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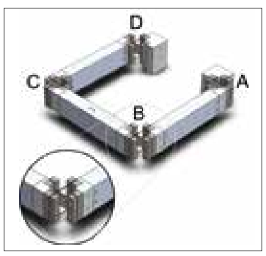

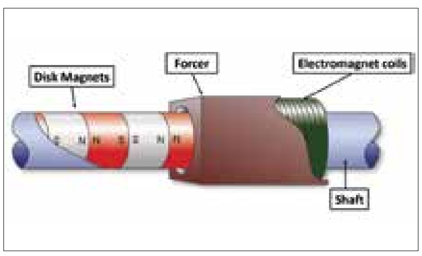

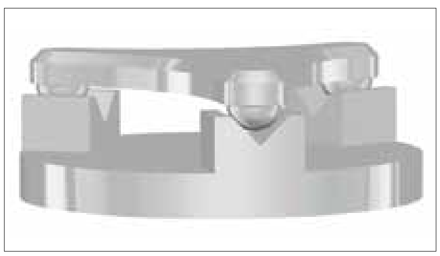

- KINETIC ART
- PRECISION IN DEEP BRAIN STIMULATION
- HIGH-TECH SYSTEMS 2019 PREVIEW
- MISALIGNMENT AND SELF-ALIGNMENT

DSPE

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The main cover photo (featuring beach animal 'Umerus silent beach') is courtesy of Theo Jansen (photo: Loek van der Klis). Read the article on page 12 ff.

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ROLE OF DEVELOPMENT & ENGINEERING IN THE MANUFACTURING INDUSTRY

After having worked in R&D at OEMs (Philips, FEI) for the biggest part of my working life and now since one year as MD for the Development & Engineering (D&E) Division of NTS-Group, I am starting to get a feel for the role that D&E should play in the manufacturing industry.

First things first, the goal should always be to delight and (positively) surprise the customer. D&E is a major contributor in reaching this goal and they need to play many roles. To start with the first one: ownership of the technology roadmap. To delight customers the technology roadmap should not only be driven by the customer's roadmap but also by the technology trends that we see in the world. This translates to proactively investing in technology and people development, which is a daunting task as questions need to be answered such as: what technologies to invest in and how to differentiate from others in the same industry?

On the customer roadmap: whatever we propose to a customer needs to be aligned with his needs. Customer intimacy (preferably going as far as the customer of the customer) is therefore key. D&E can play an important role here when properly linked to the customer's D&E department: they speak the same language and an early insight in customer's D&E activities will help to forecast what the relevant future technologies are and how they affect near-future direction in efficient modular machine development to enable phasing-in of these technologies.

The other role that D&E owns is joining forces with manufacturing to ensure that customer requests are properly addressed. For starters, D&E should be involved in assessing the initial customer request. In case the design is customer-owned, D&E should assess whether the design has been optimised for manufacturing (including the maturity of the design) and, if not, proactively propose alternatives to avoid future supply issues. Involvement of D&E in the requirements and design phase of the customer project is even better as we can insert the manufacturing knowledge upfront preventing additional costs in the later phases of the project. The additional advantage is that future maintenance and factory support is much easier due to the technical knowledge build-up in D&E in the design phase. The earlier a supplier is involved in the customer design process the better, for all parties.

Next to the initial involvement, D&E should also support the factories in the more mature phases of manufacturing. Manufacturing of high-tech equipment is never easy, there will always be issues where D&E can and should support: technical issues need to be fixed, new technical insights could lead to new opportunities for existing products, such as cost/performance improvement, but also proposals for a next-generation product. This will only work when there is a close cooperation between D&E and manufacturing, with no organisational, financial, physical and emotional barriers. To the latter point: we should strive to exchange D&E and manufacturing personnel whenever possible.

D&E plays an essential role in the manufacturing industry, but not in isolation: an intimate relation with manufacturing is essential to drive customer delight.

Hans Scholtz
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DETERMINING CRITICAL MISALIGNMENTS

Overconstrained compliant mechanisms are often avoided in precision machines since they are sensitive to misalignments, which deteriorate their behaviour, reflected for example by a lowered support stiffness or buckling. However, below a certain degree of misalignment the performance is unaffected. Obtaining this critical misalignment by simulations or experiments is often time-consuming and complicated. A more convenient method has been developed. It was applied to a three times overconstrained compliant four-bar mechanism and validated with simulations and an experiment.

WERNER VAN DE SANDE, RONALD AARTS AND DANNIS BROUWER

Introduction

Compliant mechanisms have attributes that make them useful in precision machines. Lack of play, backlash and friction, and low hysteresis make their behaviour predictable. Overconstrained designs jeopardise the predictable nature of compliant mechanisms. An overconstrained design constrains undesired motion in a particular direction more than once. As such, these mechanisms are sensitive to misalignments arising due to assembly, fabrication tolerances or heat sources, causing internal stress which will lead to undesired behaviour, such as buckling or lowered support stiffness. This is worrisome since in compliant mechanisms the difference between a degree of freedom and a constraint is a difference in stiffness by a couple of orders of magnitude.

Therefore, exactly constrained design is often applied to ensure the mechanism has the exact amount of constraints so none of these negative side-effects emerge. However, exactly constrained designs often suffer from, for example, a limited load carrying capability, limited support stiffness and complex design.

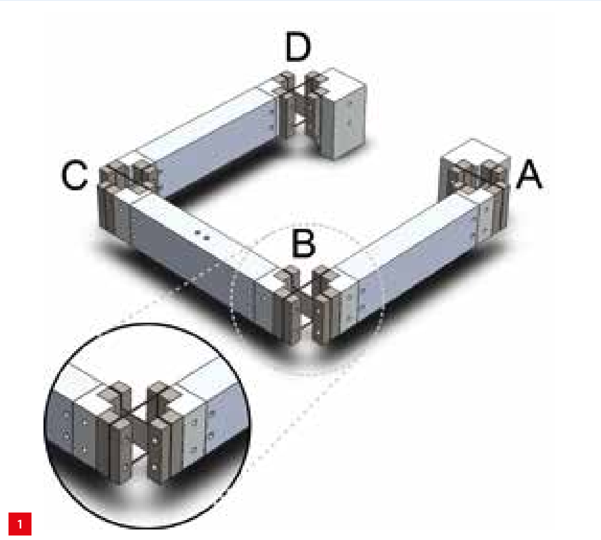
The effects of misalignments on a once overconstrained parallel leaf spring guidance have been investigated and this showed that a small misalignment in the overconstrained direction caused changes in the mechanism behaviour [1-2]. However, below this misalignment level the overconstraint has a negligible effect. This knowledge can be applied to make use of the benefits of overconstrained design while avoiding the drawbacks and create mechanisms with improved performance.

There can be more than one overconstraint in a mechanism. In each overconstrained direction there will be a certain amount of misalignment above which the behaviour of the mechanism is no longer acceptable. Modelling the entire mechanism and running simulations to analyse the behaviour is time-consuming.

A method has been developed to quickly identify the critical misalignments of a multiple overconstrained four-bar mechanism. Buckling of a flexure is taken as the point where the mechanism loses support stiffness and no longer performs as desired. This method compares the buckling loads of the flexures with the loads in the mechanism induced by the misalignments. This comparison yields a value of the critical misalignment in an overconstrained direction.

System topology, kinematics and constraints

Here, the effects of misalignments on an overconstrained compliant four-bar mechanism are investigated (Figure 1).



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Overconstrained four-bar mechanism with exactly constrained cross-pivot flexures as hinges.

AUTHORS' NOTE

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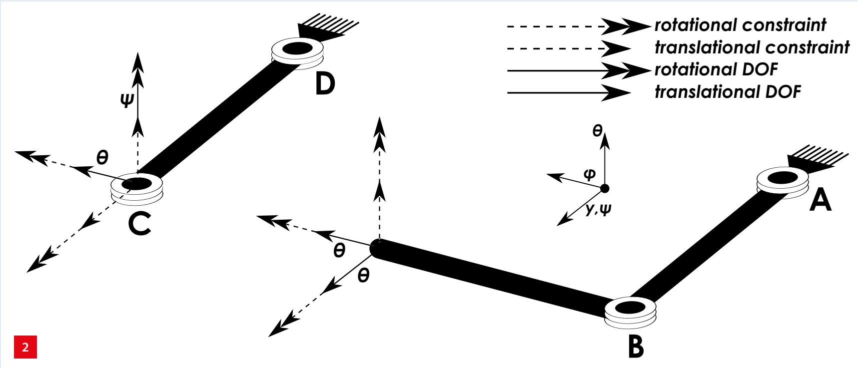


The freedom and constraints of a four-bar mechanism illustrated by opening the loop at hinge C.

The mechanism consists of three rigid bars connected by four compliant hinges to each other and the fixed world at hinge A and D. These four hinges are equal in dimension and topology, but different in orientation.
The hinges consist of a leaf spring and two parallel wire flexures that are placed perpendicular to the leaf spring. This creates an exactly constrained hinge. The four-bar mechanism itself has three overconstraints; these can be illustrated by opening the kinematic loop at one of the hinges (Figure 2). The left chain has two hinges and two links; the right chain has two hinges and a single link. Both chains have two degrees of freedom.

The mobility of the end-effector mechanism can be determined by taking the degrees of freedom both chains share. In this case both chains share the translation in the x-direction. The overconstraints can be determined in a similar manner; the constraints that both chains share are in effect doubly constrained, i.e. overconstrained. The out-of-plane directions are constrained by both chains; the mechanism is overconstrained in the rotation around the x- and y-directions, i.e. the φ- and ψ-directions, and overconstrained in the translation along the z-direction.

Determining the critical misalignments

The four-bar mechanism has lumped compliance; all significant compliance is in the flexures. As such, only the flexures are prone to buckling. In this compliant hinge there are two buckling modes of interest: axial buckling of a wire flexure and lateral buckling of the leaf-spring flexure. Lateral buckling of a leaf spring can occur due to a force in the direction of the height of the flexure and a moment in the plane of the flexure. Axial buckling of a wire flexure could occur when an axial force on one of the wire flexures becomes too large. This force can also arise from a moment in the plane of the wire flexures. The buckling loads in the neutral position can be determined with the classical equations described by Timoshenko [3].
In this parallel configuration of the cross-pivot flexure, the stiffness of the flexure is the sum of the stiffness contributions of the leaf spring and the wire flexures.

The flexure is designed such that the centres of compliance of the leaf spring and wire flexures overlap. The centre of compliance is the point in certain flexures where a force or moment in a certain direction will only cause a displacement in that same direction [4]. Consequently, this will yield a diagonal compliance matrix.
The misalignments are applied to the manipulator at the centre of compliance of hinge D (see Figure 3). This can be seen as setting the location and orientation of the fixed world at hinge D.
The relation between a misalignment and the resultant loads at hinge D is expressed by the stiffness of the mechanism at hinge D. The four-bar mechanism is connected to the world at hinge A. Therefore, the mechanism can be seen as a serial chain of links and hinges towards hinge D.
The compliance of each hinge is expressed in its local reference frame. As such, the compliance of each hinge must be transformed to the mechanism reference frame. This can be achieved by a 6x6 transformation matrix:

$$H_{i,m} = \begin{bmatrix} R_{i,m} & T_{i,m}R_{i,m} \\ \mathbf{0} & R_{i,m} \end{bmatrix}$$

The transformation matrix, H, describes a transformation from the local coordinate system, i, to the mechanism coordinate system, m. It is made up of the rotation matrix, $\mathcal{R}$, which rotates the coordinate systems, and a translation matrix T, which translates the origin of the coordinate system. The translation matrix is the so-called cross-product matrix of the translation vector between the two origins of the coordinate systems [5].

The transformed compliances of all hinges are added together to obtain the compliance at hinge D:

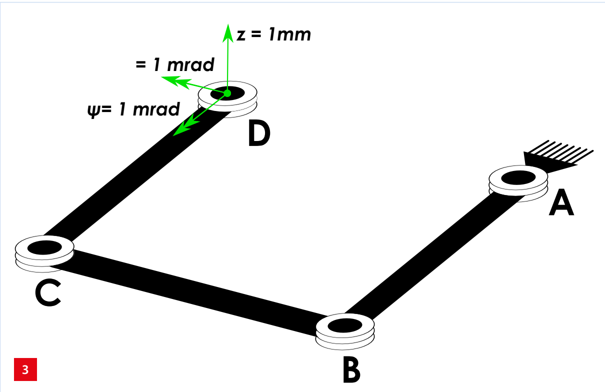
$$C_{tot}^{m} = \sum_{i=1}^{n} H_{i,m} C_i H_{i.m}^{T}$$

This compliance matrix is inverted to obtain the stiffness matrix, which enables the calculation of the loads in the overconstrained directions at hinge D as a result of chosen misalignments of the fixed world. These are chosen to be 1 mm in the z-direction and 1 mrad in the other overconstrained directions.
The load at hinge D, f, is determined using the applied misalignment, δ, in one of the overconstrained directions and the stiffness of the mechanism at hinge D, K. The load is still in the global coordinate system:

$$f_{D,j}^{m} = K_{tot}^{m} \delta_j$$

The resultant load vectors at the hinges are determined using a transformation matrix from hinge D to the hinge in question:

$$f_{i,j}^{m} = H_{D,i}^{-T} f_{D,j}^{m}$$



Unit misalignments of the fixed world at hinge D, all other directions are kept zero.

This results in 12 unique load cases: one for each of the four hinges due to one of the three possible misalignments. Each of the 12 unique load cases is compared to each of the three buckling scenarios to obtain the buckling multipliers. These ratios link the load required for buckling to the load due to a unit misalignment.
One of the buckling scenarios will occur first: the scenario with the lowest buckling multiplier. The critical misalignment is the one associated with the lowest buckling multiplier found in the entire mechanism.

Validation

The buckling loads of the cross-pivot hinge were obtained using the program SPACAR [6]. The buckling multipliers could then be determined, see Table 1. The lowest buckling multiplier for each hinge is listed in bold. In the case of a z-misalignment there is no preference. In the other overconstrained directions this is hinge D and C. The orientation of the hinges ensures that in every case the wire flexures buckle first.

These results have been checked against a full multi-body simulation, also performed using the SPACAR software. Gravity was not considered here, but constrained warping was. The results can be seen in Table 2. The mechanism

Table 1
The buckling multipliers of the hinges; the buckling scenario is listed (w) for wire flexures and (l) for leaf-spring flexures. The lowest value for each hinge is shown in bold.

	z (mm)	φ (mrad)	ψ (mrad)
Hinge A	**2.64 (w)**	10.87 (l)	26.2 (w)
Hinge B	**2.64 (w)**	26.2 (w)	26.43 (w)
Hinge C	**2.64 (w)**	26.43 (w)	**8.79 (w)**
Hinge D	**2.64 (w)**	**8.79 (w)**	10.87 (l)

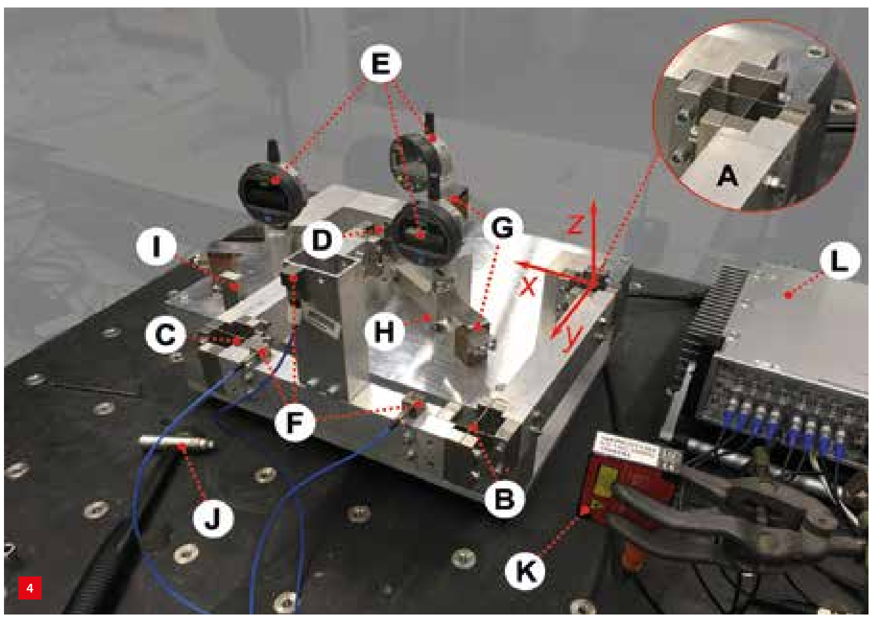
Table 2
The derived and simulated buckling multipliers of the mechanism without gravity.

	z (mm)	φ (mrad)	ψ (mrad)
Simulation	2.10	8.48	8.48
New Method	2.64	8.79	8.79

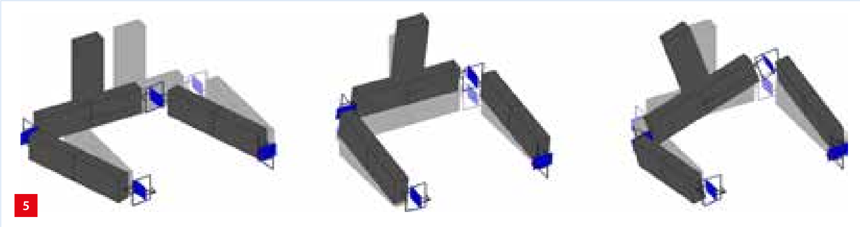
simulation shows overall lower values for the critical buckling multipliers when compared to the values obtained with the new method. The hinge that buckles first in the simulation is the same as obtained with the new method.

Experiment

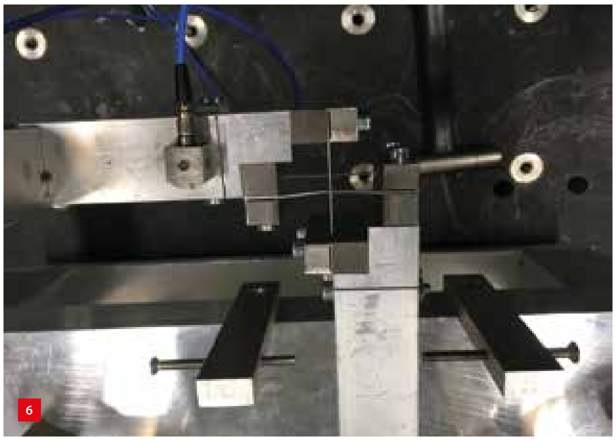
An experiment was set up to check the results of the method and the multi-body simulation, see Figure 4. Another multi-body simulation, this time with gravity included, was performed; this simulation better matches the conditions of the experiment. The simulations and the experiment also yield modal data.
Three rigid-body modes of the end-effector have been compared for all three types of misalignments (Figure 5). The misalignments were varied using the manipulator and increased until buckling was observed, see Figure 6.
The results of the simulations and the experiment can be seen in Figure 7 for the z-, φ- and ψ-misalignments, respectively.



The experimental set-up, with four cross-pivot flexures (A through D). The manipulator at hinge D allows for applying misalignment in the three overconstrained directions. The manipulator is connected to three folded sheet flexures (G); these constrain the in-plane directions. The height of each of the three arms can be set by a screw (H); the arms are preloaded against the screws with three helical springs. The height of the arms is measured by three dial gauges (E). The vibrations of the end-effector are measured using three accelerometers (F). The end-effector is excited using a modal hammer (J). The eigenfrequency of the degree of freedom is measured using a laser displacement sensor (K); to avoid nonlinear effects the compliant mode is positioned against a stop (l).



The first three modes of the end-effector (left: x-direction; centre: z-direction; right: ψ-direction).



Buckling of a wire flexure due to a misalignment.

The critical misalignment values found in the experiment are larger than those of the simulations and the new method. This is difficult to see in some of the figures since the results of the experiment and the simulations are not aligned. Table 3 lists the distance between the positive and the negative misalignments for better comparison. This distance denotes the range where misalignments have a negligible effect. It is not always centred around zero misalignment. In the experiment there are misalignments which could not be eliminated at the initial alignment of the system. Gravity causes different values for the positive and negative critical misalignment in both the experiment and the simulations.

Table 3
The distance between positive and negative critical misalignments (between brackets as a percentage of the value from the simulation without gravity).

	Δz (mm)	Δφ (mrad)	Δψ (mrad)
New Method	5.3 (126%)	17.6 (104%)	17.6 (104%)
Simulation without gravity	4.2 (100%)	17.0 (100%)	17.0 (100%)
Simulation with gravity	4.2 (101%)	17.4 (103%)	17.0 (100%)
Experiment	5.0 (119%)	20.0 (118%)	20.0 (118%)

The experiment exceeds both simulations by nearly 20%. The deterioration of the modal frequencies in the support directions is limited. In the worst case, a ψ-misalignment, the frequency of the second mode decreases by 20% at most. Other effects, such as hardware and assembly errors can also lead to a critical misalignment. For instance, extra compliance in the flexures as well as small alignment errors in the clamping of the flexures lower the overall stiffness of the mechanism (which is unwanted in itself) and lead to a slower build-up of the forces. This can allow for a higher critical misalignment.

Conclusion

The method for identifying critical misalignment can ascertain the amount of misalignment where buckling occurs; this buckling indicates the limits of optimal stiffness behaviour in the mechanism. The method is far less complicated and time-consuming than modelling the entire mechanism.
The dynamic behaviour observed in the simulation was compared with that observed in the experiment. A decrease of the modal frequencies is seen when the misalignments approach their critical values. At worst, the modal frequency in one of the support directions drops 20% at the critical misalignment.

Importantly, the critical misalignments can be obtained without using complex simulations. The values obtained from the method compare well with multi-body simulations and the experiment. These misalignments can be used to determine the manufacturing tolerances of a mechanism. The approach outlined in this article can be adapted to fit other types of compliant mechanisms.

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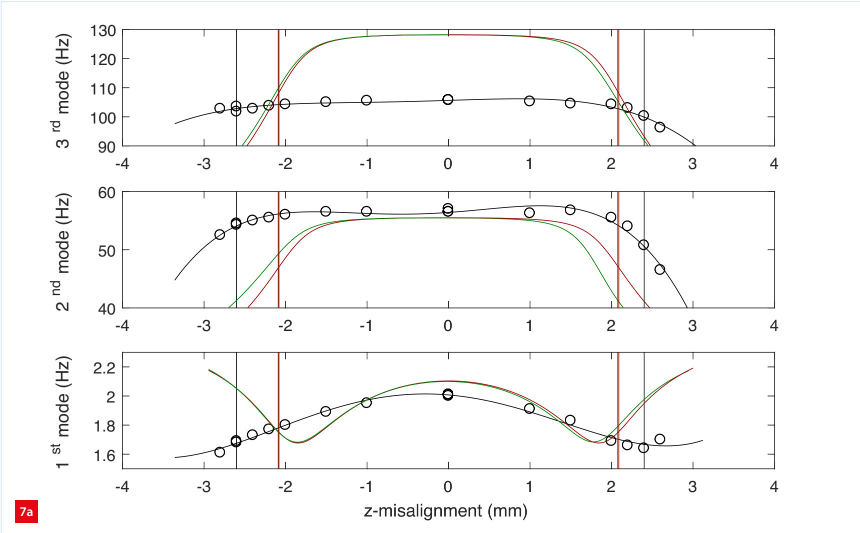

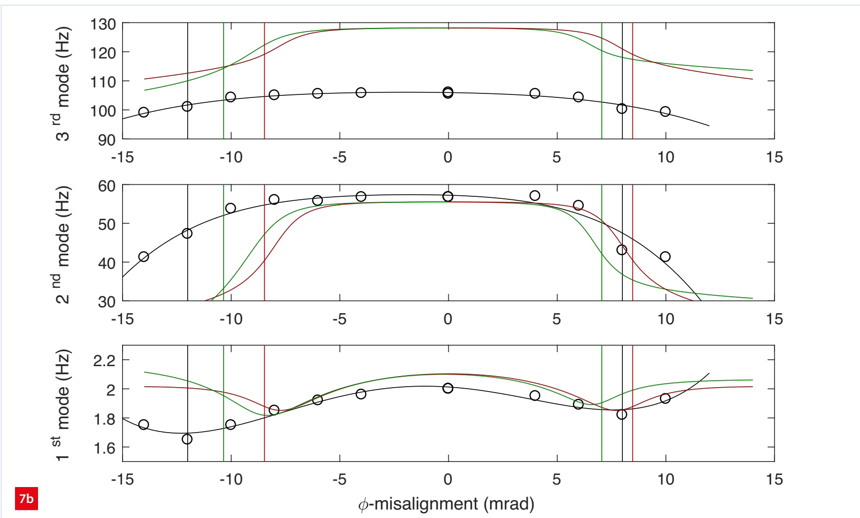

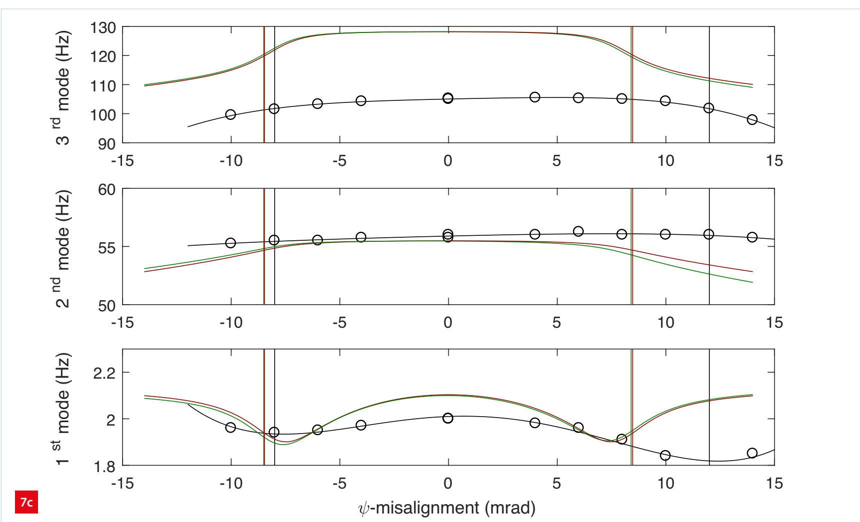

Changes in three modes due to a misalignment in one direction.
(a) The z-direction.
(b) The φ-direction.
(c) The ψ-direction.
The vertical lines denote the critical misalignments.
Red: simulation without gravity
Green: simulation with gravity
Black: experimental data (data points as circles)

WIM VAN DER HOEK (1924-2019)

Wim van der Hoek was born in 1924 in Kapelle-Biezelinge, Zeeland (NL), and passed away on 12 January, 2019 in Eindhoven (NL) at the age of 94. His working life began at Philips in 1949 and his participation in Philips Internal Technical Education started around 1951. As a part-time professor from 1961 to 1984, Professor van der Hoek held the Design and Construction Chair of the Department of Mechanical Engineering at Technische Hogeschool/Universiteit Eindhoven (Eindhoven University of Technology, TU/e).

WOUTER VOGELESANG

1

Wim van der Hoek, approx. 1985. (Photo: TU/e Archive)

With his warm personality, Prof. Wim van der Hoek focused on stimulating creativity among his students. Most important in his approach was that a design works, and works according to plan; and if it does not work according to plan, then the first question should be: "Why not?" And then: "What are you going to do next?"

The developments that Prof. van der Hoek brought from Philips to the university consisted of ideas about precise movement and precise measurement of position, the zero-play and stiff construction, with play as the cause of a jump in speed, acceleration and its derivative.

Central to his approach was discussing the designs, i.e. constructions, as expressed by the title of his inaugural address, *Construeren als Confrontatie tussen Critiek en Creatie* ("Constructing as Confrontation between Critique and Creation"). This was reflected in his 'Monday sessions' with his final-year students, in which he, via a large sheet of yellow drawing paper on the table for sketches and calculations, invited mutual comments, spontaneous generation of ideas and everything you could think of, the order of which was never fixed beforehand. All involved were learning, as summarised by the title of his farewell address, *Leren construeren? Vallen en opstaan!* ("Learning to construct? Falling and rising!").

On the one hand, this approach relied on creativity in constructive insight; on the other hand, on the confrontation of those ideas with approximations and, where necessary, thorough numerical analysis, from theoretical mechanics, applied mechanics, material science and control engineering; what Wim called the 'indispensable auxiliary sciences'.

Results of graduation projects on how to design for stiffness and avoid play formed the DDP, *Des Duivels Prentenboek* ("The Devil's Picture Book"). This together with numerous numerical analyses on stiffness and precise positioning, resulted in the lecture notes *Het Dynamisch Gedrag en Positioneringsnauwkeurigheid van Constructies en Mechanismen* ("The Dynamic Behaviour and Positioning Accuracy of Constructions and Mechanisms", which later became the book Constructieprincipes ("Design Principles").

On the occasion of Wim van der Hoek's 80th birthday, Ad Weeber, Frans Geerts and the undersigned wanted to

AUTHOR'S NOTE

Wouter Vogelesang is director of VH Consult Lasertechnology & Engineering.

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In 2007, Wim van der Hoek was appointed honorary member of 'Vereniging van Werktuigbouwkundig Ingenieurs Eindhoven' (Society of Mechanical Engineers Eindhoven). (Photo: Bart van Overbeeke)

honour him, given his merit in regard to design education at this unique university level. Aat, his wife, joined us in the conspiracy to give Wim a surprise party, in which almost all of Wim's graduates, with their partners, were present. Each brought with them a bottle of wine that had a label referring to their graduation project or their special relationship with Wim.

He was proud that, so long after his retirement from Philips and the TU/e, his name was to be linked with a design award. The Wim van der Hoek Award has now been awarded 13 times and is an important incentive for young designers.

Stimulating creativity in the form of education as instituted by Prof. Wim van der Hoek contributes significantly to the design quality of mechanical engineers. The DDP way of thinking about stiffness and accurate position measurement has great significance for the precision industry in the Netherlands. For TU/e too, this form of education is a gem in the mechanical curriculum: it leads to many new confrontations between critique and creation.

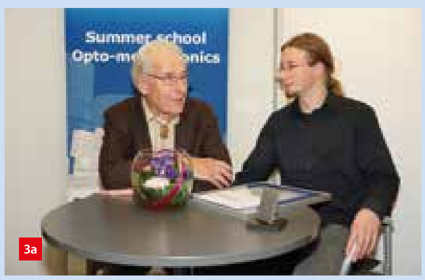
Passionately discussing designs

A remarkable, amiable, accessible and brilliant man! I met him in my student days when I took and completed a number of his courses; that also meant being at the table with the other students and staff. I saw him again soon after my studies, at VDT/Van Doorne's Transmissie, where he had been brought in by Nort Liebrand (then technical director at VDT) to consult on the product and the complex production process of the drive belt. Again there were robust, substantive discussions in which he, in a pleasant manner, held nothing and no one in awe. His non-conformism in terms of language was striking, but in one way or another he used it in such a way that it matched the atmosphere. Many improvements emerged from these discussions.

Later on, I also saw him a few times at Te Strake, where we were involved in technical discussions about weaving machine systems. Since 2008, I have had the honour of being the jury chairman of the Wim van der Hoek Award on behalf of DSPE. The quality of the design, substantiation and innovation, as well as the possibility of serving as an example in the book *Design Principles*, are the criteria that we are allowed to impose on the recent graduates' final-year projects.

We hope to continue this for a long time. Support from current jury members Wouter Vogelesang, Hans Steijaert, Maurice Teuwen, Johan Vervoort and Marc Vermeulen along with the Leiden Instrument Makers School, Eindhoven University of Technology, Mikrocentrum and DSPE (organisation by Annemarie Schrauwen) is crucial.

Jos Gunsing
Founder/owner of MaromeTech and DSPE board member



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Wim van der Hoek engaged in conversation with recipients of 'his' award. (Photos: Jan Pasman)
(a) Alexander Mulder (2011).
(b) Gihin Mok (2015), looking at the trophy, made by the Leiden Instrument Makers School, based on one of Van der Hoek's designs.

Memorial issue and book

DSPE has taken the initiative to publish a special edition of *Mikroniek* in June: the Wim van der Hoek memorial issue. Contributions on designs in the spirit of Wim van der Hoek are welcome.
In addition, DSPE is preparing to publish a book devoted to the life and work of Wim van der Hoek, to be presented at the 2019 Precision Fair in November.

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THE BEAUTY OF MOTION

Kinetic art, with its moving elements, uses technology more than any other art in the realisation of its expression. Its creators, however, do have an entirely different way of working than the engineer. This article aims to introduce kinetic art and present some Dutch and foreign artists. Maybe they can inspire engineers to take a more creative approach in order to find new solutions to design challenges. And kinetic art is also just fun to look at!

RINI ZWIKKER

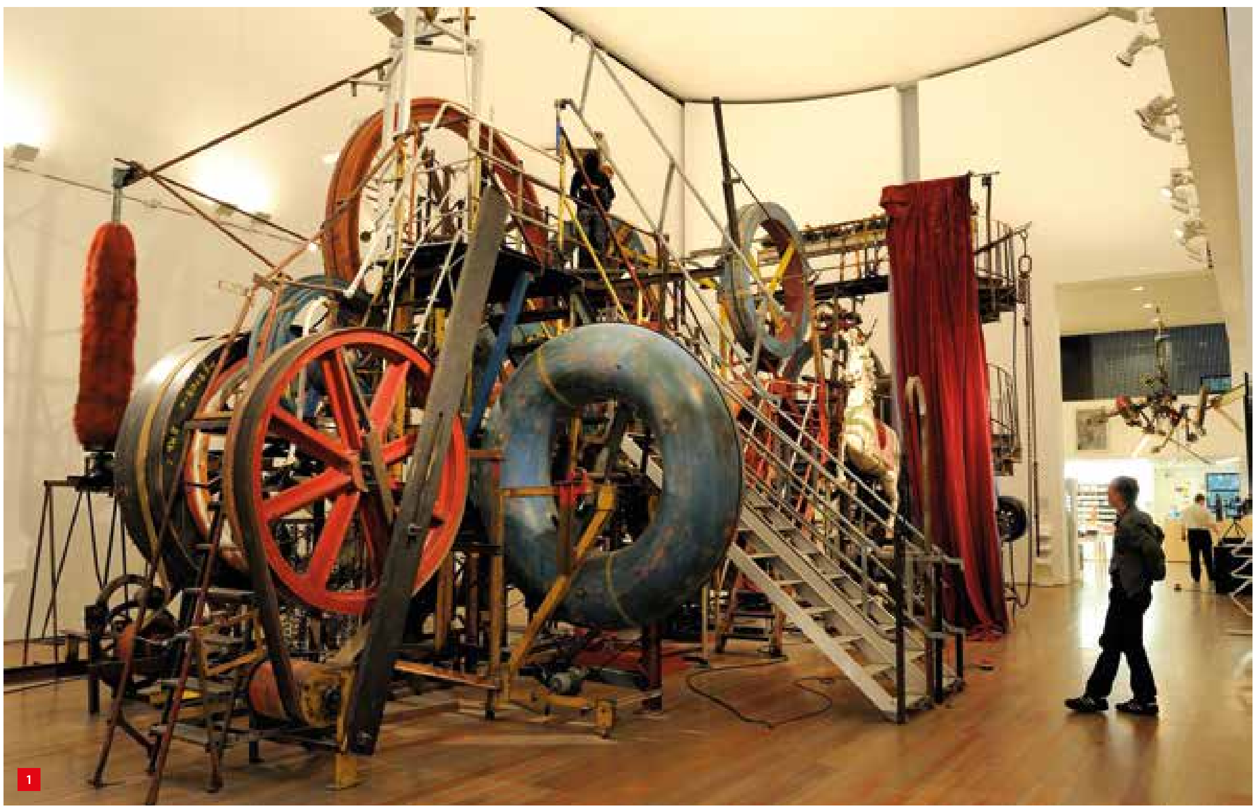
What is art?

This question has probably already been discussed since the first man made a painting on the wall of a cave. It is certainly more than just an aesthetically pleasing decorative object. The jury of the 'Volkskrant Beeldende Kunstprijs' (Volkskrant Visual Arts Prize) 2018 listed a number of useful criteria. The most complete artist:

- is admired for his/her attention to detail;
- surprises by the craziness of his/her art;
- shows good technical craftsmanship;
- celebrates beauty without setting it above everything;
- (includes current themes in a casual manner).

The author considers the second criterion important to distinguish art from decoration: art must surprise, excite (not shock), captivate, touch the viewer, and may even change his view on the world. And also, the third criterion is essential for real art: the craftsmanship with which it has been made.

Art is usually non-functional but wants to express an emotion and capture the senses. It includes a wide range of objects and performances, from paintings and sculptures to poetry, theatre and film. But there is no sharp distinction



1
Jean Tinguely, Grosse Meta-Maxi-Maxi-Utopia (1987), Tinguely Museum, Basel. (Copyright: Hemis / Alamy Stock Photo)

AUTHOR'S NOTE

Rini Zwikker is a freelance systems engineer in mechatronics. He worked as a mechatronic systems engineer at Demcon (2001-2017) and professor/senior researcher Mechatronics at Saxion University of Applied Sciences (2012-2017), both in Enschede (NL).

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between art and design. Designer objects usually do have a user function, with a good design giving added value in use and appreciation. Design aims at mass production, and art is unique or has a limited print. But are the buildings from Gaudi, the furniture from Rietveld or the 3D-printed dresses from Iris van Herpen art or design?

Early history

Art is a mirror of the time in which it is made. This applies both to the subjects and the technology used. The invention of the paint tube around 1840 enabled painters to work outdoors. Photography and film were invented and used for artworks. So, when mechanical moving elements became available these were soon included as well. This is what we now call kinetic art, where the motion is essential for the experience of the artwork.

Usually considered to be the earliest example is the bicycle wheel with fork mounted on a stool by Marcel Duchamp in 1913, one of his provocative 'ready-made' artworks. But the real start is considered to be the sculptor Alexander Calder in 1930, with his hanging mobiles, set in motion by air flow. In the 1930s a few artists, like László Moholy-Nagy, included electric motors in their moving sculptures, using the effects of mechanical noise and light and shadow as well. Around 1950 more artists followed, like Nicolas Schöffer and the best known early kinetic artist, the Swiss Jean Tinguely (1925-1991).

Tinguely created complex mechanisms with multiple motions using rods, wheels and belts. The author uses a picture of the Gigantic Kinetic Toy (see Figure 1 and video [V1]) in his workshop on systems engineering to show what the result may be of an unstructured incremental engineering process. His way of working is a really good example of how engineers should not work.

Tinguely taught himself to weld, and mostly used waste material for his creations. These were (intentionally?) badly constructed, with mechanical play making the motion non-deterministic, and the rattles and squeaks adding to the experience. The type of mechanisms he used were rather limited: most were based on the ordinary crank mechanism. Just like early professional automated machinery, the devices were capable of only one prescribed and repeated motion, with no 'intelligence' from sensors or processing. He used old washing machine motors to drive the mechanisms, which now poses a problem to museum curators, as they have to find similar replacements when these fail. Some of the machines he made were intentionally self-destructing, but most failed after some time anyhow. The website of the Tinguely Museum contains short videos of a number of his creations [1].

Tinguely was the first kinetic artist to use natural elements like tree branches and animal skulls in his work. In this way he wanted to investigate and show the connections or conflicts between the technical and the natural worlds. Most kinetic artists since include natural elements in their work in some form. It may make the viewer to identify himself with the machine and to repulse it at the same time.

The Netherlands

There are quite a number of artists making kinetic art in the Netherlands. A short presentation of six of them may serve to show the differences in their aims and ways of working. It also demonstrates the development from mechanics to mechatronics.

Theo Jansen

This artist designs and builds *strandbeesten* (beach animals), which are fully mechanical driven by external power from the wind. These are multi-legged creatures mainly made from yellow plastic tube connected by cable ties and nylon cord. They come to life on the beach when driven by the wind in sails attached to some outriggers. Their structure resembles pre-historic skeletons.

Jansen compares the plastic tube to proteins in nature: widely available and cheap. His way of working is by means of evolution. The creatures experience a one-year evolution cycle: designed and built in winter, born in spring, tested and improved in summer, declared extinct in autumn. Over several decades the species has made an evolution to improve strength, speed and stability. This evolution leads to increased complexity, with sometimes reduced reliability.

2 *Theo Jansen, beach animal Animaris Umerus (2009), Scheveningen. (Copyright: Loek van der Klis)*

In the same way as the natural evolution did not (yet) create the wheel, the motion of these beach animals still makes use of different kinds of multi-link legs. However, internally they do include 360º-rotation bearings, e.g. in crank mechanisms. Sometimes plastic bottles are used to store air pressure from a (plastic tube!) air pump powered by the wind. The material may be simple, but the result is magical (when it works). Figure 2 shows an example, which is also featured in video [V2]. Jansen's website [2] shows a nice video with a compilation of these beautiful creatures.

Mark Bischof

This artist creates beautiful installations in which glass balls roll, driven by gravity. His artworks are – both aesthetically and technically – well-designed structures made from metal guidance rails, with brass and wooden fittings. They are certainly a combination of creativity and craftsmanship, fulfilling all criteria of art. Bischof's way of working, however, is totally the opposite of that in industry. For a start, he works alone, not in a team. He does not have a strict plan and does not make drawings or calculations, but builds via trial & error, and continuous improvement.

The devices are purely mechanical, and resemble some 17th- or 18th-century machines, like the planetarium of Eise Eisinga in Franeker (NL) [3]. With one difference, however: the installations of Bischof deliberately do not have a purpose. Or maybe they have, and that is to show the importance of taking time to play and enjoy. And in contradiction to other kinetic artists he does not want to capture a natural phenomenon, but to make his own imagination visible.

3

Mark Bischof, Markrokosmos (1998-2003). (Copyright: Mark Bischof)

Bischof's most complex work is the Markrokosmos, a more than 2 meters high labyrinth (see Figure 3 and video [V3]). He started in 1998, worked on it for six years, and sometimes still makes small improvements. No technical device will ever be perfect. Due to its complexity, coincidence plays a major role in its performance. His website shows some videos and photos [4]. He gives guided tours in his basement atelier in Amsterdam on a regular basis. Markrokosmos can be seen there, just fitting in the available space.

Volkert van der Wijk

This artist may be more known to a technical audience, because he is also assistant professor at Delft University of Technology. In both capacities he works on all kinds of mechanisms [5]. His way of working is more scientific than artistic. Efficient use of energy by balancing masses is an important focal point. He obtained his Ph.D. (cum laude) on the design of balanced mechanisms. He owns a 'kineticart'-named website [6], on which he shows his creations which use the same principles to express motion.

Van der Wijk's best known project is the 'Taaie Tiller' (Tough Lifter), which he developed together with the (late) journalist and writer Henk Hofland [7]. The full-scale version, intended to be placed in the Rotterdam harbour, should slowly lift a weight of 32 tons, and then plunge it into the water from a height of 18 meters. This repeats itself in a cycle of about a day, during which wind power slowly fills counterbalance reservoirs with water. That version has not been realised yet, but a 1:6 scale version with solar power was installed in 2017 in a pond at the University of Twente (Figure 4). Hofland called the machine a tribute to the undaunted and unstoppable optimist Sisyphus, and an encouragement to the viewer to never give up [8].

Aernout Mik

An artist who cannot be omitted by an author with links to Demcon is Aernout Mik. Although he is now focusing on video art, some twenty years ago Mik came up with the idea for the AAP (Figure 5). This was then designed and built by Demcon, just after the mechatronics engineering agency had been founded. It is an early example of a really mechatronic and interactive work of art, and shows what can be achieved when an artist works together with engineers.

The basis is a robotic orang-utan sitting on a tree trunk. It has eight motors to move its eyes, head, trunk and one arm. AAP is programmed as a neural network enabling it to make – slow – random autonomous movements, like scratching its back. But it also has a play table in front of it, and an empty tree trunk on the opposite side. When a sensor detects that a person sits down on that tree trunk, a game of noughts and crosses is started. Over a number of games it regulates the level of its play in such a way that it

4

Volkert van der Wijk, Taaie Tiller, University of Twente. (Copyright: Volkert van der Wijk)

wins about 50% of the games. AAP was in service in the hall of the Sint Maartenskliniek in Nijmegen (NL) for about 15 years and then moved to the HEIM museum in Hengelo (Ov, NL) in 2013, but is now not operational any more. AAP confronts the viewer, being a participant in the artwork, with the transfer of properties from nature to technology. This is an important theme in kinetic art. But the same question arises in the design of care robots: how human should their appearance and behaviour be?

Christiaan Zwanikken

This artist continues to make mechatronic and sometimes also interactive kinetic art [9]. He builds hybrid creatures, using servo motors, linkages, springs, actuators and sensors, and combining these with natural elements like animal skulls, feathers and leaves. The result may resemble a bird, a dog or a donkey. These creatures are then programmed to perform a choreographic act like a living creature. His creations are an experimental investigation of how technology can be used to show life-like behaviour.

A good example that makes one smile is the work 'The Questionable Gods of Biomechanics' (see Figure 6 and video [V4]), where five 'masks' made from palm flower petals are attached to an aluminium tube. They move horizontally and vertically – using simple model servos and linkages – while having an incomprehensible conversation. Their talking is supported by a little red tongue which moves in and out through a mouth-hole in each leave.

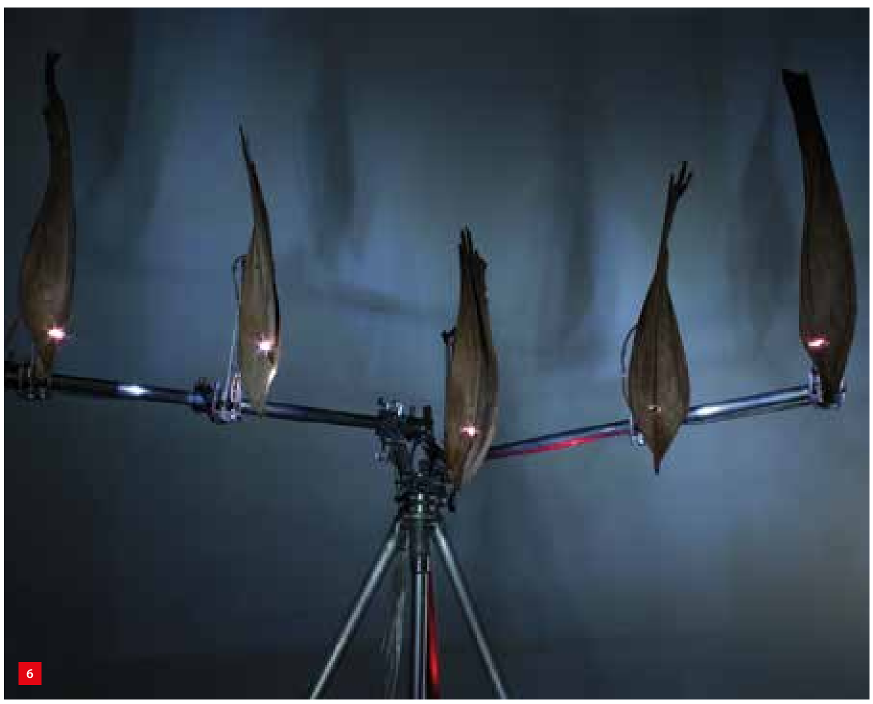
Kinetic art of a different nature is presented by Zwanikken's Hydromats (Figure 7): three transparent cylinders filled with water, in which a rotating propeller placed horizontally just above the bottom creates continuously changing vortexes. The experience is enhanced by light, sound and a voice. Natural phenomena can be so beautiful.

Studio Drift

The present technological cutting edge of kinetic (and mechatronic) art in the Netherlands must be Studio Drift, founded in 2007 by designers/artists Lonneke Gordijn and Ralph Nauta. Studio Drift makes spectacular installations in

5

Aernout Mik and Demcon, AAP (1998).



6

Christiaan Zwanikken, The Questionable Gods of Biomechanics (2007). (Copyright: Cheryl Schurgers)


7

Christiaan Zwanikken, Hydromats (2012). (Copyright: Cheryl Schurgers)

which technology and nature merge [10]. They do this with their own team of now twenty engineers, software developers and designers. Together they also started a company, called Drift Robotics, with the mission to develop and produce robot- and drone-related artworks and shows. Their aim is to create wonder about the role of technology in our society, not to create pessimism or fear; use high-tech to create magic.

In 2018 they had an exhibition in the Stedelijk Museum in Amsterdam. One of the installations there was Drifter (2017), a 'concrete' block of 4 m x 2 m x 2 m floating slowly in mid-air (see Figure 8 and video [V5]). With a technical view one could guess that it might be a canvas structure, with a Helium balloon inside, small fans blowing through holes in the sides, plus cameras and some other position sensors against the walls of the room. A sci-fi movie trailer showed a number of these blocks assembling to form a building in the sky.

Another beautiful installation is Shylight (2012), a version of which can be seen in a staircase of the Rijksmuseum (Figure 9). These are a number of ceiling lamps with silk lampshades moving up and down in a programmed choreography. Only when they move down with a certain speed the silk parachute opens, and the light loses its shyness. The realisation involved a lot of technology, both for the smooth motion and the stable opening of the parachutes.

One of their latest and most challenging projects is Franchise Freedom (2017). This is a swarm of 300 drones flying in a coordinated way like a swarm of birds. Each of the drones is equipped with a light of which the colour and intensity change with their mutual distance, to show the density of the swarm. The flight of each drone has to obey strict rules on speed and distance, hence the name 'franchise'. One evening in August 2018 they flew over the IJ water in Amsterdam. The realisation was a long process, involving cooperation with several universities and large companies.

The website of Studio Drift [11] is certainly worth a longer visit, because it contains videos of many of their projects.


8

Studio Drift, Drifter (2017).

Studio Drift, Shylight (2012). (Copyright: Studio Drift)

International artists

A number of influential kinetic artists from the past have already been mentioned, like Jean Tinguely. Today the number of artists really focusing on kinetic art is limited. Art is again developing towards a new medium: video and other optical art, based more on software than hardware. Still, three contemporary kinetic artists are worth mentioning.
The first is Jordan Wolfson, with his Female Figure (2014). This is an advanced robotic figure of a 'dirty' lady dancing in front of a mirror. It is equipped with facial recognition, and really looks at the spectator via that mirror. It has many joints and motors to generate natural motion, e.g. all bones in its fingers can move. In an interview Wolfson could or would not tell what his intentions with the work were [12]. But it is more likely to shock than to excite.

Random International are two Germans working in London. Like Studio Drift, they are assisted by a group of technicians. With their name they want to make clear that they act as a group, not as individuals. The 'random' has the message that they want to surprise the spectator: it is not about the technology but about the magic. Their best-known artwork is the Rain Room (2012). As the name suggests this is a room in which artificial rain is generated, but sensors ensure that the spectator can walk through it without getting wet.
Two of their other mechatronic works are Blur Mirror (2016) and Fifteen Points (also 2016). Blur Mirror is a segmented mirror which blurs your image as soon as you stand in front of it, by vibrating the reflecting segments. Fifteen Points is an assembly of 14 (!) SCARA arms with LED lights on their ends, which can make a coordinated motion that is intended to be interpreted by the viewer as that of a walking person.
The last artist to be mentioned is Julius Popp, who shows another new development: linking the artwork to the internet. His work *bit.fall* in the MONA in Hobart, Tasmania, continuously generates well-timed rows of water drops which create a waterfall of words, taken from daily Google searches.

What engineers can learn

Kinetic art is the type of art which is the closest to engineering. Its creators usually do not innovate but use available technologies for a totally different purpose which engineers would never have considered. It is their creative transverse thinking from which engineers can learn. This is linked to a way of working contrasting with that of an engineer in many ways. Using this may lead to finding new solutions and applications. It is complemental to the structured methods used in systems engineering [13].

Let's highlight some of the differences. Most artists do not make a plan based on an analysis, but work by trial & error. This seemingly chaotic approach stimulates creativity, leading to more unexpected results. Just trying out options is important for engineers, too.
Most artists are inspired by nature, and reshape this with their creativity. Engineers could also be inspired by nature to solve a technical problem, instead of applying theory.
Most artists need much time to create their artworks. This 'slow prototyping' contradicts with the rapid prototyping which is now in fashion in industry. But engineers need time to contemplate as well to come to the best results.
Most artists only use a limited subset of principles, materials and technology. And by focusing on that for a long time they can make wonderful objects. Many companies who excel in their field do the same (although it may limit innovation).
Most artists include some kind of 'magic' in their creations, and pay attention to aesthetics, to touch the emotions. That makes a technical object more appealing to non-technical viewers as well. This is what product designers should do as well.

Let kinetic art move you

Whether or not you like a piece of art, or get touched by it, is an emotional process. Whether or not you assign a higher meaning to it is a philosophical or spiritual process. But especially kinetic art can be viewed – and enjoyed – from a technical (rational?) viewpoint as well. What are the principles? How well is it designed? No way of viewing and interpreting is 'better' than any other. All interpretations are equal and subjective. Maybe yours is one which was not at all intended by the artist. It is not relevant what your viewing window is. What is most important is to experience and enjoy the artwork. Hopefully this article tempts you to visit an exhibition of kinetic art. Let the beauty of motion move you!

Play the videos

An article in a paper magazine about kinetic art is almost a contradiction. So, do follow the web links / QR codes and play (some of the) videos. Each year there are exhibitions, for example in the Stedelijk Museum, Rijksmuseum Twente, Elektriciteitsfabriek or Kunsthal. So, do visit a museum with kinetic art when you can, for the full experience.

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VIDEO

[V1] Jean Tinguely, Grosse Meta-Maxi-Maxi-Utopia: *www.tinguely.ch/meta/en.html?showdetail=utopia*

[V2] Theo Janssen, Animaris Umerus: *www.vimeo.com/10012330*

[V3] Mark Bischof, Markrokosmos: *www.youtube.com/watch?v=qyHNN-EknCU*

[V4] Christiaan Zwanikken, The Questionable Gods of Biomechanics: *www.youtube.com/watch?v=lPoz_0VXg-0*

[V5] Studio Drift, Drifter: *www.youtube.com/watch?v=jwDSefNS5YQ*

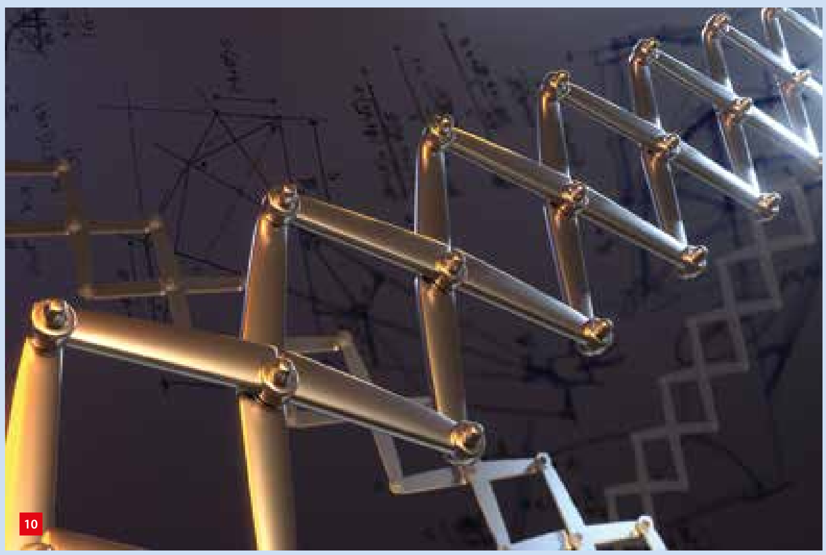
Lumino, capturing company spirit in art

On the occasion of the company's 25th anniversary, the employees of Demcon designed a kinetic artwork, called Lumino, as a present for the management.

The design constitutes a scissor linkage mechanism based on a Hoberman sphere, but shaped in a more complex and unique ovoid shape. An actuated mechanism in the ovoid enables it to grow and shrink in size. From inside out, customisable coloured light is projected onto organically shaped opaque shields mounted on the outside, which create attractive glowing patterns on the ovoid. Suspended by three retractable cables, the ovoid 'breathes' in the entrance hall of Demcon headquarters above the reception. Power is delivered to the ovoid via its suspension cables, and set-points for colours and size are transferred via wifi from the control unit on the wall. Also, a web server running on the control unit hosts a website where the artwork can be controlled and set in various modes.

The project approach to designing this artwork was somewhat divergent from the usual. In the Lumino project, all the employees of Demcon had an equal voice in the design and project flow, exactly like organising a party with friends. Issues and work for the project were picked up naturally by the team members, including for example human safety, which had been taken into account according to regulations.

Lumino (Figure 10) is intended to represent innovative high-tech mechatronics, company growth, in-house competences, flexibility, engineering spirit and, above all, togetherness.



A visualisation of Lumino; the physical version was still in the process of realisation at the time Mikroniek went to print.

WWW.DEMCON.NL/LUMINO

Promolding – excellent engineering and smart manufacturing

Promolding specialises in product design, engineering and the production of high-tech plastic products by injection moulding. Promolding presents itself as an all-in-one knowledge centre, developer and producer.

Since its beginnings in The Hague (NL) in 1997, Promolding has focused on creating and producing novel and distinctive parts and products through smart design, by applying innovative (high-performance polymer) materials and injection moulding processes. Promolding now has more than 50 employees and offers a unique range of expertises, with a large product development department, high-quality plastic material knowledge, laboratory facilities and high-tech production of injection moulding products. It serves a wide range of markets, but is specifically active in the medical, aerospace and high-tech industries.

From product design to production and assembly

With a multi-disciplinary team of specialists, combined with top-notch production resources and facilities, Promolding is able to develop innovative products and designs that are functional, problem solving and injection mouldable in the right material, in the desired quantities and according to requirements.

Promolding's production facilities.

Working from the customer's expectations and ideas, the focus is on practical and innovative solutions. Together with the customer, manufacturability and costs are considered. With a unique mix of very experienced material, process and production technologists, Promolding's designers are able to develop special and successful products.

Specialist in injection moulding

Injection moulding at Promolding is a continuous process of improvement and optimisation, with a specialisation in the injection moulding of high-tech plastic products. With a modern machine park and a wide range of 1K and 2K injection moulding machines, Promolding is able to produce very small, dimensionally accurate products, as well as larger plastic products and components, quickly and flexibly.

Cleanroom

Medical products, from disposables and commodities to technically high-grade products, are produced and assembled in a fully operational cleanroom. A clean injection moulding and assembly process can be guaranteed under ISO 14644 regulated conditions. The cleanroom is equipped with various assembly machines, laser welding equipment and a completely autonomous storage & handling system. The injection moulding machines are connected directly to the cleanroom.

Medical products are produced and assembled in Promolding's fully operational cleanroom.

All facilities in-house

The technologists at Promolding have a professional measuring room and various laboratories at their disposal, used for making advanced computer animations, conducting pressure measurements, determining flow and thermal behaviour, and performing adhesive bonding. Every phase of product validation and/or verification can be completed here.

Added value

Promolding is a total solution provider and helps clients in every phase, from product design to production and assembly, whether they have a specific question for injection moulding, a wish to improve an existing product, a desire to develop a completely new product, or to elaborate an initial concept into a reproducible design.

INFORMATION
WWW.PROMOLDING.NL

PROGRAMME HIGHLIGHTS

SMART MANUFACTURING

Internet of things is the buzzword in recent years. Now it's time to translate the visionary concepts to production plants. How can we smarten up the manufacturing process? Several inspiring examples will be presented.

ADVANCED THERMAL DESIGN

It is impossible to design ultra-precise mechatronic systems when you ignore the omnipresent thermal effects. However, many developers lack the required in-depth knowledge to compensate for this disturbances. Learn from the top experts how to avoid troublesome thermal issues.

OPTOMECHATRONICS

The barrier between the optical and mechatronic designers is crumbling down. They cannot develop an optimal system without communicating with each other. Learn to speak the common language at High-Tech Systems 2019.

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HIGH-TECH SYSTEMS

11 APRIL 2019 - VAN DER VALK - EINDHOVEN

KEYNOTES

THE OPTOMECHANICAL SYSTEM OF THE ELT

Michael Müller, *Mechanical engineer, European Southern Observatory*

The ELT is a project of the European Southern Observatory (ESO) to build and operate a 40 m class optical, near- and mid-infrared, ground-based telescope that will be installed on Cerro Armazones in Northern Chile. When it will enter into operation, the ELT will be the largest optical telescope ever built. It will not only offer unrivalled light collecting power, but also exceedingly sharp images, thanks to its ability to compensate for the adverse effect of atmospheric turbulence on image sharpness.

Keynote speaker Michael Müller will explain the major characteristics and challenges of the different optomechanical systems, including the cascade of various control loops running to keep the optical system of the ELT aligned while compensating image quality degradation due to adverse environmental conditions like gravity deflection, wind load, thermal deformation and atmospheric turbulence. To guarantee the required performance, the design is relying heavily on simulation and analysis, for which the simulation strategy of ESO is shown for the primary mirror control.

OPTIMIZATION-BASED CONTROL IN INDUSTRY 4.0

Frank Allgöwer, *Professor in mechanical engineering, University of Stuttgart*

With the vision of the smart factory of the future, the process and manufacturing industries are currently undergoing a fundamental new orientation on the basis of the cyber-physical systems and internet of things and services paradigms. Frank Allgöwer from the University of Stuttgart will investigate the potential impact of the field of optimization-based control for the fourth industrial revolution and will present two promising approaches, namely economic model predictive control and distributed, cooperative optimization and control.

Economic model predictive control (MPC) is a control technique which is based on the repeated online solution of an optimal control problem. Contrary to classical MPC, the employed cost function can be some general performance measure, possibly connected to the economics of the considered process. This allows to also consider control objectives different from the classical ones of stabilization or tracking, which makes economic MPC well suited as a tool to achieve the goals of Industry 4.0.

In his talk, Allgöwer will examine conditions to classify the optimal operational regime for a system, and propose economic MPC schemes which allow for closed-loop average performance guarantees and satisfaction of constraints.

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MECHATRONICA MACHINEBOUW

PROGRAMME

09:30 **KEYNOTE**

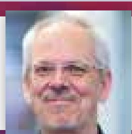
The optomechanical system of the ELT
Michael Müller, European Southern Observatory

10:30 Break

	Smart manufacturing	Optomechatronics	Advanced thermal design
11:00	Digital transformation for connected agile manufacturing Biba Visnjicki, Fraunhofer	Optomechatronics challenges for future laser communications Rudolf Saathof, TNO	Thermal qualification of precision motion systems Maurice Limpens, MI-Partners
11:30	Smart Industry: Fieldlab Flexible Manufacturing Eddie Mennen, Yaskawa	NFI's high throughput 3D metrology equipment for advance process control Hamed Sadeghiani, Nearfield Instruments	How to cope with thermal challenges in a complex system architecture Evert Westerhuis, ASML
12:00	Concurrent engineering in high tech: supply chain mock-ups Ton de Kok, TU Eindhoven	Optomechatronics for metrology and qualification of high-end optics Rens Henselmans, Dutch United Instruments	Model-based thermal analysis of a complex manufacturing machine Rob van Gils, Philips

12:30 Lunch

14:00 **KEYNOTE**



Optimization-based control in Industry 4.0
Frank Allgöwer, University of Stuttgart

15:00 Break

	Smart manufacturing	Optomechatronics	Advanced thermal design
15:30	Merging virtual and physical worlds Guido van Gageldonk, Unit040	From nano-world specifications to real lithography optics Klaus Rief, Zeiss	Controlling thermal dynamics in precision motion systems Enzo Evers, TU Eindhoven
16:00	Digital twinning in smart manufacturing Giulio Lanza, Altran	Test bench for accurate sensor placement testing Harm Wichers, NTS Optel	Temperature control at chip level Pim Kat, Technobis
16:30	AGVs and smart logistics Henk Kiela, Probotics	Optical components and sub-assemblies for industrial markets Edwin Wolterink, Anteryon	Controlling complexity Siep Weiland, TU Eindhoven

17:00 Drinks

Subject to change

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DEGREES OF FREEDOM AROUND THE HEAD

An accuracy of 1 mm doesn't make much of an impression among precision technologists, but succeeding in hitting an area in the millimeter range within the human brain, using an electrode that passes through a hole in both the hard skull and the weak brain mass, is a performance that evokes admiration indeed. This therapeutic treatment, called Deep Brain Stimulation (DBS), is facilitated by a sophisticated instrument designed by Marc Janssens, recipient of the 2013 Wim van der Hoek Award, in his doctoral research at TU/e. Simulations have already shown that it will perform better than the currently widely used neurosurgical instrument.

AUTHOR'S NOTE

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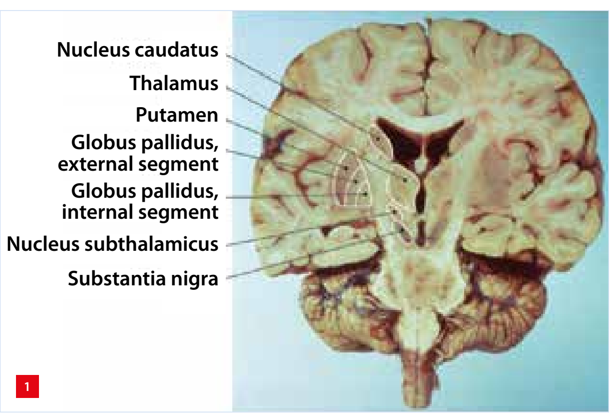
Parkinson's disease, epilepsy and other neuropsychiatric disorders can be treated by stimulating regions in the brain with electrical pulses. These pulses originate from a pacemaker implanted somewhere near the clavicle and are directed to a limited region in the brain via a subcutaneous lead. Parkinson's disease occurs when the balance between the neuro-transmitters dopamine and acetylcholine is distorted, caused by the degeneration of dopamine-producing neurons in the brain. A shortage of dopamine causes uncontrolled firing of nervous cells, resulting in motoric and tremor disorders.
To suppress the symptoms, electrical stimulation targets the lens-shaped subthalamic nucleus (STN), measuring approximately 8 by 4 by 4 mm. It is located ventral to the thalamus, which is situated just above the brain stem (see Figure 1). The STN should be stimulated in its core, which requires a targeting accuracy of 1 mm or below. See Table 1 for a glossary of medical terms.

Intervention in the brain

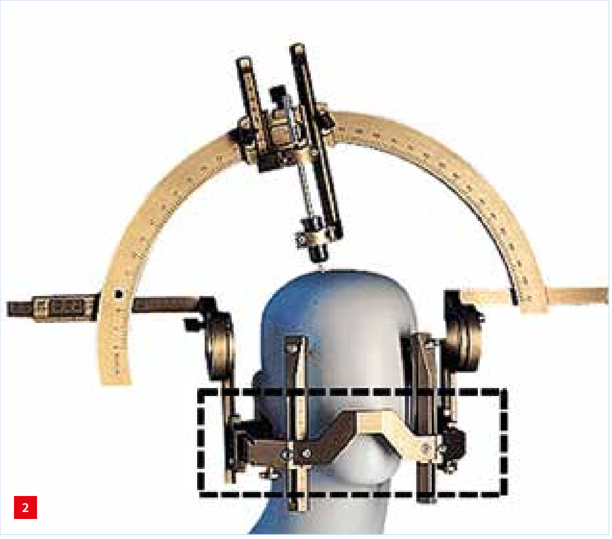
As far back as 1949, Swedish neurosurgery professor Lars Leksell had developed a positioning frame for conducting operations within the human brain. Over the years, this so-called stereotactic frame has been improved and is currently a widely used neurosurgical instrument (see Figure 2).
A base ring around the head acts as a fundamental platform for the subsequent positioning of tools within the skull. The base ring can be fixed to the skull with four pins, which point inwards through the skin and outer osseous skull layer in a circular pattern. Then the stereotactic frame is completed by fixing an angular graduation arc to the base. Together with an angular graduation on the base frame, two angular degrees of freedom are attained: rotation φ around the x-axis and ψ around the y-axis.
Despite many improvements made to the Leksell frame, the mechanics of the system have not fundamentally changed. The continuing main problem is the lack of stiffness, which results in a limited positional accuracy in the (x,y,z)-space within the skull once penetrated inside. In order to penetrate the brain, a burr hole is drilled into the skull bone, subsequently passing through the three meninges. The ensuing inaccuracy problems have led to the desire for a stiffer and more accurate alternative.



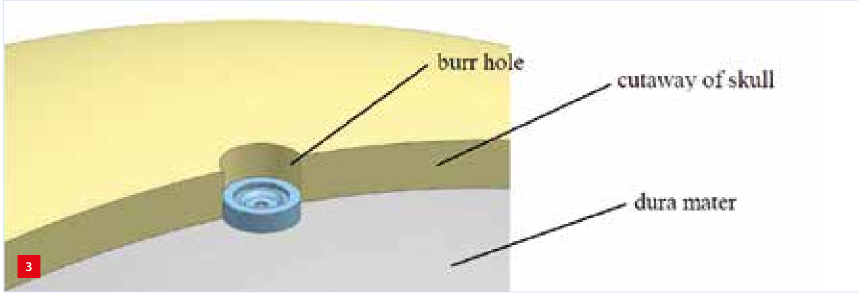
Cross-section of the human brain. (Courtesy Tidsskriftet den Norske legeforening, 2008)

Table 1 Glossary of medical terms

Clavicle	Collar bone
Neurotransmitters	Chemicals transmitting signals through the brain
Neurons	Fundamental nerve cells
STN	Subthalamic nucleus brain region
Ventral	On the abdominal side
Thalamus	Brain region acting as a kind of signal relay station
Meninges	Three cerebral membranes: dura mater, arachnoid mater, pia mater
MRI	Magnetic resonance imaging: a diagnostic tool based on the influence of a magnetic field on hydrogen nucleus spin (proton spin)
CT	Computer tomography: a diagnostic tool using X-rays to produce cross-sectional body images
CSF	Cerebrospinal fluid: colourless body fluid in the brain and spinal cord



The current Leksell stereotactic frame with the base ring traced out. (Courtesy Medscape 2018)



Placing an elastomeric seal in a 7.5-mm diameter burr hole in skull and dura mater.

For positioning electrodes within the skull, high-quality MRI and CT scans are of essential importance. Normally MRI and CT images are combined to acquire more accurate positioning outputs. One issue with MRI is that metal objects cannot be used because of the application of strong magnetic fields: up to 3 T and even higher in laboratory conditions. That's why Janssens, at Eindhoven University of Technology (TU/e), has designed two different instruments: an iron-free one made from the engineering plastic PEEK and one made from metal, mostly aluminium.

Preventing brain shift

Movement of the brain mass within the skull, called brain shift, is one of the causes of complications during deep-brain stimulation. Brain shift occurs when brain fluid (CSF) leaks away when penetrating the skull and the three meninges. To prevent such leakage, Janssens has invented a seal made from elastomeric material that can be placed in the burr hole when penetrating the skull with an electrode (see Figure 3). He aims to introduce this to the neuro-surgical world as a cheap device to eliminate brain shift during operations.

The proposed dimensions of the seal, provided with a thin internal membrane, are 7.5 mm in diameter and 2 mm in height. The elastic properties of the elastomeric material guarantee a tight seal around the electrode protruding through the internal membrane of the seal.

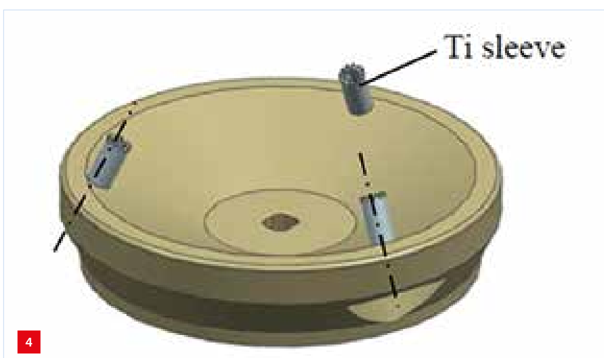
The PEEK instrument

The application of MRI-guided surgery for better electrode positioning accuracy was the reason for selecting PEEK (poly ether ether ketone) as the engineering material for one of the DBS instruments. Fully MRI-compatible PEEK is recognised by the FDA (the US Food and Drug Administration) and is approved for medical applications. It is easy to machine and, compared to other technical polymers, has excellent stiffness and high-temperature properties.

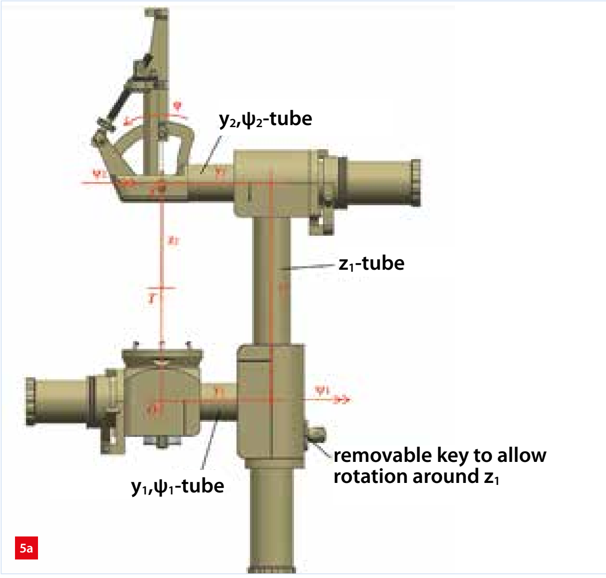
One of the first problems to solve was the fixation of the positioning instrument to the skull. For that purpose, Janssens designed a PEEK adapter disc (see Figure 4), which has three titanium sleeves. Titanium screws, as commonly used in orthopaedic surgery, fix the adapter disc to the skull by penetrating the skull bone.

To provide an accurate correlation between instrument positioning data and MRI images, the adapter disc has a triangle-shaped reference mark, which creates clear triangles in the real-time MRI images. The reference mark provides an accurate interaction between MRI images and instrument positions because of the stiff coupling of disc and electrode guiding system. The triangle centre is defined as $(x,y,z) = (0,0,0)$. The triangle sides are correlated to the x- and y-directions. The z-direction is perpendicular to the triangle plane.

Figure 5a shows the PEEK instrument: the adapter disc with titanium sleeves is on the left, just below the centre. Figure 5b shows the instrument in fictive use. Figure 5a also shows the seven degrees of freedom (DoFs) with which the electrode can be manipulated. They are the angular DoFs φ, ψ_1 and ψ_2, and linear DoFs y_1, y_2, z_1 and z_2. The instrument has been designed with stiff connections in torsion and bending between all system points, as will be elaborated below.



Adapter disc made from PEEK with three titanium sleeves for fixing to the patient's head.



The PEEK deep-brain instrument.
(a) The seven DoFs: angular φ, ψ_1 and ψ_2; linear y_1, y_2, z_1 and z_2.
(b) The (metal prototype) instrument in fictive use.

Mechanical details

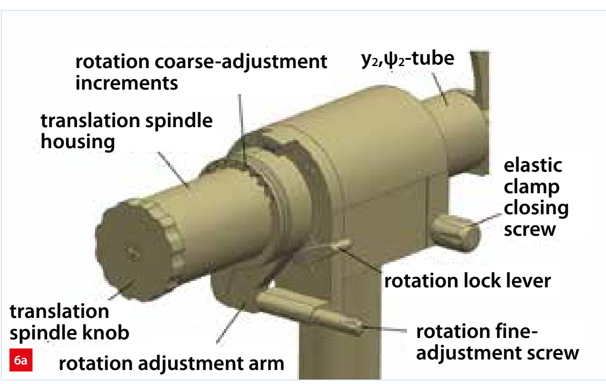
Figure 6a shows the translation and rotation adjustment for y_2 and ψ_2, and Figure 6b shows a cross-sectional detail. The translation is achieved by turning a spindle that engages a thread segment in the tube. Both rotations ψ_1 and ψ_2 have a coarse and fine adjustment. The coarse adjustment can be performed in steps of 15°. The rotation adjustment arm can be further manipulated via the fine adjustment screw with 0.5° resolution.

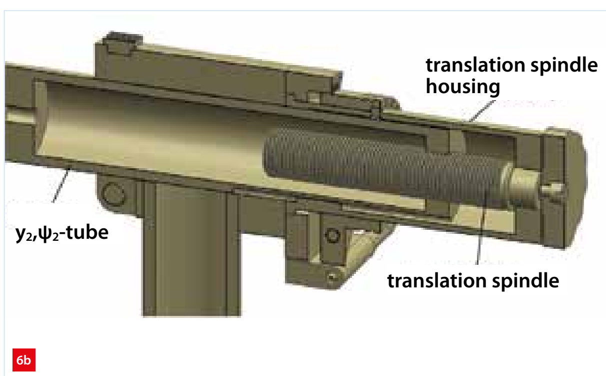
An important factor influencing the electrode implantation accuracy is the instrument stiffness, representing deflection due to load. As well as gravitational forces, the load value is dependent on the brain mass displacement forces. In literature, brain forces on a moving electrode are considered to be small, about 200 mN. Friction forces should be added, resulting in a total force of maximum 1 N as a starting value. Using FEM (finite-element method) analysis, Janssens has calculated instrument deformations due to electrode displacement in the brain mass. In the worst-case scenario, the largest displacement does not exceed 0.1 mm.

The aluminium instrument

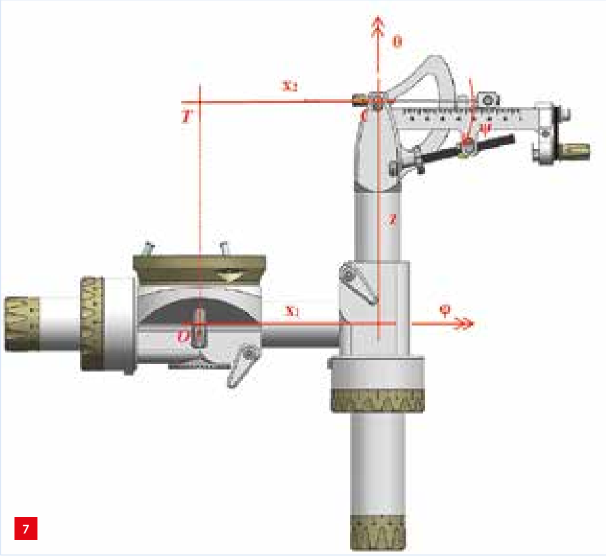
Not all DBS-practising centres have MRI imaging facilities available in their operating rooms, thus these centres do not require a completely metal-free instrument. That's why Janssens also designed an instrument built mainly from aluminium, with some stainless steel, brass and bronze. The better mechanical properties of these metals when compared to PEEK allowed for engineering with smaller wall thicknesses.

Comparing aluminium to PEEK shows a specific density of about twice for Al, a Young's modulus about 18 times higher for Al and a specific stiffness (ratio of Young's modulus to density) about eight times higher for Al. These values allowed for a greater design freedom in the metal instrument: a lightweight structure with improved stiffness. Figure 7 shows the aluminium instrument with its degrees of freedom. It differs from the PEEK instrument in the omission of the upper horizontal stage with translation and rotation. Very interesting is the compact mechanical design for the combined translation x_1 and rotation φ (see Figure 8).





Mechanical details.
(a) The translation and rotation adjustment for y_2 and ψ_2.
(b) Cross-section showing the spindle for the y_2-translation.



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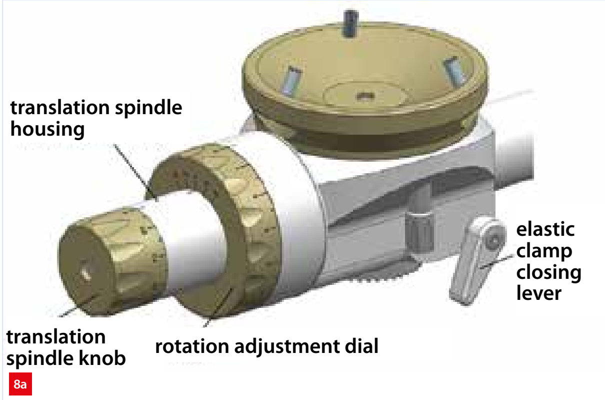
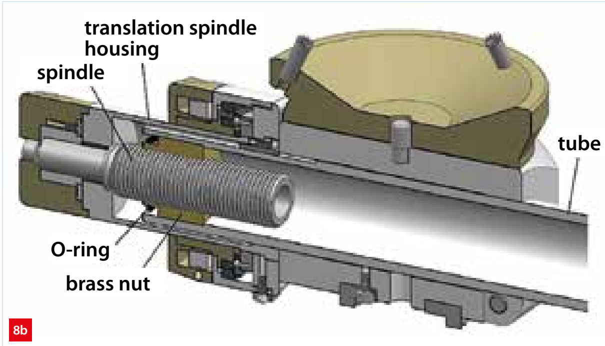
The aluminium instrument with its DoFs x_1, x_2, z, φ, ψ and θ.





The translation and rotation adjustment for x_1 and φ.
(a) External view (small knob for translation, larger one for rotation).
(b) Cross-section.

The compact gearbox shown in Figure 9 provides sensible rotation adjustment by combining an excenter with an external gear, an internal gear and a modified Oldham-coupling. The excenter pushes the external gear into the internal gear, forcing the external gear to rotate across an arc of 15°. It results in a total reduction ratio of one to 360/15 = 24.

Prospects

The success rate of deep-brain surgery can be improved from the current 72-85% to over 90%. Further experiments will have to demonstrate a 1-mm positioning accuracy. A reduction in surgery time of two hours also helps to minimise costs and infection risks. These advantages are due to the mechanical-medical mixed pioneering work by Marc Janssens at TU/e (Figure 10), to be continued in the recently started Eindhoven Medical Robotics company.

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Marc Janssens with the result of his doctoral research at Eindhoven University of Technology. (Photo: Bart van Overbeeke)

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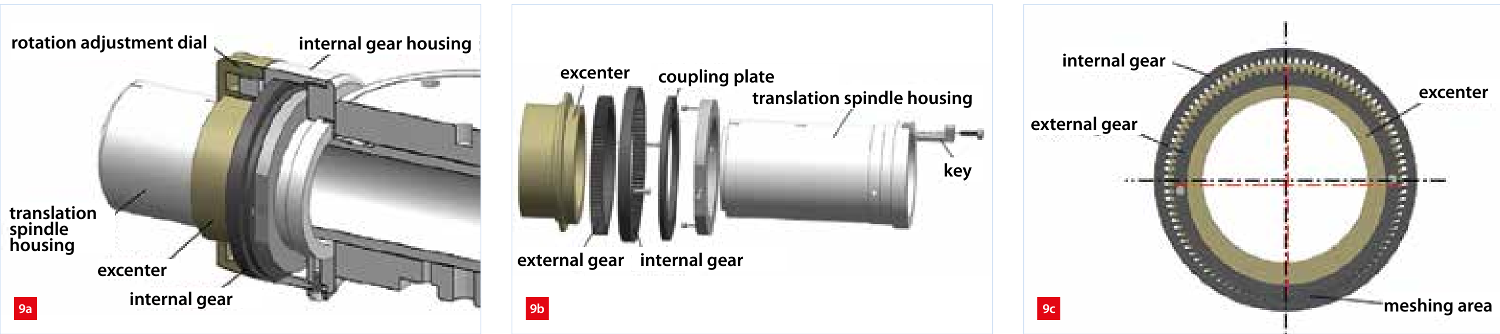

Details of the rotation adjustment gearbox, as shown in Figure 8b.
(a) Assembly.
(b) Exploded view.
(c) Working principle (the red centre cross indicates the heart of the excenter).

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FINDING THE FRICTION FORCES DIRECTION

Kinematic couplings are interfaces very commonly used in high-precision mechanics; they can connect parts together with high stiffness and repeatability. However, in order to achieve such performance, it is necessary that the system is self-aligning, meaning that it must have a tendency to spontaneously move to its centred position. Commonly used assumptions in designing such kinematic mounts may not always be correct, leading to an overestimation of the self-aligning property, hence failing repeatability of the mount.

FRANCESCO PATTI

Introduction

Self-alignment is generated by an external source of energy (gravity in most cases, but also springs, for instance) that provide forces to move the system. Friction is one of the main factors in the phenomenon of self-alignment. In fact, the system will be only able to align itself if the friction coefficient is smaller than a certain value, the so-called limiting coefficient of friction.

Traditionally, when looking for the limiting coefficient of friction, the friction forces are assumed to be in the opposite direction to the motion [1] [2]. In fact, this is a very obvious assumption, when the system is moving. However when there is no motion, this is not always the case. We will show that the direction of friction forces is strictly related to the way the involved bodies deform and in general is not correlated with the possible motion.

Intuitively, having the friction forces in the opposite direction of the relative motion works best for preventing the motion; it will be shown that this is not always the case. As a result, such an assumption could lead to an under-estimation of the ability of the friction forces to prevent motion, thus to predict a system to be self-aligning when that isn't actually the case.

AUTHOR'S NOTE

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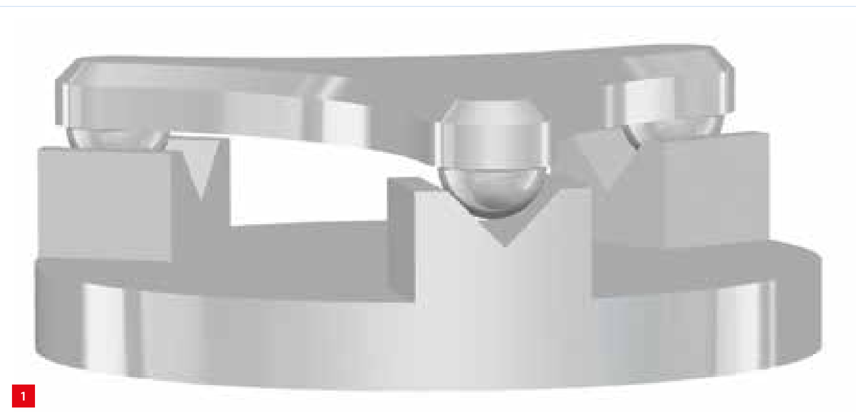


1

An example of a kinematic coupling.

Problem definition

A kinematic coupling is an interface that connects one system to another in an isostatic way; this is achieved by six contacts, in most cases between three balls and three V-grooves (Figure 1).

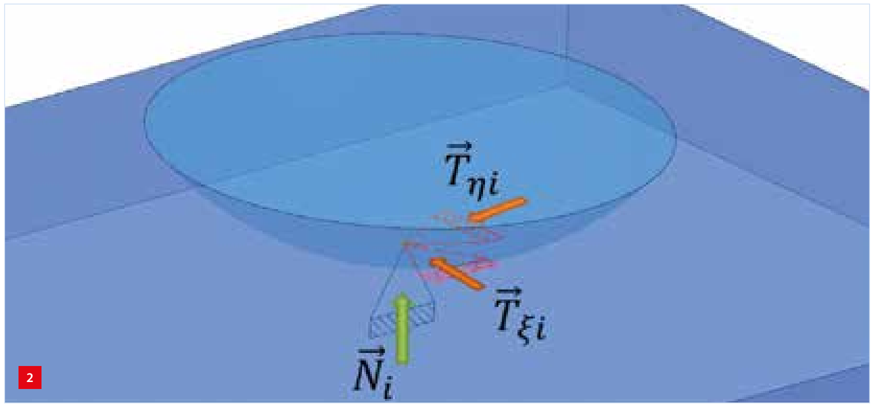
When the coupling is put together, at first it will be off-centre, meaning that not all constraints will be in contact. The question to be answered now is: will the system be able to spontaneously move towards the centred position? (See the note [3].)

The answer can be found by studying the equilibrium of the system, in all possible off-centred positions. Thanks to energy-based considerations [1], it is possible to restrict the study to just six cases that are the most difficult for the motion to occur.
At the beginning of the positioning phase only a few constraints (ball-face contacts in Figure 1) will be in contact. Assuming there is a self-aligning system, it will move towards the centred position. As a result, the number of constraints in contact will increase, until all six constraints are in contact.
The tendency of the system will be to move in such a way that the minimum amount of energy will be dissipated; the fewer the number of active constraints, the more the freedom of the system to follow the least resistive path.

Therefore, when only one constraint is left, the system will only be able to move in one specific path, which in general will be far from being the least resistive. This leads to the conclusion that if a system is able to move in all of the six paths identified by removing the six constraints one at a time, then it will always be able to move towards the centred position.

Therefore, there will be six studies of equilibrium, each one with only five active constraints. The most resistive path will be identified by the smaller limiting coefficient of friction, which will measure the self-aligning property of the coupling.

The state of equilibrium considered will be the so-called incipient motion. This is a static state such that any reduction of friction coefficient would break the equilibrium. In other words, the system is on the verge of motion.



Friction force treated as extra constraints.

Model definition: naming convention

As stated previously, the study will be limited to a very small area around the centred configuration of the system. This means that it will be possible to consider the contact points coincident with the nominal ones, identified by the position vectors $\vec{r}_i$, where i = 1, 2, ..., 6 is the index assigned to the six constraints.

Furthermore, every contact will constrain only one direction, identified by the unit vector $\vec{n}_i$, which is defined as the normal of the tangent plane of both faces at the contact point, oriented towards the body to be positioned.

The constraint reactions contain a normal component $\vec{N}_i = N_i\vec{n}_i$ and a tangential component representing friction $\vec{T}_i$. The external force which provides the energy for the alignment is $\vec{F}_e$.

Orientation of friction forces

When friction forces are present and there is no motion, the equilibrium problem of a kinematic coupling is undetermined. This can be demonstrated by the following considerations.

The unknown quantities are:

- 5 normal reactions $\vec{N}_i$ with known direction → 5 variables;
- 5 friction forces $\vec{T}_i$: each force has a known magnitude (μN_i) and is normal to the $\vec{N}_i$ → 10 variables;
- 1 friction coefficient μ → 1 variable.

In total, there are sixteen unknowns. The equations available instead are:

- 3 equations for equilibrium of forces;
- 3 equations for equilibrium of moments;
- 5 equations defining the friction coefficient $\mu = T_i / N_i$, i = 1, 2, ..., 6 except j (the removed face).

This means that in order to solve the equilibrium problem, we need 16 – 11 = 5 more equations.

An approach that is often followed to solve this indetermination is to assign a specific direction for the five friction forces; it is assumed that friction is oriented as if there were motion. In this way, five more equations become available and the system becomes determined. Such equations are the expression of the virtual displacement compatible with the constraints at each contact point. Although this is often a good approximation, as will be shown later, in reality friction has a different orientation.

A more accurate way to address this problem is to consider the friction forces as reactions generated by extra constraints, and follow the usual approach to study hyperstatic (statically undetermined) structures. This involves introducing the deformations, which will provide extra equations.

Figure 2 shows the contact between two objects, the normal reaction $\vec{N}_i$ and the friction force $\vec{T}_i$ split in two directions ξ and η. The idea is to imagine that these two friction forces are not generated any longer by friction, but by two extra constraints. In other words, the contact between ball and plane of Figure 2 is 'glued'. Applying this approach to the five contact points of the kinematic coupling, five friction forces are replaced by ten simple reactions generated by ten extra constraints, two for each friction force. In fact, every friction force lies on a plane, thus is represented by two simple constraints. By adding these extra constraints, the problem becomes formally overdetermined. Such problems can be solved by considering the involved bodies as a solid, therefore introducing their deformations, which allows the addition of a number of extra equations (the compatibility equations).

To simplify the problem, we will assume that the main frame (the lower body in Figure 1 with the three vees) is much stiffer than the moving body. The compatibility equations will therefore express that the body will deform in a way that the five contact points will not move.

In this case, the unknown variables are:
- 5 normal reactions $\vec{N}_i$ with known direction → 5 variables;
- 10 reactions coming from the added constraints; their direction is known → 10 variables.

In total, there are fifteen unknown variables to be solved.
And the equations are:
- 3 equations for equilibrium of forces;
- 3 equations for equilibrium of moments;
- 9 compatibility equations imposing the deformations, such that the mutual distances of the five contact points will not change.

Thanks to the added compatibility equations there are a total of fifteen equations that will allow the fifteen unknown variables to be found; the problem becomes determined.

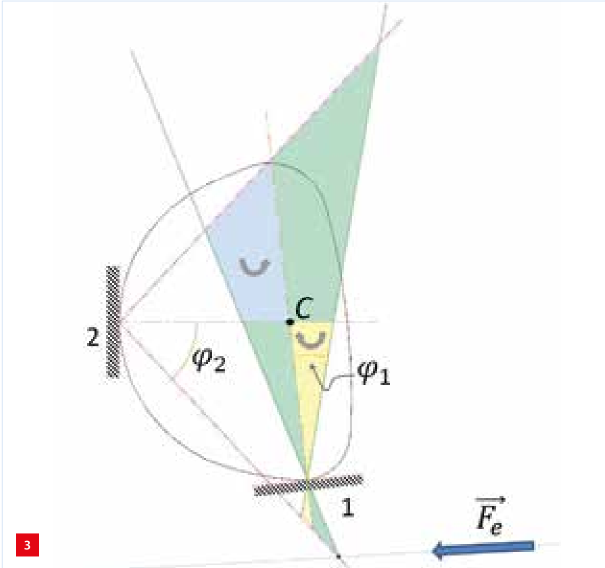
It is interesting to notice that in this process the possible motion of the system is not involved at all. Moreover, the ratio $T_i / N_i = \mu$ is not part of the equations. These two considerations lead to the following general conclusions:
1. The friction forces will not be oriented against the motion.
2. The friction coefficient required for the equilibrium will be different for each constraint.

Conclusion 1 shows that assuming the friction forces are oriented exactly against the motion is not correct (although in many cases is a good approximation). In some circumstances this could result in underestimating the effectiveness of friction in blocking the motion. In other words, in general there are other directions for which friction forces can be more effective, thus even being able to block the motion with a lower friction coefficient.

Conclusion 2 instead leads to the following: assuming the friction coefficient is equal for all constraints, the condition of incipient motion is characterised by only one constraint where the reaction lies on the cone of friction, and not all of them.

The approach just explained shows that when friction forces are involved in equilibrium problems, and there is no relative motion, the deformations of the bodies play an important role. The orientation of friction forces depends on the internal deformations and it influences the efficiency of friction in preventing the motion.

This behaviour can be visualised as follows: when a coupling is put together, the moving body at some point starts touching the counterpart at a number of points. This will generate constraint reactions; the body will deform under this load. Assuming these deformations are so small that there won't be relative displacements at any contact point, these deformations will generate friction forces that will oppose the deformation itself in order to prevent sliding. Friction forces will therefore be oriented against such sliding, which is not provoked by rigid movement, but merely by local deformations of the bodies.



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A simple problem in 2D.

To see the effect of friction orientation in reaching equilibrium, a simple case in 2D is shown (see Figure 3); the problem is studied with the graphical method explained in [2]. A body is constrained in two points, therefore having one degree of freedom; the friction coefficients defining the two cones of friction are $\mu_1 = \tan \varphi_1$, $\mu_2 = \tan \varphi_2$. Will the external force be able to move it?

Following the usual approach, that is friction must be oriented against the relative motion in every contact point, the only intersection of friction angles to be considered is the one in yellow, since the external force can only produce a clockwise rotation. According to this assumption, since the line of action of the force does not intersect the yellow area, equilibrium cannot be met and the body will move. For a kinematic coupling this would be a good result, since the system would be self-aligning.

However, if friction forces are allowed to be oriented towards the relative motion (after all, there is no motion initially), the three areas in green must be added. Thanks to this extension, the conditions for equilibrium are met, since the external force is intersecting the green area; the body will not be able to move.

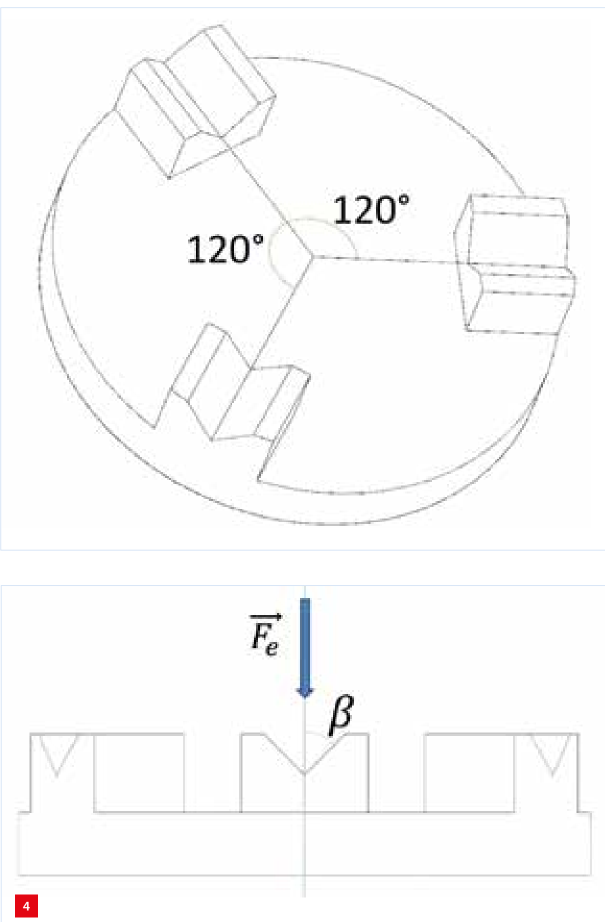
In conclusion, if we allow friction in constraint 1 to be oriented towards the possible motion, friction becomes more efficient in preventing such a motion.

Evaluating the limiting coefficient of friction

In spite of the simplicity of the kinematic coupling, writing its equations of equilibrium is quite tedious. Therefore, the calculations will not be shown in this article; they can be found in [4].
Moreover, as explained earlier, to solve this problem we also need the compatibility equations, describing the elastic behaviour of the system. These are much more complex than the equilibrium equations, and require a lot more information about the kinematic coupling object of the investigation. Such information is normally not available at the time of concept definition of the coupling.

To overcome this problem and provide the designer a tool to judge the self-aligning property at concept phase, we have developed a worst-case scenario approach. The limiting coefficient of friction is expressed as a function of the friction forces orientation, which are considered to no longer be related to the motion; such a function is then minimised by using a computer algebra program. This makes it possible to find the worst-case scenario, without getting into the details of internal deformations.

The result is a set of friction orientations together with the associated smallest limiting coefficient of friction.



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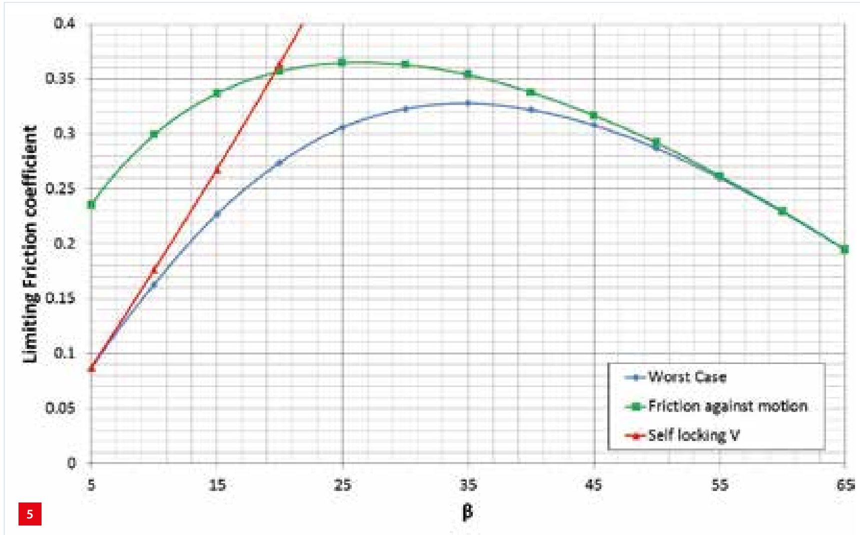
V-grooves of a standard kinematic coupling.



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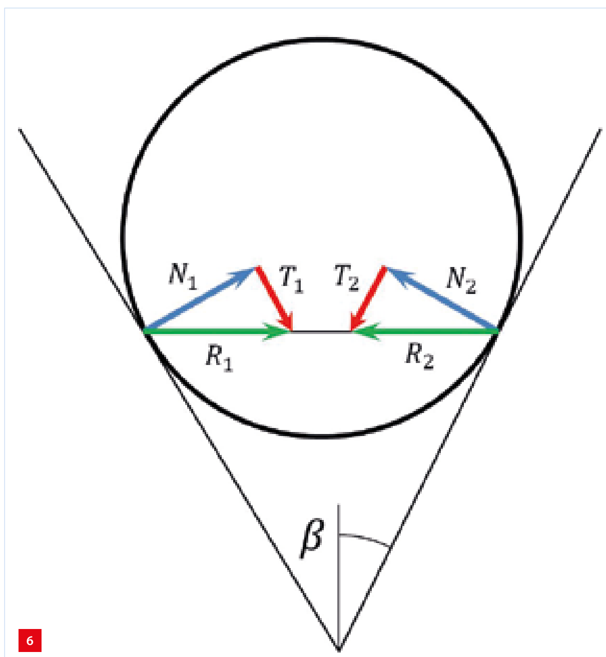
Comparison of worst-case analysis and friction-against-motion approach.

It expresses the case where a certain elastic behaviour of the bodies produces a particular set of friction orientations such that equilibrium can be reached with the smallest coefficient of friction.

Friction against incipient motion versus worst-case analysis

The two approaches are now applied to the common case of a kinematic coupling with three grooves at 120°. Here, β, the half angle of the V, is kept variable (see Figure 4); the external force is vertical, applied at the centre of the system.

Figure 5 shows the limiting coefficient of friction evaluated in case of friction forces oriented against the relative motion



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Example of self-locked ball in a vee.

(curve in green), and oriented in a way that friction has the greatest efficiency in preventing the motion (curve in blue), respectively. Furthermore, a third curve is represented (in red); it describes the so-called self-locking behaviour of each vee.

This phenomenon (represented in Figure 6) happens when the coefficient of friction is such that, for the given angle β, it is possible that the two reactions R_1 and R_2 are in equilibrium. In that case, even without any external force the ball is squeezed by the vee (see the note [5]). If the ball is pushed against the vee and then released, the ball remains stuck in its position. The deformations induced by the initial load generate the normal reactions necessary for friction to restrain the ball from further movement. It is clear that for a kinematic coupling this condition must be avoided.

Figure 5 shows that around the standard configuration with $\beta = 45°$ the two approaches give almost the same result. Therefore, it is safe to use the green line: friction forces oriented against the incipient motion are already very efficient in preventing the motion. When instead the angle β gets smaller, the difference is no longer negligible; the green line underestimates the efficiency of friction. Moreover, it is interesting to note the green line does not take into account the phenomenon of self-locking, which is instead included in the blue line. This is because self-locking is caused by the deformations of the bodies in contact, which are only taken into account by the blue line.

Conclusions

This study has shown that evaluating the self-aligning property of kinematic couplings by considering friction oriented as if there were motion is a good approximation for the standard kinematic coupling of Figure 1, but it might not be accurate in other situations. When a standard geometry cannot be chosen (see the note [6]), deformations can change the direction or friction forces, making friction more efficient in preventing the motion.
In such cases it is possible to have a first evaluation of the limiting coefficient of friction with the worst-case approach. However, more detailed analysis and/or experiments are needed to validate the first results and establish the real contribution of deformations to the self-alignment of the coupling.

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[2] M.P. Koster, *Constuctieprincipes voor het nauwkeuring bewegen en positioneren*, Uitgeverij Universiteit Twente, pp. 335-337, ISBN 9036508320, 1996.

[3] In the following analysis, it is assumed that the initial velocity will be zero, which is basically a worst-case scenario. Furthermore, only initial positions close to the centred one will be considered.

[4] F. Patti and J.M. Vogels. "Self-alignment of Kinematic Couplings: Effects of Deformations", *Proceedings DSPE Conference on Precision Mechatronics*, 2018.

[5] Self-locking is widely used when relative motion needs to be prevented, for instance in the conical coupling between crankshaft and flywheel of a combustion engine.

[6] Sometimes the layout of the system does not provide enough space for the standard kinematic coupling. At other times the external forces are very asymmetric and the coupling needs to be adapted accordingly.

THE SIMPLE DESIGN OF TUBULAR LINEAR MOTORS

Linear motors provide direct thrust for positioning a payload, eliminating the need for rotary-to-linear conversion. The three main direct-drive linear motion systems on the market today – iron-core, U-channel, and tubular linear motors – each have distinct advantages and disadvantages with respect to specific applications, for example regarding form factor, achievable force density, and efficiency. Understanding the differences will enable a designer to select the best motor option.

Iron-core motor

The basic structure of the iron-core motor (Figure 1) is similar to that of an unrolled rotary motor with discrete stator and magnetic poles. It has a set of electromagnetic coils wrapped around an iron core. The end effect of this is to increase the amount of magnetic field generated by the coils, as the iron will contribute to the generated field through realigning microscopic magnetic domains in the iron with the magnetic field from the coils. This is the major advantage of the iron-core motor: for a given input of current, a significant amount of force can be generated.

However, there are some disadvantages/behaviours that have to be considered:

- Cogging
  This is the movement of the motor's iron forcer so as to align itself with the magnetic poles of the permanent magnets, due to the attractive forces created by the magnetic fields in the iron induced by the permanent magnets. This deteriorates the smoothness of motion.
- Eddy currents and heat
  The use of time-varying magnetic fields in iron-containing motors induces eddy currents, creating an opposing magnetic field and generating heat in the iron components.
- Magnetic saturation
  When the generated forces are pushed beyond the normal operating range, the iron will reach magnetic saturation and the force-to-current relationship becomes non-linear, making control more difficult.
- Large footprint
  The basic construction of iron-core motors requires a fairly large footprint.
- Lateral and attractive (often non-useful) forces
  These forces are inherent to the motor design and require additional constraints.

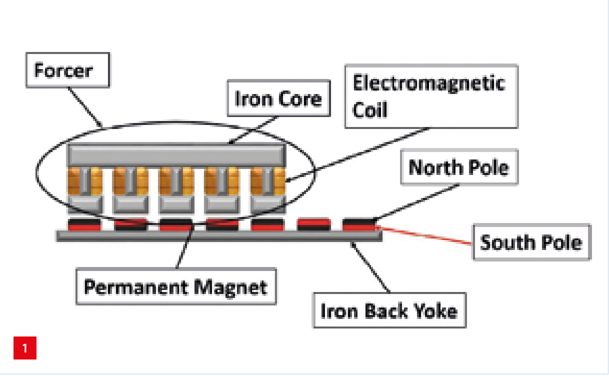
U-channel motor

One of the main features of the U-channel motor (Figure 2) is the absence of iron from the critical locations in the motor. This eliminates cogging and the non-linear force-current relationship due to magnetic saturation. To increase the amount of force generated by the motor, an additional set of permanent magnets has been added to the motor in a double-sided configuration. Additionally, the forcer is manufactured with electromagnetic coils that are epoxy-mounted to the non-ferrous forcer plate, typically made from aluminium.

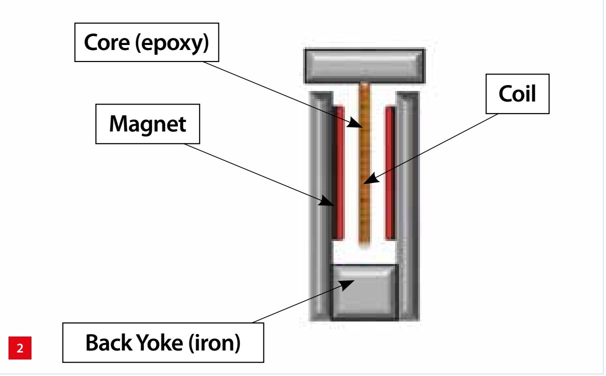
EDITORIAL NOTE

This article was contributed by Dynetics, a specialist in high-quality, high-precision mechatronic components, based in Best (NL). One of the companies represented by Dynetics is Nippon Pulse Motors (NPM), a leading manufacturer of OEM motion control products, including the innovative linear shaft servo motor (or tubular linear motor).

www.dynetics.eu
www.nipponpulse.com



1 *Schematic of an iron-core motor.*



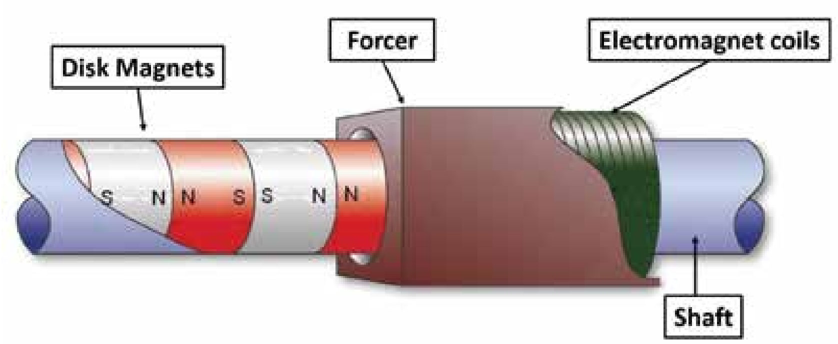
2 *Schematic of a U-channel motor.*

This motor type typically has a rectangular structure and can be mounted in either a vertical or horizontal orientation, depending on the space constraints. The motor can have a low flat profile to fit in limited-height spaces. On the other hand, there are a few disadvantages (as compared to the iron-core motor):

- Lower stiffness
  This is due to the epoxy stiffness and the shape factor of the electromagnetic coils, resulting in a reduction of the force output.
- Reduced heat dissipation
  The geometry-induced reduction of air flow and the very low thermal conductivity of the epoxy mounting mechanism result in reduced heat transport and the need for an additional heat sink in thermal control.
- Lower operational temperature
  The loss of a significant amount of the material strength and stiffness at elevated temperatures for epoxies and plastics requires a lowering of the operational temperature.
- Higher cost
  Costs are higher due to the second set of magnets needed to increase the force output.

Tubular linear motor

Instead of having the electromagnetic coils interacting with the permanent magnets by riding over flat magnets, the tubular linear motor (Figure 3) has the coils surrounding disk-shaped magnets. The orientation of the magnetic poles of this magnet shape creates a magnetic flux oriented at 90° relative to the coils.
As can be seen in Figure 3, the tubular linear motor coils completely surround the magnets and thus will utilise all of the magnetic flux of the permanent magnets. The forcer is constructed so that the current which is injected is adjusted across the three phases so that the magnetic field distribution within the forcer can line up with the poles on the shaft. The magnetic field distribution can be infinitely varied within the forcer, and provides exceptional positioning control.



3

Schematic of a tubular linear motor. (Source: NPM)

The utilisation of all of the magnetic flux improves force-generation efficiency while keeping the costs low in comparison to the other two linear motor designs. In addition, this makes the air gap non-critical. As long as the forcer does not come into contact with the shaft there is no variation in the linear force. The magnetic flux cuts motor windings at right angles for maximum efficiency. All sides of the coil are positioned to allow for maximum dissipation of heat. The more efficient linear shaft motor (or tubular linear motor) requires less power in a more compact design and produces a comparable force to that of a similarly-sized traditional linear motor.

The structure is placed in a protective stainless steel tube. When the non-ferrous rod is tensioned in the protective stainless steel tube a very rigid shaft is produced. This patented process allows the tubular linear motor to achieve very large strokes (max. 4.6 m).

There are a number of distinct advantages to the tubular linear motors over other cylindrical linear motors, almost all them originating from the construction on the shaft, as shown in Figure 3, leaving no space between each rare-earth-iron-boron permanent magnet. As the magnetic field strength depends on the spacing between the like magnetic poles, the tubular linear motor produces a very strong magnetic field.
However, tubular linear motors are not capable of generating the forces of the iron-core motor. On the other hand, they do not exhibit cogging, non-useful forces, non-linear force-to-current relationships or eddy-current generation.

While the forcer completely surrounds the magnets in the shaft, the movement of the forcer over the shaft and the (non-critical) air gap provides more efficient cooling than in the case of the U-channel motor. The tubular linear motor forcer also benefits from a greater stiffness than that of the U-channel motor, due to the alignment of the coil cylindrical geometry with the direction of force generation.

Consequently, the (patented) shaft design of the (non-contact) tubular linear motor offers a number of advantages:

- No need for precision air gap.
- High efficiency.
- Coreless design with ultra-high stiffness.
- No lubrication/adjustment maintenance necessary.
- No-noise/no-dust operation.

Specifications

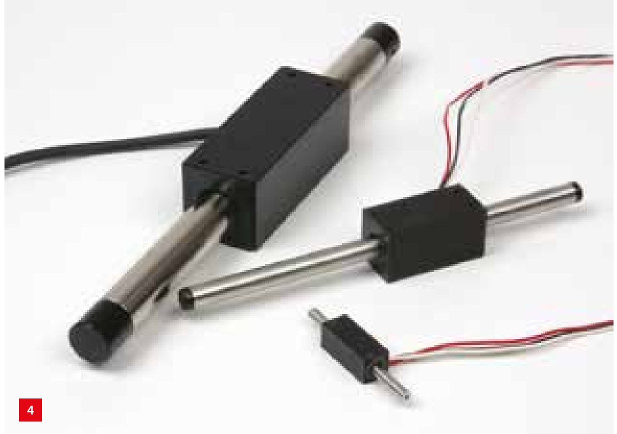
All cylindrical linear motors will be specified by a similar force/duty curve, the difference is in the duty peak. For most linear motors 1 sec or 1% duty is designated as their peak. For the tubular linear motor, on the other hand, 40 sec or 10% duty will be specified as its peak, which is more relevant in practice. For continuous force/current applications the specifications will usually be based on the use of a rather large aluminium heatsink plate (approx. 4 kg) being attached to the motor, whereas the tubular linear motors are rated for continuous force/current on the motor operating in open air with no cooling or heatsink. Table 1 shows typical specifications.

Table 1
Typical specifications for a tubular and another linear motor type.

Force (N)	S250D tubular linear motor from NPM	A typical cylindrical linear motor
Continuous, 100% duty, no heatsink	40	42
10% duty (40 sec)	150	140
1% duty (1 sec)	350	312
Published peak	150	312

Table 2
Typical features of tubular linear motors. (Source: NPM)

High thrust, up to 100,000 N.
Quiet due to the absence of friction.
Simplified unit construction allows a high stroke (max. 4.6 m).
High precision, max. 0.07 nm (limited by encoder resolution, machine stiffness).
High-speed drive (> 10 m/s) with acceleration up to 20 g.
Low-speed drive (8 μm/s).
Parallel drive using only one encoder and one driver.
Virtually no speed fluctuations (± 0.006% at 100 mm/s).
Durable construction, capable of operation underwater or in a vacuum.


4
Display of tubular linear motors. (Source: NPM)

Conclusion

Iron-core motors are great mass movers due to the forces they generate, but they are not good at smooth and precise motion due to cogging. U-channel motors provide smooth motion at lower force ranges but have difficulty with heat dissipation. Due to their simple design, tubular linear motors (Figure 4) overcome a lot of the disadvantages of the two other motor types, but they are not as well known. Tubular linear motors are commonly viewed as a replacement for pneumatic cylinders, but they can be so much more than just that (see Table 2) in, for example, high-force applications and high-resolution/high-accuracy applications.

EUROPEAN PERSPECTIVE ON GAS BEARING TECHNOLOGY

Gas bearings are important components or integral technology in many advanced precision instruments and machines. The first and second Gas Bearing Workshops were organised in 2015 and 2017, respectively, to present and discuss the state-of-the-art in gas bearing technology in the Netherlands, Belgium and Germany. The 2019 edition will broaden the European scope by starting off with overviews of gas bearing research and applications in Italy, France and the UK, both in academia and industry. These presentations will be given by, respectively, Terenziano Raparelli (Politecnico di Torino, Department of Mechanical and Aerospace Engineering, Turin), Mihaï Arghir (Université de Poitiers), and Duc Ha (Omega Dot).

The third Gas Bearing Workshop will be held on 25 March 2019 in Düsseldorf, Germany. The workshop will be organised by the VDE/VDI-Society Microelectronics Microsystems and Precision Engineering (GMM) from Germany and DSPE from the Netherlands. Partners in support of the workshop are the *Bond van Materialenkennis* (a Dutch network of experts in the area of material technology) and the Consulate-General of the Netherlands in Düsseldorf.

Once again, the workshop will bring together manufacturers and vendors of gas bearing components; companies employing gas bearings; companies supplying gas bearing-based machine tools; and scientists and researchers working in this field. The one-day workshop covers the state-of-the-art as well as the requirements from an application point of view. The aim is to establish and reinforce a network of gas bearing engineers to intensify the communication and collaboration between manufacturers, users and scientists. The programme includes a table-top exhibition and poster presentations. The venue is Hotel Courtyard in Düsseldorf Seestern.

Following the European overview, Prof. Farid Al-Bender (KU Leuven University, Belgium) will kick off with a presentation on theory, design and applications of air bearings. Various presentations will focus on air foil bearings and air bearing design. For example, Andreas Lange (Technische Universität Kaiserslautern, Germany) will talk about simulation-driven design and rotordynamic stability analysis of aerostatic spindles. Ron van Ostayen (Delft University of Technology, the Netherlands) will discuss gas bearing designs with a difference...

WWW.GAS-BEARING-WORKSHOP.COM

UPCOMING **EVENTS**

13-14 March 2019, Veldhoven (NL)
RapidPro 2019
The annual event showcasing solutions for prototyping, product development, customisation and rapid, low-volume & on-demand production.

WWW.RAPIDPRO.NL

13-14 March 2019, Sheffield (UK)
Lamdamap 2019
Thirteenth edition of this event, focused on laser metrology, coordinate measuring machine, and machine tool performance.

WWW.LAMDAMAP.COM

19-20 March 2019, Wetzlar (DE)
15th xMR Symposium
The symposium has established itself as a leading international platform for presenting the latest technological developments and innovative applications in the field of magnetoresistive (MR) technology and magnetic systems. Application fields for MR sensors include robotics, aerospace, biosensors, medical equipment, non-destructive testing, industrial automation and electromobility.

WWW.XMR-SYMPOSIUM.COM

19-22 March 2019, Ede/Veenendaal (NL)
Demoweek 2019
Eight companies demonstrate their automation offerings for the metalworking industry: software, robotisation, control, measurement, 3D printing and machining.

WWW.DEMOWEEK.NL

25 March 2019, Düsseldorf (DE)
Gas Bearing Workshop 2019
Third edition of the initiative of VDE/VDI GMM, DSPE and the Dutch Consulate-General in Düsseldorf (Germany), focused on gas bearings as important components or integral technology of most advanced precision instruments and machines. See also the preview on page 36.

WWW.GAS-BEARING-WORKSHOP.COM

26 March 2019, Dordrecht (NL)
ZIE 2019
The Zuid-Holland Instrumentation Event 2019 is organised by Holland Instrumentation, a network of high-tech companies, institutes and universities, aimed at promoting Zuid-Holland's instrumentation industry. This year's theme is 'Investing in tomorrow's high-tech makers'.

WWW.HOLLANDINSTRUMENTATION.NL

26 March 2019, Veldhoven (NL)
CLEAN 2019
This theme day, organised by Mikrocentrum, provides an expert's view on cleanliness. Speakers from academia and industry will present new developments, discuss process and cost optimisation, review quality control and share best-practice applications.

MIKROCENTRUM.NL/EVENEMENTEN/THEMABIJEENKOMSTEN/CLEAN-2019

11 April 2019, Eindhoven (NL)
High-Tech Systems 2019
One-day conference and exhibition with the focus on high-end system engineering and disruptive mechatronics in, for instance, smart manufacturing, thermal design, smart logistics, scientific instruments, design principles and medical systems. See the preview on page 20 ff.

WWW.HIGHTECHSYSTEMS.EU

15-16 May, Leuven (BE)
Materials+Eurofinish 2019
At this joint event material science meets surface technology. Combined, these ingredients help to achieve sustainable designs and innovative ideas, from (new) materials, material analysis and surface technology to binding techniques. The fair provides a complete overview of the entire value chain: from raw materials to a finished product.

WWW.MATERIALS.NL

3-7 June 2019, Bilbao (ES)
Euspen's 19th International Conference & Exhibition
This event features latest advances in traditional precision engineering fields such as metrology, ultra-precision machining, additive and replication processes, precision mechatronic systems & control and precision cutting processes. Furthermore, topics will be addressed covering robotics and automation, Industrie 4.0 for precision manufacturing, precision design in large-scale applications and applications of precision engineering in biomedical sciences.

WWW.EUSPEN.EU

6 June 2019, Enschede (NL)
TValley Annual Congress 2019
The congress will provide a state-of-the-art overview of robotics and mechatronics R&D activities of the TValley network and its industrial partners. The Tvalley agenda includes mechatronics education, knowledge exchange, specific projects on robotics and smart industry, and profiling of the high-tech industry in the east of the Netherlands.

WWW.TVALLEY.NL

12-13 June 2019, Veldhoven (NL)
Vision, Robotics & Motion 2019
This trade fair & congress presents the future of human-robot collaboration within the manufacturing industry.

WWW.VISION-ROBOTICS.NL

20 June 2019, Den Bosch (NL)
Dutch System Architecting Conference
The second edition of this conference features system architecting as a distinguishing discipline in the development and commercialisation of complex systems, products and machines.

WWW.SYSARCH.NL

ECP² COURSE CALENDAR

COURSE (content partner)	ECP² points	Provider	Starting date
FOUNDATION			
Mechatronics System Design - part 1 (MA)	5	HTI	30 September 2019
Fundamentals of Metrology	4	NPL	to be planned
Mechatronics System Design - part 2 (MA)	5	HTI	4 November 2019
Design Principles	3	MC	13 March 2019
System Architecting (S&SA)	5	HTI	24 June 2019
Design Principles for Precision Engineering (MA)	5	HTI	17 June 2019
Motion Control Tuning (MA)	6	HTI	to be planned
ADVANCED			
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	19 March 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 (Q3/Q4 2019)
Green Belt Design for Six Sigma	4	HI	2 September 2019
RF1 Life Data Analysis and Reliability Testing	3	HI	1 April 2019
Ultra-Precision Manufacturing and Metrology	5	CRANF	16 September 2019
SPECIFIC			
Applied Optics (T2Prof)	6.5	HTI	to be planned (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/Q4 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	to be planned (September 2019)
Tribology	4	MC	12 March 2019
Basics & Design Principles for Ultra-Clean Vacuum (MA)	4	HTI	11 June 2019
Experimental Techniques in Mechatronics (MA)	3	HTI	25 June 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/Q4 2019)
Passive Damping for High Tech Systems (MA)	2.5	HTI	16 April 2019
Finite Element Method	5	ENG	in-company
Design for Manufacturing – Design Decision Method	3	SCHOUT	in-company

ECP² program powered by euspen

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

WWW.ECP2.EU

Course providers

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

Content partners

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

New fieldlab RoboHouse officially open

The new fieldlab for advanced cognitive robotics RoboHouse is now officially open. During the well-attended opening ceremony last month, the initiative of Delft University of Technology (TU Delft), TNO, RoboValley, Festo and ABB received the official smart industry fieldlab status.

RoboHouse is based on the TU Delft Campus, next to the RoboValley headquarters, and offers a state-of-art industrial setting where companies and organisations can discover and develop new robotics applications. The new smart industry fieldlab reaches out to developers and students as well. They can become a member and use all facilities. In addition, RoboHouse offers a variety of courses, for example about programming a robot arm or linking up a sensor to a neural network.

WWW.ROBOVALLEY.COM/ROBOHOUSE

Online gas spring calculation program

ACE Stoßdämpfer, based in Langenfeld, Germany, specialises in automation, motion and vibration control as well as in safety products. The company has recently introduced online easy-to-use software for calculating and designing tailor-made gas springs. The most common applications of gas springs can now be calculated in a few structured steps. The exact matching ACE gas spring and the required mounting accessories are specified precisely. In addition, a mounting sketch can be generated with the help of the online tool.

WWW.ACE-ACE.COM

New chair of Smart Manufacturing at Fontys University of Applied Sciences

In autumn 2018, Fontys University of Applied Sciences in Eindhoven and Venlo (NL) has established a new chair, Smart Manufacturing, devoted to disruptive technologies and their incorporation in the Dutch manufacturing industry. These disruptive, 'smart' technologies include blockchain, artificial intelligence, virtual & augmented reality, fast networks, quantum computing, drones, 3D printing, autonomous mobility and 5G. Their adoption will disrupt the high-tech industry, which is founded on precision engineering and mechatronics, and promote the introduction of so-called cyber-physical systems.

Cyber-physical systems are at the heart of Industrie 4.0, which was introduced in Germany in 2011. Within modularly structured 'smart factories', cyber-physical systems facilitate and monitor physical processes, create a virtual copy of the physical world and make decentralised decisions. Over the Internet of Things (IoT), cyber-physical systems can communicate and co-operate with each other and with humans in real time.

In the Netherlands, this is called Smart Industry (*www.smartindustry.nl*) and it is aimed at realising the world's most flexible, digitally connected production network by 2021. VDL Nedcar in Born (NL), for example, is already BMW's most flexible factory regarding changing car model. Smart Manufacturing is the subset of factory automation and high-tech systems within the domain of Smart Industry. Below a number of examples are given.

Smart manufacturing and smart assembling are, among other things, a way to improve sustainability: reducing yield loss by employing IoT solutions in the factory for measuring and processing the acquired big data using deep learning/artificial intelligence.

In the Netherlands, Smart Industry is aimed at realising the world's most flexible, digitally connected production network by 2021. VDL Nedcar in Born (NL), for example, is already BMW's most flexible factory regarding changing car model. (Photo: VDL Nedcar)

Ambulance drone developed at Delft University of Technology.

In the development and operation of production processes and machines, prediction, modelling and simulation will help to improve performance. The development process will be further accelerated by using a digital twin: by simulating the hardware (mechanics, electronics, mechatronics) on a computer, the software can be developed, tested and improved without needing to have the physical hardware already available.

As part of 'smart maintenance', preventive maintenance will boost yield and reduce downtime, facilitated by data collection, data analysis (big data, deep learning) and IoT communication. Systems will be able to autonomously demand maintenance. For example, a preventive maintenance system can detect wear in a particular module in a car and automatically order a replacement module. Upon delivery to the car workshop, the car owner will be automatically invited to come in with their car for module replacement.
For high-tech systems, service engineers often have to visit the customer, which requires large, expensive worldwide customer service organisations. The majority of service can be provided remotely. Sharing data (view of the situation, performance monitoring, augmented reality) can help the remote service engineer instruct the local technician in how to repair the system.

Regarding precision engineering, eye surgery for example requires higher accuracy than humans can normally deliver. It is performed minimally invasively with 0.5-mm needle-shaped instruments, which are manipulated by hand in four degrees of freedom. Steady hand movements and high-precision instrument manipulation are required. Here, robotically assisted surgery can help the surgeon, who remains in control of the instruments by operating haptic (i.e. touch-based interaction) interfaces.

Using artificial intelligence, drones can find their own way, as demonstrated by the following, not so hypothetical, application. If when walking down the street you see someone having a heart attack, you send an alert using an alarm app on your smartphone. Then an ambulance drone, equipped with an AED defibrillator, flies in, analyses the situation and instructs you in how to handle it. In principle, all this is possible with existing technology.

In the spirit of these examples, the new chair of Smart Manufacturing at Fontys University of Applied Sciences prof. Hans Krikhaar will, with his group of researchers and students, conduct applied research in collaboration with industrial partners. The main topics will be the development of mass products and their production processes, (just-in-time) small-series production, digital twin, factory automation, high-tech systems, human support devices, production optimisation, edge computing (local processing for fast response) and smart logistics. Disruptive technologies that will be exploited include fast networks (5G), artificial intelligence, big data, deep learning, IoT, and virtual & augmented reality. This spring, prof. Krikhaar will deliver his inaugural address.

(The input by ir. Frank van Gennip and dr. Jan Jacobs, both of Fontys Technology & Logistics in Venlo, is acknowledged)

High-precision distance measurement on any material or surface

Keyence, a world leader in industrial inspection solutions, introduces its CL-3000 series of confocal distance sensors for highly accurate measurement tasks. This ultra-compact coaxial laser range sensor has been developed for quality improvement and productivity enhancement.

Typical applications for the CL-3000 include thickness measurement of metal plates, wafer surface measurements and sealing control in all possible production environments. The multi-colour confocal method provides performance levels that are not possible with conventional systems. The emitted light is more stable and has a higher brightness over a wider wavelength range compared to typically white LEDs, thereby allowing for higher accuracy.
The CL-3000 guarantees (without special heads) high accuracy on any type of material and surface, whether transparent, reflective, curved, stepped, uneven or rough. Unlike conventional laser sensors, detection is even possible under a large angle of incidence at the target object. The compact sensor heads, with a diameter of 8 mm, are the smallest in the industry and can be installed in tight locations, meeting the growing need for miniaturisation in production equipment. The CL-3000 series does not contain electronic components, but only lenses, so that measurement errors due to heat generation, electrical noise or optical axis deviations are prevented.

A typical industrial inspection application for the Keyence CL-3000 range sensors.

WWW.KEYENCE.EU

New Heidenhain Application Centre

The new Heidenhain Application features a high-tech 5-axis machining centre for training purposes.

During the Demoweek 2019 in March (with eight companies in the Ede/Veenendaal (NL) region demonstrating their automation offerings for the metalworking industry), Heidenhain will present its new Application Centre in the Netherlands, which will include a high-tech 5-axis machining centre for training purposes and room for workshops and presentations.
Jaap Bazuin, director of Heidenhain Nederland: "The idea behind this Application Centre is to show that there is more profit to be gained from a machine with a Heidenhain control. The best way to achieve this is by having our target groups in the Application Centre experience for themselves what the many possibilities are. It is primarily intended to support end-users, especially operators, with tutorials about the applications, linked to Heidenhain's practical solutions. They can work with the latest products, systems and software in the Application Centre."

The Application Centre is also interesting for, for example, CAD-CAM software suppliers, automation companies building robots and linking them to machines, up to the machine manufacturers. "This is also important in the light of Industrie 4.0, or Connected Machining, because from one Application Centre we gather and inform, as well as inspire, all parties involved in the latest technologies."

WWW.HEIDENHAIN.NL

New castability tester

Designers generally have little knowledge of casting. The result is that in the manufacturing process of their design defects can occur during casting. Casting specialists are reluctant to disclose their professional knowledge as long as an order has not yet been confirmed. Simulation software can help the designer, but the existing packages are very expensive and require specific training.

The Dutch casting consultancy Lautus Castings has found a solution for this. In a European CrossRoads2 innovation project, Lautus Castings, together with two Flemish partners, developed a tool that can test the castability of products in the design phase. The product consists of a creditcard-sized box containing a processor with software in which the designer only has to enter his CAD model, the type of cast alloy, the moulding material and the mesh size. Subsequently, a complete solidification simulation is calculated in ten to thirty minutes.

This helps designers and foundries to obtain a very quick and reliable initial analysis of how castable the designed part is. A report is generated based on an STL file showing a clear overview of the part's geometry and mesh, temperature, liquid zones and shrinkage. Using this report, the designer can adapt his design so that the manufacture of the product can be improved with less waste. The castability tester provides the process knowledge and data in a number of languages, including Dutch, English, German, French, Chinese and Italian. This promotes direct communication between designer and casting specialist.

The castability tester is now commercially available at a fraction of the price of a high-end simulation package.

WWW.LAUTUSCASTINGS.NL

New modular photonic alignment system

The new F-131 Modular XYZ Photonic Alignment System has been introduced by Physik Instrumente (PI) as an excellent foundation for developing, studying and pursuing manufacturing and testing of photonic components. It integrates a reconfigurable stack of three precision, closed-loop DC motor stages with 15-mm travel range plus a closed-loop XYZ Nanocube piezo flexure stage capable of high speed and 2-nm resolution.

The F-131 is equipped with all-digital controls providing integrated commands for fast and low-vibration scanning; additionally, there is a built-in data recorder for mapping, optimisation and characterisation of devices and couplings.

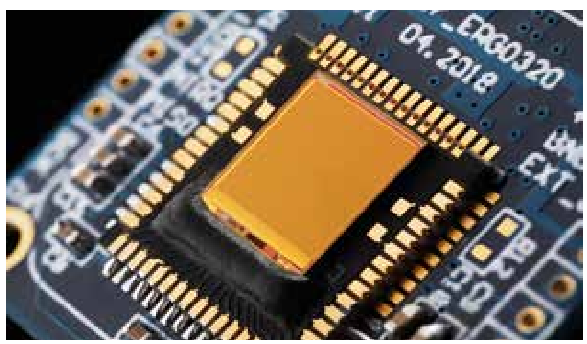
WWW.PHYSIKINSTRUMENTE.COM

A sticker that can see

Last November, CSEM (Centre Suisse d'Electronique et de Microtechnique) announced that it has developed the world's first fully autonomous camera that can be deployed like a sticker, via an adhesive patch or magnet, opening up new possibilities for surveillance and Internet-of-Things (IoT) sensors.

The patented Witness IoT camera is solar-powered and includes a specially designed CMOS image sensor consuming less than 700 µW in active mode, fully covered by a flexible, high-efficiency photovoltaic cell with an adhesive surface. An innovative high-dynamic range (120-dB) CMOS image sensor generates images at 10 fps (frames per second) for 320 x 320 pixels. Intelligent embedded software allows triggering by scene-activity detection. The camera records fixed images at 1 fps and stores them in flash memory for later USB read-out.

WWW.CSEM.CH



The Witness camera prototype measuring 80 x 80 mm^2. The diameter of the camera button is 30 mm, its thickness 4 mm. On the right, the ERGO sub-mW CMOS image sensor.

New Delft professor of nanomechanics aims for 'nanoscale floating'

According to professor Peter Steeneken, head of the Dynamics of Micro and Nanosystems section at Delft University of Technology (TU Delft), nanoengineering is required to bridge the gap between nanoscience and concrete nanomechanical applications. Last December, his inaugural address "Dynamics in Nanomechanics" focused on 'movement'. Examples include the movement of microscopic floating and rotating motors and switches, powered by electrostatic charges, which were recently produced at TU Delft. "I want to make these sorts of mini-robots a great deal smaller, quicker and more precise."

Making devices smaller reduces production costs and energy consumption, and allows working more precisely. Modern telephones are therefore packed with microscopic moving devices such as clocks, microphones, filters, switches and sensors. Making these types of devices even smaller and thinner is therefore a real advantage, as is making them faster and more precise. However, doing so presents a major challenge.

One way of reducing the size of the architecture is to use new materials, such as graphene: a membrane that is only 1 atom thick. Graphene is not only ultrathin, but is also very light and strong. These unique aspects make it possible to produce interesting new actuators and sensors. However, these architectures behave very differently at the nanoscale than at the microscale, making it difficult to measure and predict their behaviour. At the nanoscale, frictional and adhesive forces are also extremely strong; if two surfaces touch, it is almost impossible to separate them again.

Steeneken believes that there is only one way of moving architectures frictionless at high speeds over long distances: floating at the nanoscale. "At the large scale, we have aircraft and maglev trains, but at the microscale, it's already difficult to move and rotate floating objects. Over the past year, we've taken the first steps by making 100-μm-thick floating and rotating motors and switches that are powered by electrostatic charges. Understanding, quantifying and predicting the movement of floating microstructures is quite a challenge. However, if we're able to restrain them, they offer us new possibilities for significantly improving the performance of nanomechanical systems."

Such small, fast-moving, floating architectures could serve as sensors, mirrors or clocks. There are also potential applications in micromanufacturing, so Steeneken. "The advantage of floating microrobots is that they can be very cheap and can all do their work at the same time. Like ants in an anthill, they can create architectures with a precision and energy efficiency that is impossible to replicate with large machines."

WWW.PME.TUDELFT.NL

Sensor fusion and tracking toolbox

Last December, MathWorks introduced the Sensor Fusion and Tracking Toolbox, which equips engineers working on autonomous systems in aerospace and defense, automotive, consumer electronics, and other industries with algorithms and tools to maintain position, orientation, and situational awareness. The toolbox extends Matlab-based workflows to help engineers develop accurate perception algorithms for autonomous systems.

Engineers working on the perception stage of autonomous system development need to fuse inputs from various sensors to estimate the position of objects around these systems. Now, researchers, developers, and enthusiasts can use algorithms for localisation and tracking, along with reference examples within the toolbox, as a starting point to implement components of airborne, ground-based, shipborne, and underwater surveillance, navigation, and autonomous systems. The toolbox provides a flexible and reusable environment that can be shared across developers. It provides capabilities to simulate sensor detections, perform localisation, test sensor fusion architectures, and evaluate tracking results.

WWW.MATHWORKS.COM

Solar Team Eindhoven adopts Dezyne

The ambition of Solar Team Eindhoven is to build the most practical solar family car in the world and drive the use of solar energy to the next level through the use of smart innovation. The team's predecessors won the Bridgestone World Solar Challenge in 2013, 2015 and 2017, a feat that the 2019 team plans to repeat. Verum Software Tools, based in Waalre (NL), has decided to support Solar Team Eindhoven by sponsoring the team's software engineering activities with commercial Dezyne licences and technical support.
Squeezing the maximum amount of energy out of the Sun and converting it into motion requires, amongst other things, highly effective and reliable embedded software for controlling the power management system of the car and the control of the motor.

Building software with Dezyne is a first-time-right approach that results in a significant reduction of costs in the overall software lifecycle. Verum claims that Dezyne can speed up the development of control software by 300%, shorten development time by 20% and reduce field defects by 99.99%. By using Dezyne to build their control software, Solar Team Eindhoven will be able to rapidly innovate in software while also eliminating unpredictable and undefined behaviour, thereby achieving an unprecedented level of software robustness and reliability.

WWW.SOLARTEAMEINDHOVEN.NL
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Stella Vie, the 2017 version of Solar Team Eindhoven's solar family car. (Photo: TU Eindhoven, Bart van Overbeeke)

Two pilot lines for manufacturing integrated photonics

Photonics is an emerging technology with a potential multi-trillion market. Innovative SMEs are at the forefront of this development, but the R&D costs are prohibitive for them. That's why the European Commission has defined photonics as one of the six key enabling technologies of Europe and is heavily investing in this field. Recently, two EU-funded photonics projects kicked off in Eindhoven (NL).

The four-year project InPulse will offer new-entrant companies direct access to state-of-the-art manufacturing of photonic integrated circuits (PICs) based on indium phosphide. A new pilot line will enable innovators to develop products fast, for a wide range of new markets, thus being able to focus on their products rather than the technologically complex task of fabrication.

Currently there are only a handful of companies that can develop PIC-enabled products. They do this with their own in-house fabs (production lines), and a consequence is that start-ups with promising ideas have trouble entering the market. The InPulse manufacturing pilot line therefore enables new entrants to take their concepts from prototype to pilot production on industry tools and processes. InPulse connects the design process to manufacturing, testing and packaging to streamline the development cycle for businesses who do not own a fabrication plant or have production knowledge.

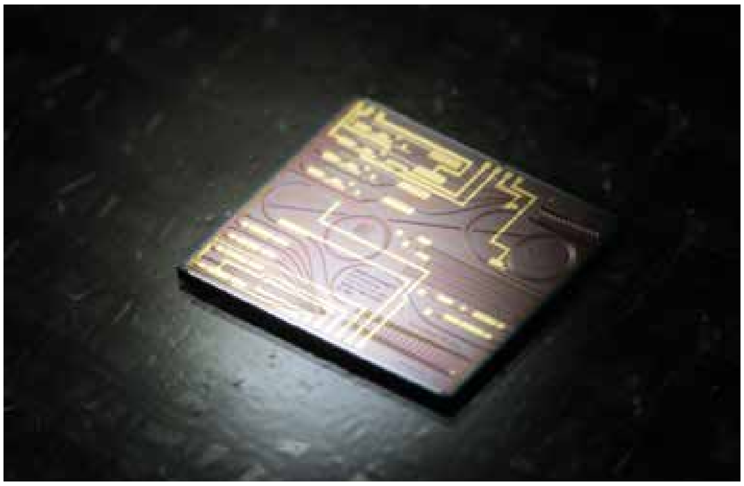
The project builds on the pioneering work of the Joint European Platform for Photonic Integration of Components and Circuits (JePPIX.eu), which is already offering PIC prototyping services. InPulse enables the transition to manufacturing. Support comes from the European Commission, the Photonics21 Public Private Partnership, and the PhotonDelta integrated photonics eco-system. Project partners include Eindhoven University of Technology (TU/e), European Photonics Industry Consortium (EPIC), Fraunhofer Heinrich-Hertz-Institut, Bright Photonics, Smart Photonics, Synopsys and Technobis Fibre Technologies.

The OIP4NWE project aims at creating an open-access pilot line that will drastically reduce costs and time for the pilot production of new products.

This new facility is projected to be the incubator of a thousand new companies and thousands of jobs. After two decades of basic photonics research, the first companies producing PICs are now taking off – sparsely. One of the main hurdles is the high cost involved in R&D. Not only does the PIC production require expensive high-tech equipment installed in cleanrooms, but currently the production processes still have a high defect rate and are too slow.

The new project, led by TU/e in collaboration with its Photonic Integration Technology Center, covers the realisation of an efficient pilot production line for shared use by European SMEs. It should take the defect rate in pilot production down and the throughput time will be shorter. All in all, this should lead to a cost reduction which significantly lowers the threshold for developing new photonic products. This should help establish a thousand integrated photonics firms within ten years after the project.

The front-end process (production of PICs on wafers) will be realised in the existing NanoLab@TU/e cleanroom. The PICs of different companies will be combined on one wafer to keep costs low. The back-end process is done at the Vrije Universiteit Brussel, Belgium (Optics for beam shaping and light coupling) and at the Irish Tyndall National Institute (Assembly of fibre-optic connections and electronics in the package). All steps require nanoscale precision to avoid product defects.



Photonic chip. (Photo: Florian Lemaitre)

WWW.PHOTONDELTA.COM
WWW.INPULSE.JEPPIX.EU
WWW.OIP4NWE.EU

Additive manufacturing process simulation

Siemens has introduced a new Additive Manufacturing (AM) Process Simulation solution for predicting distortion during 3D printing. The product is fully integrated into Siemens' end-to-end Additive Manufacturing solution, which assists manufacturers in designing and printing useful parts at scale.

When metal parts are 3D printed, the method used to fuse the layers of the print typically involves heat. As the layers build up, the residual heat can cause parts to warp inside the printer, causing various problems, from structural issues within the part itself to print stoppage. Simulation of the printing process can help to alleviate many of these problems.

Building on Siemens' comprehensive digital innovation platform and the Simcenter™ portfolio, the AM Process Simulation solution uses a digital twin to simulate the build process prior to printing, anticipating distortion within the printing process and automatically generating the corrected geometry to compensate for these distortions. This simulation is paramount for constructing a 'first time right' print, and necessary for achieving the efficiencies required of a fully industrialised additive manufacturing process.

AM Process Simulation offers the ability to iterate on a solution between the design & build tray set-up steps of the workflow, and the simulation step. The simulation data created feeds into the digital thread of information which informs each step of the printing process. This digital backbone enables the system to develop pre-compensated models and, more importantly, to feed those seamlessly back into the model design and manufacturing processes without additional data translation.

With underlying technology like XFEM analysis, the Simcenter 3D AM Process Simulation tool shows how the predicted distortion on the left is confirmed by the comparison of the real-world part to the original CAD data on the right.

WWW.SIEMENS.COM/PLM/ADDITIVEMANUFACTURING

PROGRESS IN **THERMAL CONTROL**

Just before Christmas last year, the High Tech Systems Center (HTSC) at Eindhoven University of Technology (TU/e) organised a Research Meet devoted to 'Advancements in Thermal Control'. Nowadays, thermal effects can play a critical role in the development of precision systems and machines. As accuracy, productivity and optimisation demands increase, it is paramount to further improve performance from the perspective of thermal control.

"Thermal problems are dominant in mechatronics control", said Frank Sperling, university researcher at HTSC and co-founder of Nobleo, when he introduced the topic of the Research Meet. Three years ago, this issue motivated the high-tech companies ASML, FEI/ThermoFisher Scientific, IBS Precision Engineering, Philips, VDL and Segula to initiate the Advanced Thermal Control Consortium (ATC Consortium). The primary objective of the consortium was to fund Ph.D. projects in this area, in collaboration with TU/e and Delft University of Technology (TUD). The ATC Consortium now operates under the wing of the HTSC.

The Research Meet provided a broad overview of the field, with excursions into thermodynamics and machine building. This last area was addressed by Theresa Burke, innovation director at IBS Precision Engineering. She talked about thermal control and compensation techniques in high-precision machining and the solutions IBS has developed, using instruments such as its Rotary Inspector for the calibration of 5-axis machines.

Two presentations concerned ATC Consortium-funded projects. Prof. Siep Weiland from the TU/e Department of Electrical Engineering addressed some of the more fundamental issues connected to modelling thermal systems. Modelling techniques based on energy exchange à la bond-graph methods are not readily translated to thermal systems. From a mathematical point of view, concepts that support bond graphs can be constructed, but they lack the 'natural' physical interpretation that we know from the mechanical and electrical circuit domains.

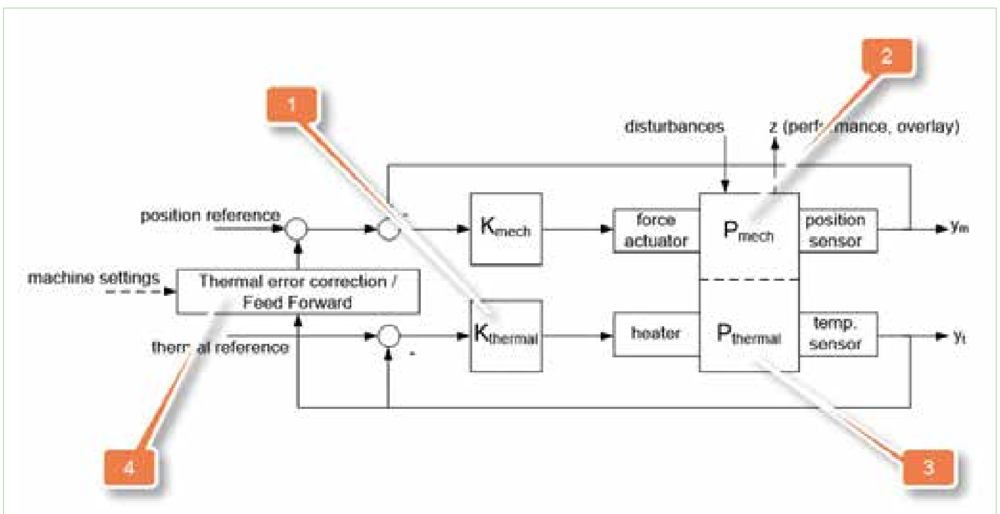
Fred van Keulen, TUD professor of Structural Optimization and Mechanics (SOM), discussed the integration of thermal effects in topology optimisation (TO). TO offers extensive design freedom resulting in complex geometries that can only be realised with additive manufacturing (AM). For example, AM-only cooling channels can be included in the design of a precision system in order to achieve optimal thermal performance. However, including (transient) thermal effects in the nonlinear optimisation increases the computational complexity. Delft researchers are addressing this issue, for example by exploring model reduction techniques.

To conclude, Joris van den Boom, domain leader active thermal control at ASML, presented some challenges and opportunities in developing advanced thermal control applications. In the next generation of ASML's EUV lithography machines, the resolution (or critical dimension) will be smaller than 10 nm, whereas the EUV source power will be raised to more than 200 W. So, thermal loads increase while unwanted structural displacements, e.g. those due to thermal deformations, have to be further reduced.

Naturally, design and modelling will be stretched to the utmost to prevent problems. For countering the effects of the remaining unwanted thermal loads, there are in principle two solutions. The first involves active control: not accepting thermal error loads and solving the problem in the thermal domain by feedback control using thermal sensors and actuators. The second method is error correction: accepting thermal errors and compensating for them in a different (mechanical) domain by estimating displacement and motion set-point adaptation. See the figure for the concrete issues addressed in the ATC Consortium-funded projects by ASML.

The forthcoming April issue of Mikroniek, featuring the theme of thermomechanics, will dive deeper into thermal control.

WWW.TUE.NL/HTSC



Main issues in thermal control research at ASML illustrated in the general thermomechanical control model:
1. *How to improve on deformation instead of temperature?*
2. *How to improve a design on thermomechanical behaviour?*
3. *How to improve thermal modelling including model reduction?*
4. *How to make a model real-time while still being accurate?*
   How to connect sensors to observer?

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