-DoF) nanopositioners, and micro-assembly and precision alignment systems (DoF = degree of freedom). For this purpose, spherical notch joints or short-wire flexures are typically used to provide the required spherical motion. These joints can be realised in a small, compact design that allows for easy manufacturing (Figure 1a).

They only provide, however, a limited range of motion (typically a few degrees) due to their localised compliance, which results in high stress levels at even small deflection angles. Therefore, they are mostly used for optical alignment systems that require only small rotation angles of the spherical joints. Larger ranges of motion can be obtained by a stacked arrangement of wire flexures (Figure 1b) or by concatenating three single-DoF flexure joints in

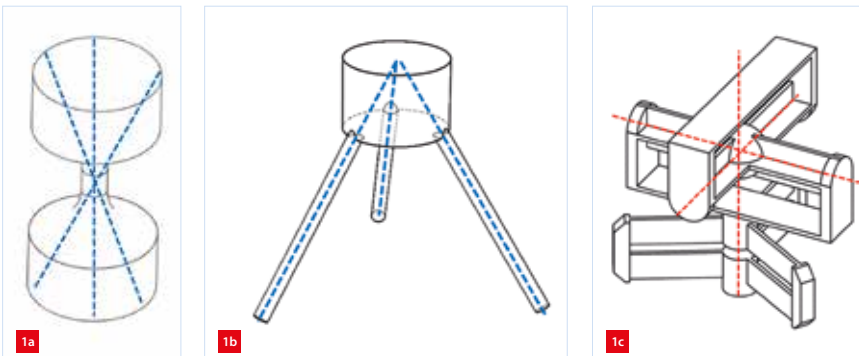
series in order to obtain the required DoFs (Figure 1c). However, these types of joints typically suffer from a limited support stiffness, as well as a large decrease of this support stiffness with increasing deflection angle due to the large deformations involved.

To allow for a larger range of motion in combination with high support stiffness, a flexure-based spherical joint design is presented here that uses folded leafsprings as flexible elements to obtain the required DoFs. A folded-leafspring-based design for a spherical joint has been presented before by Schellekens et al. [1], who combined three parallel folded leafsprings. This design allowed for a high support stiffness and load capacity, although only a limited range of motion was obtained.

In order to extend the range of motion while maintaining high support stiffness, an advanced stacked folded-leafspring-based spherical joint has been developed for use in a fully-flexure-based hexapod system with a large range of motion. A schematic overview of this system is illustrated in Figure 2 and a CAD rendering is provided in Figure 3.

## Folded-leafspring-based spherical joint

A spherical flexure joint is characterised by the property of allowing motion in the three rotational DoFs, while

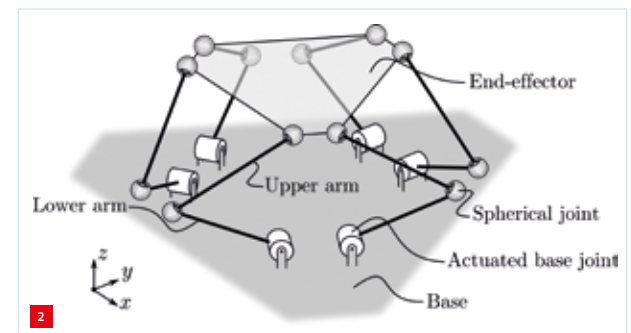


Flexure-based spherical joints.

(a) Spherical notch joint or short-wire flexure.

(b) Wire-flexure-based spherical joint.

(c) Spherical joint constructed by concatenating three single-DoF joints.



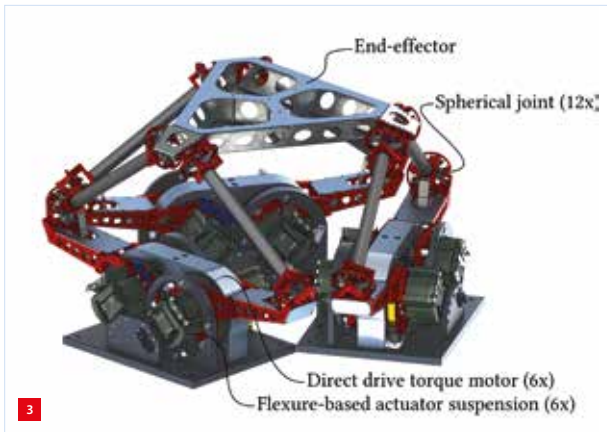
Schematic of the kinematics of the hexapod system (T-flex).

### AUTHORS' NOTE

Mark Naves (Ph.D. student) and Dannis Brouwer (professor) are members of the chair of Precision Engineering, and Ronald Aarts (associate professor) is a member of the chair of Structural Dynamics, Acoustics & Control, all in the Department of Mechanics of Solids, Surfaces & Systems at the University of Twente, Enschede (NL).

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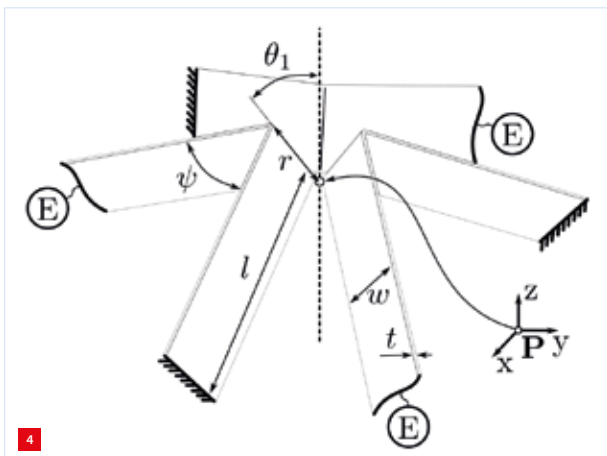


Rendering of the fully-flexure-based hexapod system (T-flex).

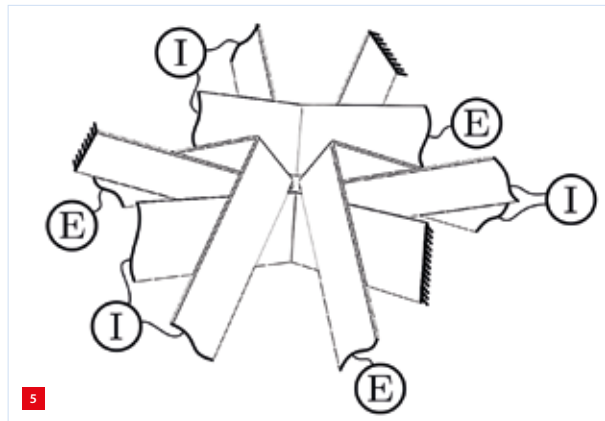
constraining motion in all translational directions (the directions in which load-bearing support is provided). For many applications, a spherical joint with coinciding rotation axes is required to concentrate all rotational motion in a single point.

In order to obtain the three rotational DoFs for the spherical joint, flexible elements were required that provide the necessary constraints. Wire flexures are suited to this purpose, but they do not allow for both a large range of motion and a high support stiffness [2]; see, e.g., the wire-flexure-based design as presented in Figure 1b. Therefore, folded leafsprings were used, which also constrain a single translational DoF that is located along the fold line, equivalent to the wire flexure. Compared to wire flexures, the folded leafsprings typically allow for a larger range of motion with a higher level of support stiffness and load capacity.

The most elementary topology for a folded-leafspring-based spherical flexure joint consists of a set of folded leafsprings directly connecting the fixed world and the end-effector. An exactly constrained design was obtained with three folded leafsprings as illustrated in Figure 4.



Parameterised folded-leafspring-based spherical-joint topology with 'E' representing the connection with the end-effector.



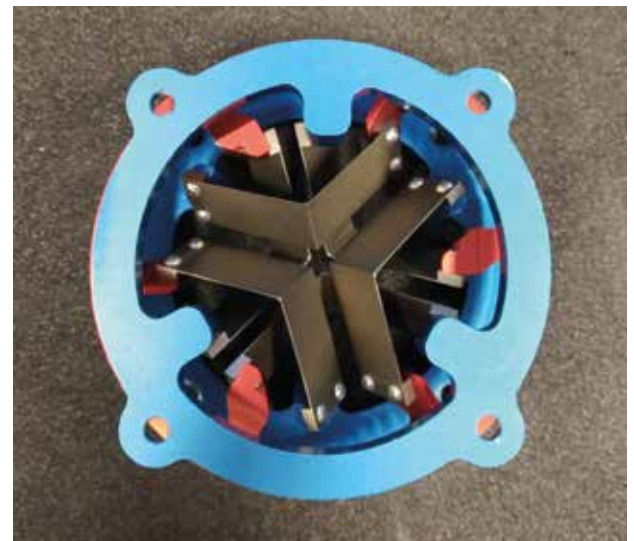
Serially stacked folded-leafspring-based spherical-joint topology with 'E' representing the connection with the end-effector and 'I' representing the connection to an intermediate stage.

To increase the range of motion of this folded-leafspring-based spherical-joint topology, a serially stacked equivalent topology was suggested. This topology consists of two sets of three leafsprings, with the first three leafsprings connecting the fixed world and an intermediate body, and the second set connecting the intermediate body and the end-effector. Effectively, this leads to two spherical joints stacked in series with coinciding rotation axes, each contributing to half of the motion.

Additionally, by properly stacking the folded leafsprings, they can be placed close together (and intertwined), leading to a compact design. As the deflection per stage is halved, the stress levels in the flexures are reduced, allowing for thicker leafsprings, which results in increased support stiffness. Furthermore, because the support stiffness decreases progressively nonlinearly with the deflection, halving the deflection leads to (far) less than half the stiffness loss over the range of motion. A schematic overview of the serially stacked folded-leafspring-based joint topology, referred to as the SFL-joint, is provided in Figure 5.

It has to be noted that the intermediate body is only constrained for translational motion and therefore contains three redundant rotational DoFs (the intermediate body is three times underconstrained). For most flexure mechanisms, underconstrained intermediate bodies dramatically impair support stiffness (particularly when the mechanism is in a deflected state) due to the coupling of external loads and the underconstrained DoFs, such as the compounded parallel leafspring guidance without slaving [3].

For the SFL-joint, however, the instant centres of rotation of the intermediate body and the end-effector coincide, and barely change position for an increasing deflection angle. Hence, external loads on the end-effector do not result in reaction moments in the DoFs of the intermediate



Two views of a realisation of the SFL-flexure joint. Diameter of the red intermediate body is 140 mm and the height of the joint is 70 mm.

body. Additionally, as the rotation centres coincide, rotational motion of the intermediate body does not contribute to translational motion of the end-effector. Due to this special property, support stiffness does not deteriorate due to the underconstrained intermediate body and the position of the end-effector is not influenced by the motion of the intermediate body.

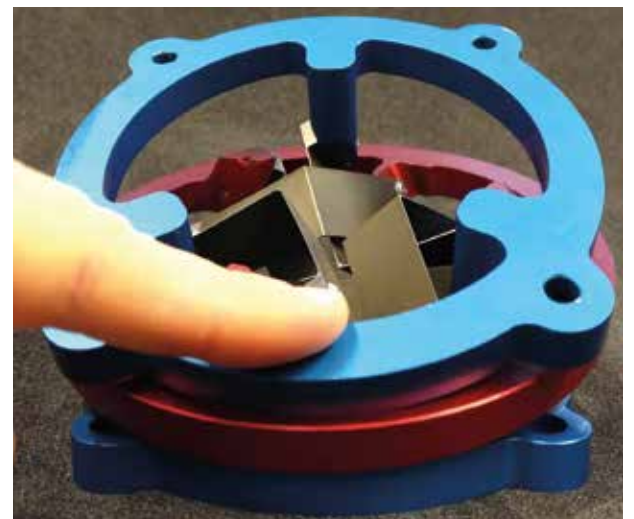
However, with respect to the dynamic behaviour of the joint, having an underconstrained intermediate body can result in unwanted vibrations in the system due to its low eigenfrequency. These vibrations can be reduced by adding damping to the intermediate body (e.g. eddy-current damping) to reduce the magnitude of the vibrations [4].

#### Optimisation of the joint geometry

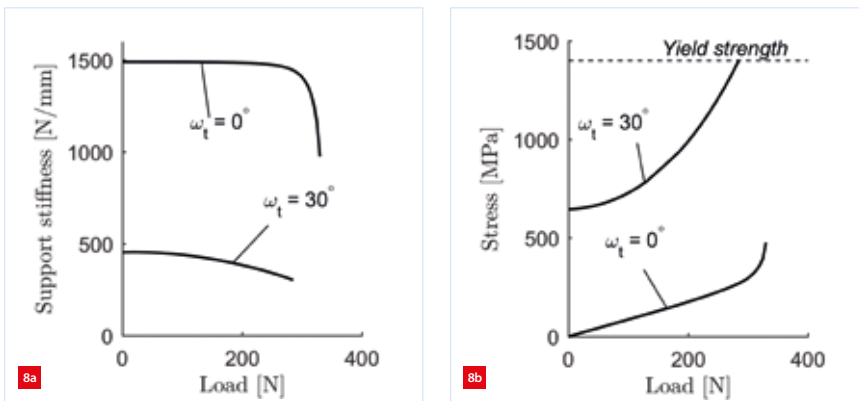
Due to the complex spatial geometry of the spherical flexure joint as presented in Figure 5, deriving a 'good' geometry

that results in a high-performing design is a far from trivial task, especially when considering the possibility of collision of the flexures given the large range motion. Predicting mechanism designs that are free of collision can be hard, given the 3D nature of the motion in combination with the large deformations.

Therefore, the design of the flexure joint was optimised by a shape-optimisation algorithm that searches for the optimal geometry for the flexure joint. The algorithm maximises support stiffness, taking into account the workspace and collision of the flexures. For this optimisation, the flexible multi-body software SPACAR [5] was used to evaluate the deformations, support stiffness and maximum stress in the flexures for a given geometry in combination with a specifically developed collision-detection algorithm [6]. For the optimisation, we considered a range of motion of 30° tip-tilt ( $\omega$ ; rotation around the  $x/y$ -axis) and 10° pan



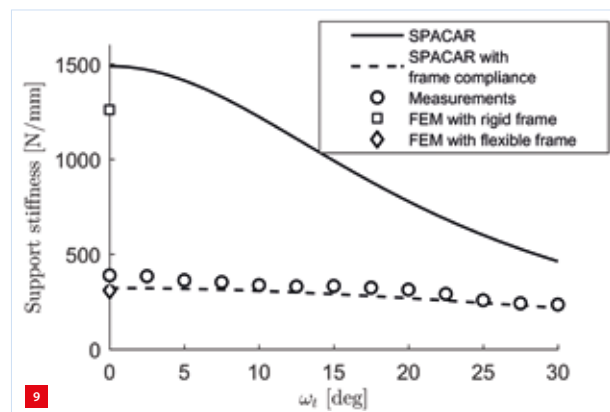
Two views of the SFL-flexure joint in a deflected state.



Flexure behaviour as a function of load applied along the pan axis.  
(a) Support stiffness along the pan axis.  
(b) Simulated (von Mises) stress.

( $\omega_p$ : rotation around the z-axis). Tool steel (yield strength: 1,400 MPa) was the material of choice, amply allowing the imposed stress limit of 600 MPa. Based on the optimisation results, a prototype of this spherical joint has been constructed. A realisation of the prototype in undeflected and deflected states is provided in Figures 6 and 7. This prototype was constructed from tool steel flexures of 0.4 mm thickness combined with three aluminium frame bodies (the base and end-effector anodised in blue, the intermediate body anodised in red).

The resulting optimal design showed a support stiffness of the flexures in the main load-carrying direction (along the vertical z-axis) of about 1,500 N/mm when not deflected and a stiffness of almost 500 N/mm at a maximum tilt angle of  $30^\circ$ . Furthermore, the joint allows for a maximum load (in the same direction) of approximately 300 N. The support stiffness and maximum stress in the flexures for increasing load (for both  $0^\circ$  and  $30^\circ$  tilt angle) are provided in Figure 8. Note that at  $0^\circ$  tilt, load capacity is limited by the buckling of the flexures, resulting in an instantaneous, strong decrease in support stiffness at a load of approximately 290 N. However, at a tilt angle of  $30^\circ$ , load capacity is limited by the maximum stress in the flexures, exceeding the yield strength at about 300 N.



Experimental validation including flexible multi-body simulations (SPACAR), FEM simulations (SolidWorks Simulation) and measurements.

### Experimental validation

To validate the support stiffness, an experimental validation was conducted. To that end, the joint was deflected up to the desired tilt angle and kept at this angle by means of a fixture. Furthermore, load was applied to the joint by a micrometer connected to the joint via a single wire flexure (attached to a force sensor to measure the applied load). Deflection of the joint was measured by a capacitive displacement sensor. As both the applied force and deflection were measured, this allowed for the evaluation of the support stiffness of the joint.

An overview of the measured and simulated stiffnesses as functions of the tilt angle ( $\omega_t$ ) is provided in Figure 9. Especially with small tilt angles, the measured stiffness (circles) is substantially lower than simulated (solid line). This difference in support stiffness can be related to additional compliance introduced by the frame parts that connect the leafsprings, and the way folded leafsprings typically load connecting parts by moments. During the design of the spherical joint, care was taken to ensure high stiffness of the frame parts.

Despite this, restrictions on the design freedom imposed by avoiding any collision of the flexures and frame parts over the range of motion inherently limit the stiffness of the frame. Therefore, the additional compliance of the frame has to be taken into account to accurately assess the support stiffness of the entire joint.

To evaluate the effect of frame compliance on the overall support stiffness, a finite-element method (FEM) analysis (Solidworks Simulation) considering zero tilt-angle was conducted, both for a flexible and a rigid frame. The overall stiffness of the joint appeared to be  $1.3 \cdot 10^3$  N/mm considering rigid frame parts. Stiffness decreased to  $3.1 \cdot 10^2$  N/mm for a realistic representation of the frame. From these values, an approximation of the frame stiffness could be computed, assuming the flexures and frame stiffness are in series, resulting in an equivalent frame stiffness of  $4.1 \cdot 10^3$  N/mm.

By adding this equivalent frame stiffness in series to the stiffness obtained from numerical simulations, an approximate stiffness could be estimated (dashed line). When frame compliance was added to the simulations, a good match was obtained between experiment and simulations. Additionally, the maximum load capacity of the joint was verified, which showed a load capacity of at least 150 N. Higher loads have not been validated in order to prevent plastic deformations of the flexures that would compromise other measurements.

### Spherical joint redesign

Based on the results and the experimental validation, a redesign of the spherical joint with  $25^\circ$  tip-tilt and  $10^\circ$  pan





Realisation of the redesign of the SFL-flexure joint. Frame parts are given in orange, diameter 90 mm. Note that the connections with the intermediate body are concentrated at three locations, in contrast to the six locations in the design presented in Figure 6, thus reducing frame compliance.

(a) Full spherical joint.

(b) Spherical joint with top and bottom frame parts detached.

motion was proposed, offering a higher level of support stiffness (500 N/mm at maximum tilt angle including frame compliance), as illustrated in Figure 10. This increased support stiffness was primarily obtained by changing the stacking order of the flexures in order to connect the folded leafsprings more closely together on the intermediate body, thus reducing frame compliance. Furthermore, the size of the joint has been reduced to a diameter of 90 mm and a height of 60 mm, allowing for an additional reduction in compliance of the frame parts and a reduction of its footprint.

## Conclusion

A large-range-of-motion spherical flexure joint can be obtained by using a topology with three or more folded leafsprings in parallel, of which all folding lines intersect at a single point. Range of motion can be greatly increased by effectively stacking two spherical joints in series, each having three folded leafsprings in parallel. With this design, the deformations of the flexures are halved, allowing for stiffer flexures at the same level of stress. This results in a significant increase in support stiffness, although it comes at the cost of an underconstrained intermediate body with a potentially low eigenfrequency.

Structural optimisations on this flexure joint have resulted in a flexure-based spherical joint that allows for 30° tip-tilt and 10° pan motion. At maximum deflection, this joint maintains a support stiffness of over 200 N/mm, which is more than an order of magnitude higher than the current state-of-the-art spherical flexure joints with similar range of motion. Furthermore, a load capacity of almost 300 N

at maximum tilt angle has been obtained. Experimental validations verified the simulated performance and confirmed the high support stiffness and load capacity over the entire range of motion.

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## Wim van der Hoek's design principles

The design principle 'control of degrees of freedom' underlies the kinematic concept described here.

A (remote) centre of rotation has been created by having three wire flexures point at one location. The equivalent kinematic structure can then be created by exchanging each wire-flexure for a folded leafspring to increase off-axis stiffness and load capacity.

# BALANCING POSITIVE AND NEGATIVE STIFFNESS

A passive vibration isolation system has been designed to fit within a compact design space by decreasing the positive stiffness of a gas spring with the negative stiffness of multiple buckled leafsprings. It is insensitive to production tolerances and payload variations, and meets the requirement for dynamic stiffness. Analytic equations have been used to prove the feasibility of this design. Furthermore, dynamic analysis has shown that the requirement for dynamic stiffness has been met with some minor design changes and only a few percent of damping.

ROY JACOBS

## Introduction

Photolithography is the most common IC manufacturing process, for which ASML is the largest manufacturer of lithography machines. During exposure, a light (extreme ultraviolet, EUV, in the latest versions) beam is focused and sized by multiple lenses and/or mirrors, attached to a so-called projection optics box. The lithography machine needs to operate with high accuracy and precision, and is therefore sensitive to vibrations. A vibration isolation system (VibIS) is used to create an isolated machine architecture and thereby minimise the effects of ground and base-frame vibrations on the sensitive parts. Vibration isolation relies on the principle of dynamic decoupling by placing the sensitive parts (with a large mass) on compliant springs.

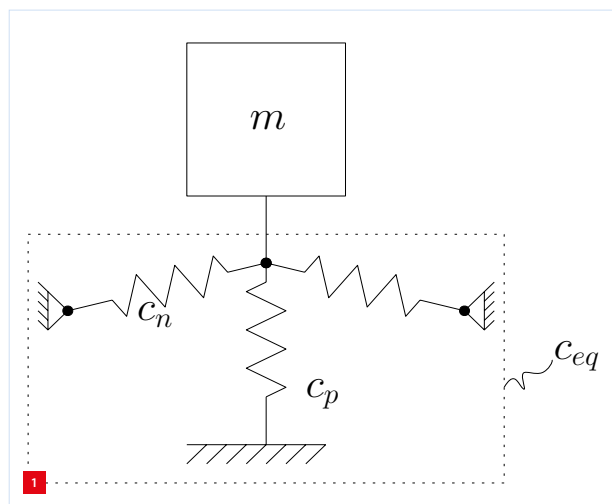
Vibration isolation systems typically use a gas spring for decoupling the payload in the vertical direction with respect

to the fixed world. The associated pressure vessels often exceed the available design space. The challenge was to design a passive VibIS for supporting the projection optics box that meets a more stringent requirement for the design space: 410 mm x 410 mm x 400 mm = 67 ℓ (note that the typical volume of the additional pressure vessels of the currently available vibration isolation systems is approximately  $2 \cdot 10^2$  ℓ). The payload has a mass of 14,000 kg and is supported on four points. Hence, each vibration isolation system needs to support a mass of 3,500 kg. The requirement was to decouple the payload at 0.3 Hz in the vertical direction with respect to the fixed world. The decoupling mechanism(s) for the horizontal directions were considered to be outside the scope of this project.

The concept used for the VibIS is illustrated in Figure 1. In this figure, a mass ( $m$ ) is supported by a spring with positive stiffness ( $c_p$ ). The equivalent positive stiffness of the mechanism is reduced by placing a spring with a negative stiffness ( $c_n$ ) parallel to it [1]. The equivalent stiffness of the mechanism then becomes  $c_{eq} = c_p + c_n$  [2]. This principle is used to decrease the stiffness of a gas spring to obtain a VibIS with the required decoupling frequency in the vertical direction that fits within the design space.

## Design overview

Figure 2 shows the resulting design based on the concept described above. The positive spring – a gas spring – is depicted separately in the bottom right part of the figure. Positioned inside the tank volume of the gas spring is the negative-spring mechanism, consisting of (among others) multiple buckled leafsprings. It is depicted separately in the top right part of the figure. A strut, stiff in the vertical

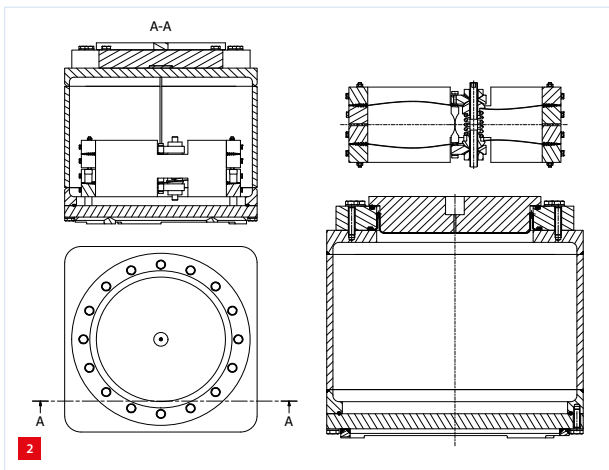


A mass  $m$  is supported by a spring with positive stiffness ( $c_p$ ). The equivalent stiffness of the mechanism ( $c_{eq}$ ) is reduced by connecting a spring with negative stiffness ( $c_n$ ) in parallel.

### AUTHOR'S NOTE

Roy Jacobs graduated on the subject of this article from Eindhoven University of Technology (TU/e), chair of mechatronic system design (prof.dr.ir. Hans Vermeulen, also senior architect EUV Optics System at ASML, and dr.ir. Nick Rosielle). For his work he received a nomination for the Wim van der Hoek Award 2018. He is now working as a mechatronic system designer at MI-Partners in Eindhoven (NL).

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Design of the vibration isolation system (VibIS).  
Bottom left: Top view.  
Top left: Sectional view A-A.  
Bottom right: Positive spring.  
Top right: Negative-spring mechanism.

direction and compliant in lateral directions, is used to connect the negative-spring mechanism to the piston of the gas spring.

### Positive spring

Gas springs are often applied in the field of passive vibration isolation because of the compressibility of the gas in the system [3]. As a result of this property, a gas spring can support a large load with a relatively low stiffness in a compact volume. The detailed design of the gas spring is presented in Figure 3.

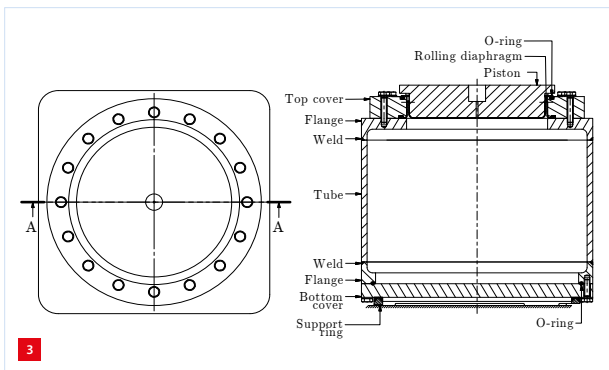
The pressure vessel consists of a thick-walled tube with a square cross-section onto which two flanges are welded. The flanges contain the interfaces for the top and bottom covers. The top cover contains the hole for the rolling diaphragm that supports the piston. The piston with the rolling diaphragm is able to translate in the vertical direction. The flanges need to be sealed to prevent any gas leaking into the vacuum chamber of the lithography system. These elements are sealed with an o-ring. The rolling

diaphragm is the seal between the top cover and its flange. Should the rolling diaphragm fail, the piston will lower in the vertical direction and land on the top cover. Then the o-ring in the top cover will minimise any leakage of pressurised air into the vacuum. The support ring has three contact surfaces with the fixed world and is welded onto the bottom cover.

A rectangular design was chosen to make optimal use of the design space, because it results in a larger gas volume and thus a lower positive stiffness. Furthermore, it allows for easy assembly of the negative-spring mechanism. The outer dimensions of the pressure vessel are chosen to fit within the design space; the wall thickness of 10 mm is assumed to be sufficient to withstand 7 bar of pressure.

The stiffness of the gas spring in the vertical direction is calculated using  $c_z = \gamma p_i A^2/V$  [3]. The internal pressure in the vessel is denoted by  $p_i$ . The effective surface of the rolling diaphragm and the volume of the pressure vessel are denoted by  $A$  and  $V$ , respectively. Since there is no energy dissipation between the gas spring and the environment, the polytropic exponent is assumed to be  $\gamma = 1.4$  for the compressed air.

The equation for the stiffness of a gas spring is only valid when the environmental pressure of the VibIS is zero (i.e., when placed in vacuum) and the change of volume due to the vertical stroke of the piston is negligible ( $A\delta h \ll V$  for a vertical stroke of  $\delta h = \pm 0.25$  mm during operation). Furthermore, it is assumed that the rolling diaphragm has negligible stiffness and hysteresis in the  $z$ -direction. Therefore, the stiffness in  $z$ -direction equals the stiffness of the gas volume. The volume of the pressure vessel as depicted in Figure 3, from which the volume of the negative-spring mechanism is subtracted, equals 45 l. The pressure in the vessel is determined by the payload and the effective area of the rolling diaphragm ( $A = 4.71 \cdot 10^4$  mm<sup>2</sup>) and equals 7.3 bar. The resulting positive stiffness equals 52 N/mm.



Detailed design of the gas spring.  
Left: Top view.  
Right: Sectional view A-A with all the parts indicated.

### Negative-spring mechanism

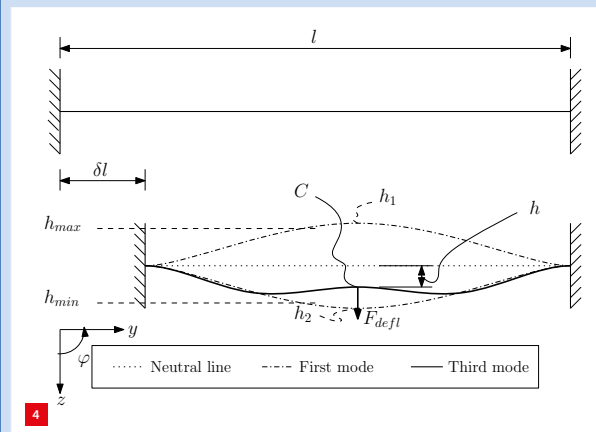
The negative stiffness is provided by multiple buckled leafsprings. This stiffness property of a leafspring is elucidated in the box on the next page. For concept design, analytic equations have been used which are validated using FEM in Figure 6.

Figure 7 shows the negative-spring mechanism. As can be seen, the negative stiffness is provided by four buckled leafsprings. They are connected in the middle to an adjusting mechanism, which is used to adjust the magnitude of the negative stiffness. The ends of the leafsprings are clamped by eight clamping blocks that are preloaded by

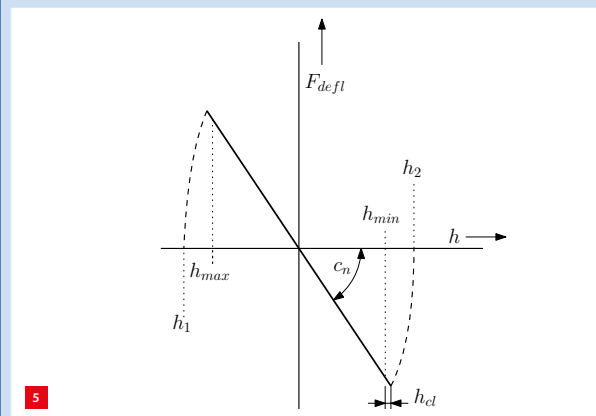


## Negative stiffness of a buckled leafspring

A buckled leafspring has a trajectory of negative stiffness when its centre node is transitioned from the first buckling mode to a higher-order buckling mode by displacing the centre in the vertical direction [1]. Figure 4 shows an unloaded leafspring at the top with length  $l$ . In the bottom part of the figure, the leafspring is compressed over a distance of  $\delta l$ , resulting in the first buckling mode where the centre point  $C$  is deflected into position  $h_1$  or  $h_2$ . Displacing the point  $C$  from  $h_1$  towards  $h_2$  (or vice versa) causes the buckled leafspring to transition to a higher-order buckling mode. Figure 4 shows the third-order buckling mode. A leafspring is considered to be buckled in the third mode when edges are clamped and the side view of the leafspring can be described using a polynomial with three extreme values.



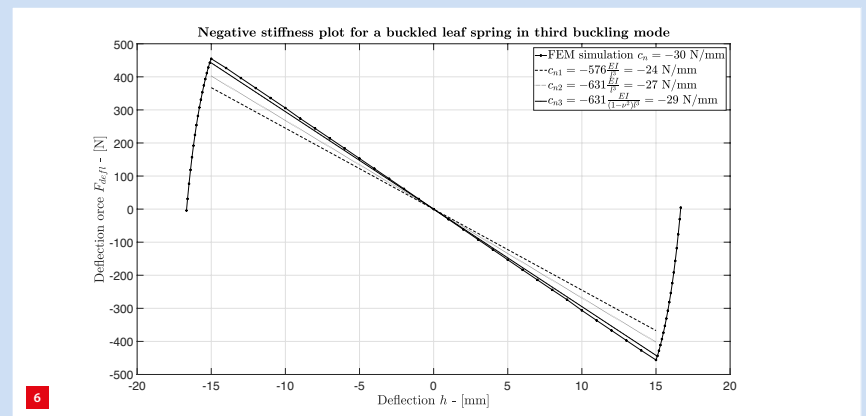
2D representation of a buckled leafspring transferred from the first- into the third-order buckling mode.



Force-path diagram of a buckled leafspring in the third-order buckling mode.

Figure 5 shows the force path diagram resulting from the load case as discussed in Figure 4. The continuous line shows that the stiffness is negative and (nearly) constant [4]. For safety reasons, some clearance  $h_{cl}$  is advised, resulting in an effective range of the buckled leafspring from  $h_{min}$  to  $h_{max}$ .

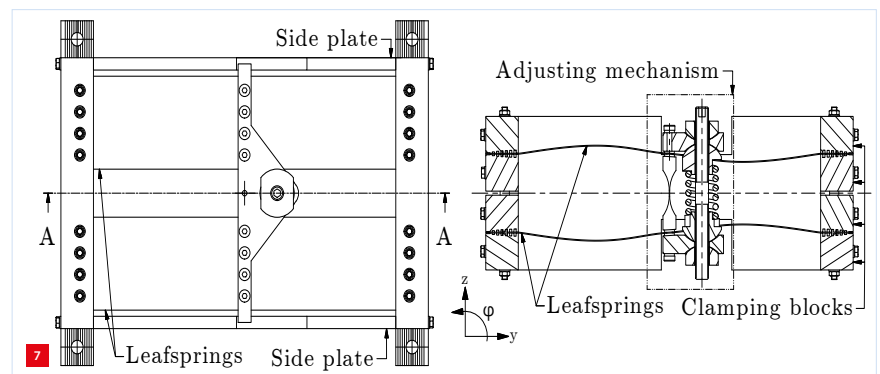
During the concept design, analytic equations were used to determine the dimensions of the leafsprings. Literature provides multiple analytic equations to calculate the negative stiffness of a buckled leafspring in third-order buckling mode. The equations from [4] and [5] were compared to the finite-element method (FEM) results in Figure 6. The closest agreement was found for  $c_n = -631 (EI / l^3) / (1 - \nu^2)$  [4]. Here, the Young's modulus is denoted by  $E$ , the bending moment of inertia is denoted by  $I$ , and the length of the unbuckled leafspring is denoted by  $l$ . The Poisson's ratio of the material is denoted by  $\nu$ .



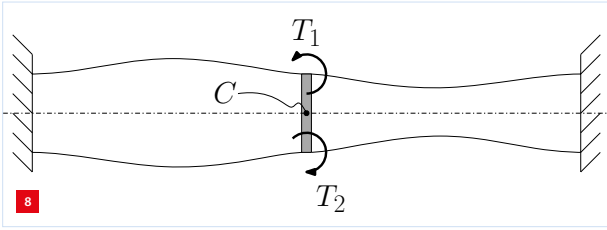
Analytic equations for the negative stiffness of a buckled leafspring in third-order buckling mode compared with FEM results;  $c_{n1}$  from [5] and  $c_{n2}$  and  $c_{n3}$  from [4].

bolted connections on either side. The clamping blocks, together with the two side plates, create a force frame. The force frame generates the necessary force for the leafsprings to stay buckled. Dowel pins (not depicted) ensure that the parts of the negative-spring mechanism are aligned with respect to each other.

The magnitude of the negative stiffness of a buckled leafspring is dependent on multiple parameters (e.g. geometry, material properties and compression length [4]). Tolerances on these parameters result in a deviation of the stiffness. The ability to adjust the magnitude of the negative stiffness (and thus adjust the equivalent stiffness) results



Negative-spring mechanism. Left: Top view. Right: Sectional view A-A.



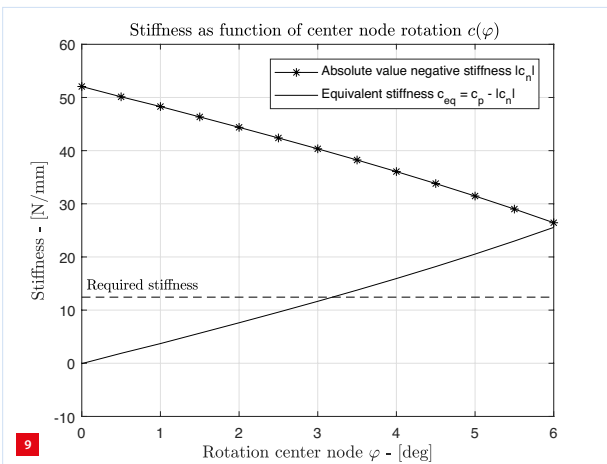
Two leafsprings in mirrored third-order buckling shape (with respect to the centre line) prevent the rotation of centre body C, as a result of a torque equilibrium.

in a design that allows for the correction of tolerances and potential mass deviation of the payload. The negative stiffness can be adjusted using the adjusting mechanism. The functionality of this mechanism is based on two principles: the torque equilibrium of two mirrored buckled leafsprings and the negative stiffness as a function of the rotation of the centre line.

A method to constrain the rotation of the centre node is given in [5] and is here explained using Figure 8. This figure shows two leafsprings connected to a body with centre node C. Both leafsprings are buckled in the third-order buckling mode and are mirrored along the horizontal centre line with respect to each other. The centre body exerts  $T_1$  and  $T_2$  on the leafsprings and as a result of the mirrored buckling shapes, the torques have opposite directions.

For identical geometry and material properties of both leafsprings, the magnitude of both torques is equal but opposed in sign (i.e.  $T_1 = -T_2$ ). Hence, the sum of all torques on the centre node C is equal to zero and its rotation is equal to zero. The centre body needs to be stiff to prevent the rotation of each individual leafspring.

Note: in practice it is unlikely that four 100% identical leafsprings will be found and, as a result, some rotation of the centre node C will occur; this rotation influences the negative stiffness, but it is assumed that this deviation can be compensated for with the adjusting mechanism.



Absolute value of the negative and the equivalent stiffness as a function of the  $\varphi$ -rotation of the centre line;  $c_n(\varphi)$  is calculated using FEM.

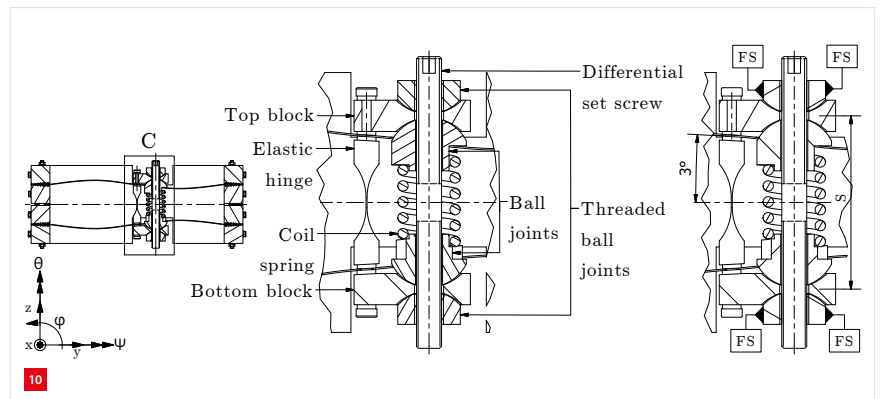
One method to adjust the negative stiffness is to adjust rotation of the centre line of the leafspring [6]. Figure 9 shows the absolute value of the negative stiffness as a function of the  $\varphi$  rotation ( $|c_n(\varphi)|$ ). In the figure, the equivalent stiffness is calculated using the analytic equation as stated before. The positive stiffness of the gas spring is calculated to be  $c_p = 52$  N/mm. As can be seen, the equivalent stiffness of 12 N/mm can be varied with a tolerance of  $\pm 12$  N/mm for an initial rotation of  $\varphi = 3^\circ$ .

The four leafsprings were designed (using FEM) to provide the total required negative stiffness of  $-40$  N/mm for an initial rotation of  $\varphi = 3^\circ$ . Hence, each leafspring needs to have a negative stiffness of  $-10$  N/mm. The dimensions of the leafsprings: width  $w = 72.5$  mm, thickness  $t = 0.7$  mm and a free buckling length of  $l = 280$  mm. The selected material for the leafsprings is 17-7 PH stainless spring steel (X7CrNiAl17-7).

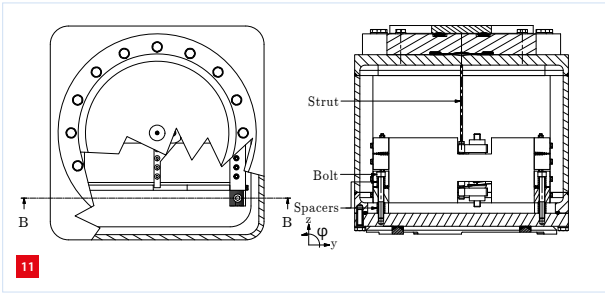
The principles described in Figure 8 and Figure 9 are combined in the adjusting mechanism presented in Figure 7. The combination of top and bottom blocks, the elastic hinge, the coil spring, the differential set screw and the four ball joints create a stiff path and, as a result of the torque equilibrium, the  $\varphi$ -rotation of the adjusting mechanism is equal to zero.

By adjusting the differential set screw and the ball joints, distance  $S$  is prescribed and thereby the rotation of each leafspring. The set screw is only able to rotate the leafsprings through a range of  $3^\circ < \varphi \leq 6^\circ$ . To cover the range of  $0^\circ \leq \varphi \leq 3^\circ$ , a coil spring is used. Once the required negative stiffness is obtained, the set screw is fixed with a glued connection.

The initial rotation of each leafspring equals  $3^\circ$  due to the chamfered contact surface of the elastic hinge with the top and bottom blocks. In this configuration, the elastic hinge needs to allow a rotation of  $\varphi \pm 3^\circ$ . Each ball joint is in contact with a convex surface of either the top or bottom



Sectional view of the negative-spring mechanism on the left. Middle and right: Detail view C.



The assembly of the positive and negative springs in the VibIS. Left: Top view with a partial cut out. Right: Sectional view B-B.

block. This type of contact allows the individual  $\varphi$ -rotation of the top and bottom blocks, while keeping the holes for the set screw aligned.

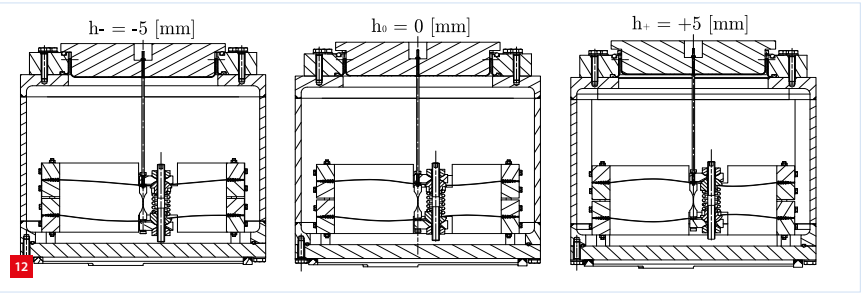
The force frame safeguards the buckled shape of the leafsprings and consists of eight clamping blocks and two side plates that are connected with a bolted connection as depicted in Figure 7. The side plates have two cut-outs that serve as an end stop for the buckled leafsprings. The clamping blocks are preloaded by threaded studs and nuts in the vertical direction. As a result of this preload and the friction between the leafsprings and the clamping blocks, a clamping force occurs. The clamping force prevents the leafsprings from slipping between the clamping blocks. Bristles in the clamping blocks minimise hysteresis.

### Assembly

Figure 11 shows the assembly of the positive and negative springs. In the sectional view on the right, it can be seen that the negative-spring mechanism is placed in the vessel volume of the positive spring and is bolted (with four bolts) onto the bottom cover of the positive spring. The spacers ensure that there is sufficient clearance for the negative-spring mechanism with the bottom cover. In theory, this connection is statically overdetermined. However, the force frame of the negative-spring mechanism has an internal degree of freedom; it is assumed to be compliant around the  $y$ -axis.

In the concept design, a strut was selected to couple the positive and negative springs because of its horizontal compliancy. During this design phase, the assumption was made that the rolling diaphragm was sufficiently compliant to decouple the payload horizontally. The assumption on the horizontal stiffness of the rolling diaphragm has not been validated within the scope of this project.

For determining the operating position of the buckled leafsprings, the stability of the strut and required operating range are taken into account. The  $x$ - and  $y$ -position of the end points of the strut are ill-defined: loading the spring in compression results in a potentially unstable position



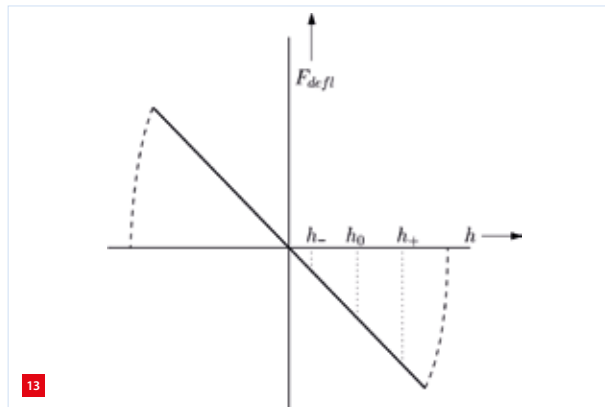
Three sectional views of the VibIS, with  $h_0$  the operating position. The range for assembly is from  $h = -5$  to  $h = 5$  mm.

of the strut, while loading the strut in tension results in a stable configuration.

Secondly, the VibIS is required to have a range of  $h = 0 \pm 5$  mm (for assembly purposes). Figure 12 shows a sectional view of the VibIS in the lowest, operating and highest position from left to right, respectively. The operating position of the buckled leafsprings ( $h_0$  in Figure 12) corresponds to  $h_0$  in Figure 13. In this figure it can be seen that the strut is in tension over the full range.

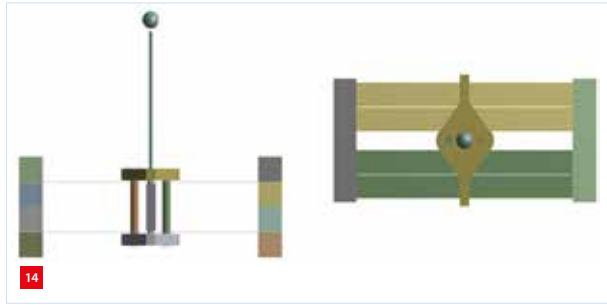
Once the negative-spring mechanism is positioned within the pressure vessel volume, the negative stiffness needs to be adjusted to the correct value prior to assembling. A test set-up is required to determine the correct value of the negative stiffness. The test set-up needs to allow for a stiffness measurement of the equivalent stiffness and for the adjustment of the negative stiffness.

Negative stiffness has been applied in the field of passive vibration isolation before. In [7] the positive stiffness of a mechanical spring is reduced with buckled leafsprings. Here, the negative stiffness can be varied by adjusting the buckling length. Using a gas spring for the positive stiffness – instead of a mechanical spring – allows for a larger payload within the same design space. Moreover, adjusting the negative stiffness with the centre node rotation – instead of the buckling length – allows for a larger adjusting range on the equivalent stiffness.



Force-path diagram of the negative-spring mechanism with the operating position  $h_0$  as indicated. The strut is loaded in tension over the full operating range.





Visual (Ansys) of the iterated design based on the results of the modal analysis.

### Design towards dynamic performance

The dynamic performance of the VibIS is crucial to its functionality. Therefore, the dynamic stiffness in the vertical direction of the VibIS, as shown in Figure 11, has been calculated using modal analysis. Four of the critical eigen modes are the  $\varphi$ - and the  $\psi$ -rotation modes of the adjusting mechanism, the first bending mode of the strut in the  $y$ -direction, and the torsion mode of the leafsprings. Based on these results, an iterated design was proposed, as shown in Figure 14.

Three modifications were applied to the negative-spring mechanism in Figure 14 compared to the mechanism as described in Figure 7. The mass of the adjusting mechanism is balanced by mirroring the mechanism; the centre of the adjusting mechanism's mass is aligned with the centre line of the strut. The rotation mode of the adjusting mechanism still occurs; however, its influence on the dynamic stiffness is minimised by attaching the strut to the centre of mass of the rotation point. During this rotation mode, the end of the strut is no longer displaced horizontally (only rotated).

Secondly, the strut is modelled as a hollow tube to improve its stiffness-to-mass ratio. The third modification in the design is slicing each leafspring in the length direction. This cut

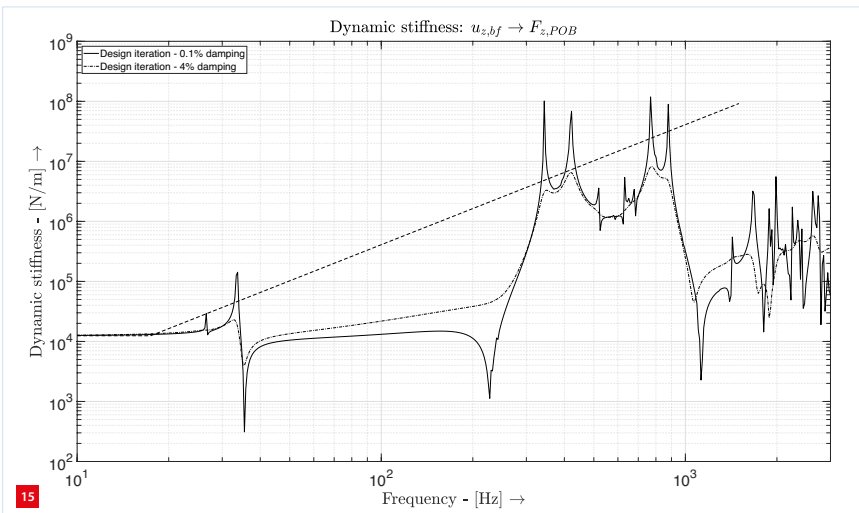
increases the torsional frequency of each individual leafspring. The dynamic stiffness of the iterated design has been calculated and these results are presented in Figure 15. Here, the transfer function from the vertical displacements of the base frame ( $u_{z,BF}$ ) to the force on the projection optics box in the same direction ( $F_{z,POB}$ ) is presented. This figure shows that the design of Figure 14 with 0.1% damping exceeds the requirement (dashed line in the figure). The first critical mode is a pendulum mode in the  $y$ -direction of the adjusting mechanism on the stiffness of the strut. The remaining critical modes are bending modes of the buckled leafsprings. Furthermore, this figure shows that 4% modal damping results in a design that meets the requirement.

### Conclusion

A passive vibration isolation system has been designed to fit within a compact design space by decreasing the positive stiffness of a gas spring with the negative stiffness of multiple buckled leafsprings. As a result of these two springs in parallel, the oversized pressure vessel in the currently available vibration isolation system has been significantly reduced in size. Implementing a mechanism to adjust the negative stiffness has resulted in a design that is corrected for production tolerances and payload deviations. A patent on the design has applied for and approval is pending.

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Dynamic stiffness of the iterated VibIS design in the vertical direction with 0.1% or 4% damping.

## Wim van der Hoek's design principles

The principles and the way of working taught by Wim van der Hoek have inspired the design of a compact passive vibration isolation system that is insensitive to production tolerances and payload variations, and meets the requirement on dynamic stiffness. The feasibility of the design has been proven analytically. Dynamic analysis has shown that the requirement on the dynamic stiffness has been met by applying some minor design changes and commonly used damping techniques.

# FIGHTING FRICTION WITH DESIGN PRINCIPLES

Typically, 'design principles for precision mechanisms' is narrowed down to flexure and leafspring designs. But this is an unjust simplification. When designing for extreme precision applications, it's primarily about creating a predictable design. On the one hand, by minimising unpredictable effects like friction, play and hysteresis. On the other hand, by maximising the predictability of the (dynamic) input-to-output relation by using high-stiffness, lightweight and thermally balanced designs. When following these fundamental design principles carefully, astonishing precision can be achieved with relative ease, as is shown in the design presented here.

MAURICE TEUWEN, RICHARD ALBERS AND EVERT HOOJKAMP

## Introduction

In the field of fundamental research and technology, the use of vacuum environment conditions has been common practice for a long time. But it has been the continuous pursuit of semiconductor industry to follow Moore's law that has led the broader precision engineering community to face the challenges that come with vacuum environments.

Here, the most prominent design constraint is given by the prevention of outgassing. This drastically limits the number of allowed materials and treatments. One of the consequences is that friction is a much larger 'enemy' in vacuum precision-motion designs. The ultra-clean surfaces and the limited availability and/or performance of low-outgassing greases or coatings result in much higher friction forces compared to atmospheric conditions.

## The challenge

For a specific high-precision application, a large-stroke linear motion stage needed to be developed. The travel of the stage was specified to be several hundreds of millimeters, in a vacuum environment. Within this application, there is extremely little margin to induce thermal or dynamic interaction with the rest of the system, given the fact that the overall application is dealing with sub-nanometer motion accuracies. This requirement is materialised, amongst other things, by enforcing (by specification) a usable control bandwidth of the drive in the order of 20 Hz; far below any mechanical resonance in the system. Table 1 summarises the main requirements.

## Fix the cause, not the effect

Knowing that the application is in a vacuum environment, it can be easily foreseen that friction is a critical feature with respect to the performance of the system. In literature,

**Table 1**

Main requirements for the large-stroke linear motion stage.

Feature	Requirement
Range	250 mm
Position accuracy	< 1 $\mu$ m
Control bandwidth	< 20 Hz
Full-stroke move	< 2 s
Dissipation	< 5 W
Payload	10 kg

options have been described to deal with this challenge, such as implementing impulsive control [1] or using a control implementation based on detailed modelling of the running characteristics of recirculating linear ball bearings [2].

However, both studies mainly address how to cope with a given level and variation of friction force, whereas it would be more effective to put effort in reducing the level of friction in a controlled way – especially in the current case. Firstly, because the control will not provide much options given the low bandwidth restriction; the actual motion characteristics will have to lean on a feed-forward control strategy. This can only be done in case of a constant system behaviour, which means constant-friction behaviour in this application.

Secondly, there is an obvious need for low-friction behaviour. This will reduce the dissipation both during movement as well as during standstill, but it will also benefit position accuracy due to the reduction of stick-slip behaviour (limit-cycling).

### AUTHORS' NOTE

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Linear cross-roller bearing

### Concept design

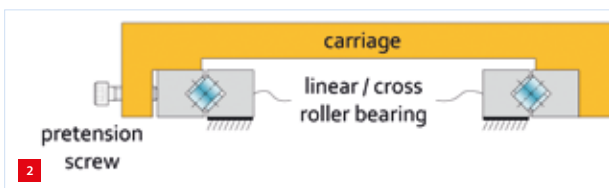
As described above, a linear guiding solution is required with minimal- and at least constant-friction behaviour. A flexure guiding would easily fulfil these requirements, but such a concept is not compatible with a motion range of 250 mm.

When looking to standard guiding types with low friction and smooth (constant) running performance, the obvious choice is to use linear bearings (Figure 1). There are many suppliers that provide these bearings and most of them do also offer (part of) their range as 'vacuum-compatible'.

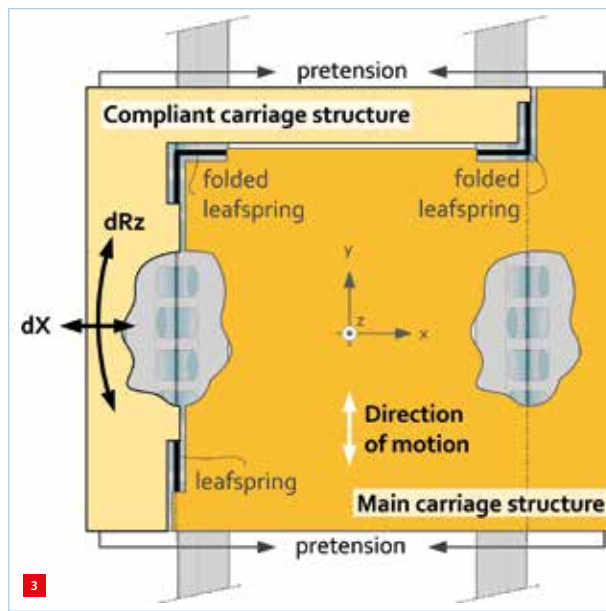
An apparent drawback of this type of bearing is that it is not an integrated unit. This means that the bearings should be integrated and pretensioned in the construction. The method of pretensioning is typically prescribed by the supplier: push the guides from the backside by fastening (set) screws with a given torque, as shown in Figure 2.

This mounting strategy is acceptable for most use cases, but disadvantages can be identified when aiming at low and constant friction:

- When using vacuum-cleaned parts, the fastening of the pretension screw will be affected by friction. Thus, the relation between fastening torque and pretension force will have a large spread, which results in unpredictable guide pretensioning.
- There is no 'designed' compliance in the pretensioning. By fastening the pretension screw a certain deformation is introduced into the structure. For a typical design (stiffness values in the order of  $10^7$  N/m per roller element, 10 rollers engaged in the guiding, a targeted



Classic way of pretensioning a linear bearing.



Precision engineering way of pretensioning a linear bearing.

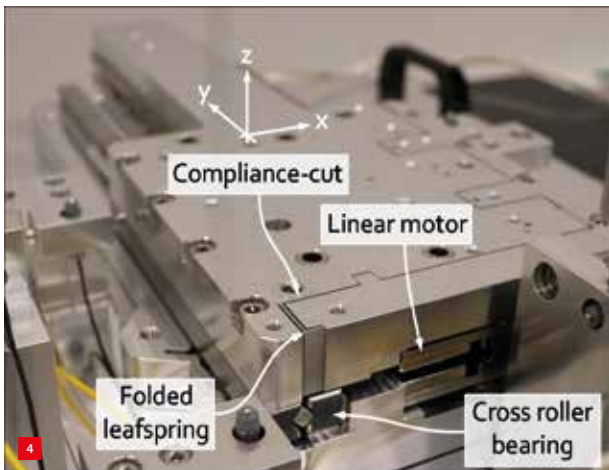
pretension level of 25 N per roller), this means a deformation of a couple of micrometers. Any misalignment (e.g. non-parallelism), mounting deformation or wear in the guides in the same order of magnitude will thereby significantly affect the level of pretensioning. Similarly, it can be stated that thermal (CTE) deformations in the micrometer range have a significant effect on the pretensioning (reference: for aluminium deformation is approximately  $4 \mu\text{m/K}$  for a dimension of 200 mm). Thus, variations in guiding behaviour over the movement range and over time can be expected.

In order to overcome these drawbacks, a different concept was conceived (Figure 3). The carriage is divided into two bodies; a 'main structure' and a 'compliant structure', though both halves are still connected with leafspring elements. The configuration of these elements is chosen such that the X and Rz degrees of freedom have become compliant between both sides of the carriage structure. In this way any deviation in the distance between the guides over the direction of movement does not significantly affect the pretensioning of the bearings and thus ensures smooth running behaviour over the entire stroke. The other degrees of freedom (Y, Z, Rx, Ry) are still rigidly connected between both sides of the carriage, which ensures an optimal connection to the stiffness available on both sides of the guide.

### Realised system

Figure 4 shows a close-up of the carriage of the realised drive. The 'compliance-cut' which separates the monolithic carriage in two halves can be seen prominently, as well as one of the leafspring elements. A closer look shows that the leafspring element is perfectly aligned with the centre (in





Close-up of the compliance in the carriage.

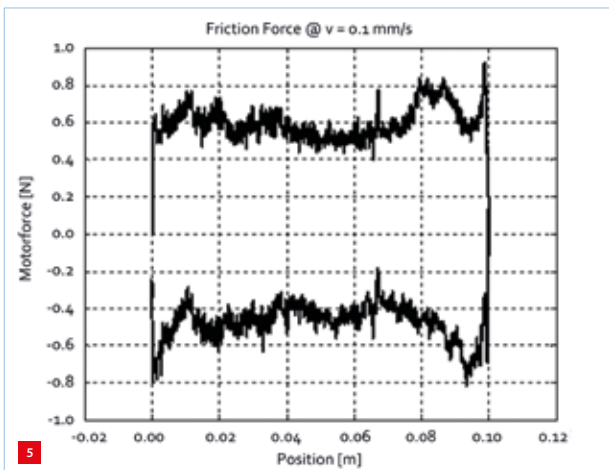
X-direction) of the cross-roller bearing. In this way the force path from the carriage to the base is straight without any bending load acting on the construction, which is a typical design principle to maximise stiffness.

The motion of the system has been realised by using a vacuum-compatible linear motor. The coil unit of the motor has been mounted on the base. This ensures the best possible thermal 'grounding' from the dissipating coil towards the temperature-conditioned main frame of the overall system. Another advantage of the moving-magnet concept is that there are no cable connections to the moving carriage, which avoids any disturbance forces during moving and positioning in this respect.

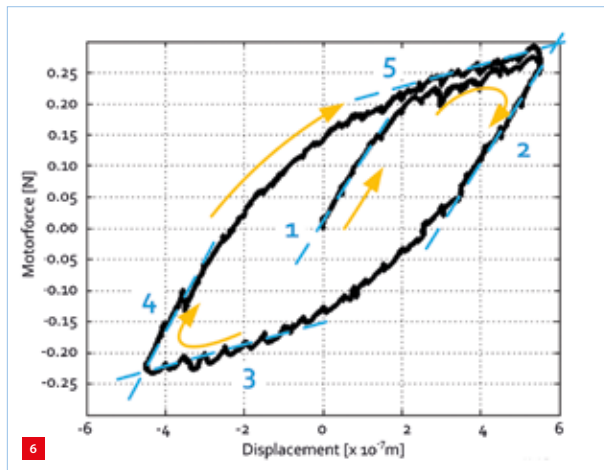
A typical drawback of a moving-magnet concept can be the larger mass of the magnet unit(s) as compared to the coil unit. However, in this application with relatively low-dynamic requirements this is not relevant.

## Measured friction behaviour

As a design verification, the friction force or rolling resistance of the guiding was measured over a part of the



Friction force for back and forward motion.



Static friction behaviour.

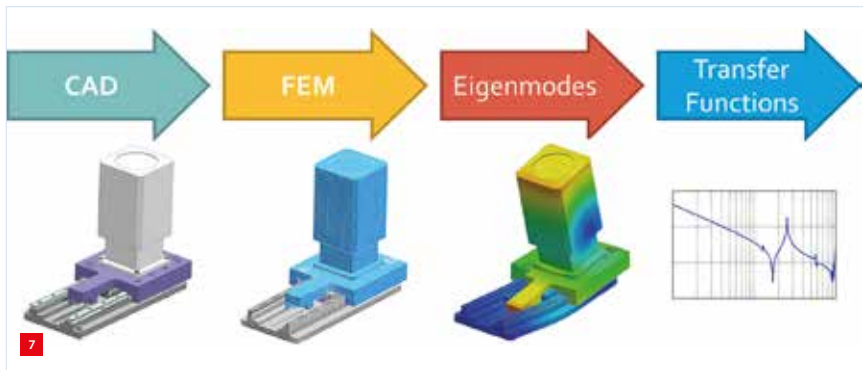
total stroke. The result is shown in Figure 5. With a total preload force of the guides close to 600 N (applicable for each pair of guides as they are loaded against each other), the friction force is relatively low with an average level around 0.6 N. Expressed as a coefficient of friction this would come down to approximately 0.0005.

Another feature that was observed during the design verification is the static friction characteristic. Both for control tuning as well as static positioning behaviour it is interesting to understand the behaviour of the system when excited with small force amplitudes that are below the level of static friction. An experiment was done in which the position was increased in steps of 50 nm, and the related force was derived via the motor constant and the controller current measurement. The result is presented in Figure 6.

It can be observed that the static friction causes a certain stiffness in the drive direction. The stiffness depends on the amplitude of the movement, and ranges in this case between approximately  $10^5$  N/m (section 3, 5) and  $10^6$  N/m (section 1,2,4). This behaviour has also been described in literature, as the Dahl or LuGre model [3].

## Transfer functions and model-based design

Before realisation, the performance has been evaluated by employing a dynamic model of the system. This dynamic model, in the shape of dynamic transfer functions, was obtained from the eigenmodes of the system computed using a finite-element model (FEM). Figure 7 displays the procedure followed to obtain the dynamic transfer functions. The success of this evaluation depends on the accuracy of the model, which is subject to some 'unknown' features: the stiffness of the linear bearing, structural damping, and the assumed interface contact between the module and the overall system. Following the design principles, these features can be made predictable and 'known'.



Procedure to obtain the system transfer functions from the design.

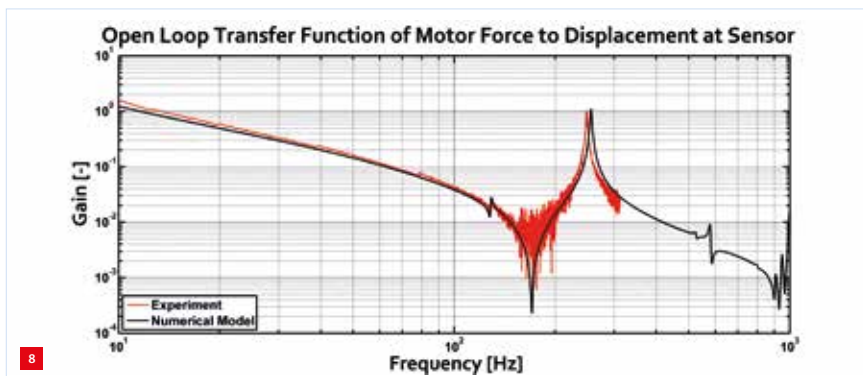
Verification of the transfer function was performed and showed excellent agreement with the predicted transfer function, as shown in Figure 8. Thus, predictable design complements the model-based design approach.

### Conclusion

Design principles for precision engineering go beyond the straightforward implementation of flexure elements. It is about the elementary understanding of the working principles and the physics of the application and using these insights to create highly predictable designs. The design of a linear drive for use in a vacuum application has illustrated that consistent use of elementary design principles provides an intrinsically high positioning-performance level, even with limited feedback motion control.

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Excellent agreement between the measured transfer function (red) and the transfer function obtained by the modelling approach as shown in Figure 7 (black).

## Design principles for precision engineering

Wim van der Hoek was one of the Dutch pioneers in the field of precision engineering. By using his unique ability to capture the true essence of a problem and his inherent attitude to combine creativity with elementary analytical considerations in the search for solutions, he inspired and educated countless students and fellow engineers on both a technical and a personal level.

Huub Janssen graduated in 1984 under his inspiring supervision and shared his passion for solving technical problems by implementing basic design principles. Ever since, Wim van der Hoek has closely followed Huub Janssen's personal and professional life, as he did with many of his former students.

It is evident that this background played an important role in his decision to start his own engineering company, Janssen Precision Engineering (JPE), in 1991. As a personal tribute, but also as a general acknowledgement of Van der Hoek's contribution to the leading position of the Dutch precision engineering community, JPE's conference room was named the 'Wim van der Hoek conference room'. Wim van der Hoek officially opened 'his' room in 2016 as part of the company's 25th anniversary celebration (Figure 9).

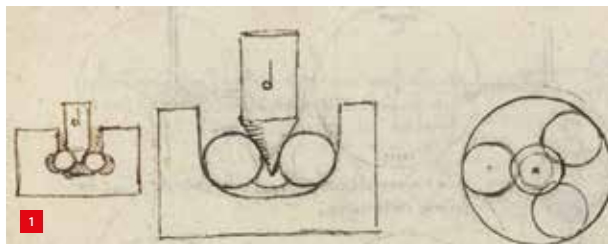


In 2016, Wim van der Hoek officially opened the conference room named after him at Janssen Precision Engineering.

# MULTI-BODY KINEMATIC MOUNTS

This work generalises two-body kinematic couplings to multi-body kinematic mounts with a focus on the 3-body case. Like kinematic couplings these multi-body kinematic mounts serve to achieve repeatable assemblies. This article provides a novel set of representative examples, the results of first experiments, and applications of 3-body kinematic mounts.

JOHAN KRUIS



The 3-ball bearing and axis example provided by Leonardo Da Vinci in Madrid Codice I, written between 1490 and 1499 [1, p. 102].

## AUTHOR'S NOTE

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## A short history on kinematic design

Kinematic design principles have been applied for more than 500 years. An example from 1490 and one of the earliest kinematic design examples known to the author, is the roller and ball bearings for cone-tipped vertical axes by Leonardo Da Vinci [1, p. 102]; see Figure 1. In his work, Da Vinci described that for the correct functioning of this type of bearing it is necessary to have exactly three ball bearings and not four, i.e. exactly three contact points between the coned shaft and the ball bearings.

Kinematic design was further advanced into the principle of isostatic assemblies. An isostatic assembly is a configuration of bodies in which each degree of freedom between the bodies is constrained exactly once. This enables the realisation of assemblies that require less

stringent manufacturing tolerances and allows repeatable positioning of two bodies with respect to each other.

## Introduction

Kinematic couplings are isostatic assemblies of two bodies using six contact points and their nesting forces (forces that make sure the bodies stay in contact). The first written examples of kinematic couplings were given by James Clerk Maxwell [2, pp. 507-508] and William Thomson (Lord Kelvin) [3, pp. 500-504].

More recently, kinematic couplings have been extensively researched [4] and applied to wafer scanners [4], AFMs [5] and high-precision microscopes [6]. For kinematic couplings a  $3\sigma$  position repeatability of  $0.3 \mu\text{m}$  translation and  $2.8 \mu\text{rad}$  rotation have been obtained [7].

This article presents kinematic mounts as a complete solution to a hereafter defined isostatic 3-body problem. Figure 2 shows a kinematic coupling and a kinematic mount. First, the necessary definitions and conjectures are introduced that result in seven non-equivalent examples of kinematic mounts. Next, experiments on and applications of kinematic mounts are presented. The results reported here are part of the work described in the author's Ph.D. thesis [8], which was also presented in more detail in various conference proceedings, e.g. [9], [10].

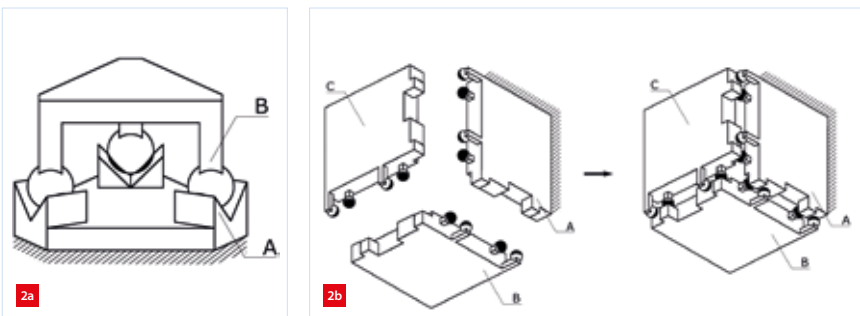
## 3-body kinematic mounts

In order to have a limited list of kinematic mounts, definitions are given to constrain the problem statement, including the concept of equivalent kinematic mounts. This problem statement yields an exhaustive list of seven non-equivalent configurations generated using screw theory as in Whitney [11].

## Definitions

The most important definitions required to define the problem statement are:

- Bodies: Unions of spheres and cuboids whose edges



Examples of a kinematic coupling and a kinematic mount.

(a) A three-Vee kinematic coupling with bodies A and B.

(b) Three-body kinematic mount configuration C7 (see below, Figure 3) with bodies A, B and C in unassembled and assembled state.



are parallel to the X-, Y- and Z-axis, respectively, when assembled.

- Constraint line: If P is a contact point of two bodies, then the constraint line is the line containing their normals at P.
- Interface: The set  $I_{AB}$  of all contact points between two bodies A and B. The interfaces  $I_{BA}$  and  $I_{AB}$  are considered to be the same.

#### Detailed problem statement

To propose examples of kinematic mounts assembled with up to three interfaces whose contact points lie on the axes of a set of orthogonal coordinates (the intersection point of these axes is excluded in this work). All constraint lines are parallel to one of the three orthogonal axes

#### Conjectured conditions of 3-body kinematic mounts

There are a total of four conjectured conditions for kinematic mounts:

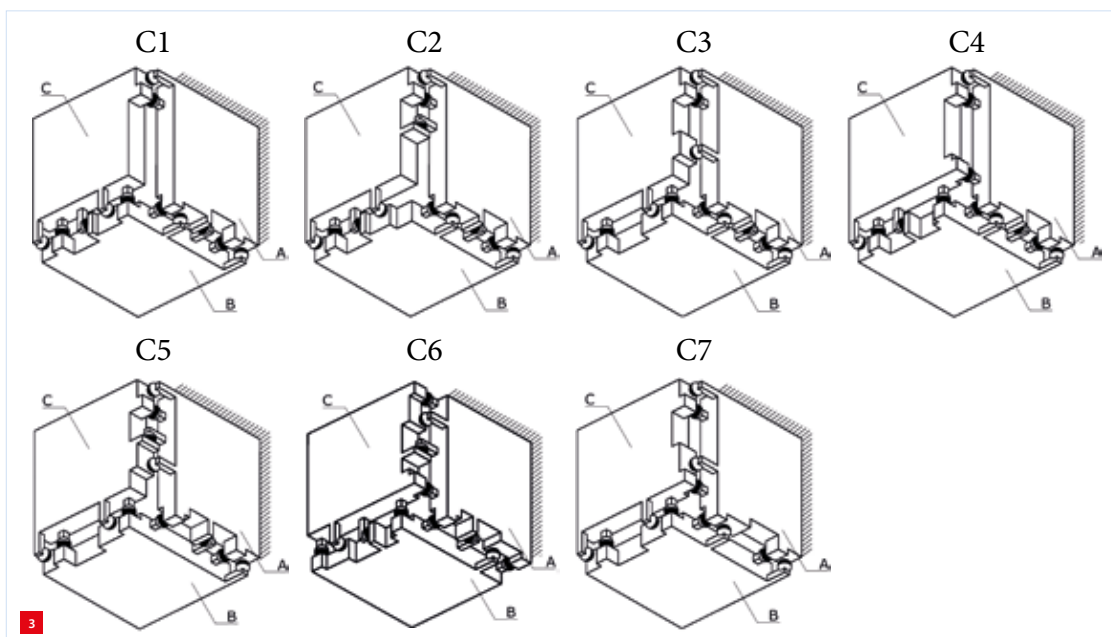
1. A 3-body kinematic mount requires 12 contact points.
2. An interface cannot have collinear constraint lines.
3. An interface cannot have more than two parallel constraint lines.
4. Every orthogonal axis has four constraint lines parallel to it.

#### Equivalence relation for 3-body kinematic mounts

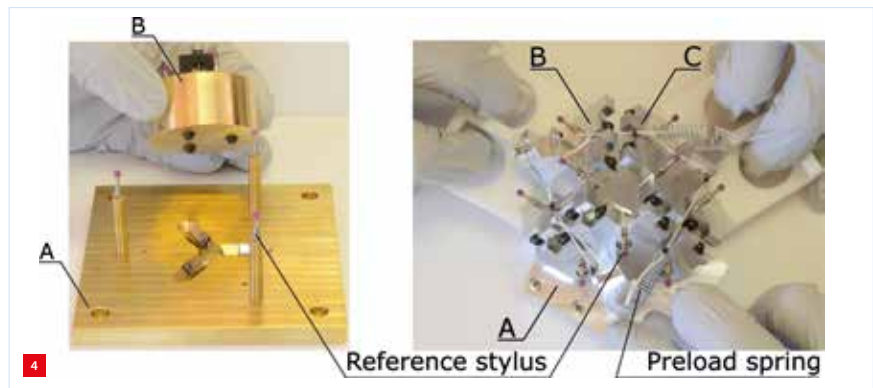
If the orthogonal axes containing the contact points are relabelled, e.g., the X- and Z-axes are interchanged, then the resulting kinematic mounts are considered to be equivalent.

#### Examples of 3-body kinematic mounts

The detailed problem statement yields the seven non-equivalent 3-body kinematic mounts shown in Figure 3. For physical demonstrators of all the configurations see [8].



The seven non-equivalent kinematic mount configurations each consisting of three bodies with their respective contact points marked with black hemispheres.



Two prototypes. Left: Three-vee kinematic coupling. Right: C7 kinematic mount realised for positioning error measurements.

#### Measurements

Two different sets of measurements were conducted, at centimeter- and millimeter-scale, respectively.

#### Centimeter-scale metallic kinematic mounts

In order to test the performance of kinematic mounts versus kinematic couplings, two prototypes (Figure 4) were constructed. The distance between the contact points is in the order of 1 cm.

The contact points have been realised by grade-3 silicon nitride spheres in contact with custom-cut steel gauge block flats. For the kinematic coupling the preload is provided by gravity, whereas the kinematic mount uses preloaded springs. The measurements were done at the Swiss Federal Institute of Metrology (METAS) using the Micro-CMM [12] having a 50-nm measurement uncertainty. For each body three reference styli with ruby spheres were measured to determine their position in the assembled position. The first

results of these measurements are given in Table 1. Ten measurements were performed on the three-Vee kinematic coupling and three on the 3-body kinematic mount. Because the project budget for measuring on the Micro-CMM only allowed a limited number of measurements, the average positioning errors for the metallic kinematic mounts are listed rather than their standard deviations. The first measurements on the Micro-CMM show that the designed kinematic mounts have translation errors that are less than 1 micron and angular errors that are in the order of 10s of microrads, as detailed in Table 1.



**Table 1**

Average translational and angular positioning errors; measured on classical (metal) parts. See the note in the text on the presentation of average values rather than their standard deviation.

	Three-vee	Configuration C7	
Body	B	B	C
Translation error (nm)	178	902	712
Angular error ( $\mu\text{rad}$ )	5	42	31

#### Millimeter-scale silicon kinematic mounts

A second set of measurements (Table 2) was conducted on silicon parts  $20 \times 20 \times 0.5 \text{ mm}^3$  in size, using a custom-developed set-up [9]. The nesting force was applied with small NdFeB magnet pairs at each contact point. For configurations C1, C2 and C6 the number of measurements were 27, 23 and 33, respectively. The non-symmetric configurations C1 and C2 perform significantly worse than the symmetric configuration C6; see Table 2. In addition, it should be noted that the angular error of C6 is approaching the resolution of the autocollimators and thus characterisation can be further improved. In conclusion, the symmetric configurations such as C6 and C7 seem the most promising. With the C6 kinematic mount it is possible to obtain  $3\sigma$  position repeatability of micrometers and tens of microrads.

#### Applications

To demonstrate how to apply kinematic mounts three applications are presented.

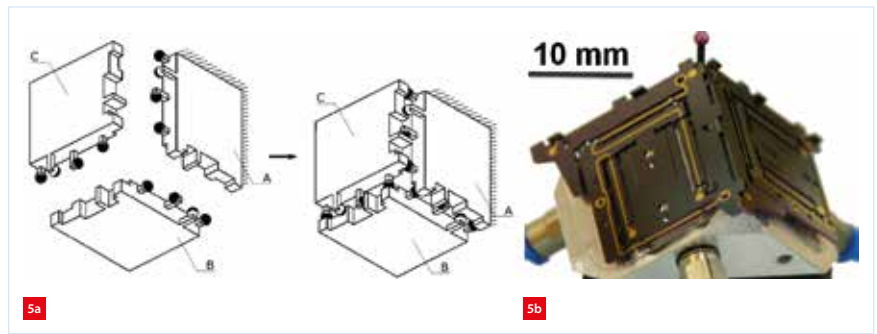
##### Miniature touch probe

A miniature touch probe with 20-mm edges is shown in Figure 5. The kinematics of the touch probe are those of a delta robot. The three individual, identical silicon slabs contain sacrificial fasteners, to allow unlocking the mechanisms after assembly, as further detailed in [13]. The C6 kinematic mount configuration was applied to the miniature touch probe, because there was an assembly yield

**Table 2**

Standard deviation of the translational and angular positioning errors on body C for the C1, C2 and C6 kinematic mount configurations realised in silicon; measured on a custom set-up [9].

Configuration	C1	C2	C6
Translation error ( $\mu\text{m}$ )	4.7	4.1	1.8
Angular error ( $\mu\text{rad}$ )	730	616	14



Touch probe assembly.

(a) Kinematic mount configuration C6 in unassembled and assembled states.

(b) Miniature touch probe with kinematic mount configuration C6 integrated for assembly.

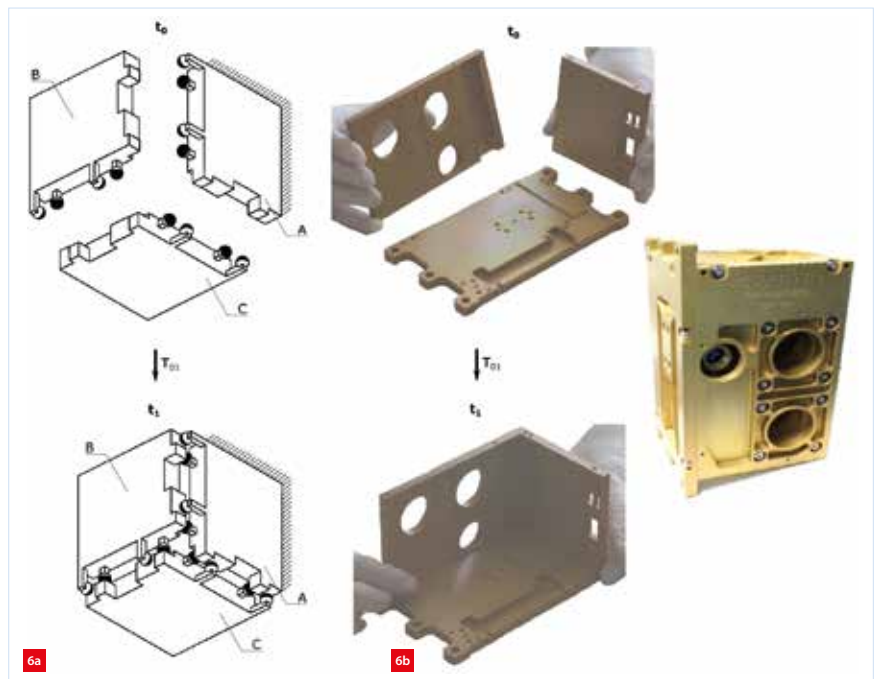
problem in prior work. By using the kinematic mount, it was made sure that overconstraints were avoided and hence no unnecessary stresses were applied to the miniature touch probe. This novel procedure significantly improved assembly yield and accuracy as compared to previous work [14], resulting in 100% yield for seven assemblies of the miniature touch probe.

##### A satellite assembly

To correctly align and assemble a lidar system (a system measuring distance using pulsed laser light) for a satellite aimed at removing space debris, kinematic mounts were applied. The assembly consisted of three slabs: the driving electronics, optics and laser. For this assembly (Figure 6) the C7 kinematic mount configuration was applied.

##### A capacitive force sensor array

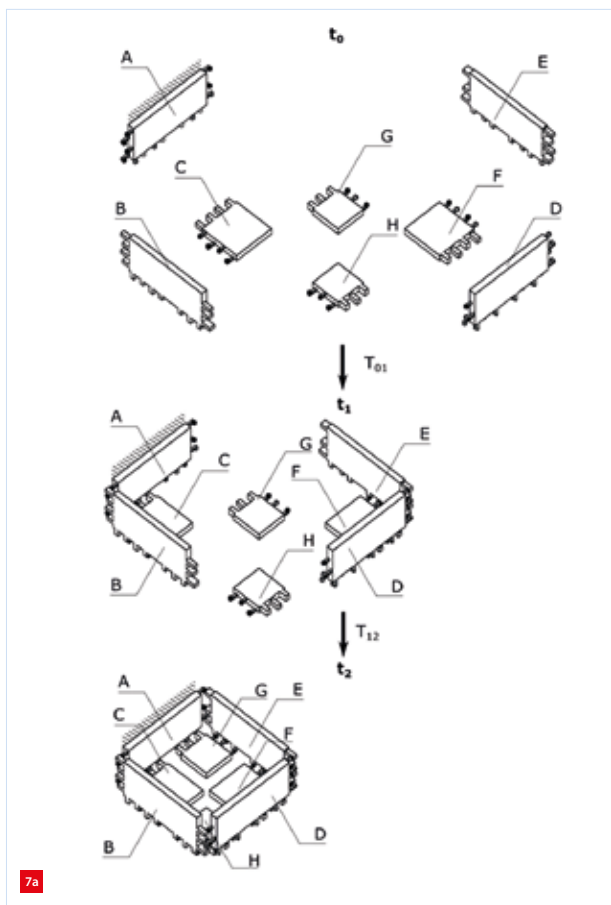
A sensing platform was required to characterise the weight and



Lidar system assembly.

(a) Kinematic mount configuration C7 in unassembled and assembled states.

(b) The lidar frame plates and the final assembly (right).



Sensing platform assembly.

(a) The kinematic mount assembly of the capacitive force sensor array.

(b) The sensor component (left) and the realised kinematic mount assembly. The sensor array volume is  $22 \times 22 \times 16.5 \text{ mm}^3$ , each sensor has a stroke of  $200 \mu\text{m}$  and maximum force of  $200 \text{ mN}$ .

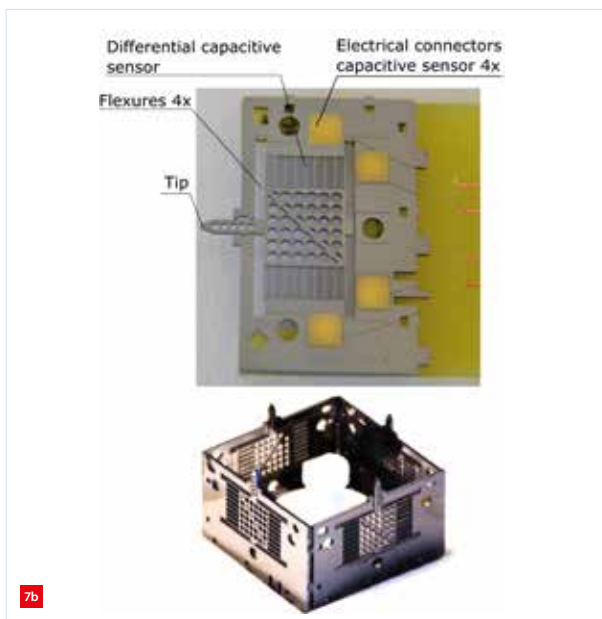
centre of gravity of parts in the 20-gram range. The assembly was realised using two C7 kinematic mounts (composed of bodies A, B and C, and D, E and F, respectively). These kinematic mounts combined with two additional bodies (G and H) resulted in the isostatic force sensor array assembly of Figure 7a. To achieve this, first individual silicon sensors were designed using a parallel-comb capacitive principle in combination with an over-constrained 4-leafspring linear guide, as illustrated in Figure 7b. A more detailed account on this demonstrator is offered in [15].

## Conclusion

A catalogue of seven three-body kinematic mounts has been presented. The measured position repeatability of the C6 kinematic mounts in terms of the standard deviation is  $1.8 \mu\text{m}$  and  $14 \mu\text{rad}$ , respectively. In addition, three applications were presented.

## Acknowledgements

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# RICH PICTURES TO SEE THE BIG PICTURE

A system architect has the task to find a best-fit solution to a set of requirements, starting with the purpose of a system and taking into account its context. Small systems may be handled by a single designer, more elaborate systems typically require a team of designers. In both cases, pictures play a crucial role.

TON PEIJNENBURG

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Pictures are a powerful means to convey information; “a picture is worth a thousand words”. In the single-person case, pictures may help to structure one’s thoughts and maintain an administration of a system under development. For structuring one’s thoughts, one can think of a mind map – a diagram to visually organise information. Mind maps are oftentimes used to structure information from a brainstorm session, offering a hierarchical organisation around a central theme. Another diagram oftentimes used is a block diagram. Blocks represent functions or modules, and are connected by lines that show relationships or information flow. Pictures such as mind maps and block diagrams evolve over time, and may be hierarchical to capture more detailed aspects of a system when the development progresses.

In case of design teams with multiple members, diagrams offer the additional benefit of synchronising individual ideas about the system that is being developed. The structure will be captured and explained when relations between

elements are indicated, highlighted and emphasised. The shared visual view will help team members to remain synchronised on the system scope, elements, relations, etc. Again, the diagrams are not static but evolve over time. Ideally, the incremental adaptations are made with the team present, so everyone will be on the same page with the underlying reasoning. In other cases, visual elements in the diagrams will help reconstruct the reasoning and logic.

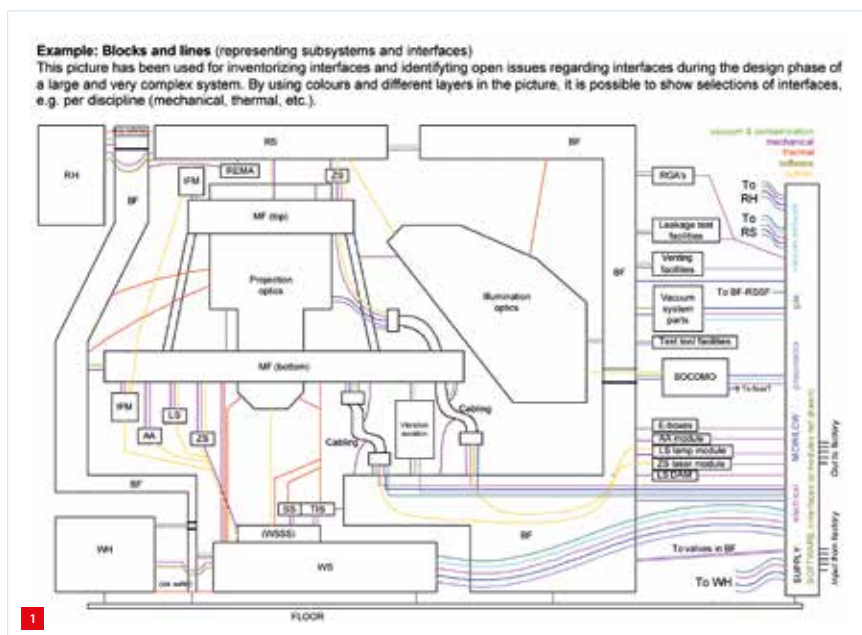
## Interface discussion drawings

At the Philips Centre for Manufacturing Technology, we spent a reasonable amount of time to develop layered block diagrams, where the blocks represented physical modules and the connecting lines indicated interaction. The lines had colours and these indicated the type of interaction: mechanical (force, displacement, structural and acoustic vibrations), heat, contamination, etc. The diagrams were called ‘interface discussion drawings’ (Figure 1), with the purposes of a) communicating about interfaces, b) laying down design rationale, and c) transfer of design knowledge.

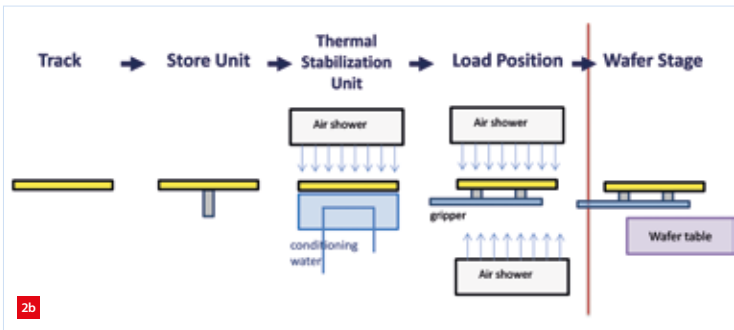
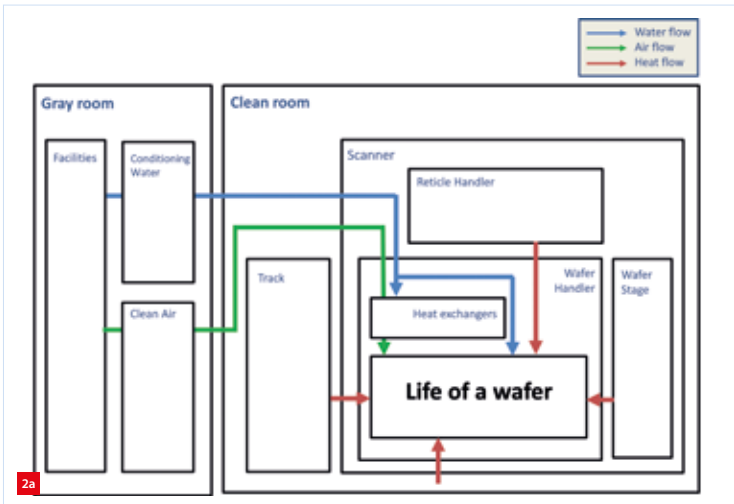
## Conceptual design

At VDL Enabling Technologies Group (VDL ETG), just like at other high-tech system suppliers in the Netherlands, rich pictures are used to explain process flows and ease the discussions about context and interactions, e.g. when reasoning about the thermal control of a semiconductor wafer (Figures 2 and 3). These pictures do not in themselves enable the golden solution, rather they facilitate the common understanding in the team as well as organise (and debug) the thinking of the author and the team.

Well-known from our Dutch school of precision mechanics and mechatronics are the pictures describing lumped-mass dynamics. In these pictures, a conceptual design of a machine is simplified to the essential elements: a process module requiring relative accuracy and stability to a substrate, and the main system components that are associated to the process and the substrate (Figure 3). The pictures can be expanded by adding the feedback



Example of an interface discussion drawing. (Source: Philips CFT, Systems Engineering & Methods group, Ine van Aken).

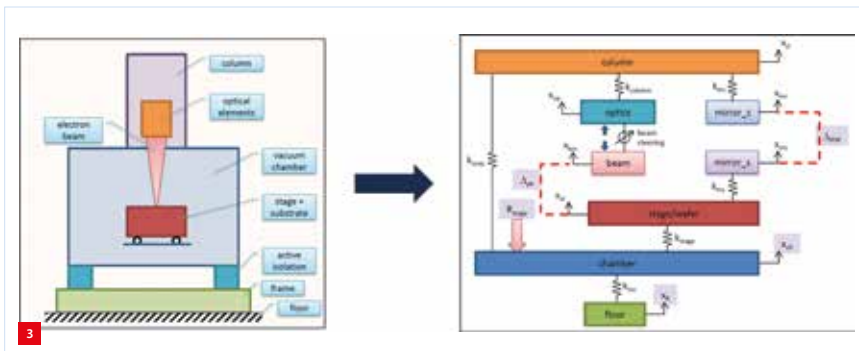


Life of a wafer from a thermal perspective. (Source: VDL ETG, Paul Blom)  
 (a) System context.  
 (b) Expansion of the "Life of a wafer" block.

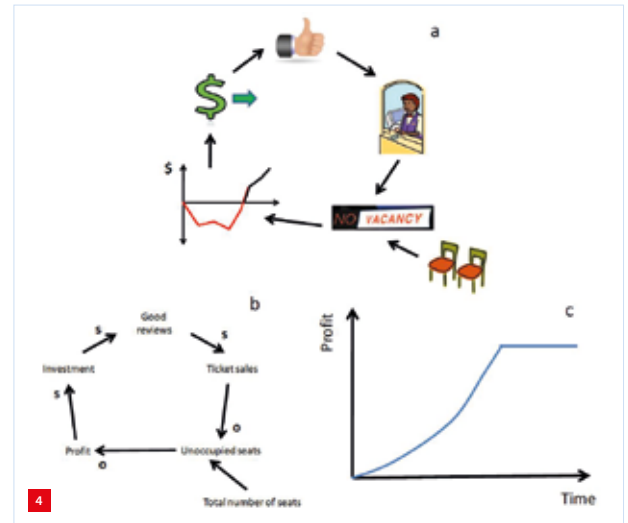
controllers, but serve to keep focus on the essential aspects of system performance.

### The engineer of 2020

During the training of mechatronic system designers at Eindhoven University of Technology in the PDEng programme, emphasis is placed on such sketches and drawings. In the final assignment of the trainees, a system design task is executed for an industrial partner during one year. Trainees are encouraged to start making drawings of their system already when starting to discuss their assignment. The schematic drawings will grow more complete over time, with elements of knowledge and design being added. During the progress presentations, these drawings



E-beam system with beam positioning relative to the substrate. (Source: VDL ETG, Maikel Bruin)



"Introducing Systems Thinking to the Engineer of 2020",  
 Chris R. Rehmann et al., Iowa State University.  
 (Source: [https://lib.dr.iastate.edu/abe\\_eng\\_conf/5/](https://lib.dr.iastate.edu/abe_eng_conf/5/))

should be shown, preferably early in the presentation to (re-)create a mental reference for the audience. This, however, is the ideal situation, which in practice is not always achieved. Sketching and drawing does not appear to be a trivial skill for academic engineers anymore.

When reading about system thinking, and how to train engineers in system thinking, I came across an article from Iowa State University that discussed how to train the engineer of 2020. System thinking skills are considered a key asset of the new engineer, and these skills are tied to three fundamental tools for system thinking: rich pictures, causal loop diagrams and behaviour-over-time graphs. These graphical tools (see Figure 4) capture key elements of systems, documenting their elements, connections and behaviour in an abstract manner.

The interface discussion drawings can be considered to be rich pictures in a sense, with a domain-specific graphical language. Like rich pictures, they document essential elements of a system in a very insightful manner, for individuals and teams to use in their development projects.

### Start sketching

In addition to the pictures discussed, there are many more visual and graphical representations that can be made of systems. Knowing that children already start using mind maps at elementary school, I believe it is critical for future engineers to build on these skills. Engineers should develop a reflex to make sketches and drawings when discussing their design work; they will be more efficient and effective in their work. If you're interested, there is a lot to be read about rich pictures and their relatives, but if I were you, I would start sketching right away – the sketches and drawings will improve based on the discussions about them, not by the theory behind them.



# 21ST-CENTURY DESIGN PRINCIPLES

**“Precision engineers require more digital skills”, wrote Egbert-Jan Sol, CTO of TNO Industry, in his editorial for Mikroniek no. 1, 2018. This article is an attempt to elaborate on his statement and provoke discussion within the precision engineering community. It is highly speculative and deliberately challenging at some points. Also, it is not an attempt to accurately predict the developments for, say, the coming 10 years, but rather to share primary observations, as well as to project some ideas onto interesting intersections between precision engineering and digital trends. Finally, this article aims to outline the desired skill set for future high-tech engineers to make optimal use of new digital trends.**

GREGOR VAN BAARS

## Introduction

‘Digital’ is everywhere nowadays: big data, artificial intelligence (AI), internet of things (IoT), the cloud, wireless connectivity, etc. In this article, the focus will be on the precision engineering/mechatronics community, which is mainly involved with the development of high-tech equipment and systems. Particularly, the system engineering process along the well-known V-model will be used as a reference to see what digital skills might add to this process. Will they help to accelerate development, give better performance, lead to more rational choices and decisions, require less human effort or even enable automated design and engineering?

Are we prepared to grasp this digital potential to the full? Or do we have to reshape and refresh our skill sets? Should education be structurally transformed to a completely new engineering profile? We have to seriously consider such

questions, to ensure that the (Dutch) high-tech precision engineering community remains a leading one for the decades to come.

Obviously, digital trends will also provide a lot of possibilities for streamlining manufacturing, logistics, assembly and supply chain processes. This, however, will not be the focus of this article. The reader is referred to, for instance, [www.smartindustry.nl](http://www.smartindustry.nl) to find a broad variety of innovations, fieldlabs and other forms of collaborations aiming to establish the digital revolution in industry.

## Looking back

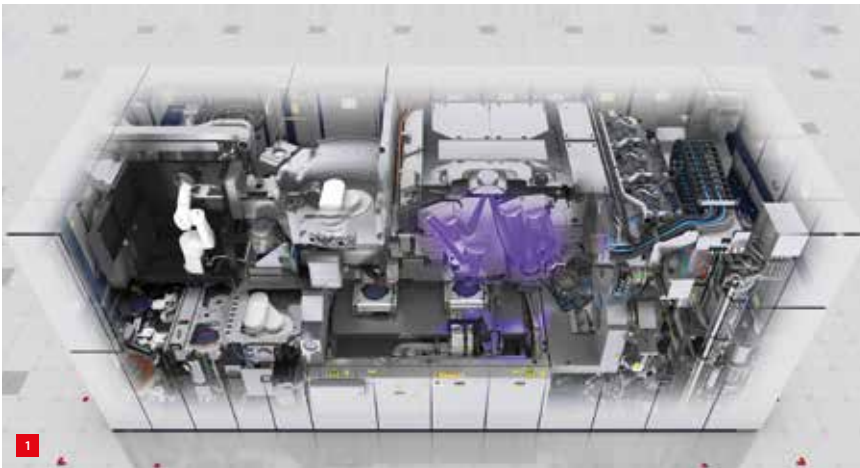
When looking back at the evolution of precision engineering in combination with mechatronics, we see an impressive development of high-precision systems in very demanding applications, such as optical recording, semiconductor lithography (Figure 1), metrology, electron microscopy instruments and printing equipment.

What originated as a unique competence and way of working within a limited group of visionary pioneers has today developed into a widespread commonality with a steady supply of young, freshly educated workers of all required levels of education. Relations between OEMs, suppliers, integrators and knowledge institutes have developed into a high-tech ecosystem, which is no longer restricted to the Eindhoven region, but has spread across the country. This provides the Netherlands with a firm basis for competing globally in high-tech engineering. However, challenges lie ahead, mainly in terms of complexity, effort, cost and time. Success has come at a price, and as with any steep development, each step forward will take increasing amounts of effort (the S-curve

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ASML's EUV lithography machines may be considered the culmination of (Dutch) high-precision system engineering, yielding unprecedented performance at the cost of nearly inconceivable complexity. (Courtesy of ASML)

**Table 1**

Digital trends and developments.

Ever-increasing computing power
Faster data transfer and communication rates
More memory and storage capacity
Connectivity and information exchange everywhere, at every scale (IoT, cloud, wireless)
More powerful data processing with AI, machine learning, data analytics
More visualisation, 3D modelling, bigger screens and displays, virtual and augmented reality
Easier interfaces and connectivity between devices and systems
Lower implementation thresholds, plug & play

is flattening out at the end). This is a growing concern, firstly from a cost perspective. In addition, complexity is increasing, making it more difficult to find solutions that satisfy all stretching requirements. Splitting the problem into smaller (simpler?) pieces and putting more resources to work is not a guarantee that the overall problem will be solved. On the other hand, speed of innovation and development has to go up, because application roadmaps greatly depend on the continuous delivery of progress and improvements.

In view of this, there are increasing doubts concerning how long we can continue to rely on the established way of development. So let us contemplate how upcoming digital tools and skills may help to bring precision engineering to the next level.

### Looking forward

If we follow the current hype on digital potential (see the digital trends and developments in Table 1), the sky seems to be the limit. But is this really the case for precision engineering and high-tech systems? There is a sense of new powers and possibilities buzzing around everything that has 'digital' as an adjective. This association is most prominent with big data and AI. All kinds of hidden relations and information will be found in arbitrary unstructured data sets, without any kind of prior system knowledge. To any mechatronic engineer, this sounds too good to be true. And in most cases it indeed is, when it comes to real engineering problems.

The questions to answer now are: will the digital tools provide us with ways to accelerate innovation and move more quickly from knowledge to ideas, and towards better systems; can we master complexity and diversity of specs with digital tools, such that we find optimal solutions, despite the fact that these will be more difficult to find when time is pressing?

We all know that tools won't do the job on their own. People tend to say that everything will be AI-based and digital. That is suggesting that the tool (AI, IoT, data analytics, machine learning) will be the solution in itself. That is a faulty perception, because only when they are skilfully used and applied will an actual job be done.

To find answers to the question above, we first have to select which digital themes will be considered. Here, we will zoom in on:

- Artificial intelligence
- Internet of things
- Big data
- Digital twin

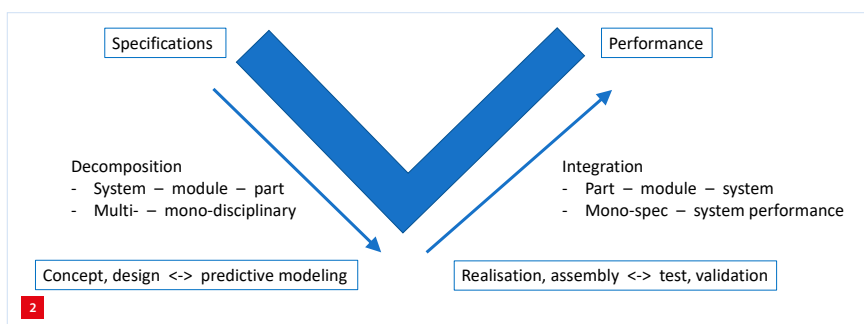
Blockchain, data sharing and cyber-security technologies are also important digital themes, but they are left out of scope here, because they seem of lesser direct impact on the primary process of system engineering.

### A 'precision' assessment of digital tools and skills

Realising that nothing comes for free, let us first try to identify interesting intersections between precision engineering challenges and digital technologies. The main driver for following the system engineering V-model has been to handle the multidisciplinary system challenge along concept, design, realisation, integration and test phases of development, such that the final system will meet the accuracy/precision performance specifications (see Figure 2).

The future will present us with new levels of complexity, more combinations and interactions to be simultaneously considered at the system architectural level. Digital tools to handle this and to help to find optimal solutions would be very welcome. Furthermore, precision and operational (throughput) performance will no longer be the only figures of merit; system requirements will become more diverse and holistic, requiring simultaneous optimisation, dealing with all kinds of transitions, mode switching, etc. Just taking care of the steady state will not be sufficient.

New types of requirements will enter the arena, such as hierarchy, distributed intelligence, autonomy and self-configuration. To keep exploiting the V-model approach, new branches to the V have to be incorporated that make use of emerging digital tools. This sounds promising, but can we just take up the new digital tools and technologies



Simplified representation of the system engineering V-model.

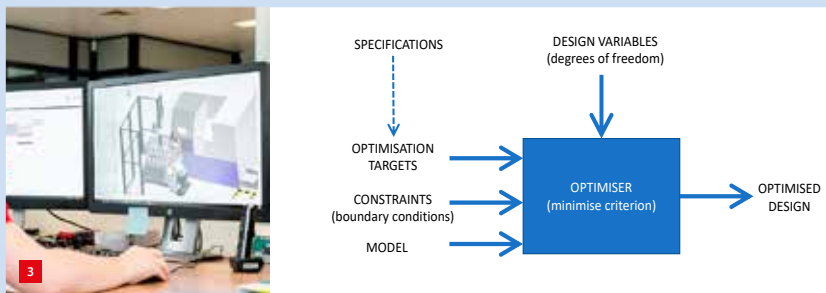
## AI perspective 1: Design/architecture

AI is a very broad notion. Only a fraction will be applicable to, for instance, positioning control in motion systems. Reported successes of AI are predominantly found in, for example, pattern recognition in 2D image data and identification of consumer behaviour patterns from online shopping. It is questionable whether AI will ever be powerful enough to master the skill of multidisciplinary system engineering, mainly because of the necessary high level of detail and the combination of physics and the enormous parameter space for structured design choices.

There is a parallel with the model-based design optimisation attempts such as topology optimisation (Figure 3). This involves a (mechanical) model, a set of design choices, boundary conditions and a target criterion to be optimised. For a single-component, lightweighting design facing simple mechanical loading, we see fairly reasonable results being generated with this technique.

A few years ago, an academic research project attempted to cast a limited mechatronic architecture design problem into a model-based topology optimisation setting. It appeared to be very difficult to generate meaningful design choices about number and placement of actuators, and position metrology points such that motion performance was optimised against system-level specs.

For now, we have to conclude that for more complex, multi-physics behaviour and system-level specifications, this is far from solved, and fundamental breakthroughs are not anticipated in the near future. As a concept, though, it remains a very interesting theme and maybe breakthroughs enabling progress will happen earlier than we now think.



Manual design and analysis (left) vs. model-based design optimisation (right).

and successfully apply those in precision engineering and high-tech system development? Probably not. Digital trends need adoption and adaption in high-precision engineering:

- **Adoption:** How to incorporate digital trends into our way of working? New tools need to bring added value and earn the trust of the users. Otherwise, people will stick to their old way of working and its associated beliefs.
- **Adaption** (a straightforward application will probably not work): There will be no seamless fit, so tools have to be adapted to fit the precision engineering challenges and way of working.

The remainder of this article will consider the above-listed digital themes within the context of precision engineering / high-tech mechatronics.

### Artificial intelligence

Out of all upcoming digital trends, AI is the one with the greatest (inflated?) expectations. One could envision an app, at some point in the future, that only needs a set of requirements and then produces a mechatronic concept including next-level design principles that deliver balanced optimisation of conflicting design considerations. This vision raises some questions:

- Following on from which stage in the V-model would this realistically be applicable, i.e. system, module or part level?
- To what extent does such an app yield technically better, faster or more cost-effective design results?
- How does this change the required skills of design engineers involved in the design?

One can try to answer these questions by looking from two perspectives: design/architecture and control/algorithms (see the boxes, on this and the next page, respectively).

### Internet of things

The developments in what is known as IoT result in both hardware and software technologies. As such, the IoT does not represent a solution on its own; it is more like an increase of infrastructural possibilities. Again, the value of IoT technologies depends on how they will be used. The idea is that excessive pick-up of information and measurement data can be obtained with cheap, small sensors with wireless data communication. Besides the obvious use of tracking and tracing all kinds of components, parts and systems, it also may open up completely new possibilities for metrology, information redundancy, state/condition monitoring and task-related decision taking.

However, the competence to adopt these new metrology architectures and possibilities has to be developed. What will be possible and what are the new 'design principles' when sensor info is cheap, abundant and non-interfering

## AI perspective 2: Control/algorithms

It is rather popular to denote recent development as being 'smart', 'intelligent' or 'autonomous', but what is really revolutionary and new? Common practice such as a tightly tuned feedback control loop is already pretty 'intelligent'. It processes data and compares these to desired values, then the optimally tuned algorithm comes up with a corrective action, which is directly applied to the real system. There is a highly developed field of control system theory and tools to do the tuning such that performance and stability are guaranteed beforehand. So far, nothing new.

Many examples of 'intelligence' in industrial engineering applications are mostly about control, decision taking and autonomous navigation. In fact, however, they often boil down to fairly low-level control. So, again it is merely the marketing terms that sound revolutionary.

Nevertheless, it is clear that algorithms will play an important role in many aspects in society. For industrial, technical systems, most of the algorithm development is based on solid system and control theory, and synthesis tools for controller design. The majority of these are performance-/accuracy-/bandwidth-driven. So far, little autonomous decision making and learning is going on in high-tech industrial systems.

As well as plain performance, great potential lies in autonomy and collaboration between systems. Autonomy is typically not driven by classical performance criteria such as precision of motion, but depends more on the ability of task completion, scheduling and planning of resources in an efficient way, and self-programming in an environment that is not exactly defined or subject to change. This is clearly an area where automated decision making and learning from the past is developing fast.

Another, often overlooked, aspect of autonomy is recovery from disturbance and error. Autonomous intelligence can have a large impact in such situations. Self-localisation and restarting to return safely to base is not an easy task, but will be needed to make autonomous developments a success. Note that 'algorithm' does not equal 'software' or 'ICT'; algorithms are sets of rules or calculation schemes that often come from many different engineering or scientific domains. To effectively implement algorithms, however, software engineering will be needed to create lines of codes and executables that are embedded in systems, can be altered by user input through adequate user interfaces, perform fast numerical calculations, and so on.

(small/light and no wires)? Does this lead to new design paradigms?

For example, in positioning dynamics we used to aim for rigid-body design and global degree-of-freedom motion metrology. In the future, by exploiting abundant metrology that becomes available with IoT, this may become very different, leading to, e.g., over-actuated system designs and more model-based active compensation of measured disturbances.

Sensor fusion is a well-known concept, but instead of aiming for overall system stability, it may be better to measure the internal instabilities, and only compensate for those that are relevant to obtain local accuracy for an application. An alternative thought, driven by the availability of distributed sensor measurement data, is to actively compensate for flexibilities and thereby obtain virtual stiffness by mechatronics.

Redundant metrology data may also be used to subtract any unwanted (but observed) behaviour and only control the real/clean performance signal. IoT also opens up the possibility of making measurement data out of the system environment available for controlling performance of the system. One example is temperature, but there are also floor vibrations, disturbance forces coming from neighbouring systems, etc.

### Big data

Data is becoming available in huge amounts and many types, and from many sources: sensors, information (status signals) already available at various levels, streaming data from internet data sources, etc. Making use of big data is often called data analytics, machine learning, smart/intelligent system engineering, among others. In practice, this comes down to more conventional data processing techniques such as filtering, estimation and system identification, which are not all that new to system engineers and mechatronic specialists.

The majority of reported successes from big data / data analytics is about pattern recognition and correlation, e.g. enhanced inspection of medical imaging data and identification of consumer profiles for marketing personalisation.

For precision engineering and mechatronics static patterns and correlation are not enough (Figure 4). We need identification of causal, real-time, input-output system relations for dynamic analysis and control design. Not any data will do in that case; garbage in will give garbage out. Experiments must be carefully designed and executed to obtain informative data sets. Quality data in this case is more important than quantity (big) data.





To make big data / data analytics work for precision system engineering, it should be more than just pattern recognition and correlation. It requires identification of causal, real-time, input-output system relations for dynamic analysis and control design.  
(Image source: College of Engineering, University of Wisconsin-Madison)

Will more data really lead to new possibilities? Should we, for instance, open up the classical system identification tools to grasp the new mechatronic possibility of abundant data availability? How to embrace the emerging data analytics tools such that they help the precision engineering solutions move forwards?

This is about model structure and fitting parameters within structure. For identifying structures and causal relations within heterogeneous data sets, the increasing powers of machine learning, AI and data science could be of added value, especially in cases outside the linear, time-invariant setting. The identification of parameter values within a model structure might also benefit from new data processing and estimation techniques, but these have to be set against the massive body of theory, knowledge and tools within the system and control field.

It would be very welcome if data analytics developments made system identification capable of dealing with

heterogeneous data sets, with continuously changing operating modes and conditions, robust against occasionally missing and redundant data. It would also be interesting to identify models that take into account other types of input, such as operator decisions, changes in the system environment, events, replacements and inputs from neighbouring systems. These could provide the basis for system control and operation beyond simply precision, and serve additional specifications like autonomy and collaboration.

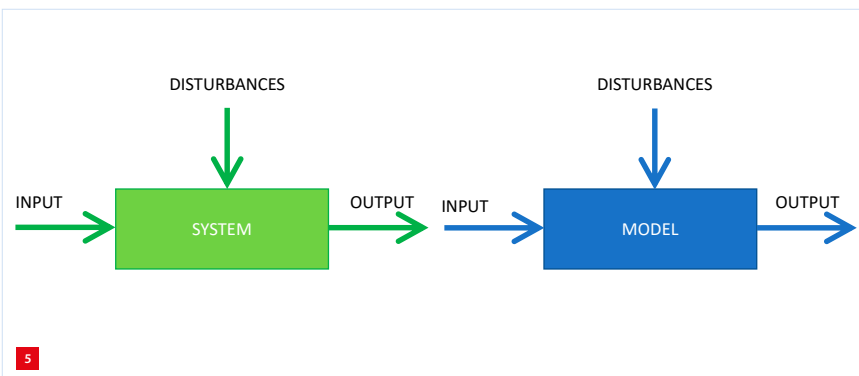
### Digital twin

Digital twin is the latest really hot topic. Applications of digital twins are seen at various stages of industrial development: virtual prototyping, scenario testing without hardware through extensive simulation of realistic cases, and condition monitoring where data from the real system are continuously being compared with simulation outputs from the digital twin. This especially includes detailed 3D representation with its almost real-time response to inputs and animation that has become available, thanks to the exploded computational power and memory/storage capacity in all kinds of computers, laptops and tablets or embedded in devices/equipment.

For system engineering challenges, digital twinning needs to fit in the predictive modelling framework (Figure 5) that we usually exploit in system concept definition and architecture (at various levels in the left branch of the V-model). In system engineering and mechatronics, it is obvious that models are simplifications and approximations of specific aspects (like dynamics, thermal behaviour or control performance), but can still describe very well the influence of certain design choices on the essential system performance aspects, for example a simple mass-spring-damper analysis. It is clear that digital twins will provide stronger and more detailed 3D visualisation to the system engineering process.

However, the fact that more detail is possible should be evaluated against its added value at the specific stage of development, and the effort that has to be put in. It seems logical that the level of detail in models should increase in proportion to the level of detail in the design choices. Producing detailed results too early in the system engineering process might distract attention away from the primary architectural choice at hand, with the risk of losing track of the big picture.

It would be interesting to do a psychological analysis of the influence of digital tools (especially of the visual kind) on decision taking. With the expected increase in the amount of data, analytics or simulation results available, the way this information is presented also



Predictive modelling requires a valid model description (for the level of detail that is needed) as well as correct inputs and representations of disturbances. To prevent 'garbage in, garbage out' some (human and/or artificial) intelligence is required.

deserves additional attention to safeguard objectivity as much as possible.

With digital twin there could be an interesting connection to rapid developments in the area of virtual reality (VR) / augmented reality (AR). There is some overlap regarding visualisation and predictive modelling. However, the scope of VR and AR is more concerned with production, assembly and integration phases, instead of system engineering and the design phase. Using all of these to evaluate manufacturability and serviceability continuously and much more effectively during the design process will connect the two legs of the V-model in a way that has not been available before.

#### *Design support*

As well as visualisation and animation, we see that model-based design is also on the rise. The diversity of requirements and the increasing design freedom are confronting system engineers with design choices at a level of complexity that will probably no longer fit in the human brain. Design support that helps to find optimal solutions and combinations within the highly complex solution space will become a necessity sooner than we would like. This has already been touched upon above on the system architecture level in relation to AI.

Here, we are considering more the actual design steps up and until component level. There are already good examples of new design optimisation tools, such as topology optimisation in freeform mechanical or flow design; however, the range of problems that can be solved has to be increased from the component-level, single criterion (e.g. lightweighting a single part for a static load) to multi-physics, system-level, functional requirements.

For this step towards multi-domain, multi-parameter trade-offs, the mathematical challenges are still huge. Yet even if these are solved, the main challenge will still be to translate properly the engineering specifications into an optimisation problem. Nevertheless, optimisation tools – even if imperfect – can already stimulate the designer to think outside the box and not to be caught in the framework of conservative design shapes and construction principles.

This should already be encouraged in the education system and supported by modules in the study curricula. Experienced engineers will probably have more difficulty in opening their minds to new tools, and letting go of (a few, not all of) their past beliefs and experiences.

#### **Wrap-up**

Yes, the future precision engineer should learn more digital skills (see the box on the next page). Yet to some extent these are not completely new to the current way of working in system engineering and high-tech mechatronics. It has been discussed how AI, IoT, big data and digital twin could be extensions of well-known system engineering notions like predictive modelling, system identification, control theory and system architecture.

It is a challenge (and will take considerable adaption and adoption) to make clever use of the upcoming digital possibilities that will support, simplify and speed up our work. The well-known steps remain, but should be finished more quickly and with less effort. Can we increase the predictability of the V-model? Will it be possible to arrange greater interaction between the two legs of the V and establish a continuous flow of simulation, predictions with physical data and measurement information, ranging from system level down to part level and up again?

We have to learn how to handle new tools. This will indeed involve new skills, specifically in translating our conventional problems such that they connect to the powers of the new tools. The biggest step forwards seems to be casting design problems into model-based optimisation problems, simply because finding the optimal solution will be too difficult just using the human brain. Continuous development of numerical tools that solve the optimisation problems, and improvement of the models involved in the optimisation will be required to get good solutions out of it, and preferably quickly.

From designing everything in detail ourselves, our job will gradually shift towards defining the right optimisation problem and boundary conditions, and analysing, combining and balancing the outcoming partial solutions. Obviously, this can only be done if we understand the digital tools and methods, such that we get the best out of them for our applications.

As well as looking for new possibilities, we also have to face the risks associated with these emerging digital tools. It has been stressed that excessive visualisation may suggest reality and produce misleading details that will slow down system engineering progress in the concept phase, or even lead design choices in the wrong direction.

The potential, however, is undeniable, so let's join forces and sit together with thought leaders from digital and system engineering domains. Let us try to understand each other's expertise, work out interesting intersections and line up plans for collective development.

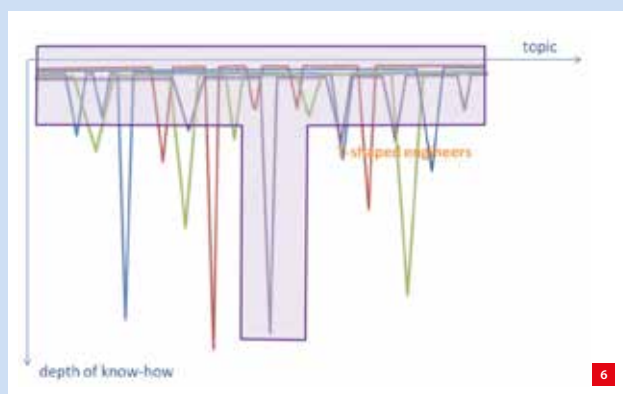
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## Future precision engineer profile/CV/skill set

Mastering many new digital tools and skills should certainly be a part of the education process, teaching young engineers to grasp the many unprecedented possibilities and, conversely, identify the associated pitfalls. A key skill will be to correctly translate design problems into optimisation problems, including assigning weights to conflicting requirements that need to be satisfied simultaneously.

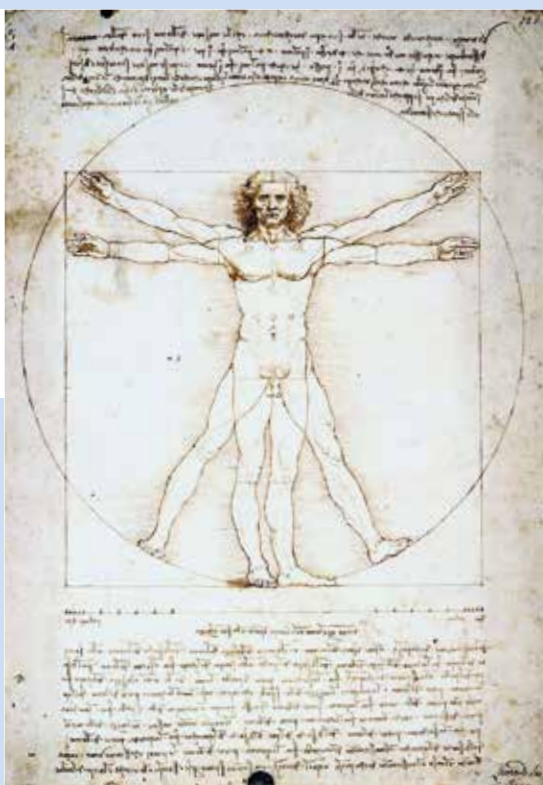
Education should encourage students to be curious and think differently about conventional ways of working, design principles and so on. Let tools work for you, but remain in control and understand what comes out. Younger generations are more able to think outside the (old) box and come up with creative new approaches, just because they have already grown up immersed in a very digital world. Making use of big data and analytics for engineering problems deserves serious attention. Hierarchy in metrology and making use of heterogeneous and redundant data coming from all kinds of sources should be part of the mindset of future precision engineers. This involves thinking within cascaded system boundaries (area of interest, system level, surrounding environment, chain of equipment, ...).

Will this lead to a shift from a multidisciplinary collaboration of experts to a stronger 'homo universalis' profile, of one who is able to orchestrate the disciplines without being an expert at a single one? Or do we still need the T-profile, the combination of depth in a certain field with multidisciplinary awareness and ability to communicate with other disciplines? See Figure 6.



Will the future precision engineer have a T-shaped profile (source: Ton Peijnenburg) or be more of a 'homo universalis' (source: Leonardo da Vinci)?

How education should be aligned towards that profile is an open question. Of course, the remarks above are highly speculative because the necessary competence and knowledge have not even been developed, or only marginally explored. The early involvement of educational institutes and thought leaders from industry and knowledge institutes may help to find directions for educational tracks.



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# KEEPERS OF THE DDP PHILOSOPHY

Philips Innovation Services (PInS) is the successor of Philips Centre for Manufacturing Technology (Centrum voor Fabricage Technologie, CFT), where Wim van der Hoek worked and played a key role. The original focus on manufacturing equipment and processes has since been extended to also include product development, fabrication of MEMS and micro devices and optimisation of innovation processes. The philosophy of Wim van der Hoek (see the article on page 5 ff.), however, as recorded in "The Devil's Picture Book" ("Des Duivels Prentenboek" in Dutch, or DDP), is fully alive at PInS and finds application in the design of both high-tech production equipment and consumer products.

## EDITORIAL NOTE

Input was provided by Herman Soemers (technology manager), Erik Manders (senior architect mechatronics) and Michel Loos (senior mechanical designer), all working at Philips Innovation Services global headquarters in Eindhoven (NL), and taken from the textbook "Design principles for precision mechanisms" by Herman Soemers (T-Pointprint, Enschede, 2010).

[www.innovationservices.philips.com](http://www.innovationservices.philips.com)

Until his retirement in 1984, Wim van der Hoek worked at Philips CFT, dedicated to production mechanisation for various Philips main industry groups. As a result of the spinning off of Philips business units (yielding companies such as ASML, FEI and Assembléon), for which CFT continued to work, and the strategic choice to widen its base, CFT also started working for external clients. As a result of reorganisations at Philips, under pressure from changing market conditions, CFT in 2005 merged into Philips Applied Technologies (AppTech). In 2011, AppTech merged with Philips MiPlaza and Philips Lighting's production mechanisation department, to become Philips Innovation Services (PInS). In addition to mechanisation, automation and process development, attention for product development has grown over the years.

## Key areas of expertise

These days, PInS covers a large number of key areas of expertise, from Medical Devices Design & Engineering to

Environment, Health & Safety. The two areas that have the strongest link with Van der Hoek's work are High-Precision Engineering and Manufacturing Systems & Industry 4.0.

### High-Precision Engineering

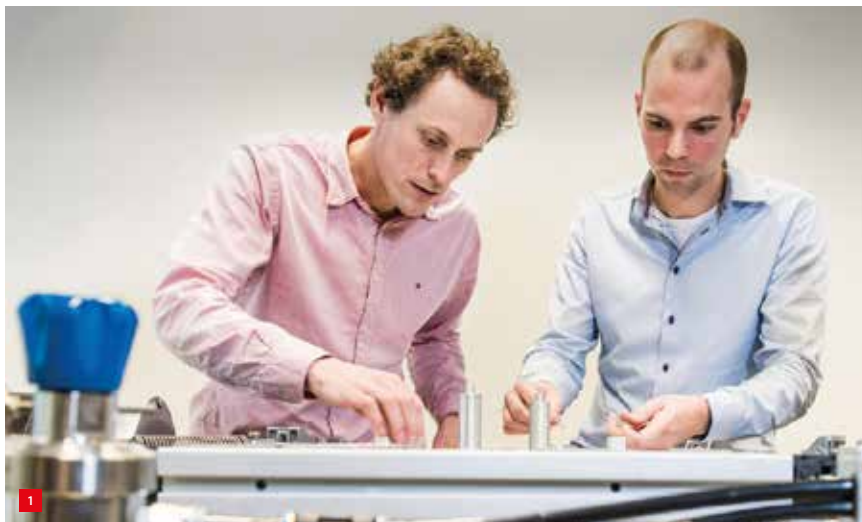
For challenging high-tech equipment and mechatronic systems (Figure 1), PInS helps customers to make innovation work and improve quality and reliability, following a first-time-right, model-based development approach. A prominent example are the contributions to developing (sub)nanometer accurate positioning systems for ASML's lithography machines; think of magnetic levitation stages with planar motor. Concrete examples of other projects include thermal control using thermo-electric coolers, and robotic vision for high-precision dispensing robots.

### Manufacturing Systems & Industry 4.0

PInS system architects and process engineers contribute to the development of manufacturing processes (Figure 2), production lines or machines, embedding the latest technologies such as additive manufacturing, intelligent robotics and manufacturing data management ('Industrie 4.0'). Examples include high-volume, flexible assembly platforms and high-speed inspection systems.

A specific topic, in the spirit of Wim van der Hoek, who early in his career started studying the effect of machine dynamics on manufacturing quality and repeatability, is structural dynamics & vibration analysis. Here, PInS competences include design for dynamic stability (drawing on first principles as well as simulation), experimental vibrational analysis, and drop test simulation and experiments.

Anyway, PInS does not deny its mechanical roots (Figure 3).



High-Precision Engineering is one of the key areas of expertise at Philips Innovation Services (PInS).



2 Process development, in this case using thin-film technology, is at the core of PInS.

### Community of practice

At the moment, Philips is in the process of setting up various 'communities of practice' in order to bundle expertise in specific domains and to make domain experts more accessible to the entire (global) Philips organisation. Naturally, one of the communities will be devoted to mechanical/mechatronic engineering and design principles. The courses on these subjects, building on DDP, for example, will be part of this community, as well as the design approach that was introduced by Wim van der Hoek. It should be noted here that the profession of designer has to be learned in practice, by taking up concrete design and technology challenges, figuratively and literally speaking.

In that sense, PInS is the keeper of the DDP philosophy, together with a company such as ASML, which largely owes the success of its lithography machines to 'Van der Hoekean' thinking. ASML's version of lithography is a very specific high-precision application, for which PInS provides technology support and design consultancy, but PInS also covers a much wider application area.



3 PInS does not deny its mechanical roots.

### Design thinking

The main drivers for proper precision design are dynamics and predictability. From the dynamics point of view, the aim is to design constructions that have a high stiffness and low mass, since the ratio of these two quantities determines the lowest eigenfrequency as an important parameter for the achievable dynamic accuracy, with or without feedback control.

At PInS, the starting point for many design challenges – and the subsequent design reviews – that involve (precise) positioning is still the question of degrees of freedom and the pursuit of statically constrained designs with minimal or preferably no play. Not that this must always be strictly adhered to. With a view to maximum stiffness and lifetime, for example, a structure can be designed as being overdetermined, i.e. with more constraints than there are degrees of freedom. But then it is always good to realise that the design principles have been 'violated' and that this comes at a 'price', so that these design trade-offs can be made consciously.

Statically constrained designs are, for example, easier to make calculations on (regarding tolerance chains, for example) and also more predictable in their behaviour, which of course is crucial for high-precision systems. But also in (low-cost) consumer products, for which PInS also provides design support, this approach can be very fruitful. In constructions with moving parts a statically determined design should prevent erratic movements that may lead to rattle and hence excessive noise.

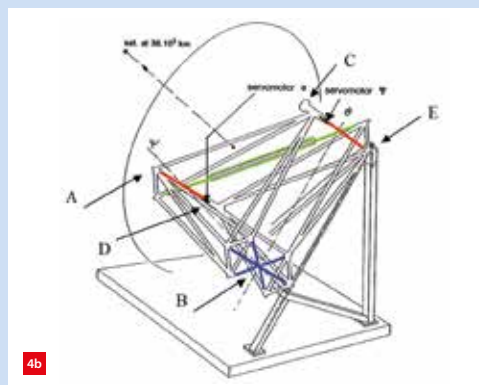
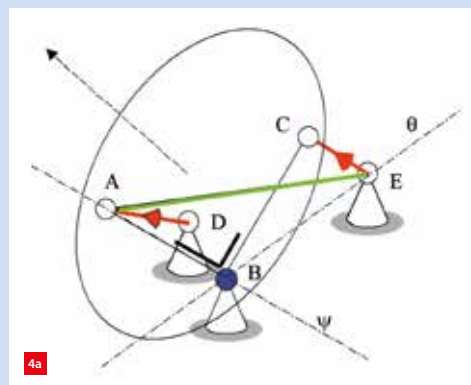
As a consequence, design according to DDP is not only about high-brow, but also about down-to-earth common sense and principles that appear in 'home-garden-and-kitchen' phenomena. Take the DDP example of opening a wine bottle: twisting the cork makes pulling out the cork much easier. The same principle in another domain: a stationary car with spinning wheels can be pushed aside using, so to speak, only one finger. Rotation in one direction reduces friction in the transverse direction. Based on the same principle, friction can be overcome in positioning applications. Wim van der Hoek's well-known wine-bottle cork example keeps on inspiring precision designers.

His coaching style has been a source of inspiration for senior mechanical engineers mentoring their junior colleagues; never be too directive. Anecdotes, analogies, critical questions, hints, tips & tricks, brief insightful hand calculations; these all are a means to trigger proper design thinking, helping to pass on the DDP philosophy to next generations of designers within Philips.

## Flexures

Elastically deforming parts, so-called flexures, are popular construction elements in the DDP universe. In mechanisms designed for relatively small displacements or rotations, flexures can be used to create (approximate) points of rotation or parallel guides with a relatively high stiffness in the constrained directions. These parts are also free of play and friction, and therefore extremely suitable for use in precision applications. It is fair to state that flexures form a key part of Wim van der Hoek's design heritage. But contrary to other design schools, Van der Hoek-style flexures are always well thought out from a degrees-of-freedom point of view.

A (not-so-typical) application of flexures, dating back to the eighties and designed in Wim van der Hoek's group at Eindhoven University of Technology, is shown in Figure 4, the manipulator for pointing a dish antenna at a satellite with high accuracy in the meridional ( $\theta$ ) and azimuthal ( $\psi$ ) directions.



Flexure-based dish antenna adjustment. (Source: Herman Soemers, "Design principles for precision mechanisms", T-Pointprint, Enschede, 2010).

(a) In meridional ( $\theta$ ) direction.

(b) In azimuthal ( $\psi$ ) direction.

The principle of the flexure mechanism is shown in Figure 4a. Ball joints A, B, C are attached to the back of the antenna dish in a plane perpendicular to the axis pointing at the satellite. Joint B is fixed with respect to the world, whereas A and C are, via linear actuator links, connected to joints D and E, respectively. Extension of actuator AD causes the dish to rotate about the meridional axis  $\theta$  and actuator CD causes azimuth rotation. Link AE constrains in-plane rotation of the dish.

Figure 4b shows the flexure embodiment of the mechanism. The flexures are steel bars measuring about 1 m in length and 12 mm in diameter. The truss frames serve to locate the fixation points and absorb the clamping moments without affecting the dish shape. The ball flexure is constructed from the same steel bars and is located at the intersection of the  $\theta$ -axis and the  $\psi$ -axis. This particular application is not sensitive to the exact location of the rotational axes, for the dish-to-satellite distance is orders of magnitude larger than the bending bar pitch. Figure 5 shows the dish antenna set-up. The 3-m dish is connected in an exactly constrained way to the upper mechanism frame so as to avoid geometry changes due to, e.g., (thermal) expansion differences as much as possible.



Three-meter dish-antenna with flexure-based pointing mechanism.



# EUROPEAN SCOPE

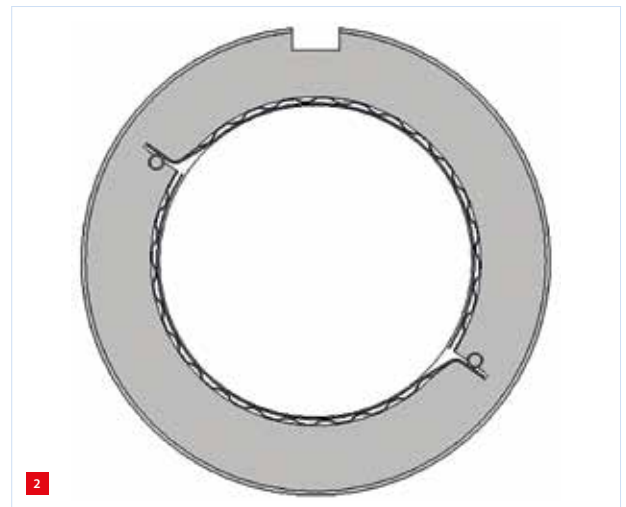
The first two Gas Bearing Workshops, in 2015 and 2017, were mainly visited by interested people from Germany, Belgium and the Netherlands. This year in the third edition, however, much attention was paid to developments in France, Italy and the UK. Accordingly, the number of attendees went up, from 40 to 60, well distributed over the participating countries. This turned out to be a fitting number in terms of quality of discussion during and between the presentations.

JOS GUNSING

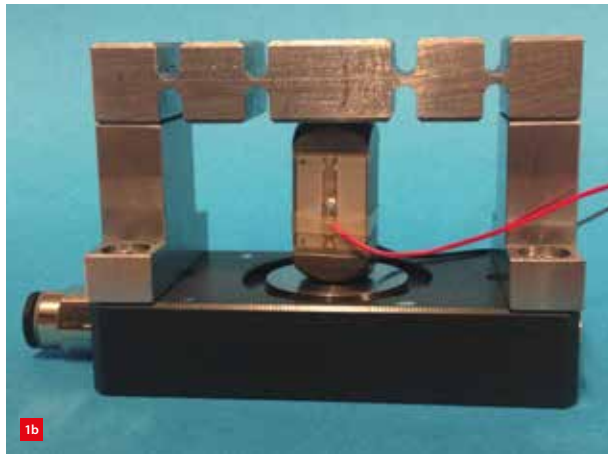
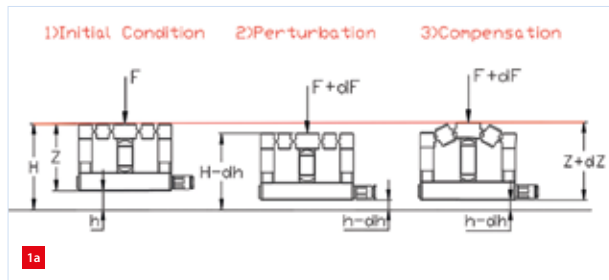
In his opening remarks to the Gas Bearing Workshop 2019 in Düsseldorf, Germany, Patrick Janssen from the Dutch Consulate on-site expressed his pleasure with the continuation of the initiative. He said he sincerely hoped that the organising partners VDE-GMM (VDE-Gesellschaft Mikroelektronik, Mikrosystem und Feinwerktechnik) and DSPE would continue to co-operate and innovate.

Next, Terenzo Raparelli, Mihai Arghir and Duc Ha started with a joint keynote speech presenting the latest developments in Italy, France and the UK, respectively.

In Italy, research is concentrated at the Politecnico di Torino, primarily aimed at air-bearing feeding with subjects like supply hole discharge coefficients, behaviour of porous



Radial air foil bearing. (Courtesy of Omega Dot)



Active thrust pad bearings with PZT/piezo technology. (Courtesy of Politecnico di Torino)  
(a) Working principle.  
(b) Physical realisation.

and metal (woven) mesh and, of course, numerical modelling. Applications are mainly found in the fields of textile industry and milling, i.e. high-speed spindles. Special attention should be paid to the research on active thrust pads with PZT/piezo technology (Figure 1) for increasing the dynamic load behaviour. A company worth mentioning is MAGER Air Bearings, which develops and builds a range of air-bearing applications.

In France, research started in the early 1960s with gyroscope air bearings. With space turbo pumps (rocket fuel pumps, Safran Group) and microturbo applications being relevant for industry, foil bearings in journal (radial) and thrust (axial) versions are important research topics. Also, refrigerant pump bearings (for Liebherr) with two-phase flow (gas-liquid) present an interesting research subject. INSA Lyon and Université de Poitiers are the places to be in France.

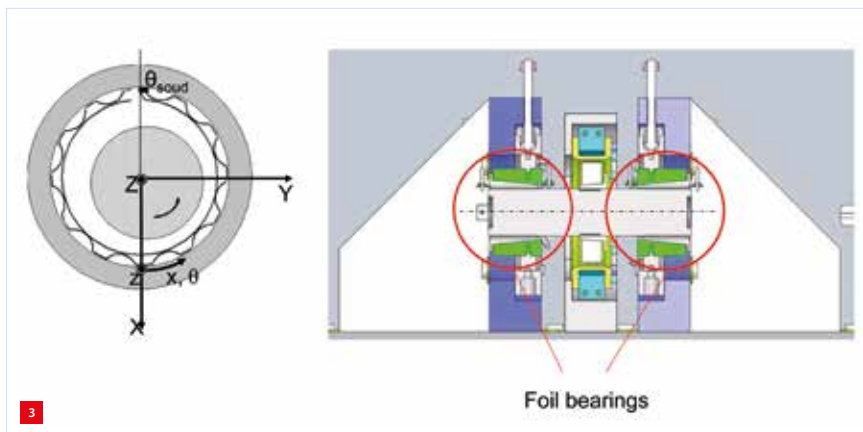
In the UK, several universities/institutes (Birmingham, Manchester, Leicester, Huddersfield, Cambridge, Queen's University (Belfast), Brunel University and Cranfield) contribute to gas-bearing research. Besides fundamental topics, there are applications predominantly in the field

## AUTHOR'S NOTE

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Test rig for aerodynamic foil bearings. (Source: Balducchi, F., Arghir, M., and Gaudillère, F., "Experimental Analysis of The Unbalance Response of Rigid Rotors Supported on Aerodynamic Foil Bearings", GT2014-25552, ASME Turbo Expo 2014)

of turbo machinery, dealing with hybrid air bearings (a combination of aerodynamic and aerostatic bearings), foil bearings (Figure 2) and squeeze-film bearings.

### Research topics and applications

Andreas Lange (Technische Universität Kaiserslautern, Germany) and Federico Colombo (Politecnico di Torino) focused their lectures on, respectively, simulation-driven design, including stability analysis and lumped-parameter models for gas bearings. They both provided useful contributions that can accelerate the design of gas-bearing applications and help to make it (close to) right first time.

Duc Ha (Omega Dot, Worcester Park, UK) is deeply involved with air foil bearings, especially in applications for turbo machinery. He presented the advantages of foil bearings (in fact aerodynamic bearings) as compared to high-speed roller bearings or hydrodynamic bearings:

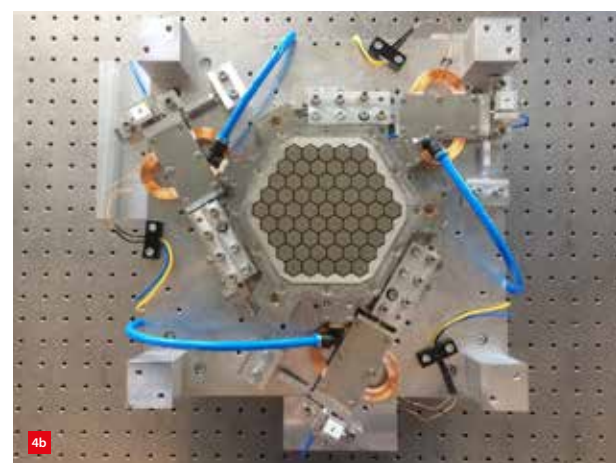
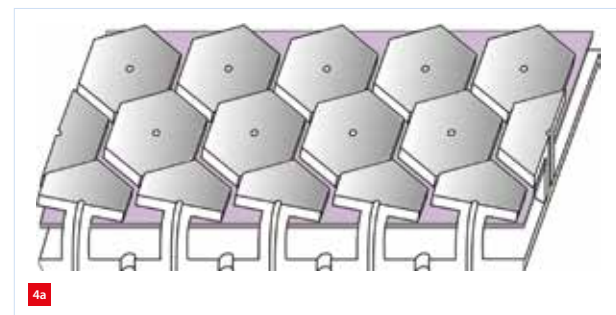
- Oil-free.
- Lower friction and operational cost.
- Low noise and vibration.
- Low maintenance.
- Zero wear.
- Self-acting (i.e., starting without an extra air supply), no extra lubrication required.
- Compliancy adaptable.

Foil bearings are particularly interesting for turbo compressors, turbo alternators (i.e. generators) and airplane air conditioner drives. Foil bearings can be applied both as journal and thrust bearings at speeds up to 200 m/s and temperatures up to 700 °C. The compliant foils accommodate for thermal expansion, e.g. shaft thermal growth. The main research topics for air foil bearings include cost reduction (as evidenced by patent literature) and recently also condition monitoring aimed at improving reliability, or reducing machine downtime.

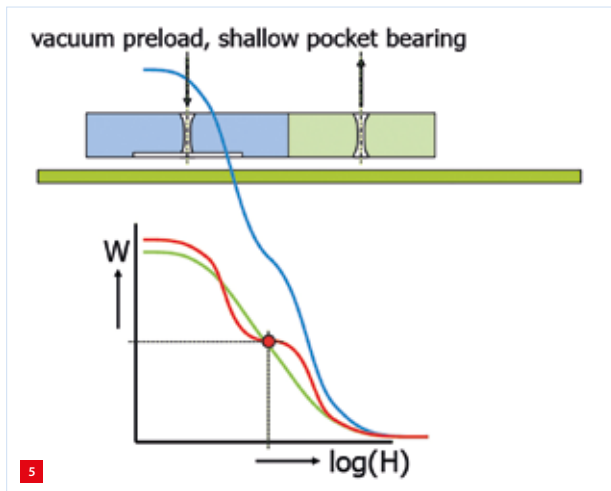
Mihai Arghir (Université de Poitiers) showed an interesting case of a rocket fuel pump (15MW pumping power in a cryogenic environment) with hybrid bearings. In hybrid bearings the static load is also carried on a gas film (aerostatically) and with increasing speed, the aerodynamic effect takes over and also contributes to the stability of the bearing-shaft combination. Arghir also investigates foil bearings, specifically the unbalance response during coast-down (gradually revving down). Nonlinear models of the compliant bump stiffness/damping and the impact on bearing start-up behaviour, bearing stability plus the impact of manufacturing errors, are his specialty. This research is ongoing (Figure 3).

### Peculiar twist

Ron van Ostayen, Delft University of Technology (TU Delft, NL), gave a peculiar twist to air-bearing design conventions when he stated that he was looking for, among other things, more friction in air bearings. Elaborating on this, he showed the latest results for the 'flowerbed' research aimed at transporting/positioning wafers with the help of air flow, where friction is indeed required (Figure 4). The flowerbed consists of air-bearing pads that can be actively tilted. This air-bearing tilt not only will result in a lifting force, but will also create drag in a specific direction, thus achieving a movement of the air-lifted substrate. This motion, as well as position or speed, can be controlled. It presents an interesting concept for very fragile substrates and also avoids the need for applying separate wafer carriers.



Flowerbed with actively tilting air-bearing pads. (Courtesy of TU Delft)  
(a) Schematic of principle.  
(b) Research set-up.



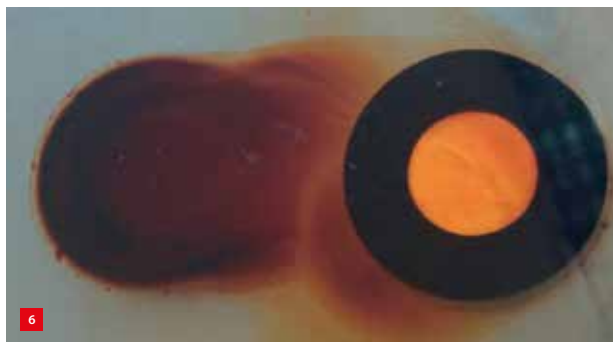
Zero stiffness: combination of vacuum preload and a shallow pocket air bearing ( $W$  = resultant force,  $H$  = air gap height). At the red dot, stiffness is approximately zero. (Courtesy of TU Delft)

Van Ostayen's next statement was that he was looking for low stiffness; preferably zero stiffness. This feature can be applied very successfully in air mounts for machine frames in order to have a perfect vibration isolation. In fact, it is a smart combination of vacuum preload and a shallow pocket air bearing acting in the same direction (Figure 5). By applying the right settings, a small area with low/zero stiffness can be created.

The last example of an apparently impossible air-bearing feature presented by Van Ostayen was a bearing without an air supply. This bearing consists of a ferrofluid ring between glass plates that encapsulates an air bubble (Figure 6), making any air supply obsolete.

## Conclusions

Firstly, the Gas Bearing Workshop provided an excellent opportunity to network in an informal setting with people from at least six countries: as well as the 'newcomers' France, Italy and the UK, this naturally included Germany, Belgium and the Netherlands. The presentations gave a good overview of air-bearing research in these countries. In two years' time, in early spring 2021, the 4th Gas Bearing



Air bubble trapped with ferrofluid ring (shaped by a magnet) between glass plates acting as air bearing without air supply. Moving the glass plate over the bearing results in a trail of ferrofluid. (Courtesy of TU Delft)

Workshop will be planned and the organisers hope to welcome a lot of interested people by then. Regarding the 2019 edition, they can look back on an exciting and open-minded Gas Bearing Workshop, where creative ideas were raised and flowed frictionlessly during the day.

## INFORMATION

[WWW.GAS-BEARING-WORKSHOP.COM](http://WWW.GAS-BEARING-WORKSHOP.COM)

## New standard work on air-bearings

Farid Al-Bender, retired professor of mechanical engineering at KU Leuven, Belgium, gave a general presentation on air bearings. It could be considered a sneak preview of his new book, "Air Bearings – Theory, Design and Applications", which will appear at the end of this year.

Al-Bender is a long-time expert in air-bearing technology. He obtained his Ph.D. in 1992 in Leuven, where he was appointed professor and was the co-founder of Leuven Air Bearings. KU Leuven has been an expertise centre for air-bearing technology since the 1970s. When Al-Bender realised that no new air-bearing textbook had been published since the 1960s, he decided to write one himself, for beginners and experts in the field (Figure 7).

### Table of Contents (600 pages)

1. Intro
2. General formulation and modelling
3. Flow into the bearing gap
4. Reynolds Equation: derivation, forms and interpretation
5. Modelling of flow in externally pressurised bearings
6. Basic characteristics of circular centrally fed aerostatic bearings
7. Dynamic characteristics of circular centrally fed aerostatic bearing films
8. Aerodynamic action of self-acting and hybrid bearings
9. Journal bearings
10. Dynamic whirling behaviour and the rotordynamic stability
11. Tilting pad air bearings
12. Foil bearings
13. Porous bearings
14. Hanging bearings
15. Actively compensated gas bearings
16. Design of an active aerostatic slide
17. Thermal characteristics of the film flow



Farid Al-Bender, "Air Bearings – Theory, Design and Applications", Wiley, 2019.

# ADDING PHYSICS AND DIDACTICS TO DDP

Following Wim van der Hoek's "The Devil's Picture Book" ("Des Duivels Prentenboek" in Dutch, or DDP), the professor's ground-breaking lecture notes on positioning accuracy of constructions and mechanisms, a number of textbooks have appeared aimed at updating and systematising its contents (see the article on page 5 ff.). The latest addition to the 'DDP line' is "Design Concepts for Precision Engineering" by Susan van den Berg, lecturer at Fontys University of Applied Sciences (UAS) in Eindhoven (NL).

When Susan van den Berg noticed a mismatch between existing textbooks and the entry-level knowledge of the students in her class at Fontys UAS, she took the initiative to write a didactically sound textbook targeted specifically at UAS students and engineers who are novices to the field of precision engineering. Only prior knowledge of mechanics (statics, stress and deformation) and basic mathematics (trigonometry and calculus) is required.

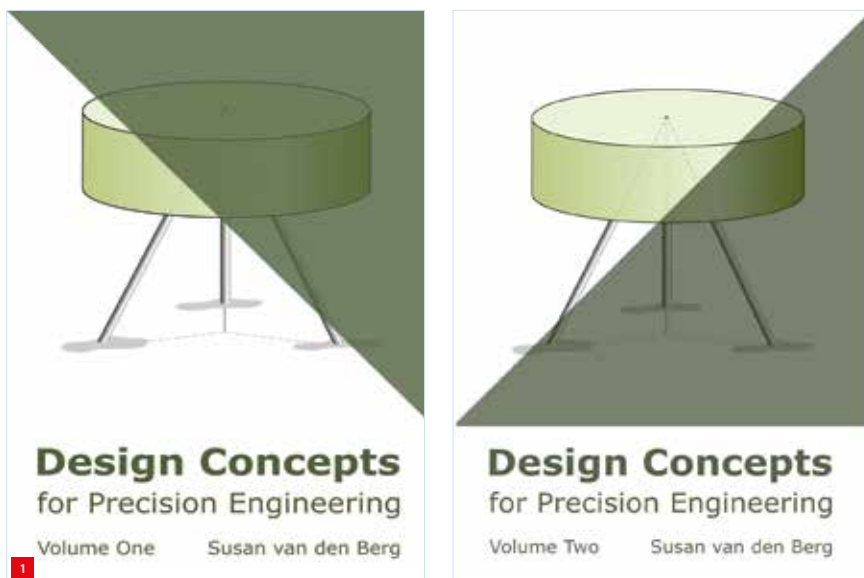
"Design Concepts for Precision Engineering" (Figure 1) will appear in two volumes (both comprising two parts), the first of which was published this spring. The first volume aims to explain the (physical) phenomena that interfere with achieving high-precision goals (part I, "Challenges for a Precision Engineer") and to provide useful tools for analysing and designing systems (part II, "Toolbox for a Mechanical Engineer"). The second volume (parts III and IV), to be published next year, will present

(many of) the design concepts that help to avoid, mitigate or compensate for some of the more 'harmful' phenomena.

In part III ("Design Strategies for Precision Engineering"), the author presents a breakdown of design principles into various design strategies. Each section offers a design strategy for precision design, including: achieving exactly constrained designs, using compliant systems, using a preload, aiming for high stiffness, aiming for low stiffness, aiming for low mass, aiming for balance, and using a temperature-invariant system. There are various design strategies and principles that can be applied to different situation to improve accuracy, reproducibility, process speed, cost, or reduce footprint and energy consumption. In part IV ("Design Concepts for Precision Systems"), design concepts are organised by functionality, for example: torque transmission, linear guidance, supports and hinges, lightweight design and fine adjustment.

With this structure, "Design Concepts for Precision Engineering" follows the 'Why, What, How' approach. The Why is described in part I: the goals and the phenomena that hinder the achievement of these goals. Part III features the 'What': the principles that counteract the effects of the phenomena. Finally, part IV addresses the 'How': how to make a linear guidance, how to convey a torque, etc. In between, Part II is required for making predictions about a system's behaviour; Figure 2 gives a sneak preview.

A designer should view both the principles and the concepts as inspiration and not assume the book contains all possible design solutions. The goal of parts III and IV is to present the reader with a way of thinking and a starting point for their own creativity in achieving their design goals. The author is open to receiving more current examples to be included in the last part of the book, which discusses functionality.



Susan van den Berg, "Design Concepts for Precision Engineering", Berg Precision Publishing; volume 1 appeared this spring, volume 2 is scheduled for next year.



### 3.2 Types of models

In this part some useful models and modelling tools are discussed. Other useful tools, for example free body diagrams, are assumed to be known by the reader.

The first chapter describes models for calculating the system stiffness for systems that consist of multiple springs. In the second chapter models are discussed for predicting the stiffness and loadability of elements in different load cases. The third set of models is for calculating contact stiffness and loadability. These latter two can be used to convert any element or contact into a spring, so that systems can be translated to a set of springs. This is expanded in the next type of model that is discussed, static characteristics. A system is converted to a synthetic schematic, where the system elements are displayed as springs, elements with friction and connections with or without play.

Once the schematic is known, the relation between force and displacement is graphically displayed in a static characteristic. The diagram helps to analyse a system's static behaviour. After a system is converted to this schematic, it is easier to pinpoint the weak parts and improve the system. The last type of model is the constraint-based design model for controlling degrees of freedom. Elements are considered to be infinitely stiff in some and infinitely compliant in other orientations. This model gives insight on how to use one or more elements to constrain an object properly.

### 3.3 Use of models

It is important that the designer is aware at all times that all models are nothing more than representations of the reality. Models are based on physical phenomena using assumptions and simplifications. The extent to which the models have to be realistic, depends on how accurate the behaviour should be predicted.

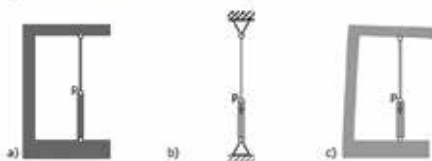


Figure 3.2: Level of accuracy of the model

In figure 3.2a a schematic is depicted of a frame and two elements that are both connected to the frame and that are connected to each other in point P. When a force is applied in point P, the position of that point will change. If the frame is very stiff compared to the elements, the model can be approximated as depicted in b. But if the

2

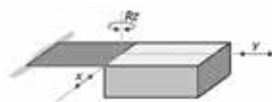


Figure 8.6: Object constrained in 3 degrees of freedom with a sheet flexure

#### Sheet flexure with notch hinge

This is a thin plate with a notch in the middle, see figure 8.7.



Figure 8.7: Object constrained in 2 degrees of freedom with a notch hinge

The rotation about the axis normal to the sheet  $R_z$  is no longer fixed, since the notch acts as a hinge. In this case the object is fixed in  $x$  and  $y$  direction and free in all other directions.

#### Folded sheet flexure

When an object is connected to a folded sheet, it is basically connected by two sheet flexures in series, see figure 8.8.

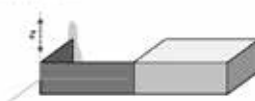


Figure 8.8: Object constrained in direction of fold line

The first sheet flexure constrains the fold line in two translations and one rotation, in figure 8.8 these are  $x$ ,  $z$ , and  $R_y$ . The second sheet flexure has an orientation perpendicular to the first one. With respect to the fold line, it constrains two translations and one rotation, in figure 8.8 these are  $y$ ,  $z$ , and  $R_z$ . Since the two sheet flexures are placed in series, the free directions must be added. After all, once a degree of freedom is free, an element in series cannot fix that. The only degree of freedom that is fixed

#### INFORMATION

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Sneak preview of pages from "Design Concepts for Precision Engineering", volume 1, part II.



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# UPCOMING EVENTS

27 June 2019, Eindhoven (NL)

## DSPE Knowledge Day

DSPE event on Engineering for Particle Contamination Control.

[WWW.DSPE.NL/EVENTS/AGENDA](http://WWW.DSPE.NL/EVENTS/AGENDA)

16-18 September 2019, Nantes (FR)

## SIG Meeting Advancing Precision in Additive Manufacturing

Special Interest Group Meeting hosted by euspen (European Society for Precision Engineering and Nanotechnology) in collaboration with ASPE (American Society for Precision Engineering). This year's SIG will focus 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](http://WWW.EUSPEN.EU)

23-26 September 2019, Rhodes (GR)

## MNE 2019

The 45th international conference on micro- and nanofabrication and manufacturing using lithography and related techniques is devoted to progress in advanced patterning, nanofabrication for functionality, nanodevices/MEMS and nanofabrication for life sciences (lab-on-a-chip).



[WWW.MNE2019.ORG](http://WWW.MNE2019.ORG)

25 September 2019, Eindhoven (NL)

## Software-Centric Systems Conference

Conference devoted to complex software development.

[WWW.SOFTWARECENTRICSYSTEMS.COM](http://WWW.SOFTWARECENTRICSYSTEMS.COM)

30 September, 1-3 October 2019, Eindhoven/Delft (NL)

## Optics & Optomechanics Week

Unique event comprising the DSPE Optics and Optomechanics Symposium & Fair, on Monday 30 September, and a new, three-day, optomechanics system design course, on 1-3 October.

[WWW.DSPE.NL](http://WWW.DSPE.NL)

1 October 2019, Eindhoven (NL)

## Photonic Integration Conference

Fifth edition of conference that covers the integration of photonics with microelectronics, cases in a variety of application areas, business models, and tools for development and packaging. The conference is part of the Photonics Applications Week (30 September - 4 October in Eindhoven), also featuring the Internet of Things event, the HealthTech Event and the Intelligent Sensor Networks Conference, as well several workshops about photonics in automotive.

[WWW.PHICONFERENCE.COM](http://WWW.PHICONFERENCE.COM)

[WWW.PHAPPSWEEK.COM](http://WWW.PHAPPSWEEK.COM)

8-10 October 2019, Karlsruhe (GE)

## DeburringEXPO

Third edition of trade fair for deburring technology and precision surface finishing.



[WWW.DEBURRING-EXPO.COM](http://WWW.DEBURRING-EXPO.COM)

9-10 October 2019, Glasgow (UK)

## SIG Meeting Precision Engineering for Sustainable Systems

The first Special Interest Group Meeting on the role of precision engineering for renewable energy covers four themes: wind, solar and oceanic energy as well as energy storage. The organising committee comprises Dr Harald Bosse (PTB), Prof. Paul Shore (NPL) and Prof. Alex Slocum (MIT), with Prof. Xichun Luo acting as local host at the University of Strathclyde.

[WWW.EUSPEN.EU](http://WWW.EUSPEN.EU)

22-24 October 2019, Stuttgart (DE)

## Parts2clean 2019

International trade fair for industrial parts and surface cleaning.

[WWW.PARTS2CLEAN.COM](http://WWW.PARTS2CLEAN.COM)

28 October - 1 November 2019,

Pittsburgh (PA, USA)

## 34th ASPE Annual Meeting

Meeting of the American Society for Precision Engineering, introducing new concepts, processes, equipment, and products while highlighting recent advances in precision measurement, design, control and fabrication.

[WWW.ASPE.NET](http://WWW.ASPE.NET)

November 2019 (exact dates to be set), Leiden (NL)

## LiS Academy Manufacturability course

5-Day course targeted at young professional engineers with a limited knowledge of and experiences with manufacturing technologies and associated manufacturability aspects.

[WWW.LISACADEMY.NL](http://WWW.LISACADEMY.NL)

13-14 November 2019, Veldhoven (NL)

## Precision Fair 2019

Nineteenth edition of the Benelux premier trade fair and conference on precision engineering, organised by Mikrocentrum.



Precision Fair

[WWW.PRECISIEBEURS.NL](http://WWW.PRECISIEBEURS.NL)

21 November 2019, Utrecht (NL)

## Dutch Industrial Suppliers & Customer Awards 2019

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

[WWW.LINKMAGAZINE.NL](http://WWW.LINKMAGAZINE.NL)

27-28 November 2019, Berlin (DE)

## SIG Meeting Micro/Nano Manufacturing

Special Interest Group Meeting hosted by euspen, focusing on novel methodological developments in micro- and nanoscale manufacturing, i.e. on novel process chains including process optimisation, quality assurance approaches and metrology.

[WWW.EUSPEN.EU](http://WWW.EUSPEN.EU)

# ELECTRON MICROSCOPY WITH EXTREME RESOLUTION

On 14 March this year, DSPE's Young Precision Network (YPN) visited the Electron Microscopy division of Thermo Fisher Scientific in Eindhoven (NL). Formerly, this location – initially the home of Philips Electron Optics – was part of FEI Company (acquired by Thermo Fisher in 2016). The inspiring presentations and tour during the YPN visit offered a comprehensive picture of how electron microscopy with extreme resolution can contribute to Thermo Fisher's mission; "to make the world healthier, cleaner and safer".

FRANS ZUURVEEN

DSPE's Young Precision Network (YPN) aims to promote precision engineering among students and young professionals. The visit to Thermo Fisher gave beginning mechanical engineers and physicists a fantastic opportunity to discover one of their potential future work fields. Presentations by Thermo Fisher electron-optical specialists and a tour of the transmission electron microscope (TEM) clean assembly facility and the demo centre (Figure 1) demonstrated the value of such YPN events.

After a short personal introduction from each of the enthusiastic young participants, host of the session Bas Cornelissen, program manager Imaging, Acquisition and Detection, gave an overall introduction of Thermo Fisher, a leader in biotechnology with 70,000 employees worldwide. The site in Eindhoven is a part of the Materials and Structural Analysis Division (MSD), along with Hillsborough (USA) and Brno (Czechia), a division proud of enabling Nobel-prize winners like Daniel Shechtman, Jacques Dubochet, Joachim Frank and Richard Henderson.

The overall MSD product portfolio can be subdivided into four application areas: electronics, natural resources, materials sciences and life sciences.

## High-resolution TEM

Bart Linssen, program manager for Non-standard Requests, explained what narrow tolerances have to be met when designing and manufacturing a TEM. Figure 2a gives a schematic representation of the column in a TEM. Figure 2b shows a picture of the high-end TEM, the Spectra 4, based on the Thermo Fisher Titan TEM platform.

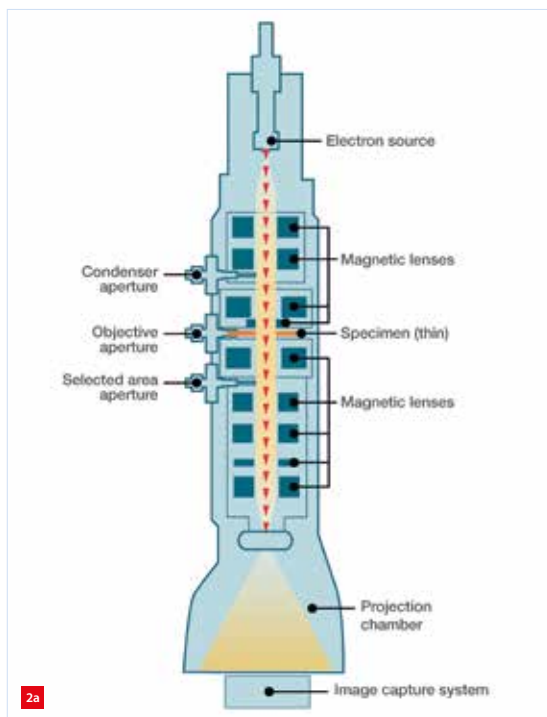
The challenges in reaching high-resolution TEM can be explained by comparing a TEM with the well-known slide projector, as shown in Figure 3. The slide projector applies visible-light with a wavelength of about 500 nm, as opposed to electrons with a wavelength of 2 pm (0.002 nm) in the TEM. These electrons originate from an electron source and are accelerated with a voltage ranging from 20 kV up to 300 kV, depending on the specimen that is being

### AUTHOR'S NOTE

Frans Zuurveen, former editor of Philips Technical Review, is a freelance writer who lives in Vlissingen (NL). The input by Thermo Fisher Scientific is acknowledged.



Impressions of the tour of Thermo Fisher's facilities during the YPN visit.



Transmission electron microscope.

(a) Schematic drawing.

(b) Thermo Fisher's most advanced TEM, the Spectra 4.



investigated. The electrons are produced by an incandescent tungsten wire or an ultra-pointed emitter by field-emission.

Electrons in a TEM should not be hindered by any molecules except for the specimen. Therefore, the 'vacuum' pressure inside the TEM ranges from  $10^{-7}$  to  $10^{-9}$  Pa. The accelerating voltage has to be extremely constant in order to prevent misinterpretation of energy loss of the electrons. At 300 keV the variation is not allowed to go above 50 milli-eV. Another challenge is the drift of the specimen in the sample stage: despite the fact that the stage is able to move in X and

Y directions plus some tilts, the drift should not exceed more than 5 Å (Ångström), or 0.5 nm, per minute. In this way longer exposures can take place.

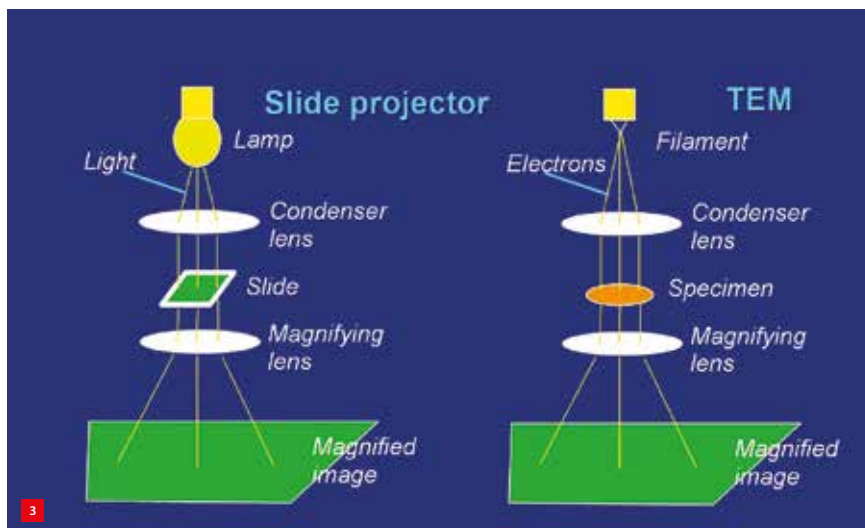
The total magnification of a Thermo Scientific Titan TEM is greater than one million times. While with an astronomic telescope such a magnification would make it possible to observe a tennis ball on the moon, a more realistic measure with which to characterise TEM performance is its resolution, i.e. the smallest distance between two image points that can be distinguished (see Figure 4). This amounts to the nearly unbelievable value of less than 0.05 nm, i.e. 0.5 Å or 50 pm (picometer).

### Cryo-EM

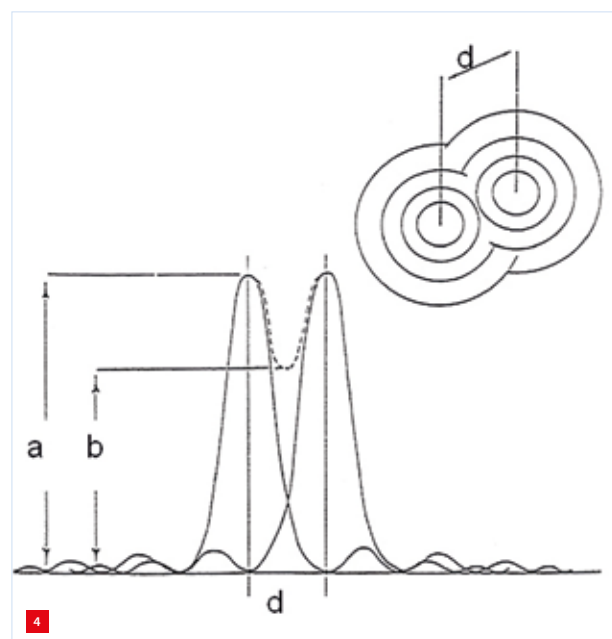
Raymond Schrijver, senior director Pharma, discussed an application in cryogenic electron microscopy where a sample has to be cooled instantly (vitrification) down to liquid- $N_2$  temperature. By examining proteins in the vitrified ice structure, a reconstruction can then be made of the biological sample using postprocessing. When an electron hits a protein, it leads to the destruction of the same protein. The boundary conditions here are that the sample inserted into a TEM needs to remain intensively cooled until the electron beam hits the sample. This Cryo-EM procedure enables the visualisation of protein molecules or virus structures, for example as has been done for the Zika-virus.

### Thermal challenges

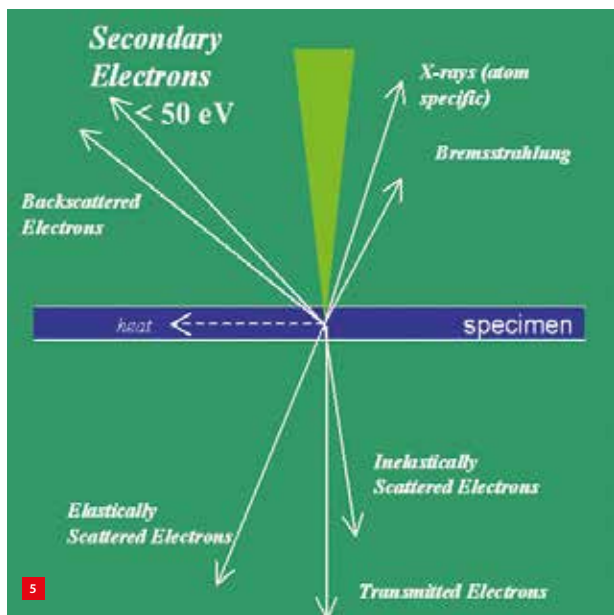
The specimen in the sample holder is surrounded by detectors that measure particle emission or radiation due to the various interactions of electrons with molecules at



Comparing the optical path of a TEM with a slide projector: electrons instead of light quanta.



Definition of optical resolution  $d$  in a TEM image, with intensity shown as a function of distance.



Interaction of electrons with molecules at the sample surface.

the sample surface (see Figure 5). The sample is only a few tenths of micrometers thick, making sample production a difficult discipline in itself.

Ronald Lamers, thermal dynamic design engineer, discussed unwanted effects due to temperature differences caused by, for example, the cooling of these detectors or the heating up of actuators. Temperature changes cause thermal deformation of the sample manipulation stage, leading to thermal drift that causes blurring of the image. Using a thermal network, the design of the specimen stage could be improved to reduce thermal drift to less than 5 Å, or 0.5 nm, per minute. FEM analyses are used to support the thermal network modelling approach.

### 10 pm sub-atomic vibration

Ab Visscher, senior machine dynamics expert, presented an impressive practical quest on a real system, to trace and solve a vibration of only 10 pm in the image. This is far sub-atomic: lattice spacing in gold crystals is 230 pm. By applying spatial Fourier analysis on the atomic patterns imaged, however, much smaller repetitive details within this gold lattice spacing are made visible, down to the required TEM resolution of 50 pm. Then such a 10 pm disturbance appears really problematic; in this case the system could not be delivered and the issue had to be analysed and solved under great time pressure.

The technique of energy-dispersive X-ray spectrometry (EDS) on an electron microscope makes it possible to do very local identification of materials, down to the individual atoms of one material embedded in the atomic structure of another material. The technique requires X-ray detectors closely oriented around the sample that must be cooled down to cryogenic temperatures. Liquid nitrogen close to the

microscope is used for this. The nitrogen is always boiling to some extent, energising small vibrations into the whole system. A new design for the EDS was introduced to this system and thus its (dynamic) construction, with the boiling nitrogen as the likely suspect for the vibration source.

Obviously, the image error is always a vector sum of a momentary beam-plus-sample position: a disturbance on either one will lead to image error. The system itself offers a powerful optical mode to exclusively measure the beam vector component, in the absence of the sample. Gains of several gigavolt per meter are achieved; that leaves just a few millivolt for the few picometers to be measured. So the vibration appeared to be on the beam, approximately 10 pm at 270 Hz, mainly in one direction.

The further system tests presented were impressive and involved a good interaction of many familiar analysis techniques, like FEM and lumped-mass model estimates, and test techniques like effective use of a mechanic shaker and practical modal analysis with a tiny accelerometer in the delicate heart of the system on the base that carries the X-ray detectors mentioned above. One (of six) supported body modes of this base could be related to the image disturbance. The coupling to the beam is explained by the principle of Eddy currents.

Several mechanical solutions were introduced, including a 'smart friction brake' concept. Comparing the ultra-high-resolution TEM images before and after having realised the several measures proved the disappearance of the initial loss of TEM resolution.

### To conclude

YPN stands for Young Precision Network and this meeting really featured each of the three terms. Young and ambitious the participants certainly were, demonstrating their eagerness to understand what Thermo Fisher speakers were teaching them by asking clever questions. Precision was the main theme of the meeting, as illustrated by the nearly unbelievable resolution value of 0.05 nm. And last but not least, the networking at the end of this highly successful Thermo Fisher visit was both informative and entertaining.

#### INFORMATION

[WWW.THERMOFISHER.COM](http://WWW.THERMOFISHER.COM)



# LEARNING TO WORK IN SYSTEMS-ENGINEERING-DRIVEN PROJECT TEAMS

The “Applied systems engineering” course presents various methods and approaches to analyse and structure design issues and to develop a clear overview. With this new course Mikrocentrum aims to help participants to adopt a proactive attitude within multidisciplinary project teams for the development, design and testing of complex machines and systems.

Design issues are becoming increasingly complex within the high-tech (manufacturing) industry. Multidisciplinary design teams, shorter lead times and major technological challenges are among the factors adding to this complexity. Not only the system architects, but certainly also the project participants, are increasingly being challenged to switch between the various abstraction levels, such as use cases, system requirements and system concepts. The project members often face challenges in the concrete translation into subsystem / module specifications, subconcepts and testability. For each team member, finding a good balance with his colleagues from the various disciplines is key in this respect.

This calls for systems engineering (Figure 1), defined as an interdisciplinary approach and means to enable the full life cycle of successful product, service and enterprise systems (source: Systems Engineering Body of Knowledge, [www.sebokwiki.org](http://www.sebokwiki.org)). Under the denominator “Structured approach to complex systems design in multidisciplinary

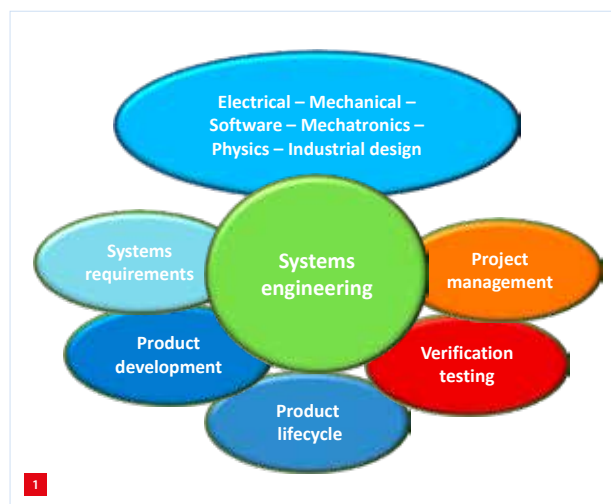
teams”, the new “Applied systems engineering” (ASE) course presents various methods and approaches to analyse and structure such design issues and to develop a clear overview.

With the ASE course Mikrocentrum aims to help participants to adopt a proactive attitude within multidisciplinary project teams for the development, design and testing of complex machines and systems.

Participants learn to assess the requirements and pre-conditions for feasibility, testability and manufacturability in such a project. The course aim is to be able to translate these aspects into balanced solutions at the concept, function, module and component level, taking manufacturing and testing into account. After having completed this course the participants are able to:

- define the set of requirements and test plans, in particular at module and component level, in such a way that cooperation between disciplines is strengthened;
- contribute to a more structured evolution of the design process;
- achieve better communication between team members in informal consultations, project discussions, presentations and documents, among other things by providing the relevant information or asking questions at the right time.

The course requires a higher vocational education (HBO, in Dutch) working and thinking level in one of the following technical disciplines: electrical engineering, mechanical engineering, mechatronics, technical software, industrial design, physics. The target group includes R&D professionals, engineers, designers and testers who work with systems engineers / system leads / system architects in multidisciplinary teams and want to operate more effectively and efficiently in a systems-engineering-driven environment.



Systems engineering calls for an interdisciplinary approach.

The course is practical and interactive in design, and covers:

- Knowledge: essence of product development processes; the different systems engineering methods; practical methodologies and models for product and system design; making a robust design of a product or system.
- Skills: translating functional requirements into a functional design, (sub)system or module; collaborating with other disciplines; translating characteristic product properties into a robustly designed product.
- Attitude: superseding domain confinements; developing a helicopter view of the design process.

The course takes five weeks, with one afternoon + evening session each week:

1. Systems and their complexity
2. Linear methodologies (such as waterfall model and V-model)
3. Iterative development methodologies (such as agile, scrum, cyclic or spiral design, and multiple-V-model)
4. Integration and testing
5. Presentation of group cases

Complex mechatronic systems to illustrate the various topics include industrial inkjet printers, 3D printers and semicon equipment such as lithography machines.

The course was developed for Mikrocentrum by:

- Jos Gunsing, innovator at MaromeTech, with extensive experience in system design in both industry, including NTS Systems Development, and education, as professor in robotics & mechatronics for Avans University of Applied Sciences from 2009 to 2017;
- Erik Puik, professor of microsystem technology / embedded systems at HU University of Applied Sciences Utrecht since 2006, with a background in both mechanical and electrical engineering and experience in system design at Océ and TNO;
- Rini Zwikker, professor of mechatronics at Saxion University of Applied Sciences from 2012 to 2017, with experience in (mechatronic) system design at DAF Trucks, Thales and Demcon.

Both Gunsing and Puik also act as teachers. The first edition of the course is scheduled for October and the course can also be delivered in-house.

#### INFORMATION

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[WWW.MIKROCENTRUM.NL](http://WWW.MIKROCENTRUM.NL)



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Dutch Society for Precision Engineering

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## PRECISION-IN-BUSINESS DAY: ONE NTS, MULTIPLE PERSPECTIVES

Last month, NTS in Eindhoven (NL) hosted a DSPE Precision-in-Business (PiB) day at its new campus in the making. NTS has grown into a first-tier systems supplier of opto-mechatronic systems and mechanical modules for large, high-tech machine manufacturers (OEMs), currently employing over 1,700 staff worldwide. Under the motto of 'One NTS', the company works on further integrating its competences of Development & Engineering (D&E), Component Manufacturing and System Assembly in order to accelerate the time to market for its customers.

### Family-owned company

For an audience of some thirty participants, Rob Karsmakers, COO of NTS since last year, kicked off with a few personal reflections on his career at Philips. His last job, as the plant manager of Philips Consumer Lifestyle in Drachten (NL), was to modernise shaver head production, resulting among other things in a 40% cost price reduction. It turned into a textbook example of making the manufacturing industry in the Netherlands healthy again, embodied in the Smart Industry movement, of which Philips Drachten has become one the figureheads.

That job being done, Karsmakers decided to pursue his career elsewhere and opted for NTS, because of its character as a family-owned company striving for customer satisfaction, employee satisfaction and profitability. Nowadays, NTS is a vertically integrated company taking care of development and engineering, production, assembly and supply chain operations.

### QLTC

Adding to the customer focus perspective, Hans Scholtz, managing director D&E, talked about NTS adding



*NTS is a first-tier systems supplier of opto-mechatronic systems and mechanical modules.*

customer value by combining D&E competences and industrial operations. He expressed customer value in terms of QLTC (Quality, Logistics, Technology, Cost), the well-known 'formula' developed by large OEMs like ASML. At NTS, Quality refers to qualified production processes as well as product design qualification. In the high-tech market, for Logistics capacity and flexibility go hand in hand, with a focus on short lead times. The 'T' not only stands for advanced Technology, but also covers efficient operations and an integrated supplier network. Naturally, the value of Cost lies in competitive pricing, but in modern OEM-system supplier partnerships coping with market dynamics can best be done by sharing risks and rewards.

Crucial for best QLTC results in the NTS philosophy is early supplier involvement, preferably already in the system architecting phase, when conceptual choices determine the future product cost structure. Adding to the equation, design for manufacturing and value engineering can help to optimise quality and logistics performance and of course reduce cost price. Scholtz: "We know more about the manufacturing side of engineering than our customers." By merging customer roadmaps and technology trends NTS can drive technology roadmaps, in order to help customers stay ahead of the competition.

Highlights from projects presented by Scholtz include realising a quick start-up of production while stabilising and improving product quality in parallel, and managing a single project team, including customer participation, from the requirements definition to the site-acceptance-test phases.



*Visual of the NTS Campus under construction. In the upper left corner, the new NTS Precision premises, where the Precision-in-Business Day was held.*





Impression of the PiB Day presentations in the new NTS Precision premises, which are currently under construction at the NTS Campus in Eindhoven.

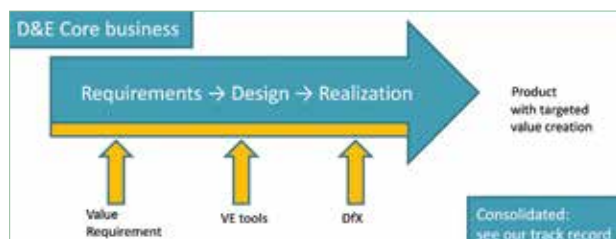
### System architect

Rens van den Braber, system architect at NTS, talked about his role as an intermediary between two roadmaps. He illustrated this with an NTS project for a fabless semicon customer requiring a new wafer processing solution (including handling and metrology) under uncertain market conditions. NTS proposed a system architecture that satisfied both the customer's and NTS's roadmap. Here, the customer required a system that can easily be configured to meet end-customer demands and adapted to market trends. In response, NTS followed its roadmap for the production of systems with standardised common modules that can be independently optimised for cost, quality and lead time.

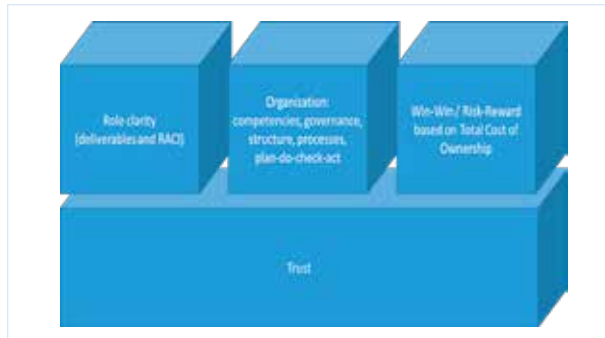
### Value engineering

Ivan van der Kroon, system engineer at NTS, talked about value engineering and DfX (Design for X, where X can be manufacturability, assembly, cost, value, etc.) by NTS. For cost-effective manufacturing during a product's lifecycle, OEMs demand Value Engineering (VE), because of shortening product lifecycles, continuous cost price pressure and their focus on innovation and R&D. NTS can satisfy this need based on its high-tech manufacturing and assembly know-how, its expertise of value chain optimisation and the availability of a structured VE tool and approach.

VE can be a complex exercise, as it requires multiple disciplines and an integral approach, covering everything



Value Engineering at NTS.



Partnership management is one of NTS's core competences.

from requirements decomposition, idea generation and assessment of alternative designs, materials, production methods or suppliers, down to costing, redesign and prototyping. And it is not just about cost, Van der Kroon stated, illustrating his point with a project in which the 50% lead time reduction was valued by the customer more than the 70% direct cost reduction.

### Printing & partnership management

The final presentation was by Wim Steenbergen, business manager Digital Printing at NTS and author of "Outsourcing Developing and Life-Cycle Management". This book describes the way of working in the Brainport high-tech ecosystem, of which NTS is a prominent member, where innovation is fuelled by technology and collaboration. Steenbergen talked about inkjet printing & partnership management at NTS. Building on 25+ years of printing experience, NTS has evolved into an integrator of inkjet printing solutions, covering the actual printing process, handling, motion, curing, maintenance, etc.

In the B2B industry, digital/inkjet printing has only recently made its entry, with the number of printing applications (graphical, 3D, functional, etc.) steadily growing. New OEMs that make their appearance lack the required printing knowledge, so they can engage in a strategic partnership with NTS. Steenbergen discussed the governance model and the management issues (such as organisation, role clarity and risk-reward sharing) for such a partnership. In the end, however, trust is the main success factor.

### To conclude

The PiB Day was concluded with a tour of the NTS Campus, which currently houses 550 NTS employees, and a social get-together for networking and talking things over. DSPE expresses its gratitude to NTS for its hospitality and the inspiring presentations.

[WWW.NTS-GROUP.NL](http://WWW.NTS-GROUP.NL)



# THE THERMAL CHALLENGES OF BIG SCIENCE

In mid-May the 'Thermal Challenges' theme meeting was held at the Mikrocentrum office in Veldhoven (NL). It was the first in a series of meetings that the ILO-net and Mikrocentrum want to organise two to three times a year under the name 'Big Science'. ILO-net and Mikrocentrum have been jointly hosting a Big Science session during the annual Precision Fair since 2012. The Dutch ILO-net – which is the network of ILOs (industrial liaison officers within scientific institutes) and part of the Netherlands Organisation for Scientific Research (NWO) – is striving to reinforce the connection between the business community and Big Science.

The aim of the initiative is to get Big Science higher on the agenda of the Dutch high-tech industry and to improve Dutch technical-scientific / industrial participation in international Big Science programmes such as CERN, ITER, ESA, ESO and ESRF (Figure 1). The meetings can help to identify promising technologies and support the positioning of these Dutch strengths towards Big Science organisations (think of presentations and ultimately tenders). Technology development for demanding Big Science applications can lead not only to contracts but also result in spin-offs for other scientific and industrial applications.

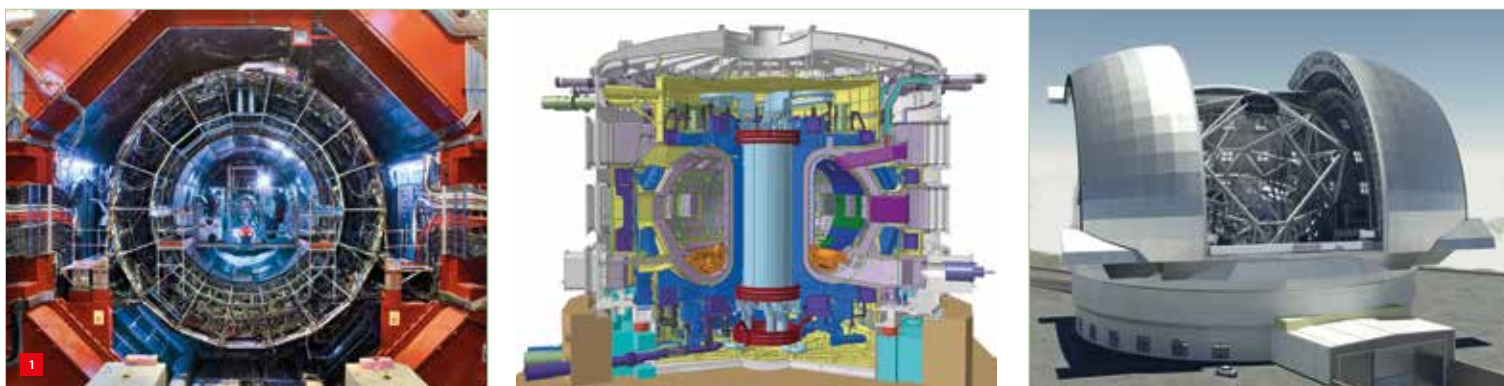
The Netherlands currently contributes around 150 million euros each year for the construction of large-scale infrastructure through its membership of various Big Science organisations. The aim is to 'earn back' at least 70% of that amount in the form of assignments awarded to Dutch industry.

The first meeting attracted some sixty participants from industry, academia and government. Covering the theme of 'Thermal Challenges', joint presentations each focused on the scientific as well as industrial aspects of a specific technology. This concerned vibration isolation of the X-ray instrument X-IFU for the European space telescope Athena (presentation by SRON and Mecon); vibration-free cooling of optical instruments for the Extremely Large Telescope and the future Einstein Telescope for observation of gravitational waves (Nikhef and University of Twente); cooling of electronics for the Square Kilometre Array, the world's largest radio telescope, designed for operation in South Africa and Australia (Astron and Thales Cryogenics); and thermal control of charged particle equipment (TU Eindhoven and VDL ETG).

In addition, two technologies were presented that can be utilised for various Big Science programmes and industrial applications: superconductivity (University of Twente) and data-driven modelling (TU Eindhoven, Nikhef and DIFFER, the Dutch Institute for Fundamental Energy Research). The conclusion of the meeting was that topics such as temperature control and cooling offer many challenges and opportunities for contributing to the development of large-scale scientific infrastructure and instrumentation.

The second meeting is scheduled for 18 September and will be devoted to another key technology for Big Science.

[WWW.BIGSCIENCE.NL](http://WWW.BIGSCIENCE.NL)



Big Science facilities that offer great opportunities for Dutch industrial contributions include, from left to right, CERN (particle accelerator), ITER (nuclear fusion reactor) and ELT (Extremely Large Telescope). (Sources, from left to right: CERN, ITER, ESO)

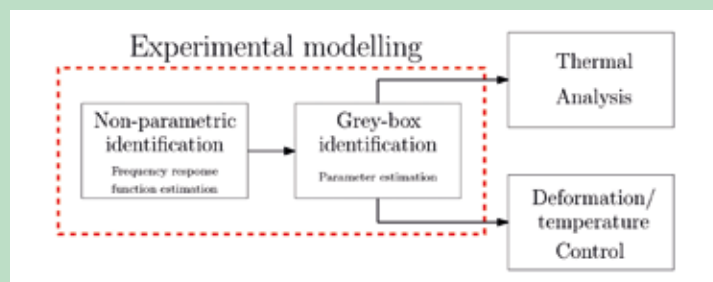
## High-Tech Systems 2019

The High-Tech Systems event in April, organised by Techwatch in Eindhoven (NL), addressed thermal challenges in high-tech systems engineering. The advanced thermal design track featured a total of six presentations. Three of them were by authors who had contributed to the Mikroniek April issue, which was concerned with thermal control. These three presentations were:

- Thermal qualification of precision motion systems, by Maurice Limpens (MI-Partners).
- Model-based thermal analysis of a glass-tube-oven, by Rob van Gils (Philips Innovation Services).
- Controlling thermal dynamics in precision motion systems, by Enzo Evers (TU Eindhoven); see Figure 2.

Siep Weiland (TU Eindhoven) talked about controlling complexity and Evert Westerhuis (ASML) proposed a change in the view on thermal design to meet future systems' requirements. Thermal challenges in lithography are increasing as the requirements for resolution and throughput become ever tighter and increasing EUV source power generates larger thermal loads on the optics system and the wafers. In the latest EUV systems, microkelvins of temperature change can already significantly impact imaging and throughput. Westerhuis discussed the design guidelines for tackling thermal issues. Eventually, closed-loop topology optimisation – considering the complete thermal system – will be required for thermal

control. The control engineer should be involved early on in the mechatronic design process, in order to achieve 'design for control'. Rolf Evenblij (Technobis) discussed temperature control at chip level in integrated photonic sensing instruments. For example, fibre alignment in these systems has to have submicron precision, but a temperature change of 20 K can already cause a shift of over 1 micron. He focused on the use of Peltier elements to stabilise the temperature of a mount in the system. However, this proved to have insufficient effect. Another option considered was the use of an alternative material for the wire bonds, to prevent heat transfer. A mechanical design modification resulted in a 99% decrease of the temperature change and a 55% decrease of the required Peltier power.



Enzo Evers' approach of thermal control.

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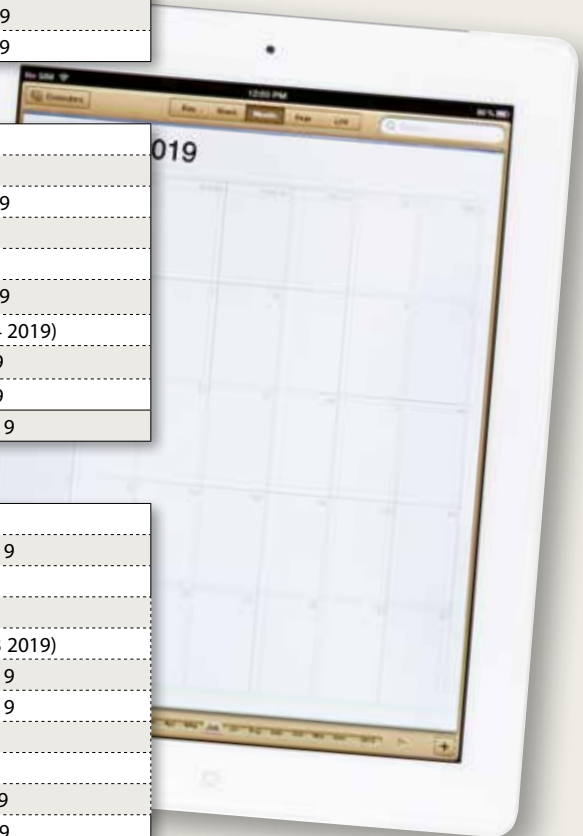
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# ECP<sup>2</sup> COURSE CALENDAR



COURSE (content partner)	ECP <sup>2</sup> points	Provider	Starting date
<b>FOUNDATION</b>			
Mechatronics System Design - part 1 (MA)	5	HTI	to be planned (Q2 2020)
Mechatronics System Design - part 2 (MA)	5	HTI	4 November 2019
Fundamentals of Metrology	4	NPL	to be planned
Design Principles	3	MC	25 September 2019
System Architecting (S&SA)	5	HTI	30 September 2019
Design Principles for Precision Engineering (MA)	5	HTI	25 November 2019
Motion Control Tuning (MA)	6	HTI	27 November 2019
<b>ADVANCED</b>			
Metrology and Calibration of Mechatronic Systems (MA)	3	HTI	29 October 2019
Surface Metrology; Instrumentation and Characterisation	3	HUD	to be planned
Actuation and Power Electronics (MA)	3	HTI	19 November 2019
Thermal Effects in Mechatronic Systems (MA)	3	HTI	3 December 2019
Summer school Opto-Mechatronics (DSPE/MA)	5	HTI	upon request
Dynamics and Modelling (MA)	3	HTI	25 November 2019
Manufacturability	5	LiS	to be planned (Q4 2019)
Green Belt Design for Six Sigma	4	HI	2 September 2019
RF1 Life Data Analysis and Reliability Testing	3	HI	9 September 2019
Ultra-Precision Manufacturing and Metrology	5	CRANF	16 September 2019
<b>SPECIFIC</b>			
Applied Optics (T2Prof)	6.5	HTI	29 October 2019
Advanced Optics	6.5	MC	19 September 2019
Machine Vision for Mechatronic Systems (MA)	2	HTI	2 July 2019
Electronics for Non-Electronic Engineers – Analog (T2Prof)	6	HTI	to be planned
Electronics for Non-Electronic Engineers – Digital (T2Prof)	4	HTI	to be planned (Q3 2019)
Modern Optics for Optical Designers (T2Prof) - part 1	7.5	HTI	20 September 2019
Modern Optics for Optical Designers (T2Prof) - part 2	7.5	HTI	13 September 2019
Tribology	4	MC	29 October 2019
Basics & Design Principles for Ultra-Clean Vacuum (MA)	4	HTI	4 November 2019
Experimental Techniques in Mechatronics (MA)	3	HTI	10 December 2019
Advanced Motion Control (MA)	5	HTI	18 November 2019
Advanced Feedforward Control (MA)	2	HTI	9 October 2019
Advanced Mechatronic System Design (MA)	6	HTI	to be planned (Q3 2019)
Passive Damping for High Tech Systems (MA)	2.5	HTI	19 November 2019
Finite Element Method	5	ENG	in-company
Design for Manufacturing – Design Decision Method	3	SCHOUT	in-company



## ECP<sup>2</sup> program powered by euspen

The European Certified Precision Engineering Course Program (ECP<sup>2</sup>) 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 ECP<sup>2</sup> certificate is an industrial standard for professional recognition and acknowledgement of precision engineering-related knowledge and skills, and allows the use of the ECP<sup>2</sup> title.

[WWW.ECP2.EU](http://WWW.ECP2.EU)

## Course providers

- Engenia (ENG)  
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- High Tech Institute (HTI)  
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- Mikrocentrum (MC)  
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- Technical Training for Prof. (T2Prof)  
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- Systems & Software Academy (S&SA)



## New chair of Robotisation & Sensoring at Avans

April 2019 saw the start of the chair of Robotisation & Sensoring within the Centre of Applied Research Technical Innovation at Avans University of Applied Sciences in Breda (NL). The chair is headed by professor Daniël Telgen, who studied electrical engineering at HTS Haarlem and then worked as a software engineer in the space industry. He obtained a master's degree Intelligent Systems in Sweden and then worked as a consultant with Alten, in fields such as embedded systems and computer vision. He left for HU University of Applied Sciences Utrecht, where he became an 'industrial resident' and later joined the chair of Microsystem technology & Embedded systems.

During this time, Telgen obtained his Ph.D. at the Utrecht University in the field of Industry 4.0, specifically reconfigurable manufacturing systems. His research focused on flexible factories that offered 'manufacturing as a service'. These manufacturing systems, called equilets, would offer autonomous generalised services to products that would also exist as 'self-aware virtual entities'. The product would be compiled by the future owner on a website, after which a 'product agent' would be created that would discuss with the factory how and when it would be produced.

At HU, Telgen subsequently worked as a teacher, researcher, curriculum coordinator, project leader and manager of various studies; Computer Engineering, Business IT & Management and Applied Artificial Intelligence (developed by Telgen himself). Now, as a professor, he has defined it as his mission to make technology contribute to a sustainable future and bring together education, research and industry in order to pursue this. This matches the mission of Avans, which strives for the 'Resilient City', the smart, liveable, sustainable and resilient city. Telgen's chair will focus on robotisation and the Internet of Things. One of the first projects will be to start Breda Robotics, an initiative to promote new robotics applications in the Breda region. Parties that are interested in collaborating with the chair are invited to contact Telgen.



Daniël Telgen.

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[WWW.BREDA-ROBOTICS.NL](http://WWW.BREDA-ROBOTICS.NL)



# HIGH TECH INSTITUTE



*Interesting natural phenomena are also discussed during the course. 'Why do we see a rainbow, why are there sometimes two and why are the colours of these two arches inverted?'*

### OPTICS

## Applied optics (AP-OPT)

Professionals who do not design (specify, test) optical systems but who are cooperating with optical designers in optical projects can increase the effectiveness of their cooperation if they know more about optical principles and applications.

This substantially adapted course focuses on the optical phenomena, principles and applications through many demonstrations and experiments and a tour. The course is developed for people with a non-optical background (e.g. electronics, mechanics, chemistry). A technical BSc or MSc is required.

Start date: 29 October 2019 (15 afternoon sessions)

Location: Eindhoven

Investment: € 2,650.00 excl. VAT

[hightechinstitute.nl/AP-OPT](http://hightechinstitute.nl/AP-OPT)



## A guide to smart manufacturing

At the end of May, Hans Krikhaar, owner of Hurli and president of DSPE, delivered his inaugural address as a professor (lecturer) of Smart Manufacturing & Integrated Systems Engineering at the Fontys University of Applied Sciences in Eindhoven (NL) and Venlo (NL). Within the department of Engineering in Eindhoven and the department of Technology and Logistics in Venlo, he will guide research into mechanical engineering, electronics, mechatronics and automotive with links to logistics, ICT, industrial design, medical technology and business.

The inaugural address was the closure of ASQ Fontys, the annual high-tech event for companies interested in collaborating with Fontys in application-oriented research on innovative technologies in the area of High Tech Systems and Materials (HTSM). Participants were able to visit three Fontys labs, devoted to 3D-printing, Mechatronics and Robotics, and Applied Natural Sciences, respectively, or attend one of the 15 HTSM knowledge sessions. At the Technology Expo, Fontys students and researchers presented their research results.

'Support acts' for Hans Krikhaar's performance were provided by Maarten Steinbuch and Egbert-Jan Sol. Steinbuch, university professor at the Eindhoven University of Technology (TU/e), stressed the importance of research at universities of applied sciences, as it meets the needs of SMEs far better than academic research and provides inspiration to students and teachers alike. He attributed Fontys an important role in the new Eindhoven Engine initiative. Located on the TU/e campus, the Eindhoven Engine aims to accelerate innovation in the Brainport (greater Eindhoven) region through challenge-based research, by students and teams of talented researchers from industry and knowledge institutes.

Until now, research has been conducted linearly, but technological developments are progressing exponentially, so research has to be organised in a different way, according to Steinbuch. Therefore, the Eindhoven Engine strives to organise multidisciplinary, multi-stakeholder research in 'student teams for adults' and build research consortia with SMEs. He reiterated on the title of Krikhaar's professorship and stated that all five words (smart, manufacturing, integrated systems, engineering) are



Cover of the inaugural address booklet, "A Guide to Smart Manufacturing".  
Hans Krikhaar: "If you want to start an industrial revolution, you need a booklet."

important. He also acknowledged the role of DSPE, presided by Krikhaar since 1998, as it celebrates precision engineering, building on Wim van der Hoek's legacy (see the article on page 5 ff.), as a cornerstone of the Dutch high-tech industry.

Sol, CTO at TNO Industry and programme director Smart Industry, promoted lifelong learning in the age of smart industry and digital (r)evolution. "Everyone aged 35+ who has attended secondary vocational training did not acquire any digital skills at school. As there is an increasing shortage of ICT professionals, everyone should master ICT skills."

In his inaugural address, Hans Krikhaar presented his vision on how to embed research in education, how to help industry innovate and how to shape the ambitions of Fontys as a hub for smart manufacturing. In Krikhaar's view, smart manufacturing is about innovating production processes, by using the latest technologies and applying smart production methods, resources and methods. Innovation should preferably be organised in an agile manner: simple, step-by-step, maximum stakeholder involvement, minimum effort, minimum designs,



Impressions of the ASQ Fontys event. (Photos: Odette Beekmans)



minimum bureaucracy. It requires flexibility, brainstorming and outside-of-the-box thinking, as well as continuous improvement through lean/six sigma approaches. Smart manufacturing will rely on disruptive technologies like artificial intelligence, big data, augmented reality, drones, 3D printing and 5G communication, but also on education.

Krikhaar presented his view on continuous learning in the Fontys curriculum, in which research is embedded via projects, internships and graduation theses. "We want to align the curriculum in such a way that students can develop a train of competences and students from different years can team up in projects to create ongoing research lines." Krikhaar's ultimate ambition at Fontys is to enhance the innovation competences of students, teachers and the university itself, in collaboration with industry and institutes like TU/e, Brainport Industries Campus and the Eindhoven Engine.



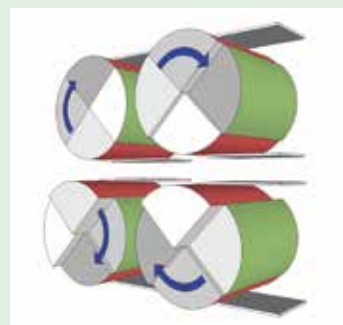
Hans Krikhaar delivering his inaugural address: "We want to align the curriculum in such a way that students can develop a train of competences, upon which they can draw in following semesters." The Fontys curriculum is divided in eight semesters, from S1 to S8. For example, the project experience from S4 and the minor specialisation from S6 can be combined in the graduation project in S8.

[WWW.FONTYS.NL](http://WWW.FONTYS.NL)

## Sioux CCM celebrates 50th anniversary

Last month, Sioux CCM celebrated its 50th anniversary. In 1969, Professor Horowitz started CCM Centre for Concepts in Mechatronics from the basement of the Eindhoven University of Technology together with three friends. Later, CCM moved to Nuenen (NL) and in 2014 it was taken over by Sioux (over 700 engineers, headquarters in Eindhoven, NL), a group of companies supporting or acting as the R&D department of leading high-tech OEMs.

Now, Sioux CCM has grown into the Sioux mechatronics competence centre, employing over 125 engineers, serving many renowned, international customers, including ASML, Philips, Thermo Fisher Scientific and Kulicke & Soffa. Sioux CCM develops and creates innovative mechatronic solutions, from conceptual design to the production of test sets, single-use machines and serial products. CCM



In the 2013 no. 3 issue of Mikroniek, CCM presented the design & realisation of a generic substrate carrier (left) using axially movable segments (right).

expertise includes precision movement and positioning, miniaturisation, vacuum technology, optical monitoring and embedded design.

## Change of management at the Leiden Instrument Makers School

Last month, Dick Harms retired as director of the Leiden Instrument Makers School (LiS). The LiS is one of the oldest vocational educational institutions in the Netherlands and over the years has retained its independent status, of which Harms has been a strong advocate. The school was founded in 1901 by the Leiden professor and Nobel Prize-winner Heike Kamerlingh Onnes, because he needed professionals who could develop and make tools for physics research.

During Harms' directorship the LiS expanded and modernised its facilities so it could double in size to a maximum capacity of 400 students, in order to meet the growing demand from industry for

good instrument makers, while retaining the quality inherent in small-scale education. As his successor, Godelieve Bun has taken over the director's position. She studied mechanical engineering at Delft University of Technology and worked in the food industry and in various educational positions, among others as a team leader in the precision engineering department of HU University of Applied Sciences Utrecht.

A forthcoming issue of Mikroniek will include more on past and future developments at the LiS.

[WWW.LIS.NL](http://WWW.LIS.NL)



The retiring and incoming director of the LiS, Dick Harms and Godelieve Bun, respectively.

## Intelligent robots in e-commerce

With an eye to the constantly growing sector of online retail, logistics and material flow are coveted playing fields for technical progress – with the goal of increasing efficiency through automation and digitalisation. Magazino, the still-young company from Munich, Germany, has set out to intelligently combine autonomous driving and robotics with one another, aiming to create the world's first self-thinking and self-acting warehouse.

Magazino's new logistics robot TORU is currently proving itself in practical tests with major shipping service providers. These use the intelligent, self-driving system above all for retrieving shoeboxes during order picking. Conceptionally, TORU is a so-called perception-controlled robot. Through the use of cameras, image processing, sensors and artificial intelligence, it is able to perceive and correctly interpret its environment and use this as a basis to make decisions.

When TORU arrives at an order picking location, the lifting column at the front of the vehicle rotates 90° towards the shelf, a gripper moves to the specified bin and TORU begins to make decisions. Using 3D camera images, the robot first produces a picture of the current situation. "Is there even a shoebox on the shelf? Is the right bar code present? Am I able to grip the carton: perhaps it was moved to the side and would jam when pulled out?" In this latter case, the robot attempts to adapt its gripper process to the circumstances. If TORU ascertains that gripping is still not possible, the job is returned to the system.

If no problems are detected, drives from Faulhaber are responsible for handling the shoeboxes. Here, integrated motion controllers, DC-micromotors of type 3242 with graphite commutation, planetary

gearheads and threaded lead screws form a linear drive system that extends and retracts a metal tongue. The task in this case is to close the gap between the vehicle and the bottom of the shelf. The path is thereby levelled, allowing the cartons to be pulled out on the flat surface with negative pressure.

For the positioning of the suction gripper along a toothed rack, Magazino uses type 3268 drives from Faulhaber. With a power of 62 watts, the brushless DC motors deliver rated torques of up to 72 mNm in continuous operation. Interesting for Magazino are the peak torques of up to 96 mNm. The overload capability is decisive for overcoming the breakaway torques when handling the shoeboxes and provides the basis for being able to use smaller motors – with a diameter of just 32 mm – and hence to reduce weight.

The idea behind TORU lies in the implementation of a sophisticated system of automation, robotics, vision and autonomous driving. When evaluating the drives, Magazino was therefore in search of solutions with optimum power density. With the DC-micromotors, the Faulhaber motion controllers form highly dynamic positioning systems. For feedback control, Magazino uses analog Hall sensors, thereby eliminating the need for a separate encoder for feedback. The integrated current control of the motion controllers limits the torque and thereby protects the electronics and motor from overload. Magazino, in turn, uses this function to detect faults in material flow.

[WWW.FAULHABER.COM](http://WWW.FAULHABER.COM)  
[WWW.MAGAZINO.EU](http://WWW.MAGAZINO.EU)





## Digital piezo controller for industry

For industrial applications of high-precision, piezo-based positioning systems, PI (Physik Instrumente) has introduced the E-727 piezo controller in a new variant. Now, the digital controller can be operated via EtherCAT by all industrial motion controllers from ACS Motion Control (in which PI holds a majority share). It can therefore be integrated into the automation environment as 'intelligent driver' for two- or three-axis piezo-based nanopositioning systems, irrespective of whether they work with capacitive, piezoresistive or strain gauge sensors.

A P-I controller with two notch filters optimised for piezo operation allows a high control bandwidth (20 kHz). Intelligent servo algorithms minimise the settling times, which allows repeatability into the subnanometer range. Further highlights of the digital controller include 4th-order polynomial linearisation for the mechanics and electronics, an integrated data recorder and subordinate, programmable drift compensation. In addition, there is the option of dynamic digital linearisation. This DDL function lowers phase shift and trajectory errors



to an indiscernible level in the case of dynamic-periodic applications. This is important for scanning applications that have to identify a particular position and reach it again accurately.

[WWW.PHYSIKINSTRUMENTE.COM](http://WWW.PHYSIKINSTRUMENTE.COM)

## New online calculation tool for vibration damping

ACE Stoßdämpfer, a shock absorber and vibration solutions manufacturer from Langenfeld, Germany, takes the next step to further digitalisation: engineers can now calculate and order custom damping solutions 24/7 online. With this new and intuitive calculation tool, ACE offers optimal visualisation of a wide range of applications. Users can calculate more than two-thirds of the most common cases themselves. This tool expands ACE's range of online calculation programmes in the fields of damping technology, speed regulation, vibration damping and safety products.

After inputting a few key data, the programme immediately calculates the machine's centre of gravity and, accordingly, the individual load per

machine base, showing all possible solutions. Robust machine bases, cone mounts for vehicle cabs, or vibration isolation cup mounts: within seconds, the innovative tool determines the most suitable ACE vibration damper. The fully graphical user interface which shows the vibration dampers in place under the machine is an industry first. ACE's free VibroChecker app can be used together with the new programme as an interface for determining the interference frequency, as well as a filter to determine whether only shear-resistant or standard products should be calculated.

[WWW.ACE-ACE.COM](http://WWW.ACE-ACE.COM)



Overview of ACE's vibration isolation products.



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## Cleanrooms

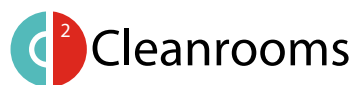


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SEGULA Technologies Nederland BV develops advanced intelligent systems for the High Tech and Automotive industry. As a project organisation, we apply our (engineering) knowledge to non-linear systems. This knowledge is comprised of systems architecture and modelling, analysis, mechanics, mechatronics, electronics, software, system integration, calibration and validation.

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## 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.

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maxon motor is a developer and manufacturer of brushed and brushless DC motors as well as gearheads, encoders, controllers, and entire precision drive systems. maxon motor is a knowledge partner in development. 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. Worldwide, maxon has more than 2,500 employees divided over sales companies in more than 40 countries and eight production locations: Switzerland, Germany, Hungary, South Korea, France, United States, China and The Netherlands.

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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.



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## Publication dates 2019

nr.:	deadline:	publication:	theme (with reservation):
4.	02-08-2019	06-09-2019	Manufacturability
5.	20-09-2019	25-10-2019	Precision sensors (incl. preview Precision Fair 2019)
6.	08-11-2019	13-12-2019	Energy technology (micro & macro)

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