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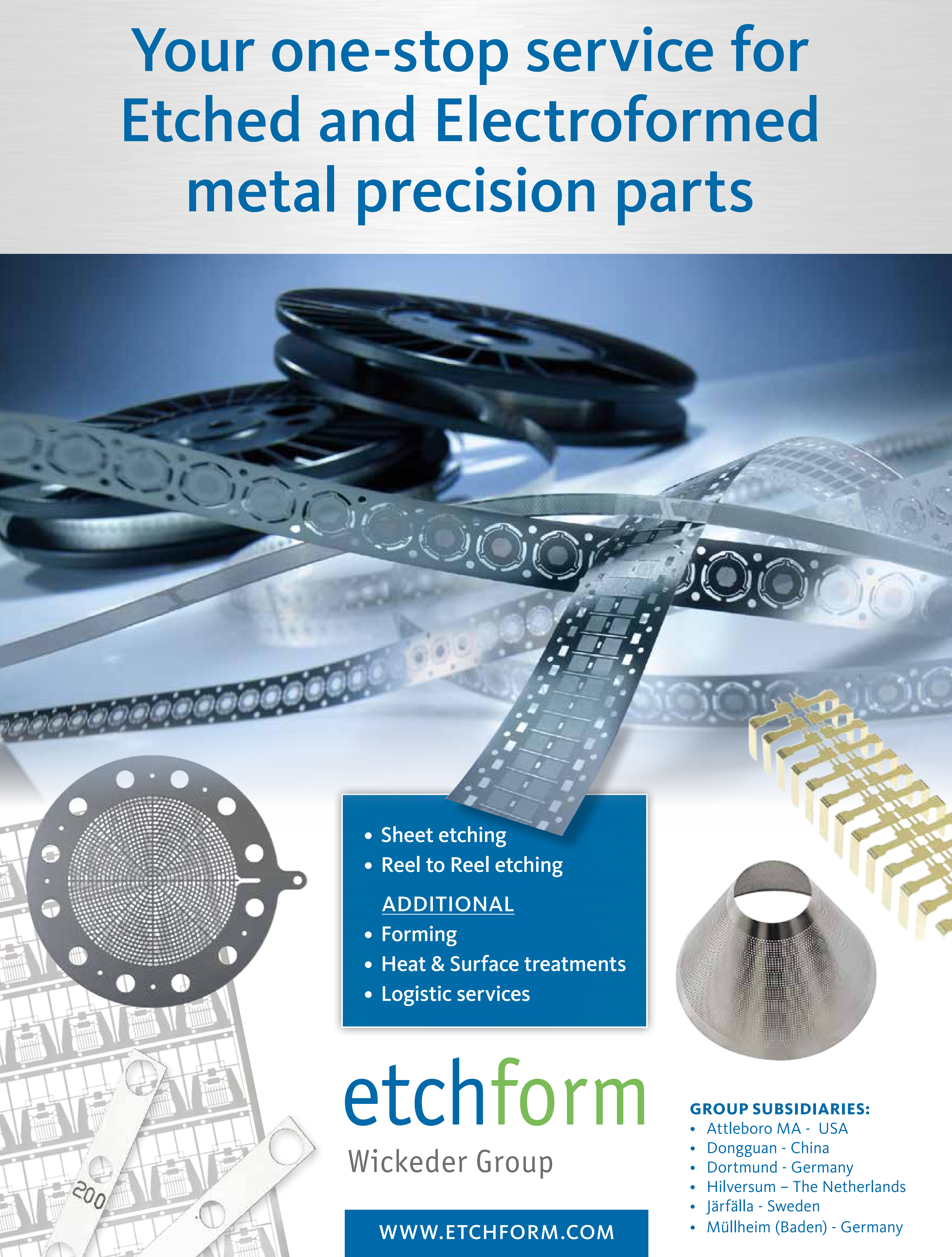
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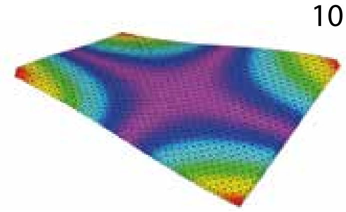

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FEATURES

PUBLICATION INFORMATION

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The main cover photo (the T-Flex parallel manipulator) is courtesy of Mark Naves, University of Twente. Read the article on page 19 ff.

PRESENTING THE CASE FOR DESIGN PRINCIPLES FOR PRECISION MECHATRONICS

The first phase in the realisation of a precision design principles 2.0 textbook has been successfully concluded. First results of this joint venture of Dutch precision mechanics and mechatronics professors, DSPE and the Dutch high-tech industry will be presented during the coming Precision Fair.

The Dutch design principles for precision mechanical engineering and mechatronics have been one of the pillars of the success of the Dutch high-tech industry for over fifty years. They originated from the Philips Centre for Manufacturing Technologies (Philips CFT) and were compiled by Wim van Der Hoek in the 1960s and 1970s. His successors Rien Koster, Nick Rosielle, Herman Soemers and Susan van den Berg refined and augmented Van der Hoek's The Devil's Picture Book (*Des Duivels Prentenboek*, DDP).

The reason for the success of the Dutch School of precision engineering is threefold. First and foremost, it presents a clear and powerful design approach based on principles such as statically constrained design, application of friction- and hysteresis-free flexures, and lightweight and stiff design. Next is the fact that all books present a variety of design examples that can be easily applied or serve as an inspiration for new designs. Moreover, all authors were or still are talented teachers who educated generations of engineers.

Two years ago, professors from the three Dutch universities of technology – Dannis Brouwer (Twente), Just Herder (Delft) and Hans Vermeulen (Eindhoven) – and the undersigned on behalf of DSPE decided to produce a new and fully reviewed version of DDP, building on the basic principles while adding new principles such as damping and over-actuation. The book will be titled "Design Principles for Precision Mechatronics" (DPPM).

Crucially, it was also decided to gather at least 100 new design cases, to be supplied by Dutch industry. To this end, an Industry Board was installed. From the very beginning, Industry Board members were very inspirational and really supportive in bringing all the cases together. This represents one of the strengths of the Dutch high-tech industry, the willingness to collaborate and share knowledge, which in the end will benefit the industry as a whole.

The Industry Board also declared that just a new book would be too limited in the current era of internet and digitalisation. Therefore, a website was developed to present 100 or more cases grouped according to the ten newly defined principles. This will offer optimal accessibility to engineers, as well as flexibility in expanding the collection of cases when engineers have become inspired to also share their knowledge.

At the forthcoming Precision Fair, on 16-17 November in Den Bosch (NL), we will present the results of the first phase in the realisation of DPPM: a website explaining the ten design principles and presenting at least 50 cases representative of the various principles. From then on you can be inspired by the first 50 cases and challenged to apply the underlying principles at *www.dspe.nl/knowledge/dppm-cases*.

As a non-profit organisation for and by engineers driven by a passion for precision engineering, DSPE offered a great network to build a strong Industry Board for DPPM. We are proud to contribute to publishing and disseminating this unique body of knowledge.

Pieter Kappelhof
Director Technology of Hittech Group and DSPE board member
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UPDATING DDP

An initiative to produce updated design principles for precision mechatronics has been developed by Dutch universities of technology in association with DSPE, in close collaboration with the Dutch high-tech industry. Building on the legacy of Wim van der Hoek, the Dutch doyen of design principles, the aim of the initiative is to collect over 100 cases that demonstrate the proper application of contemporary design principles. The cases will be presented on a dedicated website and collected in a new textbook, preceded by an extensive, in-depth introduction of the design principles.

Initiators

The initiative to update the design principles for precision mechatronics came from the professors of precision engineering and mechatronics at the three Dutch universities of technologies – Delft, Eindhoven and Twente – in association with DSPE.




From left to right:
Dannis Brouwer is professor of Precision Engineering at the University of Twente, Enschede (NL).
Just Herder is professor of Interactive Mechanisms and Mechatronics at Delft University of Technology, Delft (NL).
Pieter Kappelhof is vice president of DSPE, director of Technology at Hittech Group, located in Den Haag (NL), and hybrid teacher of Opto-mechatronics at Eindhoven University of Technology (TU/e), Eindhoven (NL).
Hans Vermeulen is part-time professor of Mechatronic System Design at TU/e and senior principal architect EUV Optics System at ASML, located in Veldhoven (NL).

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Production mechanisation

The Dutch school of design principles for mechanical precision engineering originated in production mechanisation at Philips, where in 1949 Wim van der Hoek (Figure 1) started working after having studied mechanical engineering at Delft University of Technology. In the 1950s and 1960s, production mechanisation generally concerned machines for assembling discrete products, such as electron tubes or semiconductor components, often with feeding, positioning and fixing processes, requiring accuracies of 1 micrometer or better at speeds of 2,000 to 3,000 products per hour. To gain a competitive advantage, better control was needed to improve positioning accuracies and increase production speed.

It prompted Van der Hoek, who was appointed part-time professor of Design and Construction at Eindhoven University of Technology in 1961, to focus on the dynamic behaviour of cam mechanisms. Through his work, he gained insight in the disastrous effect of backlash in a machine on the accuracy of movement and positioning, all under the dominant limitation of a mechanism's natural frequency (the first eigenfrequency). It helped him to predict the contribution of dynamics to positioning errors in a mechanism. It also resulted in qualitative and quantitative insight into the mechanical design measures that had to be taken to control these positioning errors. 'Stiffness' instead of 'strength' became the leading design paradigm.

The Devil's Picture Book

Van der Hoek included all this in his lecture notes, titled "Predicting Dynamic Behaviour and Positioning Accuracy

1

In 2020, DSPE published a book (in Dutch) about Wim van der Hoek, covering his career at Philips and Eindhoven University of Technology, his breakthrough ideas on achieving positioning accuracy and control of dynamic behaviour in mechanisms and machines, and their reception and diffusion. See also page 52 ff.

of constructions and mechanisms" (*Het voorspellen van Dynamisch Gedrag en Positionerings-nauwkeurigheid van constructies en mechanismen*). In addition, he started to collect examples of good and bad practices in precision engineering and included them in "The Devil's Picture Book" (*Des Duivels Prentenboek*, DDP). These cases were primarily intended as an invitation to engineers to consider their work in terms of design principles and, if possible, improve upon their designs.

The first topic in DDP was realising lightweight structures with high stiffness in order to raise the eigen-frequency of mechanisms in fast-moving machines; the second was avoiding backlash. The collection was soon extended to other topics: elastic elements, degrees of freedom, manipulation and adjustment, friction and hysteresis, guiding belts and wires, and energy management. Table 1 gives an overview of the design principles for accuracy and repeatability, the foundations for which were laid by Wim van der Hoek, and their evolution.

Evolution

In the last decades of the previous century, the design of mechatronic devices and machines such as CD players and lithography machines had raised the bar. To meet their challenging specifications, thermal effects had to be addressed more extensively and new design concepts introduced, such as:

- 'virtual' servo stiffness, to achieve good servo performance through high-bandwidth motion control;
- 'zero' stiffness, to eliminate disturbances due to contact with the (vibrating) environment via force actuators;
- dual stage, comprising an accurate short-stroke stage carried by a course long-stroke stage; and
- mass balancing, to filter out reaction forces to frames.

Driven by Moore's Law, mechatronic design rose to new levels of sophistication in the 21st century. This urged the design community to question established design principles, such as minimisation of hysteresis. The demand for ever-higher control bandwidths could no longer be fulfilled only by lightweight and stiff design. Therefore, passive damping,

Table 1
Overview of the design principles for accuracy and repeatability, as of ~1970, and their evolution, as of ~2000 (in green) and ~2010 (in red).

	Design principle	Implementation
1	Kinematic design	• Exact constraints • Mechanical decoupling via flexures and elastic hinges
2	Design for stiffness	• Structural loops with high static stiffness and favourable dynamic stiffness
3	Lightweight design	• Design for low mass and high eigenfrequencies
4	Design for damping	• Energy dissipation that slows down motion without introducing position uncertainty
5	Design for symmetry	• Symmetry in geometry and external loads • Over-actuation
6	Design for low friction and hysteresis	• Minimisation of friction and virtual play in high-precision structures, connections and guideways
7	Design for low sensitivity	• Thermal centre and thermal (compensation) loops with high stability • Low-expansion materials • Isolation of disturbances, e.g. via isolated metrology loop • Offset minimisation, e.g. Abbe principle and Bryan principle, and drive-offset minimisation relative to the centre of mass • High-bandwidth feedback control
8	Design for stability	• Minimisation of heat dissipation and microslip in interfaces • Minimisation of material creep and drift
9	Design for load compensation	• Weight compensation, reaction force compensation and (parasitic) stiffness compensation • Position-dependency compensation
10	Design for minimal complexity	• Balancing and hence minimisation of complexity and related cost via a multidisciplinary system approach

which was ignored for a long time to avoid the risk of position uncertainty by hysteresis, became a new design paradigm to further improve performance.

Just as revolutionary was the embracing of over-actuation, which strictly speaking violates the principle of kinematic design (with statically constraining the correct number of degrees of freedom), assuming that a force from a (Lorentz) actuator implies a particular parasitic stiffness. Over-actuation was needed to avoid excitation of internal mode shapes and thus design for symmetry became key, which required, for example, additional force actuators on actuated wafer chucks. This did not introduce significant uncertainty as long as the actuator stiffness remained small.

The design of more powerful actuators, for instance (variable-) reluctance actuators, also posed new challenges, such as nonlinearity and position dependency, which required new control and calibration strategies. Speaking of control, high-frequency dynamics and inertia effects in dynamic stiffness of actuators became dominant when designing for high bandwidth. Therefore, the focus of control shifted from the time to the frequency domain, i.e. from creating a favourable time response to shaping frequency response functions for robust controller design with good performance.

Legacy

As well as an evolution of design principles, there was also a succession of textbooks published over the years (see Figure 2). The second in the line was by Rien Koster, Van der Hoek's successor at both the Philips Centre of Manufacturing Technologies (*Centrum voor Fabricage Technieken*, CFT), and as a part-time professor (first in Eindhoven and later in Twente). He updated and restructured DDP, producing "Design principles for precise movement and positioning" (*Constructieprincipes voor het nauwkeurig bewegen en positioneren*), which was first published in 1996. This was later updated and translated into English by Koster's successor in Twente, Herman Soemers, who also worked for Philips CFT; "Design principles for precision mechanisms" appeared in 2010.

The latest addition premiered in 2019. "Design Concepts for Precision Engineering" by Susan van den Berg, lecturer at Fontys University of Applied Sciences, brings design principles education in a didactically sound manner to the higher vocational education level. The second edition (2021) is titled "Design Concepts and Strategies for Precision Engineering", to emphasise the design strategy perspective; see also page 32 ff. Appearing in 2011, parallel to the 'DDP line', was "The Design of High Performance Mechatronics" by Robert Munnig Schmidt *et al.*

Two years ago, it was concluded that a new update was required for the body of design principles. The initiative originated from the precision engineering and mechatronics departments at the Dutch universities of technology, in association with DSPE. The idea was to produce an up-to-date overview of the design principles for precision mechatronics in close collaboration with the Dutch high-tech industry. Building on the legacy of Van der Hoek's DDP, the aim is to collect over 100 cases that demonstrate the proper application of contemporary design principles.

The cases can be contributed by universities as well as companies. They should clearly illustrate actual themes in a manner that is comprehensible for a broader audience, both in industry and academia, and not cover a complete system; see the example on the next pages. In this way, they contribute to the 'collective' property of the design engineering community, which has grown steadily since the days of Van der Hoek. In return, engineers who contribute can gain 'eternal fame', receiving due credit for their cases, unless they wish to remain anonymous.

Planning

The cases will be presented on a dedicated website and collected in a new textbook, preceded by an extensive, in-depth introduction of the design principles. The website will be launched, partially complete, at the forthcoming Precision Fair. Publication of the textbook, containing a broad selection from the complete set of cases, is foreseen in 2025.

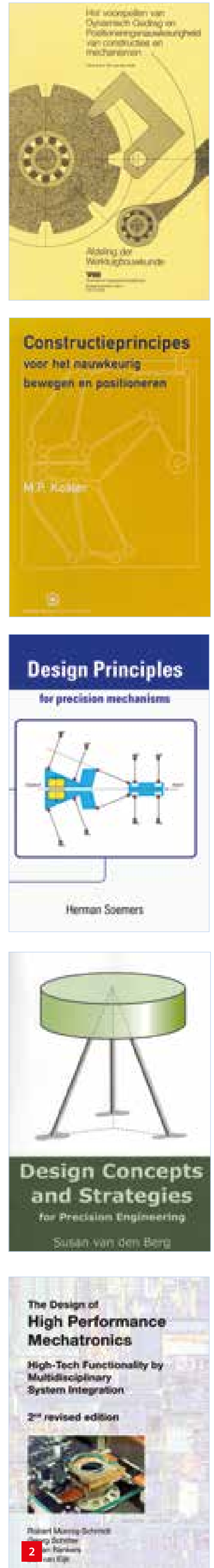
DPPM website

To be launched at the Precision Fair, mid-November.

WWW.DSPE.NL/KNOWLEDGE/DPPM-CASES

Invitation to industry

The initiators have already gathered broad industry support, embodied in an Industry Board. Currently, members include ASML, Philips, VDL ETG, JPE, IBS Precision Engineering, Hittech, Demcon, TNO, MI-Partners, Settels Savenije, Thermo Fischer, SRON, Van de Rijdt Innovation, Entechna and AC-Optomechanix. As well as acting as a sounding board, the main function of the Industry Board is to provide input. New members are welcome and companies are invited to contribute successful cases from their design track record.



Van der Hoek's textbook legacy; see the text for the titles.

DPPM case example

Symmetry in actuation – Over-actuation of wafer stages

Introduction

In his tutorial notes on precision instrument design [1], Teague recommends incorporating symmetry to the maximum extent possible in properties of machine elements (e.g. mass and force distribution or stiffness) in the entire instrument and in properties of the environment. When designing, manufacturing, assembling and operating a precision instrument, any departure from symmetry has to be weighed against the resulting compensation needed to overcome problems produced by the asymmetry.

To avoid thermal asymmetry, which can induce significant distortions of the machine components, a thermal centre as a symmetry axis for thermal expansions can be applied [2]. To overcome the effect of asymmetry with respect to the horizontal plane, caused by gravitational forces, machines can be equipped with a vertical axis; for example, see the LODTM [3]. Three-dimensional symmetry is achieved superbly by a tetrahedral structure, e.g. the Tetraform by Lindsey of NPL [4], [5], [6]. In addition to its proponents, Hocken mentions some arguments against symmetry [7], e.g. vibrational energy is not reduced by symmetric design, and in fact it is often enhanced.

Description

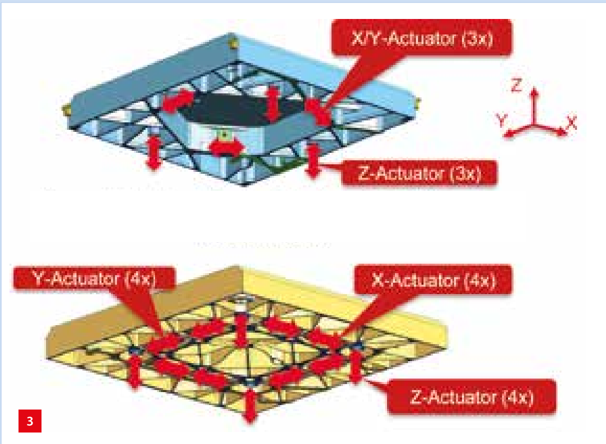
In semiconductor lithography stages, 6-DoF actuation was applied for a long time primarily to avoid unknown deformations of calibrated interferometer mirrors at the side edges of the so-called wafer chuck. Typically, three vertical and three horizontal actuators were applied in 120° symmetry (see Figure 3a), integrated into pockets for weight reduction and allowed to actuate in a horizontal plane more or less through the centre of mass, thus minimising the drive offset. Due to a small mismatch in practice, however, typically in the order of a few tenths of a millimeter, a moment load arises during acceleration, which has to be compensated for by the vertical actuators, either in push (upwards) or in pull direction (downwards). Over time, acceleration was increased to improve wafer throughput and, at the same time, better positioning accuracy was required in view of a tighter overlay budget in the lithography process. For that reason, higher control bandwidth was needed, which in turn enforced higher eigenfrequencies of vibration modes. Closed boxes were applied, and materials applied with a somewhat higher Young's modulus, which resulted in an increase of the first resonant frequency to above 1 kHz.
These improvements, however, were insufficient, and bandwidth increase was essentially limited by the (first) torsion mode that was effectively excited by the vertical actuators mentioned above, pushing and pulling the chuck to counteract the moment load due to the drive offset mentioned above.

To mitigate this fundamental limitation, over-actuation (Figure 3b) was considered and first tested in an over-actuated test rig at ASML (see Figure 4). An aluminium chuck was provided with three vertical actuators for traditional control (see Figure 5a) and next, four vertical actuators were used (Figure 5b). As long as force actuators are used, such as Lorentz actuators with (very) limited stiffness (position dependency) in the order of $1{\cdot}10^3$ N/m, hardly any over-determination is introduced. Here, over-actuation is essentially different from static over-determination, the latter introducing internal stress and uncertainty in shape. For both the traditional and the over-actuated case, the transfer functions from force to position and from moment to orientation angle were determined. By the application of X-Y symmetry via over-actuation, the excitation of the torsion mode, here at 130 Hz, was avoided, and as a result it disappears from the transfer function as experienced by the controller (Figure 6), allowing for a bandwidth increase from 65 to 205 Hz, even beyond the first natural frequency.

Principle	Application	Realisation
Application of symmetry in geometry and external loads to avoid excitation of resonant mode shapes.	Semiconductor wafer stage.	Test rig under closed-loop control to verify performance gain in terms of control bandwidth.

Development

Wouter Aangenent, Stan van der Meulen, Marc van de Wal, ASML Research (2014).



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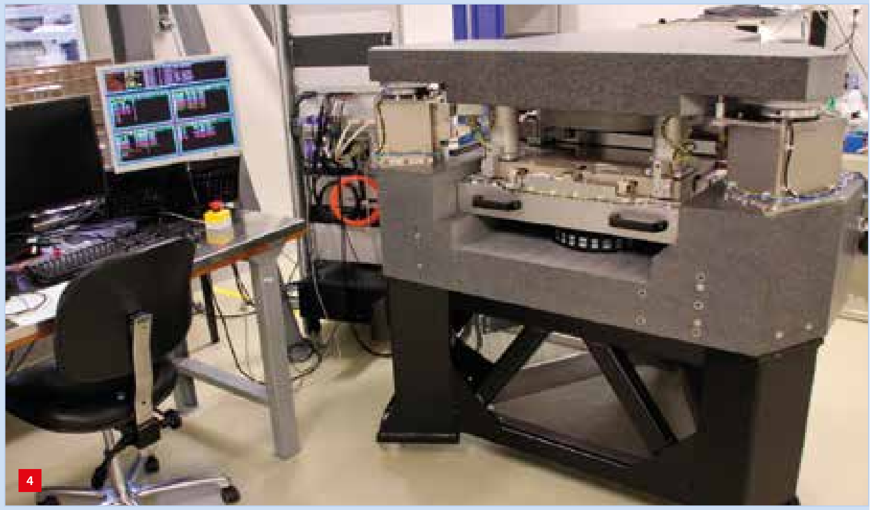

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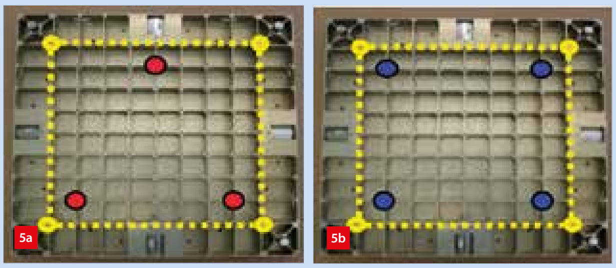
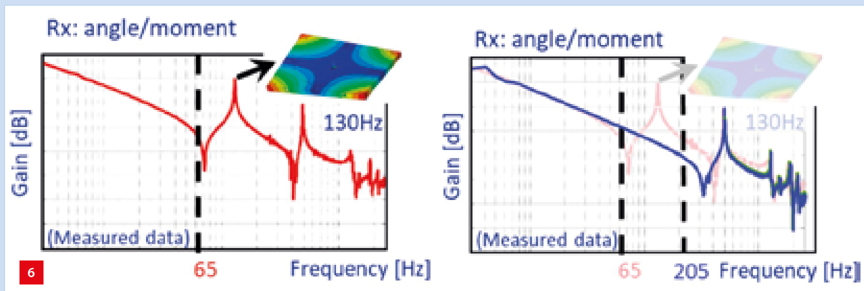
Over-actuated test rig at ASML Research.



5a 5b

Traditional (statically determined) actuation vs. over-actuation.
See text for explanation.
(a) Traditional control with 3 Z-actuators (red).
(b) Over-actuation with 4 Z-actuators (blue).



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Transfer function from moment to orientation angle (Rx) for traditional control (left) and over-actuation (right). Over-actuation avoids excitation of the torsion mode at 130 Hz (aluminium chuck), as a result of which it disappears from the transfer function, allowing for a bandwidth increase from 65 to 205 Hz.

REFERENCES

[1] Teague, E.C., "Basic concepts for precision instrument design: Designing instruments and machines to have a high degree of repeatability", NIST, Tutorial notes, ASPE Annual Meeting, Norfolk, VA, 1997.

[2] Vermeulen, M.M.P.A., Rosielle, P.C.J.N., and Schellekens, P.H.J., "Design of a high-precision 3D-coordinate measuring machine", *Annals CIRP*, vol. 47 (1), 1998.

[3] Donaldson, R.R., and Patterson, S.R., "Design and construction of a large vertical axis diamond turning machine (LODTM)", *Proc. SPIE Tech. Symposium*, pp. 433-438, UCRL. 89738, 1983.

[4] Lindsey, K., Smith, S.T., and Robbie, C.J., "Sub-nanometre surface texture and profile measurement with Nanosurf 2", *Annals CIRP*, Vol. 37 (1), pp. 519-522, 1988.

[5] Slocum, A., *Precision machine design*, Englewood Cliffs, NJ, Prentice Hall, 1992.

[6] Corbet, J., and McKeown, P., Course notes in precision engineering, School of industrial and manufacturing science, Cranfield University, UK, 1997.

[7] Hocken, R., "Principles active in the design of precision machines", course notes, 1995.

[8] Munnig Schmidt, R., Schitter, G., Rankers, A., and Van Eijk, J., *The Design of High Performance Mechatronics – High-Tech Functionality by Multidisciplinary System Integration*, 2nd revised edition, Delft University Press, pp. 850-853, 2014.

[9] Vermeulen, J.P.M.B., "Design of high performance mechatronic systems – Lithography example", Lecture notes, 4CC10 Mechatronics Design, Eindhoven University of Technology, 2021.

USING TRANSMISSION RATIOS AND MODE SHAPES FOR OPTIMISING PASSIVE DAMPING

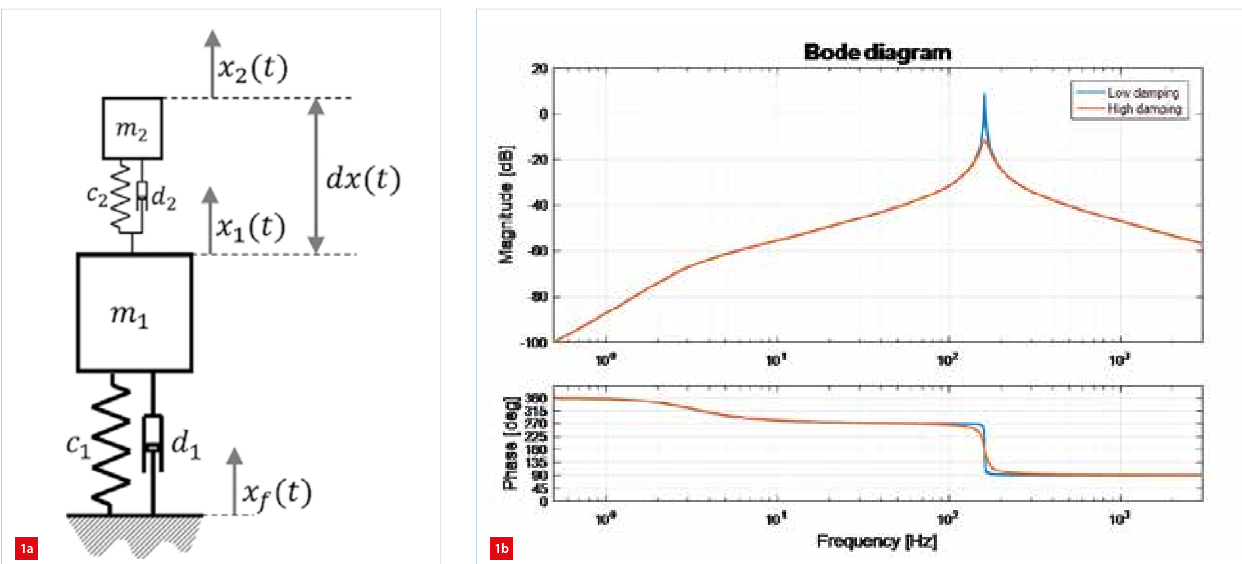
A broad range of mechanical engineering techniques, from smart design principles to advanced motion control, is available for achieving dynamic performance. Somewhere in the mix, however, the field of passive damping is often overlooked. This article attempts to extend the understanding of mechanical engineers towards thinking in terms of dynamics and mode shapes. To that end, analogies between stiffness and modal mass in terms of transmission ratios and their effect on system performance are presented. This may provide insight, not only for where to place passive dampers, but also more generally into how a control system 'feels' the different vibration modes.

KEES VERBAAN

Introduction

The precision machine building community finds itself continuously facing new challenges in terms of requirements for dynamic performance. Precision machines have become faster and more accurate over time and this trend has not stopped, and will not stop in the future, as far as we can look. A large range of mechanical engineering techniques is available for achieving dynamic performance, ranging from sophisticated mechanical design principles – such as statically determined design – to complex and intelligent control and software solutions, such as advanced motion control and feedforward solutions. Somewhere in between these topics, and often stepped over, is the field of passive damping.

Passive damping has been studied since approximately the 1960s [1], but for many years was not usually applied in precision machine designs. This is in contrast to many other fields, such as structural engineering and aerospace engineering, where passive dampers have been integrated into designs for many decades, to counteract disturbances from wind, traffic, earthquakes, etc. and effectively limit the resulting deformation – and thereby, stress – in these



The effect of damping on machine dynamics.
(a) Dynamic model with dx(t) as point of interest (POI), which is the relative displacement output between mass 1 and mass 2.
(b) The Bode diagram shows the transmissibility from floor vibrations to this POI: $dx(t)/x_f(t)$. The difference in damping value is visible at the resonance frequency around 160 Hz.

AUTHOR'S NOTE

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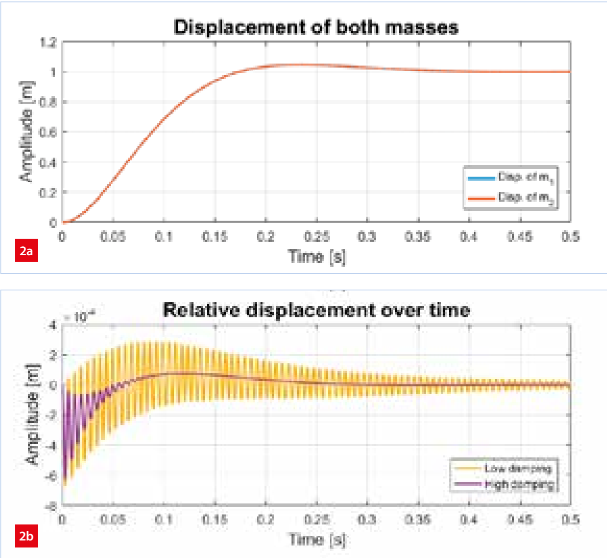


Responses of the system of Figure 1.
(a) Displacement of masses 1 and 2.
(b) Relative displacement between the two masses, at low and high damping values for the resonance at 160 Hz.

structures. The cause of this relatively late application of damping in the field of precision engineering seems to have a relation to the required accuracy of the high-tech systems involved. Accuracy, but primarily repeatability and reproducibility, need to be high, in contrast with the structures in other engineering fields that used damping much earlier. For these structures, mainly deflection was important, which relates directly to stress and safety factors. In the field of precision engineering, however, this is significantly different, as the focus lies on design for stiffness, low hysteresis, low friction, etc.
Over the last two decades, slowly but steadily, damping has been adopted in the field of precision engineering, enabled by improved computational power and ease of dynamic modelling. Material models have become more accurate [2], and experience has been gained in how to apply these materials in precision designs, as well as in dealing with the results in terms of system characteristics. Currently, this has resulted in multiple passive damper solutions in the field of precision machine design, even to being implemented in sub-nanometer precision machines.

The effect of damping

To zoom in on the topic of damping, we will divide precision machines into two categories, the first being fast machines that move quickly and need short settling times. These machines are typically limited in their performance by the high-frequency dynamics, which restricts the bandwidth of the feedback control loop and introduces transient oscillations in the settling phase (after the accelerations have ended). The second category includes machines that require good standstill performance.

In this case, the flexible dynamics is also problematic, as it is typically excited by various vibration sources, such as floor vibrations, acoustics, noise from electronics, etc.

In both cases, passive damping can help improve performance by adding damping to the flexible dynamics. For the first category of machines, this leads to short settle times, because the kinetic energy is dissipated more quickly. For the second category (standstill performance), higher damping values lead to less amplification of the oscillations at resonance frequencies, resulting in smaller steady-state vibration amplitudes.

As an example, Figure 1 presents a dynamic model of a machine. The input is – for simplicity – a random floor displacement spectrum (white noise), and the output is the relative displacement at the point of interest (POI), which is the position difference between the two masses ($\mathrm{d}x(t)$ = relative output). The transmissibility from floor displacement to relative displacement at the POI is given in Figure 1b, which clearly shows the effects of the vibration isolation characteristics at 3 Hz and the internal dynamics at 160 Hz. The blue curve shows the transmissibility for low modal damping on the flexible dynamics, the red curve for a tenfold increase of the modal damping. The result is a lower amplification factor (a lower resonance peak).

Figure 2 shows a step response of the two masses of Figure 1a in the upper plot and the relative displacement in the lower plot. When the modal damping of the resonance at 160 Hz is changed, the upper plot hardly changes, because its characteristics originate mainly from the isolation system at 3 Hz. However, the lower plot shows a significant difference in settling time. Figure 2b shows the effect of this damping increase, at the resonance at 160 Hz, on the POI and in the time domain. The increased decay rate of the oscillation is clearly visible.

Note that this difference in vibration amplitude is caused by the increased damping of the internal dynamics only. In addition, for motion-control systems it is the increase of damping at resonance frequencies that enables higher bandwidths (open-loop cross-over frequency at 0 dB). As damping is increased, the resonance peaks are attenuated (see Figure 1b) and higher feedback gains can be applied with equal stability margins.

Increasing natural frequencies first

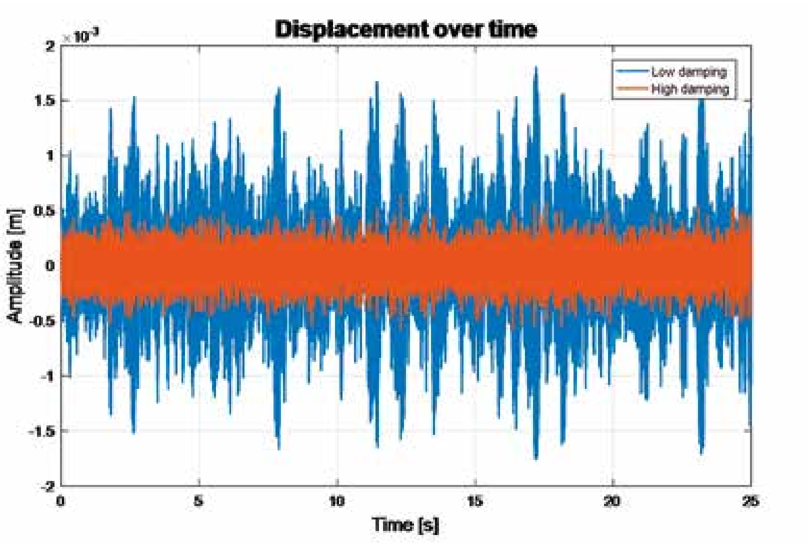
The field of passive damping adds a tool to the mechanical designer's toolbox. Once a mechanical design has been created according to the rules of precision engineering to maximise stiffness and minimise moving mass (i.e. maximise natural frequencies), damping can help to further improve performance.

Increasing the natural frequency basically solves the same problem as increasing the damping, is usually much simpler to implement and does not require additional calculational tooling and components such as dampers. Therefore, this order of engineering actions makes perfect sense. In Equation 1, the amplitude of a damped oscillation is shown as a function of time, where A_i is the initial vibration amplitude of the oscillation, ζ_i is the modal damping, ω_i is the natural frequency and φ_i is the phase shift of the oscillation.

$$x_i(t) = A_i e^{-\zeta_i \omega_i t} \cdot \sin(\omega_i t + \varphi_i) \qquad (1)$$

The first part ($A_i e^{-\zeta_i \omega_i t}$) describes the envelope of the sinusoidal oscillation over time. The expression in the exponent ($\zeta_i \omega_i t$) describes the rate of the amplitude decay as a function of time. This so-called exponential decay rate is influenced by the damping ratio ζ_i to dissipate energy in an oscillating system and equally by the natural frequency ω_i. By two times faster oscillations, settling time is shortened in the same way as by a twofold increase of the relative damping. This explains the need for high natural frequencies in a mechanical design. In addition, this high natural frequency helps to reduce the initial setpoint-induced vibration amplitude [3].

The second point is a more practical point and concerns the fact that damping is usually created by designing a damping device that makes use of a linear viscoelastic (LVE) material; see the text box. A specific group within the LVE materials are the rubbers, which are usually applied for damping applications around room temperature. In general (exceptions are possible), rubbers tend to show increasing damping values at higher frequencies, typically in the frequency range (100 Hz to a few kHz) that mechanical engineers are dealing with. This implies that the application of a rubber becomes more effective once a sound mechanical design has been created with high natural frequencies. To summarise: although there is new paradigm of designing for damping to improve performance, first the old paradigm of designing for high natural frequencies has to be pursued.



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Time domain simulations that clearly show the difference in displacement between the system with low damping (blue) and high damping (red).

Linear viscoelastic materials

Linear viscoelastic materials (LVE) show linear frequency-dependent damping. The damping is typically low for low frequencies and increases by orders of magnitude with increasing frequency. Beyond a certain frequency – depending on the material – the damping drops and ultimately vanishes. Control engineers typically deal with these characteristics every day when designing a lead filter, which shows the same characteristics as an LVE material.

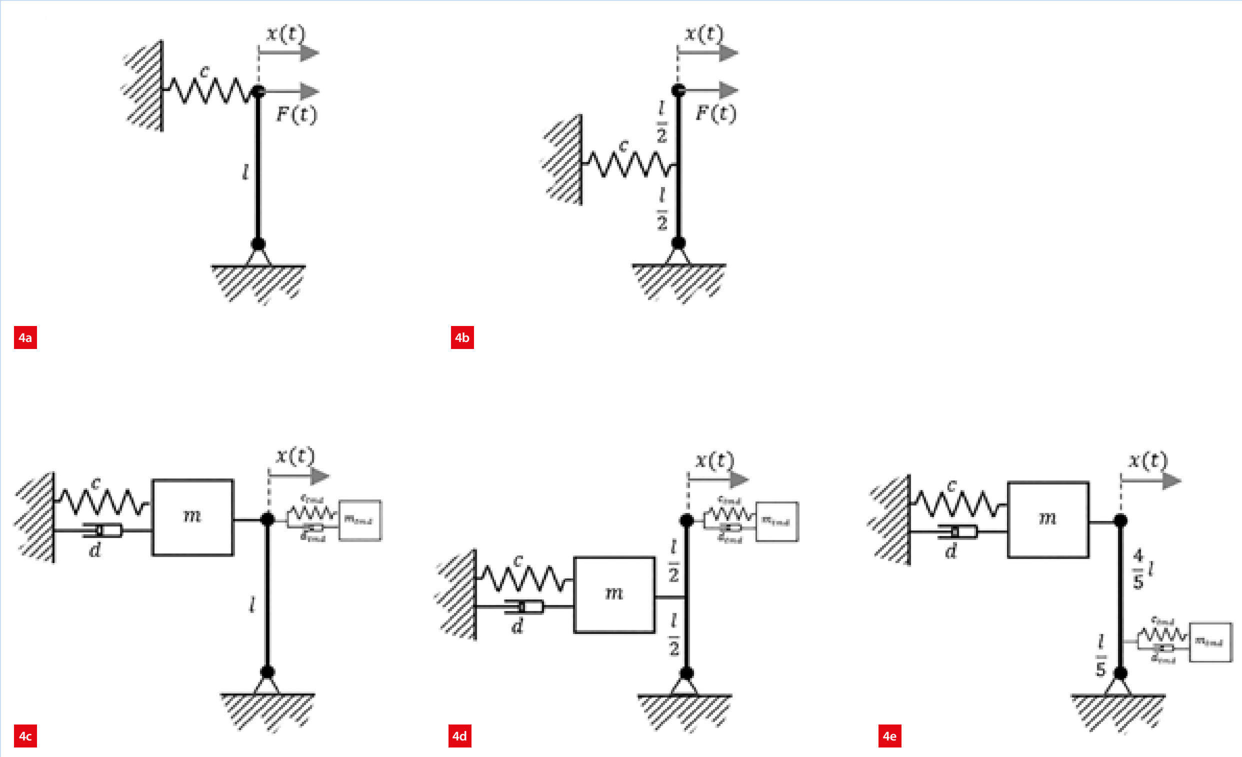
Although this feels as if it is 'nonlinear' material behaviour, it is not. This characteristic behaviour can be approximated with linear equations – mimicking a combination of springs and dampers (Maxwell model) – and, therefore, is linear system behaviour. Control engineers are familiar with this: a simple lead filter is a component from linear control theory.

Optimisation of damping

Increasing the damping of a mechanical structure in the field of precision engineering typically implies the design of additional, artificial damping mechanisms that increase the damping at the resonance frequencies; see the text box on the next page. These devices, such as tuned mass dampers (TMDs) and constrained layer dampers (CLDs), are well known and have been extensively described in literature [4,5], with many different variations on these topics. Analytical solutions exist for relatively simple problems, such as finding the optimal damping for a specific resonance frequency. For more complex problems, such as optimising the damping over a range of resonances, or optimising for other criteria (i.e. control bandwidth) including the behaviour of dampers, optimisation algorithms can help solving these questions [2].

Damper placement

An important question for engineers who want to apply damping to a structure, which has not been discussed extensively in literature yet, is where dampers should be placed to maximise performance. This depends on the type of damper, and for the remainder of this article we will dive into the placement of TMDs.



Analogy between design for high stiffness and optimal TMD placement.
(a) Effective stiffness with a transmission ratio of 1.
(b) Transmission ratio of 2, defined as output displacement x(t) over spring displacement, leading to a four times lower stiffness at the output.
(c) TMD acting on a mass-spring-damper via a transmission ratio of 1.
(d) TMD acting on a system with a transmission ratio of 2, leading to an effectiveness increase for the TMD.
(e) Transmission ratio of 1/5, leading to a very ineffective lever ratio, hence the TMD is 25 times less effective as compared to the case with a ratio of 1.

Damping devices for improving performance

Different methods of increasing damping exist, with the simplest option being to increase material damping. However, this is often hard to realise because structural materials are usually selected for other mechanical properties, and high stiffness usually implies low damping, unless composite materials are applied [6].
The alternative is to add a damping device:

- A tuned mass damper (TMD) device is specifically tuned to damp a certain natural frequency. It is very effective, but sensitive to parameter variations.
- A constrained layer damper (CLD) uses the deformation (strain) of a certain surface to add damping. It consists of a rubber (constrained) layer and a metal (constraining) layer, which is designed such that shear deformation is passed on to the rubber layer, which increases the damping.
- A robust mass damper (RMD) looks like a TMD from the outside, but uses a much higher damping value. The result is that it increases the damping at many resonances. Its disadvantage is the complex mathematics or models that need to be studied; simple analytical equations do not exist for these devices.

To be effective, dampers in general need velocity difference across them. TMDs need input displacement and velocity, so these add-on devices should be placed at locations where the displacement is maximal for the mode shape that needs to be damped, which implies that a certain understanding must be gained of the mode shapes present in the system at hand and how they manifest themselves in a dynamic system.

A TMD can be seen as an intrinsic local 'control loop', picking up the displacement and velocity at its mounting position and, in response to this, applying a reaction force back to the main structure. This description of a TMD is the mechanical equivalent of a local motion-control loop. Studying the optimal location for a TMD creates understanding about capabilities for dealing with resonances similar as in a feedback control loop. This is referred to as the observability and controllability properties of a structure [7].

In addition, the principles of damper placement are quite comparable to the rules we apply to design for high stiffness. Figure 4 shows the effect of a transmission ratio on the stiffness c that is felt at the output at point A, where force $F(t)$ is applied. In the case of Figure 4a, this is simply the stiffness c [8]. In Figure 4b, a transmission ratio of 2 is applied, meaning that the displacement $x(t)$ at point A equals two times the elongation of the spring attached at point B. This results in a total transmission ratio of 4 (defined as output divided by input), since both the force on the spring and the displacement at the output scale with the transmission ratio, which leads to doubling the elongation of the spring and a fourfold increase of the displacement at the output.

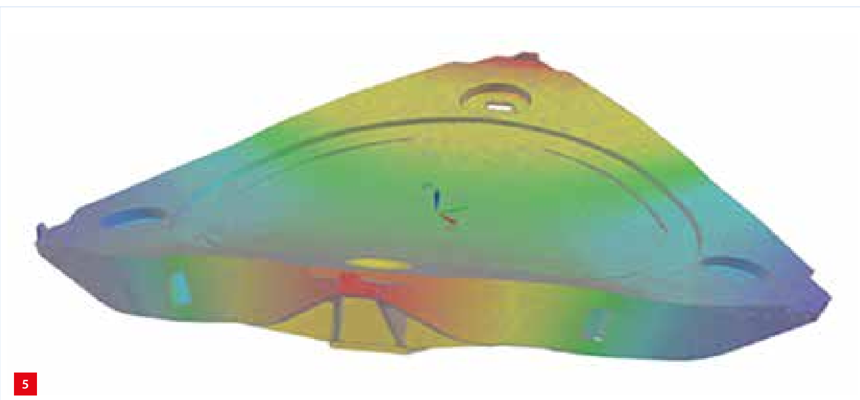
Transmission ratio impact

So, in general, the effective stiffness scales with the transmission ratio squared. This principle is well known to mechanical engineers, and an equivalent principle applies for damper placement on a mechanical system. This is shown in Figures 4c to 4e.

Figure 4c shows a lumped-mass-spring-damper system with one translational mode shape. The undamped natural frequency is determined by the spring and the mass, and a TMD is inserted to add damping to this mode. As a rule of thumb and supported by practical cases, 10% of the main mass m can be used as an educated guess for m_{tmd} to design an effective damper based on tuning rules according to [4].

Figure 4d shows the same same TMD mass attached to the main mass, but now via a transmission ratio equal to 2. The displacement $x(t)$, fed into the damper, equals the displacement of mass m multiplied with the transmission ratio. The force produced by the damper is also multiplied by the transmission ratio before it acts on mass m. Effectively, the TMD mass now feels only a fraction of the main mass m. This implies that the transmission ratio squared is also present in this case, leading to the conclusion that the TMD mass of Figure 4d can be 25% of that in Figure 4c with exactly the same effectiveness on a system level.

Likewise, the effectiveness of the TMD in Figure 4e decreases by a factor of 25 with respect to Figure 4, hence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First flexible mode of a 450-mm wafer chuck (mass about 23 kg). The natural frequency, calculated using finite-element analysis, is approximately 1530 Hz. This mode, called the torsion mode, mainly shows displacement in vertical direction.

a 25 times mass increase is required for the TMD to obtain the same effectiveness. Between Figure 4d and Figure 4e the efficiency difference is even a factor of 100. When the TMD is moved even further towards the pivot point, its effectiveness on the main system decreases to zero. Here, the modal mass that is felt by the TMD goes to infinite.

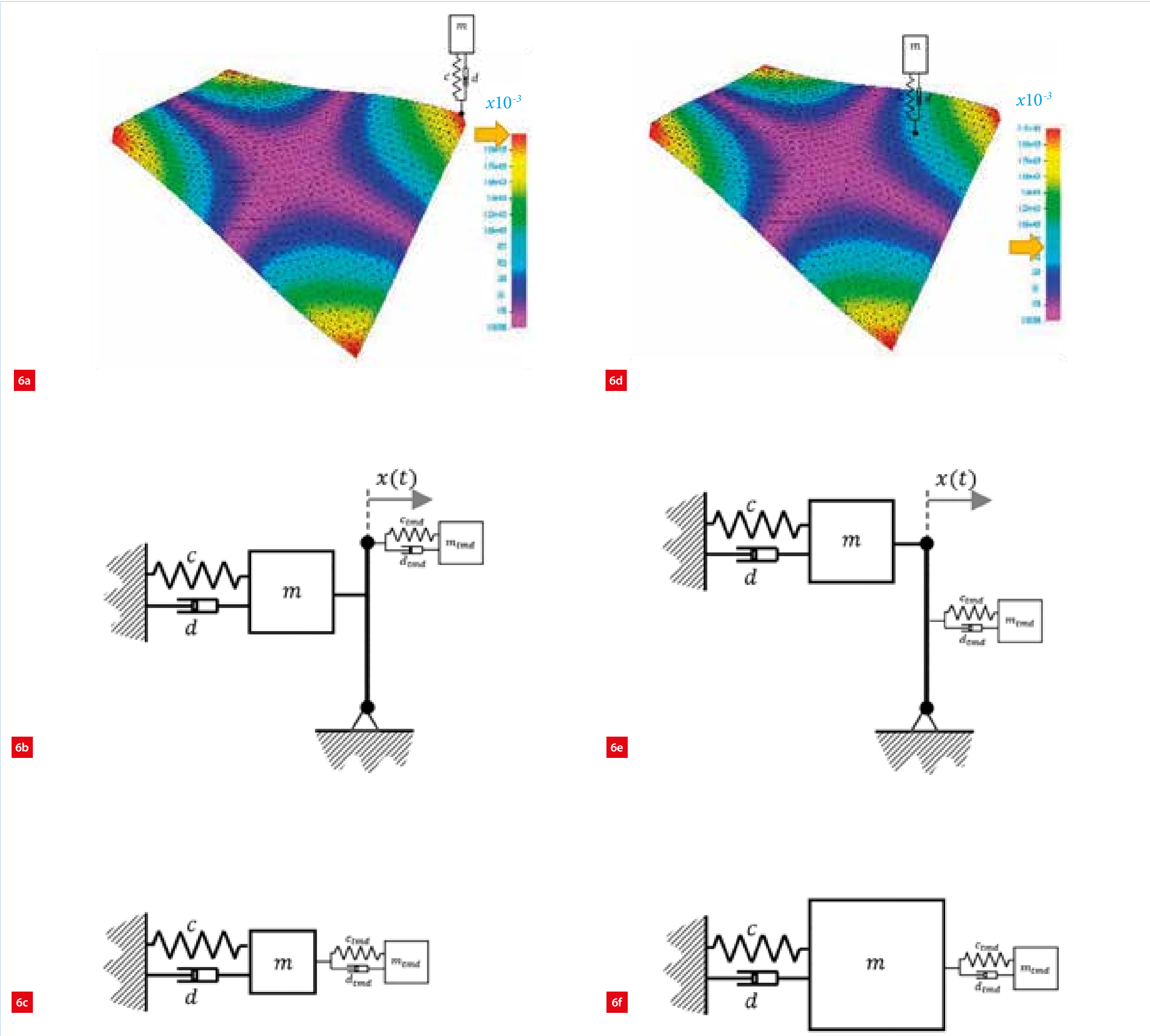
An ‘inverse way’ of thinking about the system is to look at it from the TMD side: the effectiveness of a TMD changes as a function of its location (the transmission ratio). This implies that the main mass that is felt by the TMD (called modal mass) changes with the position of the TMD. This is exactly what happened in Figure 4 when the transmission ratio changed; it affects the apparent modal mass of the main system as felt by the TMD. This observation is key to understanding mode shapes and the way they interact with other components in the system.

Mode-shape representation

Usually, the mode shapes of precision designs are more complex than the versions in Figure 4 and show complex dynamics of multiple components in different directions. Nevertheless, one particular mode can be modelled as a single mass-spring-damper system in order to study the effectiveness of a TMD implementation. In this case, the transmission ratio is not visible as shown in Figure 4, but is present in the form of the mode shape. An example of a more complex mode is shown in Figure 5, which is the first flexible mode (torsion mode) of a cordierite 450-mm wafer stage.

A simplification of this is presented in Figure 6, which shows the torsion mode for a flat plate. The natural frequency is different, but the same principles for damper placement apply. The goal is to increase the modal damping of this mode. The effect of different TMD locations is shown in Figure 6. Figures 6a, 6b and 6c show the effect of damper placing at the preferred location for this mode shape, where modal displacement is maximal. At this plate corner, the modal factor (or transmission ratio) is 2.11. This leads to a relatively high transmission ratio (Figure 6b), which is fundamentally equivalent to applying the TMD to a small main mass (modal mass). The modal mass m in this case is 0.225 kg.

In Figure 6d, the TMD has been moved towards the centre of the plate. The displacement is approximately 2.8 times less, giving a modal factor of 0.75 and leading to a much less effective transmission ratio, as shown in Figure 6e. This is essentially the same as applying the TMD to an eight times higher modal mass, visualised schematically in Figure 6f. This example shows that damper placement is key to effective suppression of vibration amplitude at a particular resonance frequency with corresponding mode shape, thereby increasing the modal damping of a structure.



TMD placement on a structure. The upper figures (a and d) show the application of a TMD on a plate in two different positions. The middle figures (b and e) show the transmission ratio induced by the mode shape. The lower figures (c and f) show the representative dynamic model. Note the difference in effective mass in the lower two figures.

In pursuing optimal performance for a particular TMD mass, it is key to understand and to apply this approach correctly. A vibration mode can be damped at any location on the structure as long as there is modal displacement, but the effectiveness varies significantly. The induced change in damping will manifest itself in the total mode shape, regardless of the position where a measure of this mode is taken. Practically, this means that if a certain mode is damped at one corner, the other corner will experience the same amount of modal damping, because a mode (mode shape) is damped, not a node (a certain location on the structure). Consequently, a certain mode shape leading to high resonances in a control loop from actuator to sensor, can often can be damped more easily by a TMD at another location (not necessarily the location of the sensor), where the displacement of this mode is maximal. At this location the TMD-mass can be relatively small.

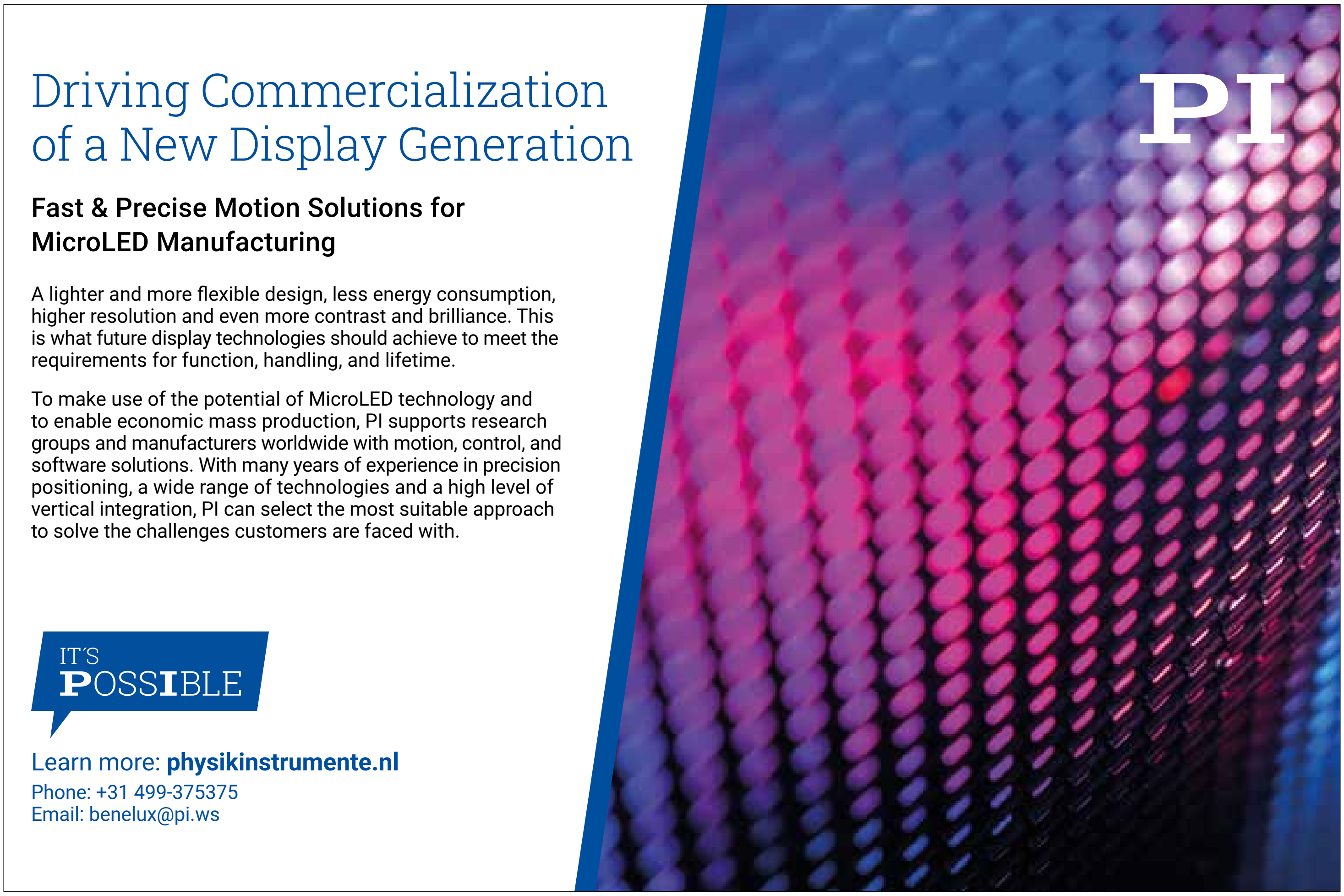
Conclusion

To summarise, the larger the modal factor (visualised as displacement in FEM results) the larger the transmission ratio (modal factor) and the lower the TMD mass required to be sufficiently effective. This implies that a TMD needs to be located at a position where the displacement – and thereby the velocity – is maximum for a certain mode shape. Intuitively, this feels right for engineers. The opposite way of thinking is usually a bit more counterintuitive: the larger the displacement at the TMD mounting location, the smaller the modal mass of the main system is. It is apparent, based on the example above, that the knowledge to understand modes in a broad sense is the key to an effective design for damping. Understanding this makes life relatively simple, because all mode shapes can be transformed into single-DoF (degree of freedom) dynamic systems, from which damper effectiveness can be calculated relatively simply.

This article has made an attempt to connect to the understanding of mechanical engineers and extend it towards thinking in terms of dynamics and mode shapes and attenuating vibration amplitudes through passive damping. To that end, the analogies in terms of transmission ratios and their effect on system performance have been used: the same quadratic equation for transmission ratios holds for stiffness and mass. In general, understanding this matter gives clear insight into not only where to place the dampers, but also in a broader sense into how a control system 'feels' the different vibration modes.

REFERENCES

[1] Den Hartog, J.P., *Mechanical vibrations*, Courier Corporation, 1985.
[2] Verbaan, C.A.M., "Robust mass damper design for bandwidth increase of motion stages", Ph.D. thesis, Eindhoven University of Technology, 2015.
[3] Koster, M.P., Rosielle, P.C.J.N., and Reker, E., "Constructies voor het nauwkeurig bewegen en positioneren (6)", Mikroniek, vol. 32 (3), pp. 68-72, 1992.
[4] Schultz, A.B., and Tsai, S.W., "Dynamic moduli and damping ratios in fiber-reinforced composites", Journal of Composite Materials, vol. 2 (3), pp. 368-379, 1968.
[5] Marsh, E.R., and Slocum, A.H., "An integrated approach to structural damping", Precision engineering, vol. 18 (2-3), pp. 103-109, 1996.
[6] Vermeulen, J.P.M.B., "Ceramic optical diamond turning machine: design and development", Ph.D. thesis, Eindhoven University of Technology, 1999.
[7] Gawronski, W.K., *Dynamics and control of structures: A modal approach*, Springer Science & Business Media, 2004.
[8] Rankers, A.M., "Machine dynamics in mechatronic systems: An engineering approach", Ph.D. thesis, University of Twente, 1998.



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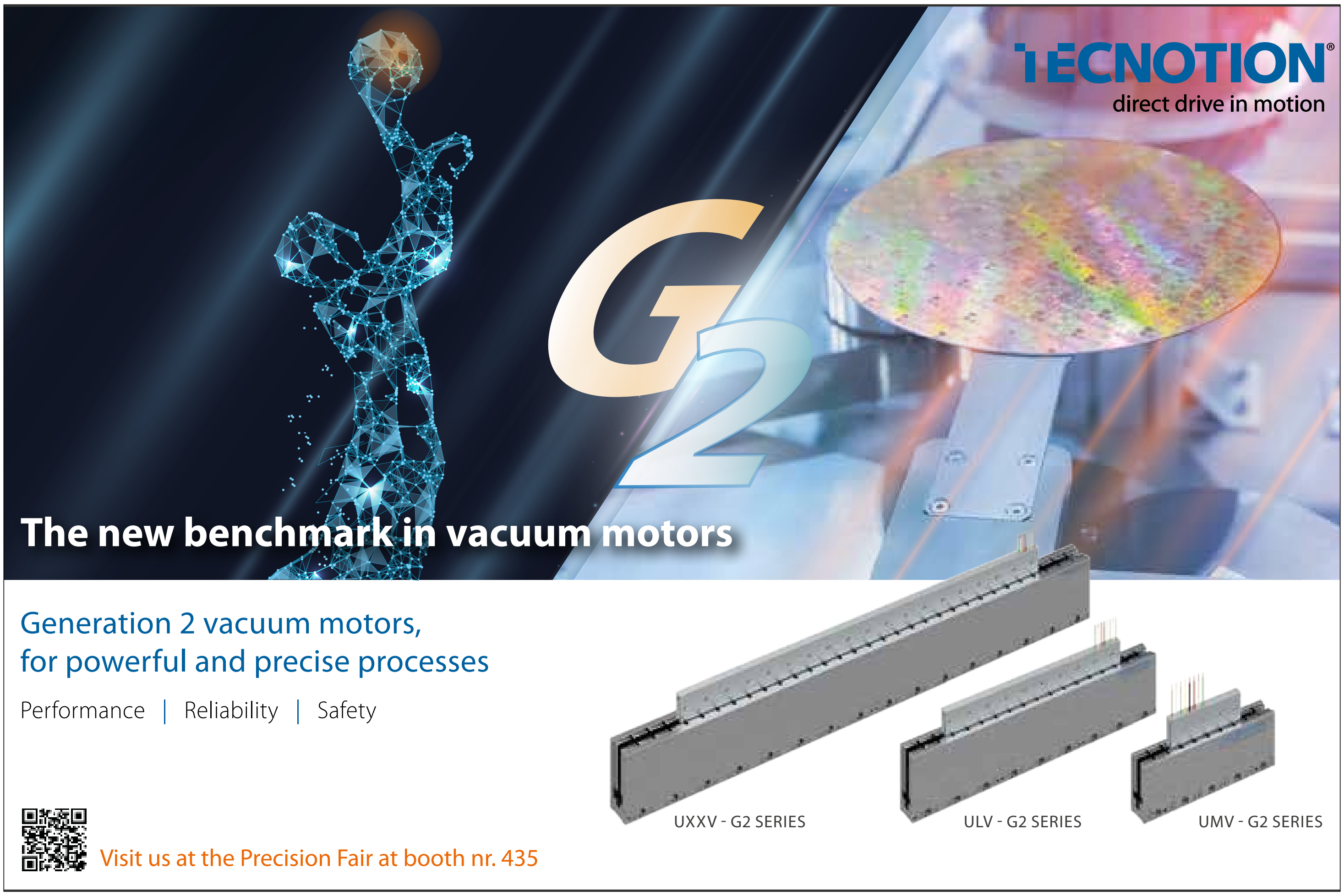

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REPEATABLE POSITIONING AND ACCURATE TRACKING WITH T-FLEX

Exploiting recent developments in flexure design, a large-stroke flexure-based parallel manipulator has been built. The hysteresis-free flexures enable high positioning repeatability, while the predictability of the dynamics allows for high-accuracy tracking by feedforward control. After the earlier introduction of the T-Flex, this article elaborates on its design, prototype realisation, control strategy and experimental results. Attention is also paid to the challenge posed by the absence of play and friction; the smallest variations in actuation force transfer to platform displacements directly. Design modifications to counteract this are discussed.

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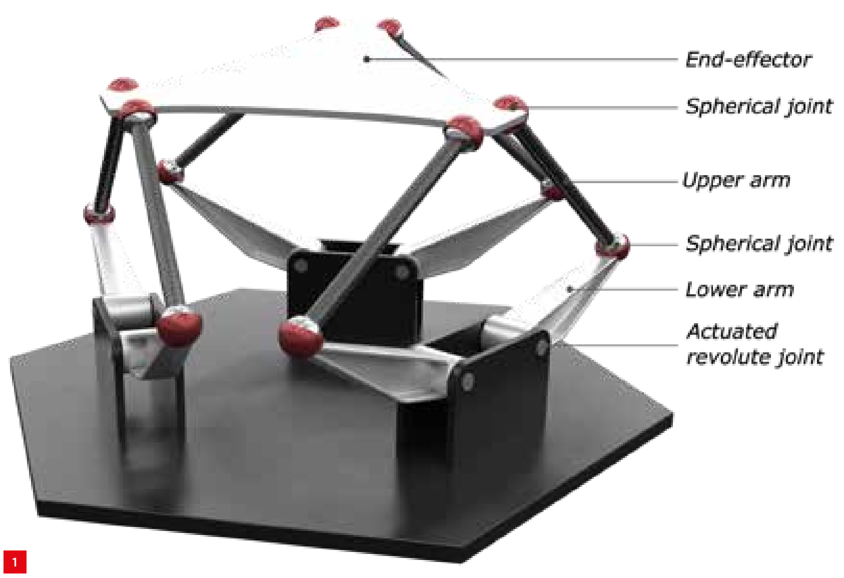
Introduction

High-precision parallel kinematic robots with traditional bearings allow for a repeatability up to a few tenths of a micrometer. To improve the precision of parallel manipulators, play and friction in the joints and actuators should be reduced or eliminated. To do so, traditional bearings can be replaced by flexure-based equivalents to enable motion that relies on elastic deformation of slender elements, instead of tribological contacts. However, the current state-of-the-art parallel manipulators with flexure joints suffer from a limited range of motion of less than 10 mm of translational travel range. Also, they often rely on walk-drive-type or inertia-drive-type piezoelectric actuators, which suffer from wear, limit the maximum actuation force and restrict the maximum travel speed to about 10 mm/s.

Following recent developments in large-stroke flexure joints and optimisation strategies [1], a flexure-based hexapod with a larger travel range, faster travel speed, higher load capacity and high repeatability has been developed by the Precision Engineering group at the University of Twente: the T-Flex. In this article we further elaborate on the design, prototype realisation, control strategy and experimental results of the T-Flex, which was introduced in *Mikroniek* in 2019 [2].



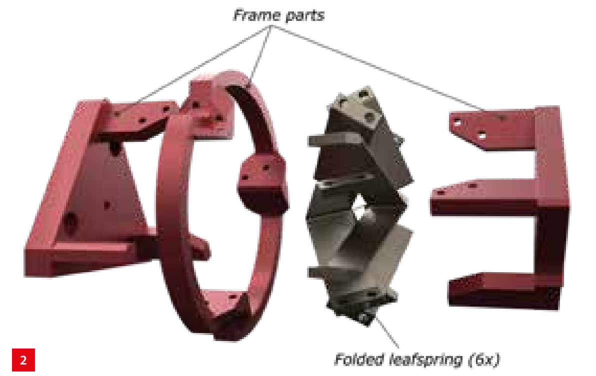
1

Schematic overview of the T-Flex layout.

Design

The T-Flex is based on a hexapod layout consisting of six links that support the end-effector (Figure 1). Each link consists of an upper arm connected via two spherical joints to the end-effector and the lower arm. The lower arm is connected to the base with an actuated revolute joint. The spherical joints are based on a two-stage folded-flexure joint design (Figure 2, [2]).

The actuated revolute joint at the base is actuated by an iron-core torque motor capable of delivering an ultimate output torque of 55 Nm (Figure 3, [3]). This actuator has been selected to enable a high load capacity (20 kg) and high accelerations (more than 10g). Due to the iron core and permanent magnets, large attraction forces can occur; these remain manageable by ensuring minimum parasitic shift of the rotation centre (otherwise causing high parasitic forces) and obtaining high support stiffness and load



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Exploded view of the spherical joint.

capacity. Furthermore, high support stiffness is required to provide resistance to the large reaction forces at the base. This is realised by using two flexure-based elements at each side of the rotor, based on an adapted butterfly hinge design.

The T-Flex has been designed and optimised for a large cubic workspace of at least a 100 mm x 100 mm x 100 mm with maximum support stiffness throughout this work-space. A more detailed description of the optimisation process and design of the T-Flex is provided in [4].

A photo of the realised prototype is shown in Figure 4, where the spherical flexure-based joints can be recognised by the aluminium frame bodies anodised in a red colour. From top to bottom, it consists of a triangularly shaped end-effector from riveted aluminium sheet metal, six spherical flexure joints, each connected via a carbon tube (the upper arm) to the lower spherical joints.

These joints are attached to the actuated revolute joints at the base, represented by the butterfly hinges at each side of the rotor in a brown-grey colour. Each actuated base joint is supplemented by two balance masses to create a centre of mass near the rotation centre of the base joints, minimising reaction forces due to accelerations and reducing the static forces necessary to maintain a position in its workspace.

Absolute encoders have been selected to be able to cope with the required high speed-to-resolution ratio. Video footage of the T-Flex [V1] includes detailed animated exploded views.

Control

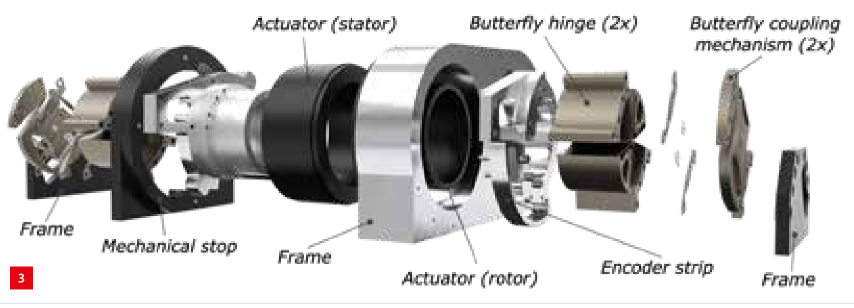
Accurate positioning is possible because of the absence of static friction in the system, which means that no limit cycling will occur when using integral control action. On the other hand, the absence of friction also makes the system susceptible to disturbances at standstill. In particular, the system will be sensitive to the noise on the provided current to the actuators, which is amplified by the high motor constant of the actuators required for the high torque output.

For designing the controller, the transfer functions between actuator torques and encoder positions of the T-Flex were estimated at the undeflected position. These are shown in Figure 5. As the lower arms of the hexapod have a relatively high inertia – among others resulting from the balance masses, the heavy rotor of the actuator containing the permanent magnets, and the mass of the lower arm – cross-talk between actuators and encoders (at different base joints) is relatively low in the frequency range up to the first parasitic frequency (between 56 and 70 Hz throughout the workspace).

The system is diagonally dominant (low cross-talk), with similar transfer functions on the diagonal due to the system's symmetry. Therefore, a decoupled feedback control strategy was adopted with six identical single-input single-output (SISO) controllers. These controllers were tuned to suppress the current noise, which is the dominant error source for stand-still positioning. The transfer from current noise to position error is given by the process sensitivity. Below the open-loop gain cross-over frequency, the process sensitivity is approximately the controller's inverse.

High noise suppression is achieved by a high control gain, resulting from integral action and a high cross-over frequency. Beyond the cross-over frequency, the process sensitivity is approximately the transfer function of the plant, which is a series composition of the built-in current controller of the drives and the mechanism.

Noise suppression at high frequencies is obtained by setting the bandwidth of the current controller only a bit higher than the cross-over, resulting in additional roll-off in the plant. Furthermore, the balance masses attached to each rotor result in a high equivalent mass and thereby contribute to a low gain of the plant at high frequency. At the bandwidth, the noise amplification is limited by sufficient phase margin, which is realised by differential control action and a limit on the bandwidth relative to the sampling frequency. Eventually, a PID controller was tuned to an open-loop cross-over at 20 Hz with 44° phase margin.



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Exploded view of the actuated revolute base joint.

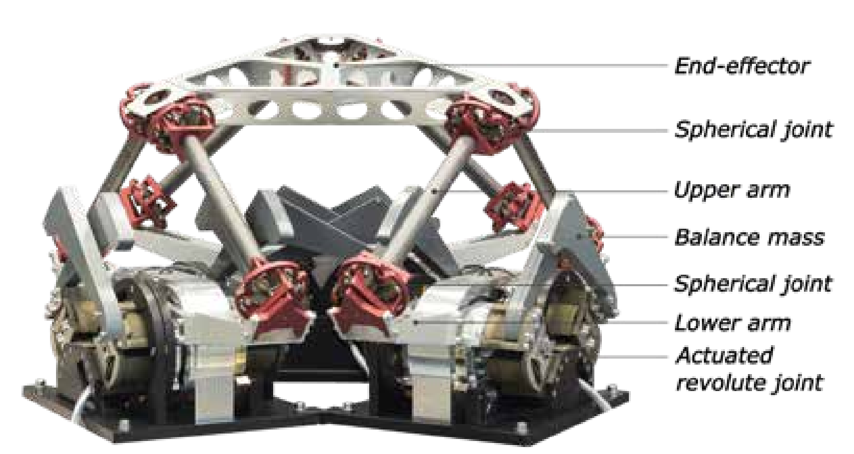

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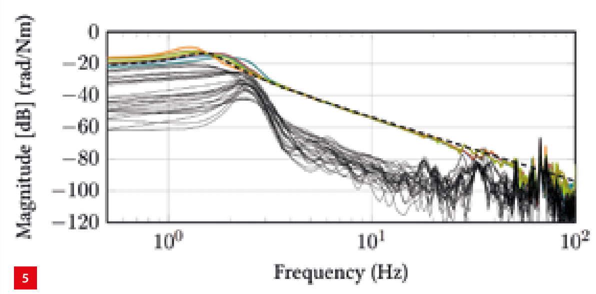
Photo of the T-Flex with the end-effector (at the top) at the centre of its workspace and tilted by 10°.



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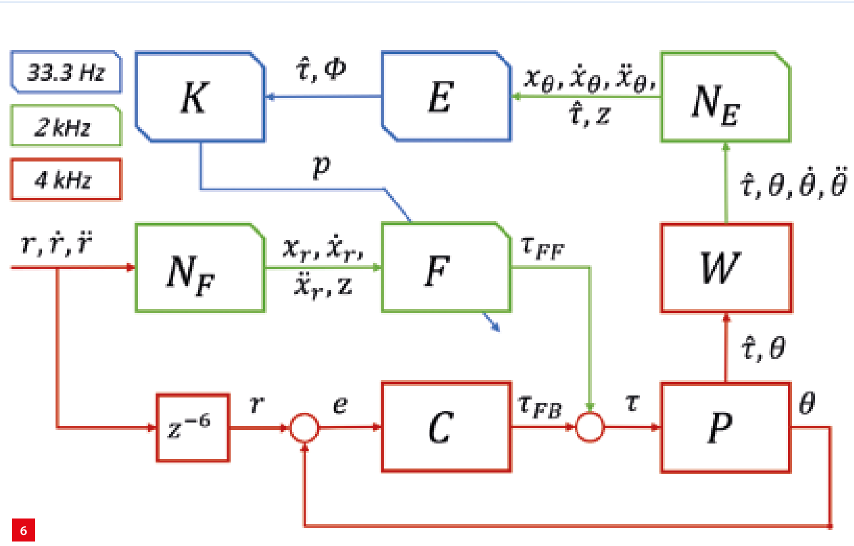
Identified transfer function from the actuator torque to rotor position in the undeflected position. Coloured lines provide the six transfer functions between actuator and encoder position of the same joint. The solid black lines represent cross-talk between different actuators.

High tracking accuracy is realised by adaptive feedforward control, which exploits the high predictability of the system's flexure mechanics. The feedforward torque is computed from the reference trajectory using an inverse-dynamics model. The feedforward model includes the rigid-body dynamics, the elastic forces in the joints and the cogging and hysteresis of the actuator. These dynamics are linear in a set of 162 parameters related to the inertia, joint stiffness and actuator dynamics, and they are adapted every 30 ms using Kalman filtering [5]. A schematic overview of the control strategy is provided in Figure 6.

Experimental validation

Repeatability was tested by moving the end-effector repeatedly in a direction with a bi-directional displacement of ±100 μm (in this case in the vertical z-direction) at an interval of 2.5 s combined with a displacement of +50 mm at an interval of 17.5 s. During this test, the position of the end-effector was measured via an additional sensor fixed to an external frame.



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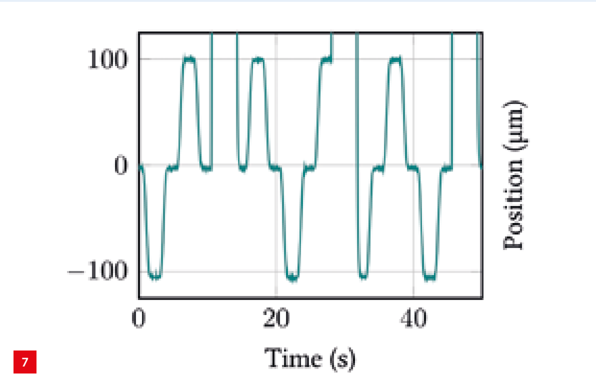
An overview of the control strategy for the T-Flex, adopted from [5]. P is the interface to the motor drivers of the T-Flex, which outputs the measured torques $\hat{\tau}$ and angles θ. C represents the feedback controller. N_f and N_e are Newton-Raphson procedures used to determine the configuration of the system (x) based on the measured angles (θ) or the reference angles (r). F computes the feedforward signal. The feedforward controller is adapted based on the estimated parameters p. W filters the incoming signals and estimates derivatives. E computes the regression matrix. K is a Kalman filter that estimates p. z^{-6} is a delay of 1.5 ms used to synchronise the feedback and feedforward reference signals.

Figure 7 shows the highly repeatable behaviour of the system, with a sub-micron repeatability independent of the direction of movement. This is a result of the absence of friction and play, which would mitigate repeatability when present. Currently, the ability of the system to reach the desired target position is merely limited by the 'stand-still' performance of the system directly caused by small fluctuations in the provided current.

Tracking accuracy was tested by moving to random positions in the 6D workspace, where the positions were connected using 0.6 s transition trajectories with piecewise linear acceleration. The resulting tracking error of the joints was measured and transformed to end-effector level (Figure 8). This resulted in an rms tracking error of 292 μm for feedback only; the error was 15.2 μm for non-adaptive feedforward and 8.8 μm for adaptive feedforward. This clearly shows that feedforward is able to realise high tracking accuracy due to the predictable dynamics. Changes in end-effector loading can be handled by the adaptation of the feedforward.



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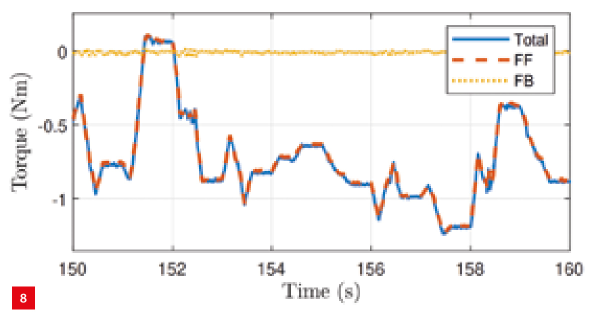
Repeatability measurement for the z-position of the end-effector.



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Feedforward (FF), feedback (FB) and total torque of one of the actuators for a random setpoint trajectory when using adaptive feedforward control for the total manipulator.


9

Rendering of the T-Flex in a deflected position, demonstrating the large range of motion.

Discussion

It has been shown that, exploiting recent developments in flexure design, a large-stroke flexure-based parallel manipulator can be built. The hysteresis-free flexures enable high positioning repeatability. Moreover, the predictability of the dynamics allows for high-accuracy tracking by feedforward control. Table 1 summarises the technical data of the T-Flex.

The downside of the absence of play and friction is that the smallest variations in actuation force directly transfer to platform displacements. Therefore, the peak current-to-noise ratio of < 1,000, typical for industrial-class PWM-based motor drivers, results in several microns of platform motion, which can only partially be suppressed by means of control.

To lower the platform noise, amplifiers with a better signal-to-noise ratio, such as linear amplifiers, can be applied. However, this is expensive, especially considering the high power requirements for the actuators. This has not been implemented in the current design of the T-Flex. Besides the amplifier quality and the control design, the sensitivity to current disturbances can be reduced by lowering the motor constant or increasing inertia, though this is at the cost of acceleration or torque capacity.

In the current T-Flex design, repeatability is only restricted by limitations of the electronics. It demonstrates an unparalleled combination of a large range of motion (Figure 9), sub-micron repeatability and a compact build volume.

Table 1

Technical data of the T-Flex. Values between brackets provide a range, where the value is dependent on the direction of movement and/or end-effector position; ± indicates a bi-directional travel range.

Simultaneous[i] travel range	±50 mm
Individual[ii] travel range	± [100 - 105] mm
Individual rotational travel range	± [18 – 21.5] °
Translational workspace	5.5 dm3
Maximum acceleration	[75 - 180] mm/s^2
Actuator torque feedback resolution	6 Nmm
Translational stiffness	[250 - 500] N/mm
Payload[iii]	20 kg
Footprint (radius)	0.43 m
Height	0.42 m

i In multiple directions.
ii In a single direction.
iii Resulting in stress up to 60% of the yield stress in the flexures.

REFERENCES

[1] Naves, M., "Design and optimization of large stroke flexure mechanisms", Ph.D. thesis, University of Twente, 2017.
[2] Naves, M., Aarts, R.G.K.M., and Brouwer, D.M., "Maintaining high support stiffness: Large stroke spherical flexure joint", *Mikroniek*, vol. 59 (3), pp. 17-21, 2019.
[3] Naves, M., Nijenhuis, M., Hakvoort, W.B.J., and Brouwer, D.M., "Large-stroke, Flexure-based: suspension for an iron-core, high-torque motor", *Mikroniek*, vol. 59 (6), pp. 24-28, 2019.
[4] Naves, M., Nijenhuis, M., Seinhorst, B. , Hakvoort, W.B.J., and Brouwer, D.M., "T-Flex: A fully flexure-based large range of motion precision hexapod", *Precision Engineering*, vol. 72, pp. 912-928.
[5] Seinhorst, B., and Hakvoort, W.B.J., "Efficient formulation of hexapod kinematics enabling real time adaptive feedforward control", *IEEE/ASME International Conference on Advanced Intelligent Mechatronics*, pp. 186-191, 2021.

VIDEO

[V1] "T-Flex: Compliant Flexure-based Large Range Precision Hexapod", *www.youtube.com/watch?v=tenxq7N5q3k*


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MANIPULATOR ARM FOR HIGH-ACCELERATION APPLICATIONS

Industrial robotic manipulators in pick & place applications require short settling times to achieve high productivity. Therefore, vibrations of pick & place manipulators have to be eliminated. This can be achieved by dynamic balancing, which is realised, in general, with the addition of counter-masses and counter-inertias. This comes, however, at the cost of increased moving mass and inertia, resulting in lower natural frequencies and again higher settling times. For a minimum settling time it is essential that a balanced mechanism has high natural frequencies with an optimal mass distribution. This article presents the design of a 1-DoF dynamically balanced manipulator arm optimised for high natural frequencies, with an experimental evaluation showing its potential for accelerations up to 21 G.

MATTHIJS ZOMERDIJK AND VOLKERT VAN DER WIJK

Introduction

To stay competitive, in the current ever progressing world, continuous performance improvement is required. In industry this leads to reducing production costs and increasing production rates. Focussing on robotic manipulators for pick & place applications in the semiconductor and packaging industries, for example, this means cycle times need to be minimised. Reducing cycle times, in general, requires higher speeds and accelerations, which on the other hand may worsen vibration phenomena and lead to increased settling times and a reduced precision.

The settling time is defined as the time to reach and stay within a certain error band of the final position after a motion has been initiated. A longer settling time means that additional waiting time is added to the cycle for vibrations to die out. Multiple design approaches exist to achieve optimal settling time in multiple-DoF (degrees of freedom) manipulators [1]. These approaches focus on the manipulator solely and assume the base to be fixed. In reality, however, the base is not fixed and therefore vibrations in the base can also affect the precision and the settling time significantly [2], not only of the manipulator itself but also of surrounding machinery.

Base vibrations can be minimised with dynamic balancing, by which its source, the fluctuating reaction forces and moments exerted by the manipulator on its base, are eliminated. In fact, dynamic balancing leads to a dynamic decoupling between the mechanism and its base; consequently, for the base no force frames and vibration isolation are required [3]. A manipulator or mechanism is considered dynamically balanced when both the sum of linear momenta and the sum of angular momenta stay constant during motions.

A disadvantage of dynamic balance solutions often is that significant mass and inertia need to be added to the mechanism, which degenerates the dynamical properties and the natural frequencies [4], while increasing the settling time. It is therefore key to find designs that are dynamically balanced with low additional mass and inertia, and have sufficiently high natural frequencies in order to achieve low settling times. Examples of experimentally verified high-speed dynamically balanced manipulators are the DUAL-V and the Hummingbird manipulator.

The DUAL-V manipulator [5] relies on actuation redundancy and is based on a duplicate pantograph architecture. Accelerations over 10 G were reached during experiments with a 17 cm motion range.

The Hummingbird [6] is a force-balanced manipulator with a separately controlled reaction wheel for moment balancing; this approach is known as active balancing. Accelerations up to 50 G were achieved for a 5 mm motion range and the first natural frequency of the mechanism amounted to 1.3 kHz. The active moment balancing in the Hummingbird resulted in a 90% reduction of the reaction

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moment, which is relatively low due to non-ideal actuators and limited control performance. For a much larger manipulator comparable to the Hummingbird, accelerations up to 10 G were reported with a 25 cm motion range; however, no further experimental information was published [7].

This article will first introduce the basics of dynamic balancing, followed by the introduction and multiple designs to balance a single pendulum. Next, the structural design of a manipulator arm with the aim to achieve high natural frequencies is presented and experimentally verified. See also [8].

Dynamic balancing basics

The concept of dynamic balancing comprises shaking-force and shaking-moment balancing. A shaking-force-balanced mechanism has a stationary centre of mass (CoM), with respect to the base, which eliminates fluctuating reaction forces exerted on the base. A stationary CoM means the sum of all linear momenta equals zero, as shown in Equation 1:

$$p = \sum_i m_i \dot{r}_i = m_{tot} \dot{r}_{CoM} = 0 \qquad (1)$$

Here, i denotes the element number, $\dot{r}_i$ the position of the CoM of the element, and m_i the mass of the element.

A shaking-moment-balanced mechanism eliminates fluctuating reaction moments on the base. In accordance with Euler's second law of motion, this requires a constant angular momentum, which is described by Equation 2:

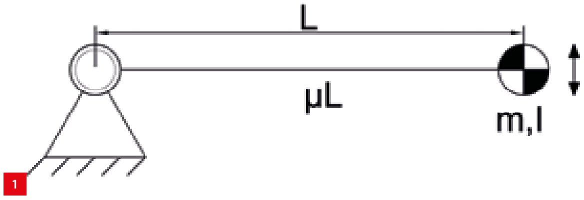
$$\dot{H}_0 = \sum_i r_i \times (m_i \ddot{r}_i) + I_i \ddot{\theta}_i = M_0 = 0 \qquad (2)$$

Here, M_0 denotes the reaction moment and I_i the mass moment of inertia (referred to as inertia) of the element. The angular acceleration of the element is denoted with $\ddot{\theta}_i$.

Satisfying both Equations 1 and 2 results in a dynamically balanced mechanism. A shaking-force-balanced mechanism is achieved by satisfying Equation 1 only.

Balancing principles

Common balancing principles were collected and compared by Van der Wijk [9]. His comparison had the aim to investigate which balancing principle had the lowest effect on the moving mass and inertia. The compared balancing principles were: counter-mass (CM), separate counter-rotations (SCR), counter-rotating counter-mass (CRCM), and duplicate mechanisms (DM). SCR balancing, CRCM balancing, and DM balancing result in a dynamically balanced mechanism, while CM balancing only results in a force-balanced mechanism. Less common is the balancing of a link by including it in an inherently balanced inverted four-bar linkage (IBinv4B) [10].



1

Single pendulum as reference mechanism.

Reference mechanism

The multiple balancing principles have been applied to a rotatable link (pendulum). The rotatable link is regarded as a representative building block in mechanism design. For instance, delta robots can be regarded as three parallel dyads (double pendulums), while planar four-bar linkages can be regarded as three single pendulums. Figure 1 shows a rotatable link with length L, distributed link mass μ, tip mass m and tip inertia I.

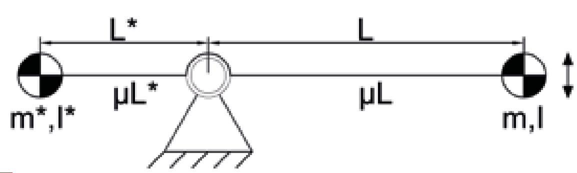
Counter-mass balancing

Adding a counter-mass to the reference mechanism in Figure 1 results in a force-balanced mechanism (Figure 2). While this principle does not remove shaking moments exerted on the base, the moving mass and inertia will be lower compared to those of fully balanced mechanisms.

SCR balancing

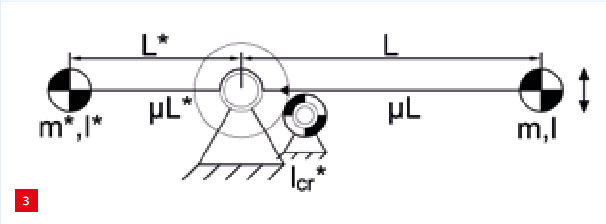
Dynamic balance with the SCR principle is achieved by adding a counter-inertia at the base of a force-balanced mechanism (Figure 3), which can be regarded as a wheel that is driven by a pair of gears to counter-rotate with respect to the link. While SCR is a common way to achieve dynamic balance due to its simplicity, it is less efficient in terms of mass and inertia as compared to CRCM balancing.

Duplicate mechanisms can be regarded as a special case of SCR balancing. A duplicate mechanism is achieved by replacing the counter-inertia for an identical force-balanced link. Here, the initial (unbalanced) link is mirrored in horizontal and vertical direction, resulting in four links connected with pairs of gears to counter-rotate with respect to one another. Duplicate mechanisms have improved inertial properties, but require more space [9]. Additionally, they are also harmonically balanced.



2

Force-balanced pendulum with counter-masses.



Dynamically balanced pendulum with separate counter-rotations.

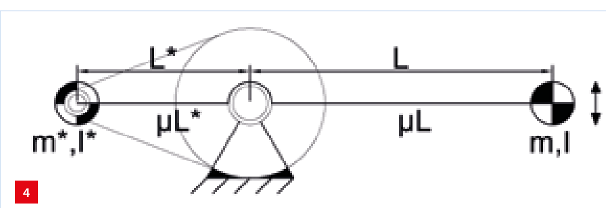
CRCM balancing
In CRCM balancing, the inertia of the counter-mass is used as a counter-inertia (Figure 4), driven by a belt drive or pairs of gears to counter-rotate with respect to the link. This reduces the total mass and inertia, because the counter-mass and counter-inertia are combined in a single element. On the other hand, the counter-moment will now be exerted on the end of the balancing link, which will put more strain on the link and degrade natural frequencies. To mitigate the effects additional stiffening of the link is required, which will increase the rotational inertia of the link and therefore requires a larger counter-inertia.

IBinv4B
The dynamically balanced inverted four-bar linkage was invented by Ricard and Gosselin in 2000 [10] and can be considered as a 1-DoF inherently dynamically balanced mechanism, since it needs – besides a specific mass distribution – no additional counter-rotating inertia (counter-inertia) for moment balance. If one link of the four-bar linkage is regarded as the manipulator arm, with the other elements solely for balancing, then the design can be used as a building block in the design of multi-DoF dynamically balanced manipulators [11].

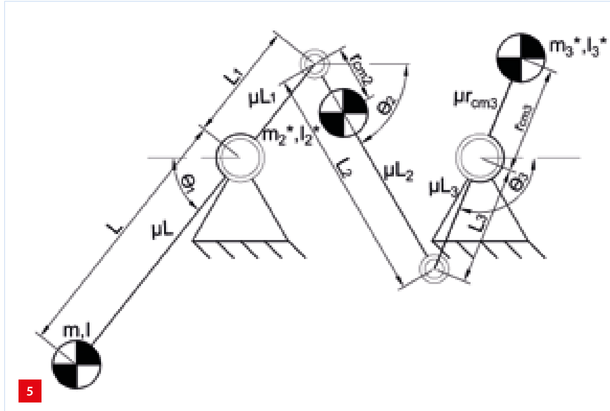
Figure 5 shows the modified inverted four-bar linkage with the pendulum arm with length L_1 and at the end the second (coupler) link is attached with length L_2. The third link is connected to a base-attached revolute joint and the coupler link; L_3 denotes the distance between the base pivot and the coupler link.

Design

Achieving dynamic balance with counter-rotating flywheel-based architectures, in general, requires a rotary transmission such as a pair of gears or a belt drive. Such a transmission adds mass, compliance and backlash to the



Dynamically balanced pendulum with counter-rotary counter-masses.

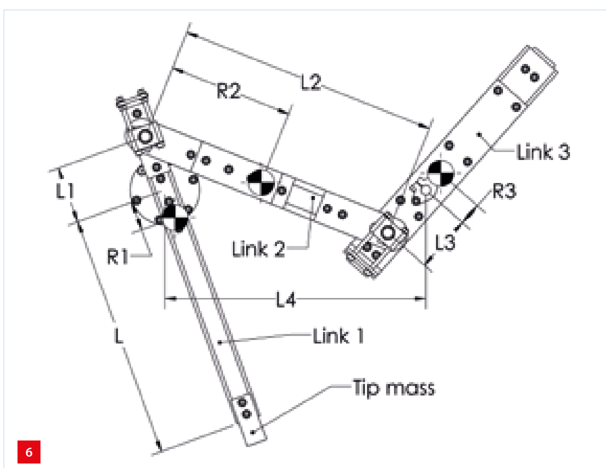


Dynamically balanced pendulum with the pendulum made part of an inherently balanced inverted four-bar linkage (IBinv4B).

mechanism, which affects the dynamic properties and the settling times negatively. In contrast, inherently balanced architectures, such as the dynamically balanced inverted four-bar linkage, only require a specific distribution of masses and inertias of its links without the need for additional elements. The IBinv4B is a closed-loop mechanism that has the highest concentration of its masses and inertias located close to the base pivots or on the coupler link, which is beneficial for achieving high natural frequencies.

The single rotatable link shown in Figure 1 can be regarded as the starting point of the structural design and can be considered as the manipulator arm that has been integrated into the inverted four-bar linkage to achieve the dynamically balanced mechanism of Figure 5. As compared to counter-rotating flywheel-based architectures, in the balanced inverted four-bar linkage, link 3 can be regarded a counter-rotation with coupler link 2 as the transmission that is stiff and has no backlash, which is a significant advantage of this solution.

A top view of the balanced mechanism with its geometric design parameters is shown in Figure 6 and the inertial and



Top view of the dynamically balanced manipulator arm link 1 with the main parameters.

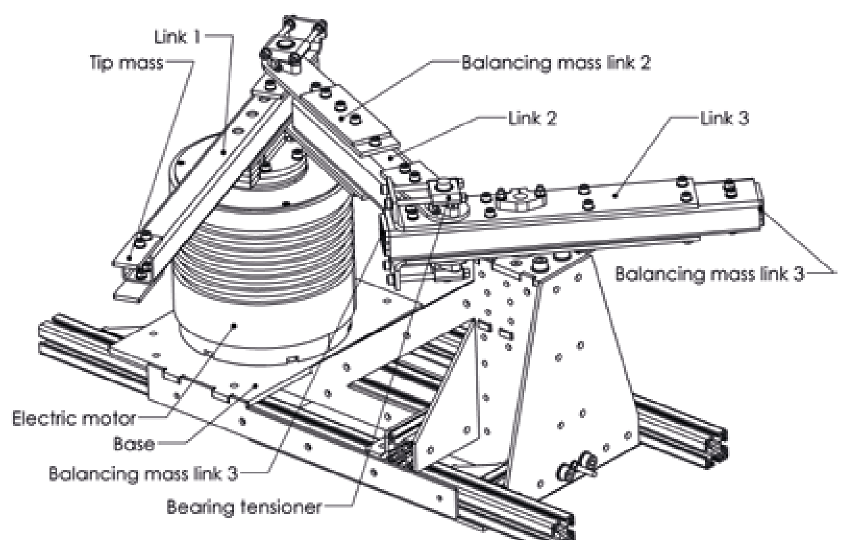
Table 1
Parameter values of the balanced manipulator of Figure 6.

Length [mm]	Mass [g]	Radius [mm]	Inertia [kgm²]
$L = 300$	$m_p = 112.12$	$r_p = 300.00$	$I_p = 0.0000377$
$L_1 = 70$	$m_1 = 2140.93$	$r_1 = 36.26$	$I_1 = 0.0295905$
$L_2 = 320$	$m_2 = 2139.95$	$r_2 = 154.16$	$I_2 = 0.0168973$
$L_3 = 70$	$m_3 = 2539.59$	$r_3 = 28.41$	$I_3 = 0.0307103$
$L_4 = 320$			

geometric parameter values are listed in Table 1. Here, link parameters m_i, r_i and I_i include all masses, radii (distances to CoM), and inertias of the link i and the tip mass, including the values for the actuator inertia. The inertia of each link is taken at the link's CoM. The admissible range of motion of the mechanism is from $\theta_1 = 60°$ to $\theta_1 = 110°$, due to internal collisions. The structural design of the prototype dynamically balanced manipulator arm is presented in Figure 7, with an actuator driving link L_1 directly.

The values in Table 1 were found by an iterative design process based on three steps:
1. initial parameter optimisation with Spacar [12];
2. detailed CAD design;
3. verification of natural frequencies with Comsol [13].

The starting point in the design was the initially unbalanced mechanism in Figure 1 with a tip mass (m) of 112.12 g connected to the actuator with a link length $L = 0.3$ m. The initial values of lengths L_1, L_2, L_3 and L_4 were determined before the detailed design phase by a genetic algorithm in combination with Spacar, a numerical flexible multi-body software package based on the Euler-Bernoulli beam theory. Incorporating the unbalanced manipulator arm in the balanced four-bar mechanism introduces additional natural frequencies. Hence, for optimal dynamic performance these frequencies need to be higher than the first natural frequency of the manipulator arm itself.



7

Final design of the dynamically balanced manipulator arm link 1 mounted on the electric motor and the base.

Since for analysis the base pivot of link 1 is fixed, the first natural frequency of the balanced manipulator arm is equal to that of the unbalanced arm. The goal of this optimisation therefore is to maximise the second natural frequency of the balanced mechanism. The magnitude of this mode is significantly higher than the mode that corresponds to the first natural frequency and therefore the second natural frequency will limit the feedback control performance instead of the first natural frequency. Constraints were considered for the cross-section of the links, to keep the tubes rectangular, and the lengths of the tubes were constrained to keep the design manufacturable.

The optimisation resulted in initial values for L_1, L_2, L_3 and L_4 of 78 mm, 310 mm, 78 mm and 310 mm, respectively, for which the second natural frequency of the mechanism was calculated as 565 Hz, associated with the second in-plane mode shape. This frequency can be assumed to represent the theoretical optimum of the design.

CAD design requires to take dimensional constraints into account. Therefore, the final parameter values are a trade-off between natural frequencies, balance conditions, dimensional constraints, and mass. For satisfying the balance conditions of the second link and the resulting dependency between mass, inertia, and CoM, it was required to shorten the length of L_1 from 78 mm to 70 mm.

Validation

Modal FEA analysis
The natural frequencies of the CAD model were determined using finite-element analysis (FEA, Comsol). To avoid internal collisions of the links during frequency sweeps, it was chosen to perform the analysis around the centre of the admissible motion range at $\theta_1 = 88.2°$.

The first natural frequency of 312 Hz in Figure 8 is located in the manipulator arm and is therefore equal to that of the unbalanced rotatable arm in Figure 1. Concerning the second and third natural frequencies, the latter is significantly higher. The natural frequency of the second in-plane mode shape depends significantly on the stiffness along the length L_1. For a construction based on tubes, a high stiffness however is challenging to obtain.

First three in-plane mode shapes from FEA at θ_1 = 88.2°. The largest displacements of a specific mode shape are shown in dark blue. The representation of the displacements is strongly amplified.
Natural frequency:
(a) 312 Hz.
(b) 353 Hz.
(c) 826 Hz.

In addition to the in-plane modes, three out-of-plane modes were observed. The first out-of-plane mode shown in Figure 9 affects link 1 and is equal for both the unbalanced rotatable link in Figure 1 and the balanced design. The second mode shown in Figure 9 is a result of the balancing mass added at the end of the third link. The excitation of this mode is limited, since the fluctuating forces in this direction are insignificant during motion. In contrast, the third out-of-plane mode shape shown in Figure 9 is easily excited during motion, as this link is then loaded longitudinally. Still, the natural frequency associated with this mode shape is significantly higher than that of the second in-plane mode shape.

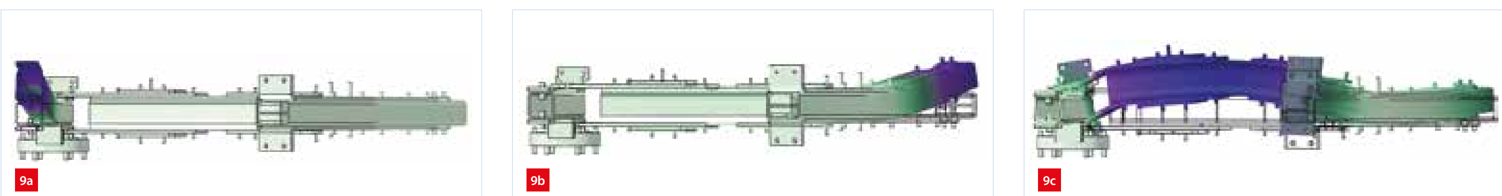
Prototype

A prototype of the dynamically balanced manipulator arm was fabricated in an experimental set-up, which is shown in Figure 10. The manipulator was fully made of stainless steel with bearing tensioners attached, while the base consists of aluminium extrusion profiles with stainless steel plates. The actuator is an ETEL RTMBi140-100 direct-drive motor with a maximum torque of 131 Nm. To allow for small movements of the base for measurements within the horizontal plane, the base is suspended by four chains from an external aluminium frame. For measuring the reaction forces and the reaction moment within the horizontal plane, three single-point loads-cells were installed as indicated with numerical balloons in Figure 11.

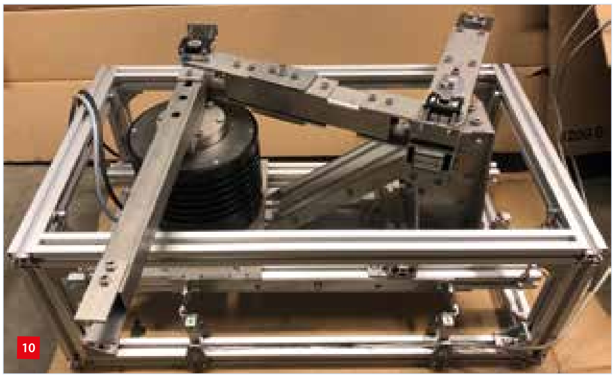
Balance quality

Figure 12 shows the shaking forces and the shaking moment exerted on the base of the prototype, as determined from simulations (including the manufacturing errors of the balancing masses) and from measurements with the experimental set-up. This concerned an S-curve motion of 30° from θ_1 = 98.2° to θ_1 = 68.2° within 160 ms, for which the tip acceleration was 51.1 m/s^2 (5.2 G). Manufacturing errors of the balancing masses were taken into account by measuring and weighing all the manufactured parts and rerunning the simulations with these values.

The measured shaking forces and shaking moments are significantly higher than the values from the simulations. However, the force balance quality (reduction of shaking forces) and the moment balance quality (reduction of shaking moments), both derived from the measurements, are 99.3% and 97.8%, respectively. The moment balance quality is slightly lower than expected, which could have been caused by deviations in the manufacturer-reported motor inertia, by the third link, which turned out to be not

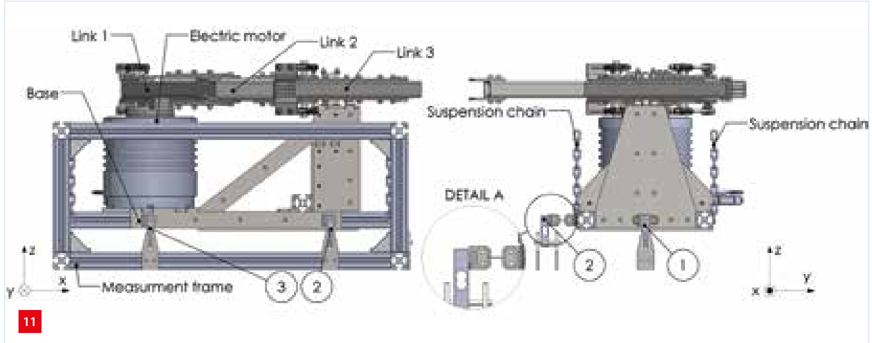


First three out-of-plane mode shapes from FEA at θ_1 = 88.2°. The largest displacements of a specific mode shape are shown in dark blue. The representation of the displacements is strongly amplified.
Natural frequency:
(a) 324 Hz.
(b) 696 Hz.
(c) 721 Hz.



10

Experimental set-up of the balanced manipulator arm with its base suspended by chains and mounted to the load cells for measurements of the in-plane shaking forces and shaking moment.



11

CAD model of the experimental set-up with the manipulator base suspended by chains to allow for small in-plane motions of the base. The numbers denote the positions of the load cells. In the right figure the measurement frame is hidden. Detail A shows the connection of a thin rod between a load cell and the manipulator base.

Table 2
Calculated (FEA) and measured natural frequencies of the balanced manipulator arm for θ_1 = 88.2°.

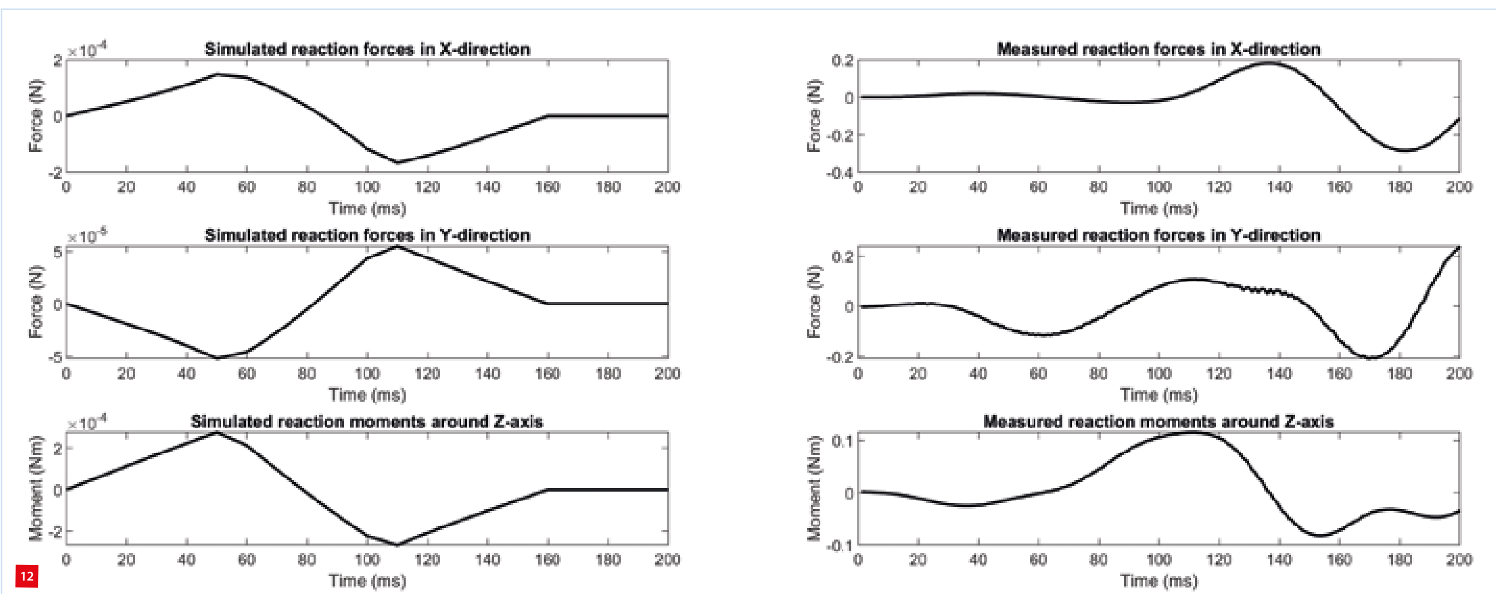
	f_1 [Hz]	f_2 [Hz]	f_3 [Hz]
FEA	312	721	826
Measurement	212	443	637

perfectly straight but slightly curved and to have no perfect rectangular cross-section, and by the limited stiffness of the base. This was not taken into account in the simulations.

Identification of natural frequencies
A frequency sweep was conducted to determine the natural frequencies of the prototype in the experimental set-up. The sweep was done in the position θ_1 = 88.2°, which is approximately in the centre of the range of motion. Table 2 presents the results of the frequency sweep and the FEA simulations.

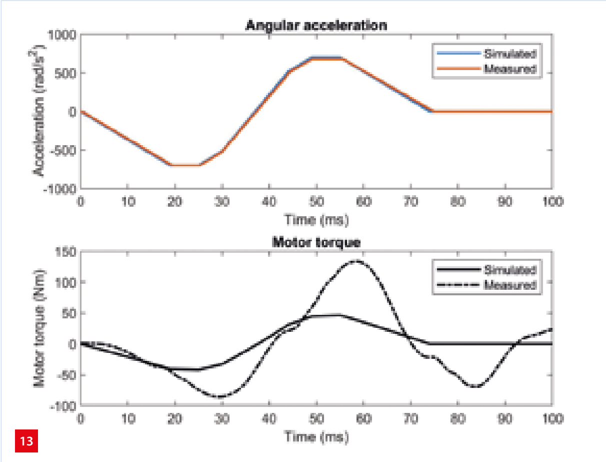
Table 2 shows that the first measured frequency is 32% lower than obtained from the FEA. The main reason for this deviation is the relatively high elasticity of the base, which was assumed rigid in the FEA simulation. This is supported by earlier experiments that were carried out with a base design with fewer structural members, resulting in even more elasticity and a 55% lower first natural frequency that was measured. This proves that the stiffness between the two base pivots has a significant influence on the natural frequencies of the mechanism. Also, the bolted connection between the actuator and the first link, which was modelled rigidly in the simulations, is expected to have contributed to the lower measured frequencies.

Although significant improvement of the prototype manipulator is still possible, cycle times of around 200 ms are within reach of the current design for this motion, resulting in cycle rates of around 5 cycles/second with a motion range of 7.8 cm. The measured natural frequencies of the prototype therefore are already sufficiently high for a realistic implementation in high-acceleration applications.



12

Comparison between simulated (left) and measured (right) shaking forces and shaking moment of the balanced mechanism, with a maximum tip acceleration of 5.2 G.



Comparison of the angular acceleration and the motor torque of the measurements and the simulations for a motion with a peak transverse tip acceleration of just over 21 G.

Maximum acceleration capabilities

Finally, the maximum tip accelerations of the experimental set-up were investigated, resulting in tip accelerations of over 21 G. Both the angular acceleration and the motor torque are shown for comparison with the simulations in Figure 13.

As can be seen in Figure 13, the measured angular acceleration is about equal to the simulation, confirming that the tip has successfully reached a transverse tip acceleration of over 21 G (21.35 G, to be precisely). Although the simulations predicted a peak actuation torque of 46.7 Nm, a peak of 133.2 Nm was measured during experiments. This is assumed to be caused by the poor PID controller and also by joint friction; both factors were not considered in the simulations. It means that the prototype still has potential to move significantly faster after optimising the PID controller and implementing feedforward control.

Conclusion

This article has presented and experimentally verified the structural design of a manipulator arm with high natural frequencies that is based on a dynamically balanced inverted four-bar linkage. The dynamic properties of the manipulator arm were evaluated by analysing the first three in-plane natural frequencies, showing that the transverse stiffness of the first link (the manipulator arm) and the second link (the coupler link) have the most influence on the natural frequencies. Concerning the robustness to manufacturing tolerances, it was shown that the manipulator is more prone to geometric deviations than to deviations of mass.

A prototype manipulator in an experimental set-up was built to verify both the dynamic balance and the dynamic properties. The prototype successfully performed high-acceleration motions with minimum shaking forces and shaking moment. When compared to the unbalanced case, a reduction of 99.3% in shaking forces and 97.8% in shaking moment was measured for tip accelerations of 5.2 G.

A first natural frequency of 212 Hz was measured, which is significantly lower than the 312 Hz obtained from simulations, primarily caused by the lower stiffness of the base design. Although significant improvement of the prototype manipulator is still possible, the natural frequencies are already sufficiently high to achieve short settling times and short cycle times during high-speed motions.

The experimental set-up achieved end-effector (tip) accelerations of 21 G. Since the prototype was fabricated with relatively basic production methods, it shows that it is relatively simple to manufacture a dynamically balanced manipulator suitable for high-acceleration applications.

REFERENCES

[1] Germain, C., Caro, S., Briot, S., and Wenger, P., "Optimal design of the IRSBot-2 based on an optimized test trajectory, *Proc. ASME Design Engineering Technical Conf.*, vol. 6A, 2013, *doi.org/10.1115/DETC2013-13037*
Briot, S., Pashkevich, A., and Chablat, D., "On the optimal design of parallel robots taking into account their deformations and natural frequencies", *Proc. ASME Design Engineering Technical Conf.*, vol. 7, pp. 367-376, 2009, *doi.org/10.1115/DETC2009-86230*
Pierrot, F., et al., "Above 40g acceleration for pick-and-place with a new 2-dof PKM", *Proc. IEEE Int'l Conf. Robotics and Automation*, pp. 1794-1800, 2009, *doi.org/10.1109/ROBOT.2009.5152193*
[2] Arakelian, V., "Inertia forces and moments balancing in robot manipulators: a review", *Advanced Robotics*, vol. 31 (14), pp. 717-726, 2017, *doi.org/10.1080/01691864.2017.1348984*
[3] Van der Wijk, V., "Methodology for analysis and synthesis of inherently force and moment-balanced mechanisms: theory and applications", Ph.D. thesis, University of Twente, 2014, *doi.org/10.3990/1.9789036536301*
[4] Van der Wijk, V., Herder, J.L., and Demeulenaere, B., "Comparison of various dynamic balancing principles regarding additional mass and additional inertia", *J. Mechanisms and Robotics*, vol. 1 (4), pp. 1-9, 2009, *doi.org/10.1115/1.3211022*
[5] Van der Wijk, V., Krut, S., Pierrot, F., and Herder, J.L, "Design and experimental evaluation of a dynamically balanced redundant planar 4-RRR parallel manipulator", *Int'l J. Robotics Research*, vol. 32 (6), pp. 744-759, 2013, *doi.org/10.1177/0278364913484183*
[6] Karidis, J.P., *et al.*, "The Hummingbird minipositioner-providing three-axis motion at 50 g's with low reactions", *Proc. 1992 IEEE Int'l Conf. Robotics and Automation*, vol. 1, pp. 685-692, *doi.org/10.1109/ROBOT.1992.220288*
[7] Raaijmakers, R., "Besi zoekt snelheidslimiet pakken en plaatsen op", *Mechatronica & Machinebouw*, 2007, *www.mechatronicamachinebouw.nl/artikel/besi-zoekt-snelheidslimiet-pakken-en-plaatsen-op*
[8] Zomerdijk, M.J.J., and Van der Wijk, V., "Structural Design and Experiments of a Dynamically Balanced Inverted Four-Bar Linkage as Manipulator Arm for High Acceleration Applications", *Actuators*, vol. 11 (5), 131, 2022, *doi.org/10.3390/act11050131*
[9] Van der Wijk, V., Demeulenaere, B., Gosselin, C., and Herder, J.L., "Comparative Analysis for Low-Mass and Low-Inertia Dynamic Balancing of Mechanisms", *J. Mechanisms and Robotics*, vol. 4 (3), pp. 1-8, 2012, *doi.org/10.1115/1.4006744*
[10] Ricard, R., and Gosselin, C., "On the Development of Reactionless Parallel Manipulators", *ASME Design Engineering Technical Conf. and Computers and Information in Engineering Conf.*, pp. 1-10, 2000.
[11] Wu, Y., and Gosselin, C., "Synthesis of reactionless spatial 3-DoF and 6-DoF mechanisms without separate counter-rotations", *Int'l J. Robotics Research*, vol. 23 (6), pp. 625-642, 2004, *doi.org/10.1177/0278364904044400*
[12] Jonker, J.B., and Meijaard, J.P., "SPACAR – Computer Program for Dynamic Analysis of Flexible Spatial Mechanisms and Manipulators", in *Multibody Systems Handbook*, pp. 123-143, Springer, Berlin and Heidelberg, 1990, *doi.org/10.1007/978-3-642-50995-7_9*
[13] Comsol Multiphysics 5.4, *www.comsol.com*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MAKING DESIGN STRATEGIES EXPLICIT

Existing textbooks on design principles for precision mechanics and mechatronics lacked didactic rigour and were too 'implicit' in their presentation of design strategies, thus raising the entry barrier for novices in the design field. Therefore, Susan van den Berg, lecturer in Design Principles, published "Design Concepts for Precision Engineering", based on sound didactics and specifically targeted at the higher vocational education level. It was well received, so the author updated it to "Design Concepts and Strategies for Precision Engineering", thereby emphasising its explicit design strategy perspective. The second edition appeared last year

In 2019, Susan van den Berg published "Design Concepts for Precision Engineering" in two volumes (both comprising two parts). She was (and still is) a lecturer at Fontys University of Applied Sciences in Eindhoven (NL), teaching courses such as Design Principles. Her aim was to present a didactically sound textbook targeted at novices in the field of precision engineering, in particular students at the higher vocational education level and also academic students. Only prior knowledge of mechanics (statics, stress and deformation) and basic mathematics (trigonometry and calculus) was required.

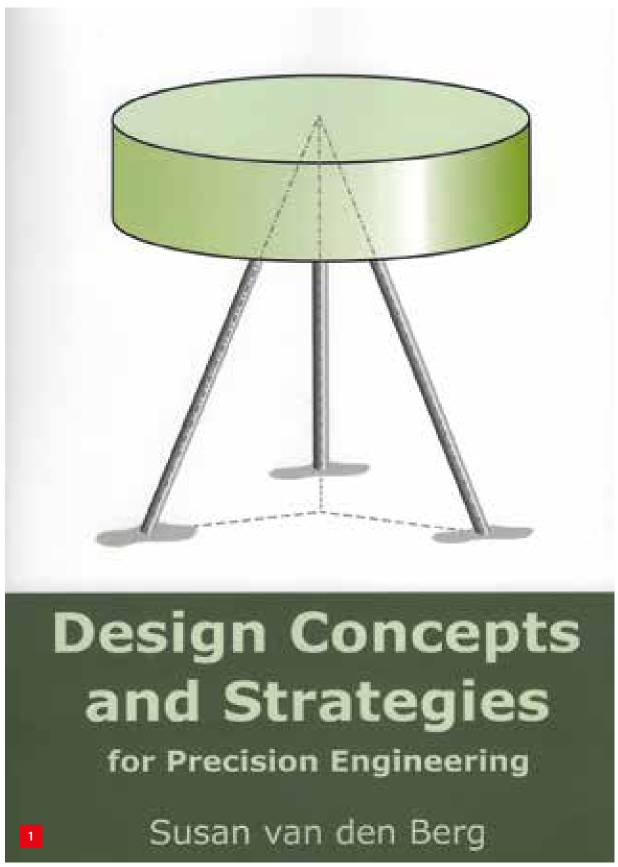
The pioneering work in this field had been done in the 1960s and 1970s by Wim van der Hoek, whose 'magnum opus' was the famous "The Devil's Picture Book" (*Des Duivels Prentenboek*, DDP), packed with examples of good (and bad) designs of precision machinery. Building on DDP, the existing textbooks, by Rien Koster and Herman Soemers, contained many complex cases based on implicit design strategies, Van den Berg learned in her daily teaching practice. With ample cross-referencing, between various designs these books offered an information overload to students, not in the least because a lot of design knowledge and experience was assumed to be common to the readers – this should be the case for (senior) engineers, but definitely was not for novices.

Therefore, the author decided to make all the required knowledge and relevant design approaches unequivocal, by explicitly describing the strategies that could be used to solve a precision design challenge deriving from a physical problem. She structured her book into four parts. The first part concerned the high-precision design goals and the phenomena that hinder the achievement of these goals. The second part presented tools to predict system behaviour. The third part covered the principles that counteract the physical effects by avoiding, compensating for, or mitigating their consequences. The fourth part showed ways in which these principles could be applied in practice.

EDITORIAL NOTE

This article was based on an interview with Susan van den Berg and passages from her book.

Beforehand, the author had received criticism for endeavouring to talk about (design) strategy; this would be too 'abstract' for students at the higher vocational education level. She did not agree. "A design strategy can be considered as the abstracted representation of the application of a design principle. So, on the contrary, by adding the abstraction step to my book, I have made it more accessible to students. They no longer have to derive the design strategy abstraction from the practical design



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Susan van den Berg, "Design Concepts and Strategies for Precision Engineering", Berg Precision Publishing, 316 pages, ISBN 978-90-829711-2-5, 2021, www.studystore.nl, € 36.00.

examples – that would have been really hard for them. I have made their lives easier."

The numbers (of copies sold) supported her point of view. The publication was well received and in particular praised for its accessibility and suitability for self-study. The textbooks were added to the curriculum at various universities of applied sciences and also at academic institutions, such as the renowned MIT in the US. This encouraged the author to update the book to "Design Concepts and Strategies for Precision Engineering" (Figure 1), with both volumes combined in one textbook, of which the second edition was published last year (see the text box).

The new edition contains several new items. One example is the paragraph on tuned-mass damping as an extremely efficient principle to passively increase the damping around a resonance peak. Another addition is the paragraph on optimising stiffnesses of compliant elements in series. Here, predictability can be increased by lowering the known stiffness of an element that is in series with an element of unknown stiffness, for example a glued connection.

In general, new design principles have a stronger electrical control content, while this book remains strongly focused on the mechanical design. The author's adage is that what can be solved with a (passive) mechanical design does not require an active electrical solution involving software, power, etc. When the author discusses active designs, she presents the electronics as being more or less taken for granted. However, smart sensor placement is addressed.

Ambitions for future updates include the publication of a separate exercise book and the addition of new topics, such as vacuum and manufacturing technology (for example, 3D printing).

Second edition

The aim of "Design Concepts and Strategies for Precision Engineering" is to provide the reader with the tools to select the proper design strategies to cope with the many physical effects that make it hard to design a precision machine. The focus of this book is mainly on the mechanical area. It is divided in four parts.

Part I addresses the challenges of a precision engineer engaged in the efficient and affordable design of tight-tolerance, high-speed systems. An engineer must know the vocabulary and schematics, and understand the physical effects that come into play. It is also important to understand what design strategy to choose in order to achieve the design goals and to be able to estimate the necessary level of predicting system behaviour.
Part II consists of theoretical models and tools to analyse systems and/or predict their behaviour.

Part III presents a breakdown of design principles into various design strategies that can be applied to improve accuracy, reproducibility, process speed, or cost, or reduce footprint and energy consumption. Starting from a design goal, a number of design strategies are elaborated; they can be applied as useful tools to satisfy the increasingly challenging goals faced by engineers. A total of five overarching design goals are presented: avoiding stress in the construction, minimising deviation from the target position, either avoiding or facilitating relative movement, and managing energy (by either storing or dissipating).
To illustrate, the design goal of minimising deviation can be achieved by a large number of design strategies, the choice between them depending on the specific case. The first strategy would be to minimise the load on the system, by applying a force frame, striving for a constant temperature, neutralising acceleration forces, reducing impact forces and/or isolating vibrations. Other strategies include striving for high stiffness, low mass, high damping and/or thermal stability, minimising position errors, and optimising measurement and control.

Many of the design strategies for precision are also useful in other fields. For example, strategies for designing for high stiffness and low mass can be used for cars or the masts of wind turbines. Using concepts for lightweight design can decrease cost and improve sustainability of non-precise systems as well, since less material is needed while stiffness is preserved.

Part IV features design concepts as the result of applying the knowledge from the previous parts. Some of these concepts have been enriched with examples from real systems designed by high-tech companies or universities.

In the new edition, the logical grouping of subjects has been improved, errors have naturally been corrected, and additions have been made, for example to the key topic of degrees of freedom and exactly constrained design, and to the emerging theme of damping.

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BIG SCIENCE AND BIG BUSINESS

This year will see the 21st edition of the Precision Fair. On 16 and 17 November 2022, the fair will be held in the Brabanthallen in Den Bosch (NL) – for the second time at this location, following the successful premiere last year. Over 300 exhibitors have already confirmed their participation and the fair will be packed with a Big Science programme, plenty of other lectures, young talent pitches, award ceremonies and a meet & match event.

From micrometers to nanometers and even picometers, the demand for ever more accurate and smaller measurement, production and construction has been increasing unabated for years. Products and technologies are also becoming more complex and smarter. Precision technology has therefore rapidly developed into the stable basis for many devices and components around us. It is not without reason that precision technology is one of the foundations of the Dutch knowledge and innovation economy. As an exponent of this industry, the Precision Fair is the meeting place for the entire precision technology value chain: from mechatronic engineering & systems, metrology, vacuum & clean, microprocessing & -motion to production for high precision.

The Precision Fair's collaboration with Big Science projects, but also with large international OEMs, has resulted in a large number of assignments for the business community and continues to do so. The limit of precision technology has not yet been reached. Meeting, collaborating and sharing knowledge are indispensable to keep up with the rapid technological developments.

At the Precision Fair, visitors can meet the top specialists from companies, training institutes, government agencies, technical universities and incubator programmes in the field of precision technology. These specialists can be found on the exhibition floor, they will share the latest developments in the lecture programme and you will participate in the Meet & Match. Special attention will be paid to young talent, with students (teams) and start-ups presenting their innovative projects in the Young Talent Program in short pitches and poster presentations.

Partially overlapping with the Precision Fair, the European Society for Precision Engineering and Nanotechnology (euspen) will organise its second international Special Interest Group on Precision Motion Systems & Control congress on Tuesday 15 and Wednesday 16 November.

Impression of the Precision Fair 2021, which was the first edition in the Brabanthallen in Den Bosch.

The euspen congress is for members only, and on Wednesday afternoon the international delegates will visit the exhibition floor and a number of presentations will be given in the public lecture programme.

To top matters off, both fair days will be concluded with an award ceremony, hosted by DSPE, for the Ir. A. Davidson Award on Wednesday and the Wim van der Hoek Award for the best graduation work in mechanical engineering on Thursday (see also page 56), which means that the final spotlight of the Precision Fair will be on young talent.

INFORMATION
Precision Fair
16-17 November 2022
Brabanthallen, Den Bosch (NL)
Information and visitor registration on the website.

Precision Fair

WWW.PRECISIEBEURS.NL

EDITORIAL NOTE

This article is based on information from Mikrocentrum, the long-time organiser of the Precision Fair and an independent knowledge and network organisation that has been supporting the technical manufacturing industry for over 50 years with training, events and business.

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206	Acclon Technologies
335	ACE Stoßdämpfer GmbH
549	Adruu the metal refinement company
433	Advanced Chemical Etching Ltd
479	Advanced Sonic Monitoring bv
264	AFYS3G
354	Agilent Technologies
478	AJB Instrument B.V.
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473	Alumeco NL BV
316	Aluro CNC
147	Analis
572	Anderson Europe GmbH
144	Andes Meettechniek BV
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245	attocube systems AG
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351	B&S Technology B.V.
466	Basco Verspaningstechniek BV
460	Bearing Design and Manufacturing B.V.
349	Bendertechniek
564	Bestronics
313	BIBUS Romicon BV
127	BIERSACK Group
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440	BKB Precision
448	BKL B.V.
139	Blum-Novotest GmbH
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105	BOM - Enterprise Europe Network
229	Bouman Industries
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110	Brainport Industries
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561	Bronkhorst Nederland B.V.
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240	Capable BV
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359	CCC Projects & Engineering
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332	De Ridder THO/SRM
474	De Rooy Slijpcentrum B.V.
197	Dekracoat BV
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553	Demcon
244	DIXI Polytool B.V.
231	DKAT
536	DMS
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559	EKK Eagle Simrax
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REDUCING SAMPLE STAGE DRIFT VELOCITY

High-contrast imaging in transmission electron microscopes requires that thermal drift of the sample stage is minimised. For this, the use of a Kalman filter strategy within the control structure of the stage has been investigated. A Kalman filter requires a thermal model of the stage construction, various inputs, and temperature measurements. In conjunction with a deformation model, this technique can compensate for drift. The compensation control strategy has been validated using simulations based on multiple measurements.

MARJOLEIN DAANEN

AUTHOR'S NOTE

Marjolein Daanen graduated on the subject of this article from Fontys Engineering University of Applied Sciences in Eindhoven (NL) in 2021. For this, she received a nomination for the Wim van der Hoek Award. She now is an M.Sc. student in Systems & Control at Eindhoven University of Technology and lecturer of Mechatronics at Fontys.

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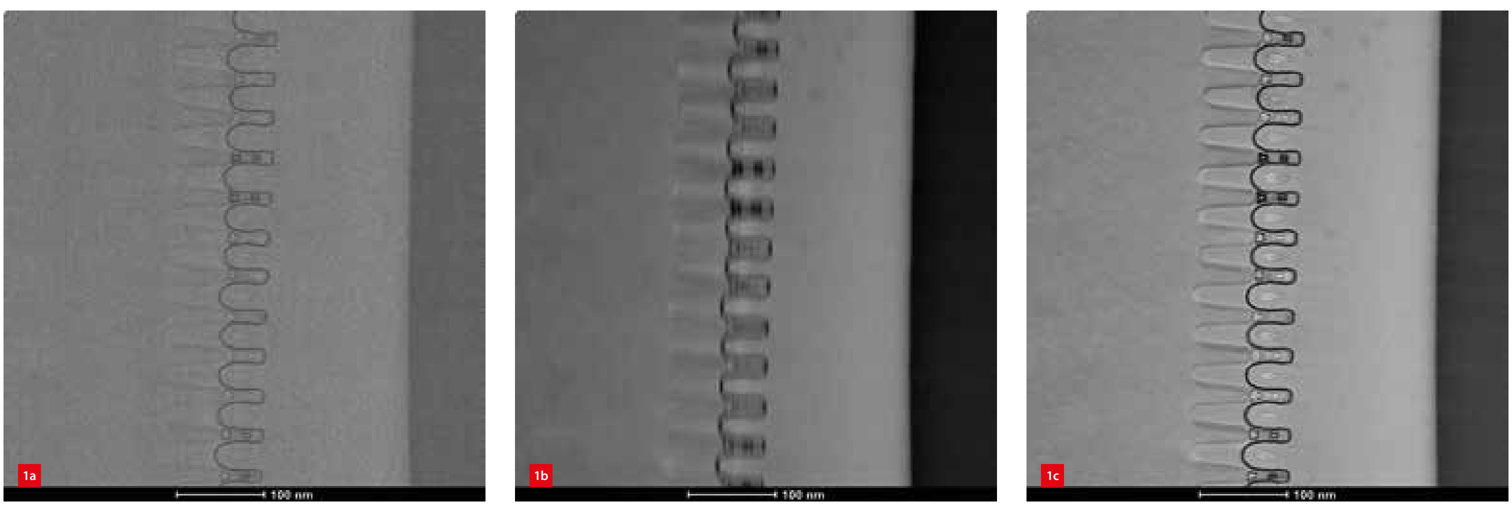
Introduction

Technology will always be evolving. Future-generation machines must be faster, while the accuracy must increase. Machines such as microscopes, milling machines and pick-and-place machines are examples of this. Currently, the accuracy of these machines is often limited by disturbances, resulting in effects such as thermal deformations.

Thermo Fisher Scientific is a leading manufacturer of transmission electron microscopes. These microscopes can create an image of a sample, down to the atomic scale. Creating such an image with picometer resolution requires high-precision technology. Hence, even the slightest disturbances deteriorate the quality of the images.

In the case of this article, the sample manipulation stage positions the sample in a microscope in three degrees of freedom. Its sub-nanometer position accuracy is affected by thermal deformations, mainly caused by variations in ambient temperature and internal heat loads generated by actuators and sensors in the stage. Temperature changes of millikelvins cause thermal deformations in the order of nanometers, resulting in undesired sample movement, known as drift. For confidentiality reasons, the geometry of the stage cannot be disclosed in this article and some quantities are only presented as normalised values.

To allow high-contrast imaging in the microscope, high exposure times are used. However, with long exposure times, the drift velocity – in the order of nm/min – will cause significant motion blur. By shortening the exposure time, the motion blur is reduced, but so is the contrast. The key to have both high contrast and little motion blur is to reduce the drift. Hence, to create an image with high contrast and good quality, the motion blur – and thus the drift – should be reduced. Figure 1 shows two images with



Three images of the same nano-wire sample.
(a) Low contrast.
(b) Motion blur.
(c) Good quality.

either low contrast or motion blur, and one of sufficient quality. To acquire images with sufficient quality, the drift velocity (normalised to the maximum allowable value) may – by definition – not exceed ±1.

The stage has been designed to fulfil various design requirements, such as high eigenfrequencies and high positioning accuracy. Although thermal effects have also been minimised, the current design still exhibits some thermal drift, which limits performance. At the same time, the thermal deformations cannot be measured. Therefore, the current stage controller cannot compensate for these disturbances.

Compensating technique

Although it is not possible to measure the thermal deformations, it is possible to measure the temperatures on various locations across the stage. In addition, the desired output of the actuator, which is a measure of the power dissipated in the actuator, and the ambient temperature can be measured. On top of that, the stage has a highly predictable thermomechanical behaviour. This allows modelling of the thermal deformations in the stage, based on the internal and external temperatures and heat loads.

Based on these findings, a new control structure design has been developed [1]. This structure aims to predict and compensate for thermal deformations caused by actuator dissipation, other internal heat loads, and ambient temperature variations. However, in this article the effects of actuator dissipation are out of scope.

For the new control structure, a thermal model has been developed, based on the lumped-element method (LEM). The main benefit of using this modelling technique over others is the low computational load, making fast simulations possible for real-time control. In addition, this method provides insight into the stage model. The details of this method are explained in the text box.

The developed model uses the desired actuator output, the estimated heat that is generated by sources, such as encoders, and the measured ambient temperatures to predict the temperatures of all the lumps representing the entire stage. In total, the thermal model contains around 200 lumps. A Kalman filter has been realised, which uses the thermal model in combination with temperature sensors. These sensors are strategically placed on the stage construction. Based on the temperature sensor readings, the Kalman filter allows real-time corrections to the thermal mode state estimations. This minimises the effect of modelling errors.

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Lumped-element method

To create the thermal model of the stage, the lumped-element method (LEM) has been used. In this method, the geometric design of the stage is reduced to a set of discrete elements (lumps). Each lump has a certain thermal capacity and is connected to other lumps. Between these lumps, heat transfer takes place.

The heat transfer between the lumps is modelled by thermal resistors. Therefore, the model is a network of thermal resistors and thermal capacities, also known as an RC-network. Based on this RC-network, the temperatures over time of each thermal capacity (lump) can be found by solving a set of ordinary differential equations.

Model representation

Figure 2 visualises the two basic steps to create a LEM model from a simple block. The final model of this example consists of three thermal capacities (lumps), which are represented with the circles C_1, C_2 and C_3. The lumps are connected in series through resistors R_1 and R_2. Moreover, heat Q enters through lump C_1. Additionally, the resistors R_3, R_4 and R_5 connect the lumps to the ambient temperature, allowing to model convection and radiation.

Biot number

Using the LEM, each lump is assumed to have a homogeneous temperature. To ensure this, the Biot number (*Bi*) [2] is used to confirm the construction of the lumps. *Bi* describes the ratio between the internal thermal resistance (related to internal conduction) and the external thermal resistance (related to convection and radiation) of the lump. If $Bi < 0.1$, the temperature at the centre of the lump will not differ more than 5% from the temperature at the surface of the lump, and hence the lump geometry concerned can be used. The *Bi* value can be found using:

$$Bi = R_{internal} / R_{external} = l_c / (\lambda A_t) \cdot hA_t / 1 = l_c h / \lambda$$

Here, l_c is the characteristic length V/A_t, where V represents the volume of the body in [m^3], A_t represents the heat transferring area of the body in [m^2], λ represents the thermal conductivity of the body in [W/(mK)] and h represents the convective heat transfer coefficient in [W/(m^{2}K)].

Model parameters

In the LEM model, the following parameter values are determined for each lump:

- thermal capacity C [J/K];
- thermal conductive resistance R_{cond} [K/W];
- thermal convective and radiative resistance R_{comb} [K/W].

The thermal capacity C of each lump is found by:

$$C = c_p V \rho$$

Here, c_p is the specific heat capacity of the material in [J/(kgK], V is the volume of the body in [m^3] and ρ is the density of the material in [kg/m^3]. The volume of the body is obtained by the 3D CAD model of the lump. The specific heat capacity and the density of the material that the lump is made of can be found in literature.

The thermal conduction between the lumps is determined by performing a finite-element analysis, where a temperature $\Delta T = 1$ °C is applied between two points. From this analysis, the heat flow Q in [W] can be determined. Based on the equation below, this heat flow is the inverse of the thermal resistance R_{cond} in [K/W]:

$$R_{cond} = \Delta T/Q$$

In the LEM model, the convection and radiation heat transfer coefficients h_{conv} and h_{rad}, respectively, are linearised because the ambient temperature varies around 21 °C within a small range of ±2 °C. Linearisation allows combining both phenomena in a single coefficient. This combined heat transfer coefficient h_{comb} in [W/m²K)] can be described as:

$$h_{comb} = h_{conv} + h_{rad}$$

This combination results in a heat flow:

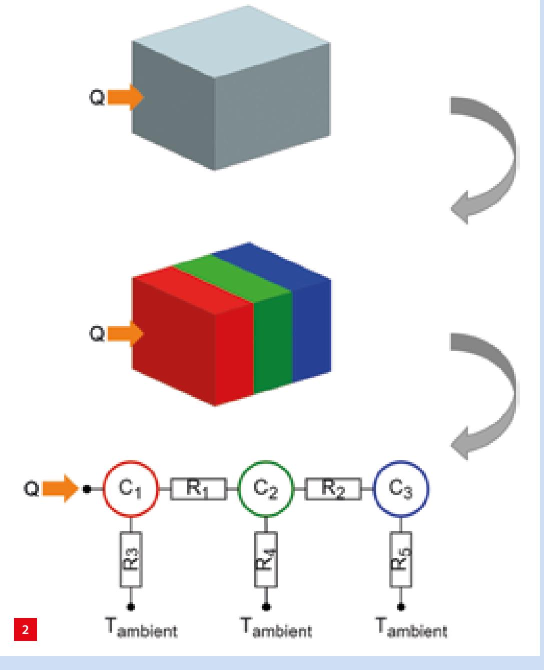
$$Q = (T_l - T_{amb}) / R_{comb}$$

Here, resistance $R_{comb} = (h_{comb} \cdot A_{comb})^{-1}$, where A_{comb} is the heat transferring surface area in [m²], T_l is the temperature of the lump in [K], and T_{amb} is the ambient temperature in [K].

For each lump, the ordinary differential equation is equal to:

$$C\dot{T} = \Sigma Q$$

Here, C is the thermal capacity of the lump, $\dot{T}$ is the time derivative of the temperature of the lump, and Q represents the various heat flows into the lump, defined positive if it increases the temperature of the lump.



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The two basic steps to create a LEM model from a simple block with a heat input Q. In step 1, the block is divided into three lumps. In step 2, the actual model is shaped, where Q enters the first lump, represented by thermal capacity C_1. The thermal capacities C_1, C_2 and C_3 are connected to each other through resistors R_1 and R_2. Finally, each thermal capacity is connected to the ambient temperature through resistors R_3, R_4 and R_5, enabling convection and radiation modelling.

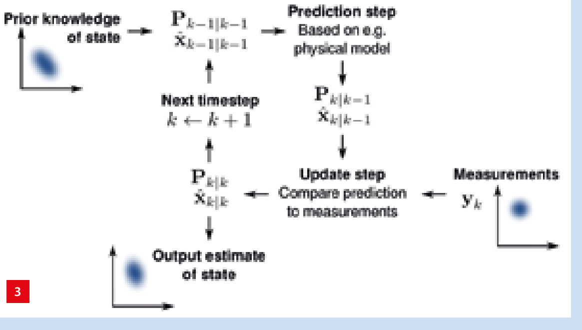
Kalman filter

If the states of a system cannot be measured directly, such as the temperatures in the stage, a state observer can be used in control theory. A state observer estimates all the – observable – internal states of a real system. This is achieved by creating a mathematical model of the system and using the known inputs and outputs of the system. In case of the thermal model used for this application, the states are equal to the temperatures in the model.

A Kalman filter (KF) is a type of state observer designed for stochastic systems. In the control structure as described in this article, a thermal model in combination with the actuator output results in a prediction of all the internal states. The KF combines this prediction with the real-time temperature sensor data, to find the optimal estimation of the states. With this combination, the filter benefits of both methods (modelling and measuring), resulting in a higher accuracy and reliability of the estimation.

When the internal states are estimated using only a model, any model mismatch or unmodelled dynamics will create an error between the estimation and reality. This error can result in an estimation that, over time, will deviate from reality. If the internal states are estimated only based on measurements, sensor noise will introduce an error. Secondly, the number of sensors is limited for practical reasons and costs. While sensor noise is typically fast, the typical behaviour of a thermal system is slow, which makes a KF ideal for thermal system applications.

A KF involves a two-step process; see Figure 3. The first step is the so-called prediction step. During this step, the model predicts the observable internal states, as described before. In the second step, the prediction is updated, based on the sensor data; this is called the update step.



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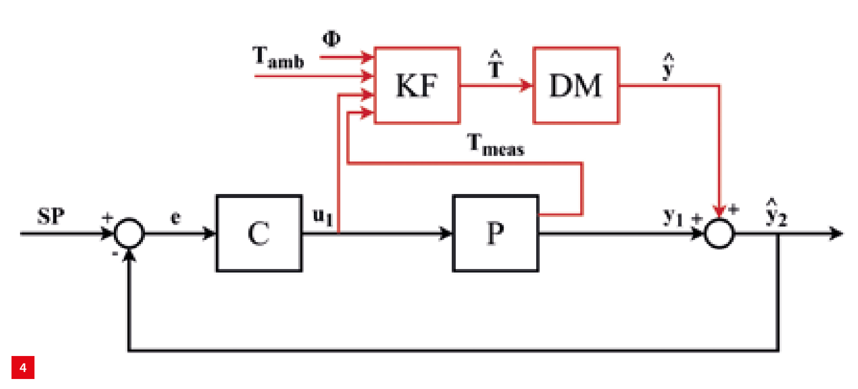
A basic flowchart describing the working principle of a Kalman filter. $\hat{x}_{k|k-1}$ denotes the estimate of the system's state x at time step k before the k-th measurement y_k has been taken into account; $P_{k|k-1}$ is the corresponding uncertainty. (Source: Petteri Aimonen, Wikipedia)



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The control structure that is used to compensate for thermal deformations in the stage, where the black diagram represents the original control loop and the red diagram represents the added control loop.

Together with a deformation model, produced from the geometry of the stage and the material properties of the used materials, an estimation of the thermal deformations can be made. With this estimation, the error in the sample position – caused by thermal deformations – can be predicted and thus compensated for. More detailed information about the theory of a Kalman filter is given in the text box.

The control structure as described previously is shown schematically in Figure 4. The original control loop for the stage, containing the controller (C) and plant (P) representing the stage, is shown in black. The added control path, consisting of components for the Kalman filter (KF) and the deformation model (DM), is shown in red.

The inputs and outputs of these blocks are defined as follows:

- SP represents the position setpoint of the sample in [m];
- e represents the sample positioning error in [m];
- u_1 represents the desired output of the actuator in [rad/s];
- T_{meas} represents the measured temperatures on the stage in [K];
- T_{amb} represents the measured ambient temperature in [K];
- Φ represents all the additional signals – such as prior knowledge about sensor heat load – required to estimate the temperatures across the set-up;
- $\hat{T}$ represents the estimated temperatures of all the lumps in the stage in [K];
- $\hat{y}$ represents the estimated deformation of the stage in the actuating direction in [m];
- y_1 represents the measured position of the stage in [m];
- $\hat{y}_2$ represents the estimated position of the stage in [m].

The predicted temperatures of each lump from the KF are used to estimate the corresponding deformations in the stage. These estimated deformations can be determined by the equation that describes the relation between a deformation and a temperature change of a lump:

$$\Delta l(t) = \Delta T(t) \cdot \alpha \cdot l_{eff}$$

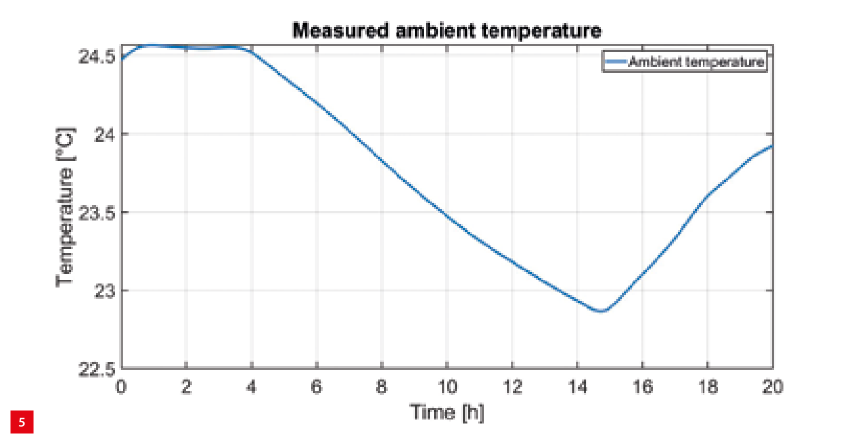
Here, $\Delta l(t)$ is the change in length over time in [m], $\Delta T(t)$ is the change in temperature over time in [K], α is the coefficient of thermal expansion (CTE) in [K^{-1}], and l_{eff} is the effective length of the lump in the deformation direction in [m]. Here, the deformation of a lump is assumed to be equal in all directions.

The CTE α is a general material property and can be assumed to be a constant, since the stage construction temperatures vary within a small range of ±2 °C around the average ambient temperature. The values for the CTEs are obtained from literature. The effective length l_{eff} of a lump is determined by the geometric length of the lump in the direction that affects the total stage deformation. In this way, each 3D lump is reduced to a 1D length. The effective length of each lump is determined using the 3D CAD model of the stage. By linearly summing all individual estimated deformations of all lumps in the stage, the total deformation of the stage can be estimated.

Controller validation / Results

Because the KF uses the thermal model for predictions, the model needs to represent the reality as accurately as possible in order to minimise errors. Therefore, multiple measurements on a stage set-up have been conducted. The measured ambient temperatures were used as inputs to a simulation, using only the thermal model, resulting in the model-based estimation of the temperatures in the set-up. The estimation was then compared to the actual temperature measurements on the set-up to obtain a measure of the errors in the model.

During a measurement of 20 hours, the ambient temperature varied within 1.8 °C, as can be seen in Figure 5. The measured temperatures in the set-up also varied within this range. Throughout this measurement, the actuator was not set in motion. The error between the temperatures



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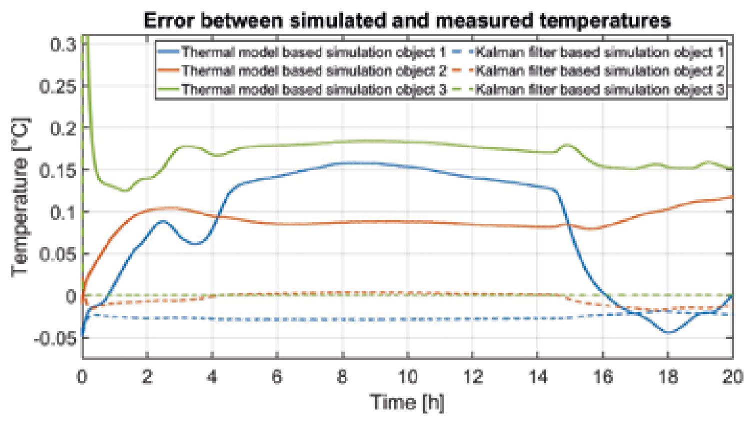
The measured ambient temperature around the stage.



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The error between the simulated temperatures, based on either the thermal model or the Kalman filter, and the measured temperatures for three selected lumps (objects 1 to 3).

of three selected lumps predicted by the simulation of the set-up, and the actual measured temperatures is shown with solid lines in Figure 6. In the first 2.5 hours, transient behaviour from the initial states to the estimated states was observed for the error based on the thermal model. In the remaining hours, the errors were within a range of ±100 mK with a maximum offset of 175 mK.

Note that around 3.5 h and 14.5 h, the temperature errors started varying. It is expected that this is caused by the constant heat transfer coefficient that is assumed within the model. In reality, this coefficient can vary in the range of 3.5 to 8 W/(m^{2}K). When the ambient temperature variation changes direction, this can cause an error in the thermal model. The measurements showed these ambient temperature direction changes around 3.5 h and 14.5 h. At the same time, the errors started varying, which can be seen in Figure 6.

Also in Figure 6, the effect of the KF can be seen. Using the same measurement as before, the temperature estimation error using the KF is shown using the dotted lines. These results demonstrate that the KF improves the temperature estimation significantly. The offset of the estimated temperatures has been reduced from 175 mK to a maximum of 30 mK. In addition, the temperature error variation has been improved from a maximum of ±100 mK to ±15 mK. Comparable results were obtained from the other measurements.

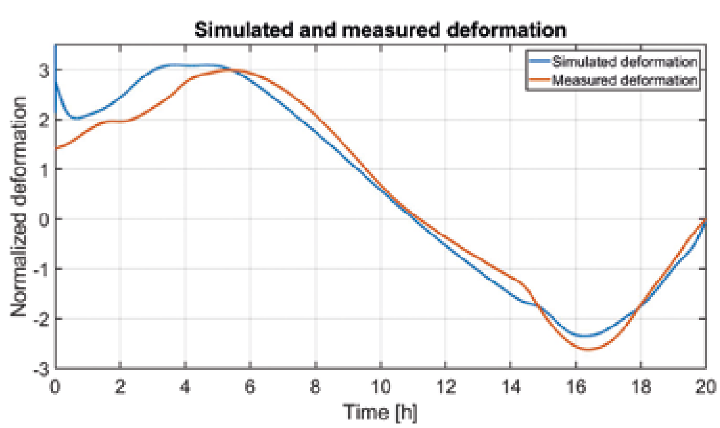
Using a dedicated test set-up, it was possible to measure the deformation of the stage at the point of interest for validation purposes. The final predicted deformation that was achieved – based on the earlier given temperature estimations – as well as the measured deformation, is shown in Figure 7. Both deformations are normalised and within the nanometer range. In the first hour of the simulation, transient behaviour was apparent. In the remaining time, the simulated deformation showed similar behaviour as the measured deformation. However, when the ambient temperatures changed direction – around 3.5 h and 14.5 h – the simulated deformation responded immediately to this change, whereas the measured deformation exhibited the effect of a much larger time constant.

Simulations showed comparable results using other datasets. Hence, this error (the deviation of simulation results from measurements) could be caused by unmodelled thermal dynamics with different time constants, which would affect the deformation induced by ambient temperature variation significantly. Most likely, a combination of unmodelled thermal dynamics and the assumed constant heat transfer coefficient as mentioned before, could have led to the deformation error.

Figure 8 shows the normalised drift velocity that occurred with and without compensation, based on the predicted deformation that could be achieved so far. In the first hour, transient behaviour was observed – indicated by the grey area. In the remaining hours, the system with compensation showed a reduction of a factor 3.5 in normalised drift velocity as long as the ambient temperatures had a constant gradient (between 4.2 h and 14.4 h).

When the ambient temperatures changed direction, around 3.5 h and 14.5 h, the compensated drift velocity was equal or slightly less than the drift velocity without compensation and the goal (i.e. normalised drift velocity within ±1) was not met. A possible explanation can be found in the modelling error that arose when the ambient temperature changed direction.

The reduction factor over the entire time range was found to be 2. In total, the drift velocity without compensation was inside the target range for 17% of the time – indicated by the orange area. The compensation technique reduced the drift velocity such, that the time the drift velocity



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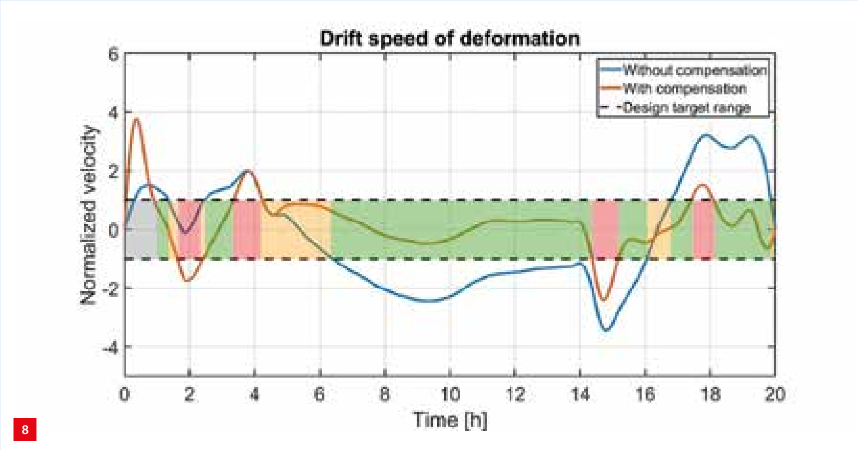
The total simulated (predicted) and measured deformation.



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The normalised drift velocity with and without compensation. The grey area shows the time when transient behaviour occurred. The green area (67%) shows the time when the velocity based on compensation was within the target range whereas the velocity without compensation was not. The orange area (17%) shows the time when the velocity was within the target range both with and without compensation. The red area (16%) shows the time when the velocity was not within the target range both with and without compensation.

was within the target range increased to 84% – indicated by the orange and green areas.

Conclusion

The aim of this project was to investigate whether drift can be reduced to the design target range by using a Kalman filter strategy within the control structure of the stage. Drift is caused by thermal deformations due to varying ambient temperatures and heat generated by actuators and sensors within the stage. The control technique used in this case employed a Kalman filter, which requires a thermal model of the stage construction, various inputs, and temperature measurements. In conjunction with a deformation model, this technique can compensate for drift.

The compensation control strategy has been validated using simulations based on multiple measurements. The objective of the project was to compensate for drift to obtain a normalised drift velocity within a range of ±1. During a 20-hour measurement in which no actuator was moved, the ambient temperature varied within a range of 1.8 °C. For this data set, the normalised drift velocity without compensation was within the design target range of ±1 for 17% of the time. Applying the compensation control technique reduced the normalised drift velocity such that the design target range was met for a total of 84% of the time.

The factors that most likely limited the performance of the compensation are assumed to be errors in the model, such as spatially and temporally varying parameters within the model, such as convection. Also, unmodelled dynamics could result in lesser performance. It is conjectured that with further research into these errors, and with more optimisation, the desired design target for the normalised drift velocity can be met. Lastly, additional research is required to validate the effect of the actuator on the results. It has been proven that the compensation technique can be used to reduce the normalised drift velocity. Moreover, this technique offers enough room for improvement and boosting its performance. All things considered, the compensation technique shows promising results in reducing drift velocity.

REFERENCES

[1] M. Daanen, "Thermal drift compensation – The implementation and realization on a three degrees of freedom sample manipulation stage", B.Sc. thesis, Fontys Engineering University of Applied Sciences, Eindhoven (NL), 2021.
[2] T.W. Davies, "Biot number", *Thermopedia*, *www.thermopedia.com/content/585*

15-16 November 2022, Den Bosch (NL)
Special Interest Group Meeting: Precision Motion Systems & Control
The second edition of this SIG Meeting is organised prior to and partly in parallel with the Precision Fair 2022 (see below).

WWW.EUSPEN.EU

16-17 November 2022, Den Bosch (NL)
Precision Fair 2022
The 21th edition of the Benelux premier trade fair and conference on precision engineering, organised by Mikrocentrum. See the preview on page 35 ff.

Precision Fair

WWW.PRECISIEBEURS.NL

22 November 2022, Veldhoven (NL)
Health Tech Event
This new conference is organised by Brainport TechLaw, Jakajima and Mikrocentrum.
It covers the interaction between innovation and regulation in the areas of medical devices, instrumentation, consumables, software, data-driven healthcare and healthcare platforms.

WWW.HEALTHTECHEVENT.EU

24 November 2022, Utrecht (NL)
Dutch Industrial Suppliers & Customer Awards 2022
Event organised by Link Magazine, with awards for best knowledge supplier and best parts & process supplier, and the Best Customer Award.

WWW.LINKMAGAZINE.NL

8 December 2022, Veldhoven (NL)
Techcafé
The next edition of this DSPE-Mikrocentrum collaboration, featuring the theme of additive manufacturing.

WWW.DSPE.NL/EVENTS

14 February 2023, Veldhoven (NL)
Manufacturing Technology Conference 2023
This conference is organised by the Knowledge Sharing Centre, an independent platform that facilitates knowledge assurance and sharing in the Dutch manufacturing industry, and Mikrocentrum. The aim is to boost the knowledge about manufacturability for engineers and help them look for possibilities that did not exist before. Presenters include representatives from ASML and Thermo Fisher Scientific.

WWW.KSCEVENTS.NL

6-7 March 2023, Tucson, AZ (USA)
ASPE Winter Topical Meeting 2023
A Precision Optical Metrology Workshop.

WWW.ASPE.NET

14-15 March 2023, Edinburgh (UK)
Lamdamap 2023
The 15th International Conference and Exhibition on Laser Metrology, Coordinate Measuring Machine and Machine Tool Performance.

WWW.EUSPEN.EU

27 March 2023, Düsseldorf (DE)
Gas Bearing Workshop 2023
Fifth edition of the initiative of VDE/VDI GMM and DSPE, focused on gas-bearing components and technology for advanced precision instruments and machines.

WWW.GAS-BEARING-WORKSHOP.COM

27-30 March 2023, Eindhoven (NL)
DSPE Optomechatronics Week 2023
This event kicks off with the 3-day Opto-mechanical System Design course, followed by the Optomechatronics Symposium & Fair on Thursday. See the announcement on page 57.

WWW.DSPE.NL/EDUCATION
WWW.DSPE.NL/OPTOMECHATRONICS

29-30 March 2023, Den Bosch (NL)
AM for Production
New knowledge and networking event about the industrial breakthrough of additive manu-facturing (AM). See also the preview on page 63.

WWW.AMFORPRODUCTION.NL

12-13 April 2023, Den Bosch (NL)
Food Technology 2023
Knowledge and network event about high-tech innovations in the food industry, working towards an efficient and sustainable future of food.

WWW.FOOD-TECHNOLOGY.NL

7-8 June 2023, Den Bosch (NL)
Vision, Robotics & Motion
This trade fair & congress focuses on smart production automation, featuring the components for a completely integrated system: from vision and optics, robotics and motion control, to data-science solutions.

WWW.VISION-ROBOTICS.NL

12-16 June 2023, Copenhagen (DK)
Euspen's 23th International Conference & Exhibition
The event features latest advances in traditional precision engineering fields such as metrology, ultra-precision machining, additive and replication processes, precision mechatronic systems & control and precision cutting processes. Furthermore, topics will be addressed covering robotics and automation, precision design in large-scale applications, and applications of precision engineering in biomedical sciences and sustainable energy systems.

DTU, the Technical University of Denmark, will provide the venue for euspen's 23th International Conference & Exhibition.

WWW.EUSPEN.EU

METAMATERIAL FOR HIGH-END LOUDSPEAKERS

Celebrating their 60th anniversary, loudspeaker builder KEF came up with a metamaterial that makes the tweeter of their LS50 Meta loudspeakers virtually reflection-free. A year later their Blade and Reference series also benefit from this very effective invention. The metamaterial consists of a fine-mesh labyrinth of channels that absorb 99% of the sound waves above 620 Hz. Unwanted rear reflection is thus a thing of the past. Sound and metamaterial expert Dr Sébastien Degraeve explains how the design came about, and how KEF succeeded in capturing an innovative mechanical noise cancellation solution in a disc that is less than a centimeter thick.

LIAM VAN KOERT

"Metamaterials are anything but new", explains Degraeve, who traded his position as an acoustic researcher at Xaar in Cambridge (UK) a few years ago for one as a senior R&D engineer at KEF to bring his expertise towards speaker construction. "The phenomenon has been around since the 1960s and has attracted ample attention, especially over the last 20 years. The principle of metamaterials is used for the electromagnetic optimisation of super antennas, but there are also special applications in optics. Think, for example, of the materials with a negative refractive index for super lenses or camouflage sheaths. For sound, however, it has hardly been applied to date." A missed opportunity according to KEF, which wanted to investigate whether they could use it to build the ultimate loudspeaker. Together with AMG (Acoustic Metamaterial Group) and metamaterial guru Ping Sheng, a research project was thus launched.

Structural properties

Contrary to what the name suggests, the unique properties of a metamaterial have little to do with the chemical composition of that material. They follow from a sophisticated structure, which makes it possible to create properties that do not occur in nature (however, bamboo is called a metamaterial by some). For example, the negative refractive index of optical elements mentioned by Degraeve is the result of structurally applied density differences. Is this similar to locally changing material properties, as is the case with functionally graded materials?

Degraeve: "Not entirely. With functionally graded materials you can indeed assign specific properties locally. You can, for instance, add additional stiffness where needed. However, this is not done on the basis of geometry, but by making one material flow into another. Metamaterials, on the other hand, are homogeneous. Moreover, loudspeaker builders are not likely to add local elasticity. On the contrary, they strive for maximum stiffness of enclosure and suspension. After all, you want to avoid any vibration that could colour the source sound."

Perfect sounds pure

Like the perfect journalist, the perfect speaker reproduces a source very faithfully. An ultimate concert sounds as if you were there live, putting yourself in the middle of the musicians. But as with the unbiased recording of professional information, in practice this is easier said than done. Assuming the source can produce a potentially unadulterated sound, there are quite a few speaker components that affect what ultimately reaches the listener.

In the case of the two-way KEF LS50 Meta (Figure 1) – the first speaker in the world equipped with a metamaterial to absorb unwanted rear sound – this applies at least to two driver arrays and their suspension, to the enclosure, and to the cross-over filters. For the wireless variant, the DSP (digital signal processing unit) with its algorithms also plays a role.

From BBC to KEF

KEF was founded in 1961 by Raymond Cooke. The BBC, where he began as a sound engineer, turned out to be very good at building monitor loudspeakers that reproduced the source very faithfully. They were so popular in the BBC studios that even after Cooke left, he continued to build speakers for the BBC, including the LS3/5A. For its 50th anniversary, KEF released the LS50 as a tribute. The LS50 Meta builds on this famous speaker.

WWW.KEF.COM

AUTHOR'S NOTE

Liam van Koert, partner of The Text Factory, obtained a degree in mechanical engineering, worked as a design engineer and then switched to technical journalism. In this role, he writes about design, engineering, machine building and industrial automation. Recently, he started Robot Magazine. This article is an enhanced adaptation of the article he published last year in Constructeur, the Dutch magazine for engineers and mechanical designers. It appears within the framework of a collaboration between Constructeur and Mikroniek for the exchange of articles.

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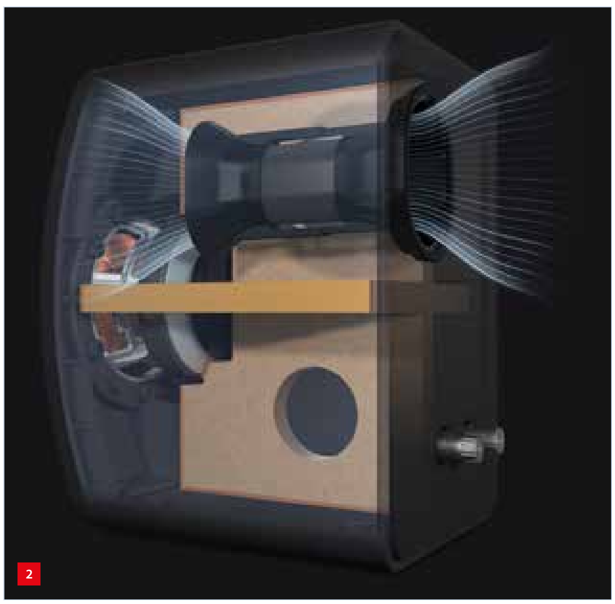
1

The KEF LS50 Meta in carbon black, back and front view.

Of all these elements, the tweeter is the most prominent one that can make or break the fidelity of the source sound. The details are found in the high registers and without a tweeter, even the most beautiful music sounds dull and grey. For the high-end spectrum, KEF already had its Uni-Q driver with 'tangerine waveguide' in its toolbox. The patented tweeter with waveguide not only sounds clear, but also provides an accurate 3D sound image.

The back problem

Yet KEF knew there was much more to be gained. After all, a loudspeaker driver produces just as much sound at the rear as at the front. For wavelengths larger than the enclosure, this is not immediately a problem. This phenomenon is even used for the low frequencies and a bass reflex port (Figure 2) is provided for a more solid bass sound. For the higher frequencies, however, the sound waves 'trapped' in the enclosure can cause unwanted background colouration. Due partly to resonance of enclosure parts, but mainly to the influence of reflection on the frequency response of the driver array itself.



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The bass reflex port has been given an offset in this case.

Like metamaterials, the 'rear-end' problem of tweeters has been known for years. The first patents to address this date back to 1940 and were based on an exponential horn that 'holds in' the quarter wavelength over the whole spectrum and extinguishes it by a phase shift of that wave. They were additionally fitted with a soft porous material for absorption. Although the method yields good results, there is one major problem. Literally. Depending on the bandwidth to be covered, the horn is easily about 80 cm long, which is not an option for compact monitor speakers such as the LS50.

KEF therefore until recently used a so-called 'vented tweeter', which eliminates the reflections at the rear to a respectable 60%. In addition, part of the 'rear problem' can also be overcome by control technology. For example, by using cross-over filters to limit the 'tweeter contribution'. Although applied by many loudspeaker builders, the solution is not very elegant. If you extend this line of thinking, then the prevention of colouration from reflection ultimately leads to the omission of the tweeter itself.

Delicate dual maze

However, a mechanical alternative also came within reach with advances in the metamaterials field. For what would happen if you gave each wavelength its own ¼ wavelength channel? Degraeve: "Together with the AMG, we investigated whether it was not only theoretically possible, but also practically feasible to develop a compact structure that absorbs the entire tweeter spectrum."

After numerous simulations in which thousands of channels were calculated in Matlab, KEF arrived at a finely meshed maze of 30 absorption channels 'tuned' for a small bandwidth (Figure 3). "We then looked at how to mould the channels into the most compact geometry possible. Although a longitudinal design was not inferior in performance, a circular configuration of two layers turned out to be the most compact in terms of construction."

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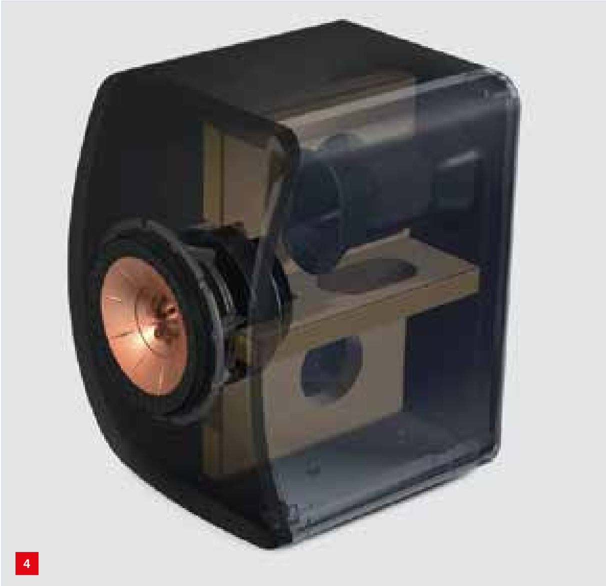
A fine ABS labyrinth with 30 channels absorbs 99% of all unwanted noise above 620 Hz.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There is also an elastic layer for damping in the suspension. KEF calls this constrained layer damping.

As for the mechanical properties of the material, Degraeve says it wasn't all that exciting. For its Meta Absorption Technology (MAT), KEF "merely" uses ABS. This material has sufficient strength, is lightweight, and can easily be printed (prototyping) and injection moulded. The latter must be done precisely. The 'tuning' is very precise and the walls of the channels are only 2 mm thick. Flatness is also important to prevent deformation during cooling.

Constrained layer damping

Another improved feature that KEF incorporated in its new jubilee editions is constrained layer damping (CLD), which involves a high-damping (often viscoelastic) material sandwiched between two sheets of stiff, low-damping materials (Figure 4). According to Jack Oclee-Brown, VP Technology at KEF UK, the technology in itself is not new and has been applied in many previous flagship loudspeakers. But in a similar way that their patented Uni-Q driver with tangerine waveguide is continuously finetuned and optimised, CLD is always improving too.

Oclee-Brown: "The function of constrained layer damping is to avoid resonance from the cabinet in which the driver arrays are mounted. A very straightforward way to tackle low-frequency resonance is to add more stiffness to the cabinet by internal bracing. Unfortunately, this only yields modest results for vibrations up to a 100 Hz. Depending on the box characteristics, bracing can even make unwanted frequencies more perceivable. A better way to deal with resonance is to use damping, which will dissipate vibrations."

Reducing ringing cabinet sounds by adding a damping material is quite common, Oclee-Brown explains. Doing it exactly right however, isn't? "As you might expect, KEF also uses a sandwich construction, containing a thin losing material that has a high damping ratio in the middle, to avoid cabinet resonance. But the key in doing this successfully lies in the precise dimensioning of the three layers, the material properties, and the way it is connected to the cabinet. We use very special sandwich materials that we developed ourselves. The laminating itself is also carried out inhouse. It is a too delicate and intellectual-property-sensitive process to outsource this."

Oclee-Brown is not at liberty to say which materials and production techniques are used exactly. "I can however disclose that the old adagio 'less is more' turned out to be true once again. Integrating precisely the right amount of damping material in the cabinet walls at precisely the right places not only proved extremely effective in our extensive simulations, but has been experienced by many audiophile bon vivants around the world." Figure 5 shows the final design and Table 1 gives some key specifications.

Table 1
Kef LS50 Meta specifications.

Speaker type	2-way bass reflex
Frequency range	47 Hz - 45 kHz
Sensitivity	85 dB
Recommended power	40-100 W
Impedance	8 Ω (with a minimum of 3.5 Ω)
Cross-over frequency(ies)	2.1 kHz
Number of speaker units	2 (Uni-Q)
Dimensions (h x w x d)	302 mm x 200 mm x 280.5 mm
Weight	7.8 kg


5a

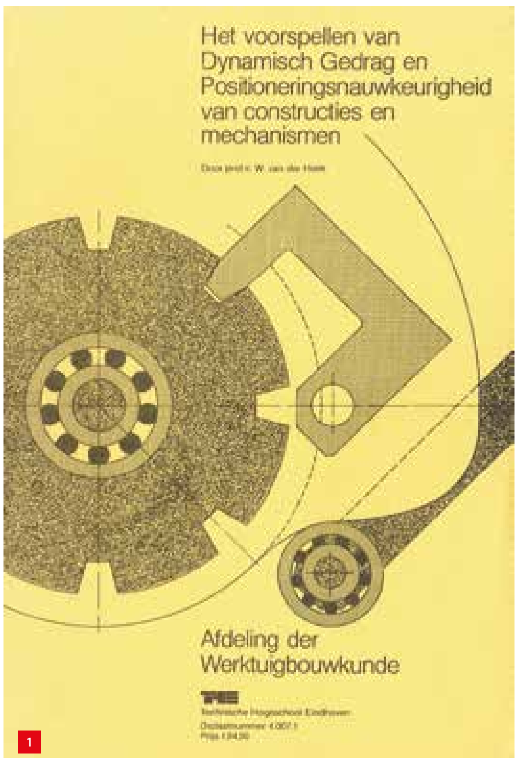

5b

Final design.
(a) Exploded view of the overall two-way system, showing from left to right the tangerine waveguide, rings, the cone, the motor, seals, and finally the fine-mesh labyrinth (in black).
(b) The addition of Meta Absorption Technology and changes to the tweeter suspension also necessitated a redesign of the tweeter cavity.

FROM BEST PRACTICES TO DESIGN PRINCIPLES

Wim van der Hoek's design principles for accurate movement and positioning derive from the practice of production automation at Philips. Driven by the need for high-precision machines, he started researching the dynamic behaviour and positioning accuracy of constructions and mechanisms. This fifth in a series of articles recounts how the best practices collected by Van der Hoek laid the foundation for his design principles, as described in DSPE's Dutch-language book "Wim van der Hoek (1924-2019) – A constructive life". These were further elaborated by his academic successors, culminating in the current initiative to update the design principles for precision mechatronics, as introduced in this Mikroniek issue.

In Van der Hoek's early years as a mechanical designer in the 1950s, his discipline was mainly focused on questions such as, "Will the structure fail or not?" and "Can wear and tear be contained?" At Van der Hoek's instigation, dynamics was included in the design issues, in particular for high-precision machines. He started researching the dynamic behaviour and positioning accuracy of constructions and mechanisms at Philips, together with ir. Diny Reddering-Lammens. Stiffness, mass, play, (virtual) friction and the motion profile became relevant concepts, and the question immediately arose: how do you construct according to these new insights?



1 *The foundation for Van der Hoek's lecture notes, used during his part-time professorship of Design and Construction at Eindhoven University of Technology since the 1960s, had been laid at Philips over the previous decade. The cover illustration shows the design for improved locking of previously overly stiff switchboard controllers.*

High usability over scientific precision

In the daily practice of the drawing room, the emphasis, according to Van der Hoek, was more on high usability than on scientific precision. This conviction formed the basis of all his thinking about and developing of the design profession; not just science for science's sake. A position that would have caused many fellow scientists to frown. After all, science involves mathematical precision or, at the very least, considerations about the accuracies achievable using the scientific results. As a designer/constructor, however, Van der Hoek wanted to speed up the design process and not let thorough analysis slow it down.

The aim of his work on dynamic behaviour as a source of inaccuracy in motion and positioning was twofold. Firstly, to bring relevant parts of the dynamics of mechanisms to the attention of the Philips production automation (and the wider engineering) community. Secondly, to develop some easily applicable, efficient design tools for modelling and dynamics. He compiled the results of this work in his lecture notes "Predicting Dynamic Behaviour and Positioning Accuracy of constructions and mechanisms" (Figure 1). This provided the impetus for the further dissemination of Van der Hoek's ideas.

Collecting examples

Only having tools for modelling and dynamics did not, however, offer enough help to the designer. After all, the question remained how one could create a stiff, play-free design that achieved sufficient accuracy in movement and positioning. To answer this question, Van der Hoek started to collect examples to make clear why a mechanism designed in a certain way would not have sufficient stiffness. Such constructions should be strongly discouraged, he emphasised. Bram Brugman, one of his first graduate students at Eindhoven University of Technology (TU/e), came up with the name "The Devil's Picture Book" (*Des Duivels Prentenboek*, DDP) for the collection of illustrative design images. This ironic name refers to the card game, which is, after all, also a collection of images and in the past was often associated with gambling, pubs and misery.

Van der Hoek learned gradually that it would be more effective to add alternatives to these 'anti-examples', as 'best practices' that showed how things could be done better. This concerned designs that had been given more stiffness without increasing their mass; sometimes the mass was even reduced. In this way, "The Devil's Picture Book" – already evolved into a kind of nickname – grew into Chapter 13 of his lecture notes. The common thread in DDP was 'light, sufficiently stiff and play-free' design based on the acquired insight into dynamics and accuracy.

Lecture notes and DDP

Gradually, however, the idea began to mature that these principles had a more generic meaning. The collection expanded to include more categories of design principles relevant to positioning accuracy (see the text box). DDP began as a package of illustrations and in 1967, the first edition of the lecture notes, including DDP, appeared in one volume. Every other year, on average, DDP was improved and expanded with new examples, eventually amounting to 250 pages. Many examples came from graduation work or designs from Philips practice, but in essence they were often ideas from Van der Hoek himself.

However, he usually gave the credit to his graduates or Philips colleagues, although he hated it when someone 'claimed' an idea. When a student came to the professor with their elaboration of a clever idea originating from Van der Hoek, he shook the student's hand and said, "Well done, youngster". As his TU/e-colleague Prof. Jan Janssen put it later, at Van der Hoek's farewell: "The way, Wim, in which you provide DDP with the names of the inventors and the improvers, so that you try to create the impression that all the beauty comes from others, is truly unprecedented. And the way in which you elicit improvements from those involved or make them complicit is inimitable." To the present day, this design principle creation and evolution process has remained alive and kicking.

"Wim van der Hoek (1924-2019) – A constructive life"

After Wim van der Hoek passed away in early 2019, DSPE took the initiative to publish a book (in Dutch) about the Dutch doyen of design principles (Figure 3). It covers his formative years, including his World War II 'adventures', his career at Philips and Eindhoven University of Technology, his breakthrough ideas on achieving positioning accuracy and control of dynamic behaviour in mechanisms and machines, and their reception and diffusion. It concludes with his busy retirement years in which he continued to tackle design challenges, technical as well as social, believing that technology should support people.

His specialism, dynamic behaviour and positioning accuracy, was the main subject of his part-time professorship at Eindhoven University of Technology, from 1961 to 1984. There, he endeavoured to enthuse first-years in the mechanical engineering profession and to teach fourth-year students (some 600, over the years) mechanical design. In his lecture notes, he built on his research at Philips. He collected examples of designs that were lightweight, sufficiently stiff and play-free with regard to dynamics in his famous "The Devil's Picture Book" (*Des Duivels Prentenboek*), which he presented as a source of inspiration for upcoming and experienced designers. Now, this book about Wim van der Hoek conveys the same enthusiasm.

Figure 3. Lambert van Beukering & Hans van Eerden (eds.), "Wim van der Hoek (1924-2019), Een constructief leven – Ontwerpprincipes en praktijklessen tussen critiek en creatie", ISBN 978-90-829-6583-4, 272 pages, €49.50 (€39.50 for DSPE members) plus €6.50 postage, published by DSPE in 2020.

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Ten chapters

At the end of his career, Van der Hoek did not consider DDP complete. There was still a lot to be desired, besides the regular updating. Images and descriptions had been added at the expense of clarity, meaning the accessibility of DDP had suffered as a result.

Van der Hoek and his successor Prof. Rien Koster (Figure 2) arrived at a reclassification, based on their conviction that for the entire area of accurate positioning there were probably only about ten problem areas that covered everything:

- Designing for stiffness
- Avoiding backlash
- Designs based on elastic deformation
- Mastering degrees of freedom
- Manipulating and setting
- Friction, hysteresis and micro-slip
- Mechanisms in which friction plays a role
- Mechanisms based on unwinding
- Belt and wire
- Power management

Wim van der Hoek, with his wife Aat, congratulating his successor Rien Koster (left) as professor at TU/e after delivering the inaugural lecture in the spring of 1986.

Millux – specialist in laser material processing technologies

Millux, located in Wijchen, the Netherlands, is a technology leader in the field of laser processing technologies. Building on its metallurgical knowledge and diverse platform of laser technologies, Millux collaborates with customers from the early design phase and the first functional prototype to a fully industrialised technological solution.

From Reith Laser to Muon Group

The company was founded by Dr Jan Reith in 1988. Since then, Reith Laser has explored and exploited the possibilities of modern laser technology for the application of precision laser processing, thus growing into an established technology specialist. In 2017, the company was acquired by the Veco Group, which later became the Muon Group, comprising specialists in the fields of electroforming, chemical etching and laser material processing. Last year, Reith Laser was rebranded to Millux, which refers to the processing of materials (milling) with the aid of light (lux, in Latin).

Pulsed-laser technologies

A laser beam introduces heat into a material to achieve a controlled material transformation, from a superficial engraving to complete cutting. Pulsed lasers enable high-power machining while preventing the thermal overload associated with a continuous energy supply. Millux uses milli- and microsecond pulsed lasers for cutting and welding, nanosecond lasers for engraving, and pico- and femtosecond lasers for drilling and micromachining.

Millux has specialised in the full spectrum of pulsed-laser technologies, including laser welding and laser cutting with Trumpf's TruLaser Cell 3000.

At Millux, a micromachining accuracy of one micrometer is achieved with GFH's GL.evo machine.

Metallurgical knowledge

Laser processing can be applied to a variety of metals, ranging from (stainless) steel, aluminium and titanium to ceramic, glass and diamond. Through materials research and practical experience Millux has gathered extensive metallurgical knowledge to facilitate the creation of a large variety of very precise products that satisfy the customer's stringent requirements on dimensional precision and finishing quality.

Micrometer to nanometer precision

Drawing upon smart process control, Millux ensures high process stability, reliability and repeatability. Advanced laser systems producing very small beam diameters can achieve machining precision in the micrometer or even nanometer area. Combined with the almost negligible heat input of short-pulsed lasers, this enables Millux to manufacture high-quality, high-precision components and products in 2D as well as 2.5D or even 3D applications, achieving new functionality and increased performance of high-end equipment.

Full service

As a laser machining specialist, Millux covers the complete product creation process, from the early design phase to full-scale automated production. In a co-development approach, Millux provides application engineering support to arrive at an optimised solution to the customer's precision product challenge. The introduction of proven production automation methodologies has enabled Millux to operate in a lean robotised fashion – ultimately achieving one-piece flow and offering cost-effective product supply for customers.

Top 10 semiconductor manufacturing solutions provider

Millux has been recognised as a "Top 10 semiconductor manufacturing solutions provider in Europe 2022" by the international Semiconductor Review magazine. "As an industry leader in laser technologies, Millux has already mastered high-precision lasers that can boost the development of first-to-market innovations in new micro products and advanced manufacturing equipment. The company leverages this expertise to offer fully customised laser solutions to semiconductor equipment suppliers. (...) Moving ahead with its proven capabilities, Millux is now poised to play a critical role in advancing the semiconductor industry beyond the current threshold and participate in more innovative strides."

INFORMATION
WWW.MILLUX.NL
WWW.MUONGROUP.COM

FIVE NOMINATIONS FOR WIM VAN DER HOEK AWARD 2022

The youngest generation of mechanical designers is still inspired by the design principles of Wim van der Hoek. The nominations for the Wim van der Hoek Award 2022 bear witness to this. The former Philips engineer and professor by special appointment at Eindhoven University of Technology passed away a few years ago at the age of 94, but his ideas are still taught and his name lives on in the prize named after him. The jury for this prize has received a total of five nominations from three universities of technology and two universities of applied sciences for students who applied existing or new design principles in their graduation work in an appealing way. The award will be presented for the seventeenth time on Thursday 17 November under the auspices of DSPE. The award ceremony will take place in Den Bosch (NL) during the second day of the Precision Fair.

The Wim van der Hoek Award – also known as the Constructors Award – was introduced in 2006 to mark the 80th birthday of the Dutch doyen of design engineering principles, Wim van der Hoek. The objective was then, and still continues to be, to promote and stimulate the discipline of mechanical engineering. This award includes a certificate, a trophy produced by the Leidse instrumentmakers School and a sum of money (sponsored by the EAISI institute of Eindhoven University of Technology, TU/e).

Best graduation project

The Wim van der Hoek Award is presented every year to the person with the best graduation project in the field of design in mechanical engineering at the universities of technology and universities of applied sciences in the Netherlands and Belgium. Criteria for the assessment of the graduation theses include the quality of the design, its substantiation and innovativeness, as well as its suitability for use in teaching design principles. This year the jury, under the presidency of DSPE board member Jos Gunsing (MaromeTech), received five nominations, submitted by the graduation supervisor/professor of each student concerned. The nominations came from Avans University of Applied Sciences (Avans UAS) in Breda, Fontys Engineering UAS in Eindhoven, KU Leuven University (Belgium), TU/e and University of Twente.

Candidates

Roy Kelder (University of Twente)

Active Vibration Isolation with an Active Stage

"Roy first followed a higher vocational education study, while having a sidejob in the technical field. Thanks to his broad education and experience, he has been able to convert theoretical insight and analyses into a functional and feasible design for an active vibration isolation system with highly favourable dynamic properties. He was one of the few students to deliver a design that our workshop technician could get to work on immediately, without having to redesign it for manufacturability. Roy has a hands-on mentality, which was evident in, among other things, arranging a free extension of the interface for our real-time hardware. With his energetic approach, he was able to get a lot done during his swift graduation period."

Alexis Van Merris (KU Leuven)

Design of soft robotics based EDM tool clamping for hard-to-reach zone machining

"Alexis has pushed the scientific boundaries of machine tools. He developed a revolutionary alternative to the rigid spark electrode which, in Electro Discharge Machining (EDM), results in complex parts having to be assembled from several parts, with all the associated drawbacks. His actively bendable tool holder makes it possible to remove material from hard-to-reach areas via EDM. The application of soft-robotics technology in the field of machine tools is anything but trivial, and can be attributed entirely to Alexis' creativity. He devised this concept and also realised a prototype system. His work is of very high quality and combines exceptional analytical skills with excellent practical insight."

Julia Poelman (Avans UAS)

Project Rapid Stop: Ontwerprapport over de ontwikkeling van een botsing detectiesysteem voor handlingrobots
(*Project Rapid Stop: Design report of the development of a collision detection system for handling robots*)

"Julia carried out her graduation project very professionally and achieved a lot with her ingratiating attitude. In addition, she searched for depth of content, investigated with a critical eye and kept digging until everything was right. She has mastered new theory in a broad assignment and actively challenged herself to achieve practical/experimental elaboration. She has delivered a very nice piece of work from a practical and theoretical point of view, technically very good with an eye for detail. Due to the practical aspects, the validation is very strong and therefore also the value of the end result."

Jeroen Raijmann (Fontys Engineering UAS)

An integrated 3D printed mounting system for optical elements that will reduce the alignment time of the light path within the ARINNA

"Jeroen has made a monolithic adjustment mechanism for an interferometer, where it was important that there are no parasitic movements. He created a design to be printed in metal, using two concepts of flexible mechanisms that he put in series. One mechanism is a linear guide with compensation for the parasitic movement due to shortening for the translation. The other mechanism is based on the so-called tetra spherical flexure joint, where three rotations can be set around one point. Jeroen has worked in a very structured way and has carried out a thorough literature study in the field of flexible mechanisms and 3D metal printing. He is social and proactive, and has a strong intrinsic motivation."

Dennis Struver (TU/e)

Design of a voice coil actuated active vibration isolator for cryogenic conditions

"Dennis has researched a voice-coil-actuated vibration isolation system for possible application under cryogenic conditions. This is one of the solutions to provide the Einstein Telescope for the detection of gravitational waves with a much-improved sensitivity. Commercially available cryocoolers produce noise, for which Dennis designed and largely realised a very elegant cryogenic active vibration isolator. He has shown that he is perfectly capable of coming up with an innovative mechanical and mechatronic design, including control, and analysing it on critical aspects. He has impressive inventive and analytical skills, and he works very independently, although he also knows how to approach people for relevant input."

LIVE: DSPE OPTOMECHATRONICS WEEK 2023

Next year will see a new, live edition of the DSPE Optomechatronics Week, featuring a Symposium & Fair, dedicated to the latest developments in optomechatronics, preceded by the 3-day Optomechanical System Design course. The event will be held in Eindhoven (NL) on 27-30 March 2023.

It will be the fifth edition of the DSPE initiative that started in 2013 as the DSPE Optics and Optomechatronics Symposium in Eindhoven (NL). Later editions were held in Delft (NL) in 2015, Aachen (Germany) in 2017, and again in Eindhoven in 2019, as part of a DSPE Optics Week, which also featured advanced courses, such as the Optomechanical System Design course.

This course premiered in 2019; it targets mechanical, mechatronic and optical engineers, and offers a broad overview of this omnipresent multidiscipline. It contains numerous design examples that illustrate the tricks of the trade in optomechanical system design, which increasingly affects the overall performance of high-tech systems. During the DSPE Optomechatronics Week 2023, the course will be held on 27-29 March.

At the Symposium on 30 March, organised by DSPE in collaboration with independent high-tech knowledge institute Mikrocentrum and the German photonics cluster Optence, the keynote speech will be delivered by Zeiss SMT. Additional presentations will be given by representatives from, among others, ASML, Research Instruments, TNO and the universities of technology of Delft and Eindhoven.

For example, Stefan Kuiper, mechatronic system architect at TNO, will talk about the development of deformable mirror technology for aberration correction in high-end adaptive optics systems in the field of astronomy, space telescopes and laser communication. Wim Coene, part-time professor at Delft University of Technology and director of Research at ASML, will discuss the imaging of nanostructures without lenses.

Other presentations include adaptive wafer table and optical measurement tool designs. The symposium is targeted at architects and engineers who are involved in the design and realisation of optical hardware. Registration is open. There is room for table-top presentations; organisations are invited to exhibit.

WWW.DSPE.NL/OPTOMECHATRONICS

VOLUNTEER IN THE SPOTLIGHT: 'MISTER LUNCH LECTURES' BJÖRN BUKKEMS

As an organisation, DSPE runs mainly on volunteers. They are selflessly committed to the society and put in many hours, often behind the scenes. With this column, DSPE wants to put its volunteers in the spotlight. The first profile introduces Björn Bukkems, senior mechatronic system designer at MI-Partners in Veldhoven (NL). Since the start in 2020, he has facilitated the lunch lecture that DSPE organises on the first Monday of every the month.

Björn Bukkems studied Control Engineering at Eindhoven University of Technology and also obtained his Ph.D. degree there, with his thesis titled "Sheet Feedback Control Design in a Printer Paper Path". He then started working at ASML, in positions including mechatronics design engineer, mechatronics/control architect, and team lead of control and dynamics teams on various parts of the lithography machines. In his last position at the Veldhoven lithography machine builder, he carried out feasibility studies for the DUV (deep UV) technology programme, on new concepts for the DUV machines.

"What I did there was comparable to what MI-Partners does: bringing ideas into reality by coming up with concepts, carrying out feasibility studies, making prototypes and testing them. That appeals to me: thinking along with the customer in the early phase of a programme or project in order to arrive at solutions and demonstrate that they work in practice." So, at the end of 2015 Bukkems switched to the 'real' MI-Partners, partners in mechatronic innovation.

He has held various roles at his current employer: senior mechatronic system designer, dynamics and control architect, and project manager. For the last two years he has been team lead Dynamics & Control. "I was looking to broaden my scope at MI-Partners and I succeeded. The projects are smaller, which means that you automatically start thinking more broadly than at ASML, which is a very large company with many specialists for everything. Here, I'm not only concerned with dynamic behaviour, but also with thermal behaviour and the control engineering of a complete system."

The subjects that are presented in DSPE's online lunch lectures are also broad. "When the Covid-19 pandemic had been going on for half a year, the DSPE board together with MI-Partners took the initiative to organise online meetings in the form of lunch lectures. The idea was to compensate for the fact that people were less able to meet in real life, and therefore less able to exchange knowledge and information. My colleague Elwin Boots kicked off in December 2020 with a lecture about a magnetically levitated stage. Our managing director Ronald Schneider, who is also a DSPE board member, had asked me to facilitate the lecture technically. I think he knew that I can easily bring things together to organise something."

Nearly two years have since gone by and there have already been over twenty lectures, on all kinds of subjects, given by researchers and engineers from various companies and research institutions. The lectures still attract a lot of interest, with between 40 and 60 unique logins each time and peaks of up to 100. Bukkems knows that several colleagues can be hidden behind one login. "Even when Covid-19 had faded into the background and people were able to visit each other again, there was still an enthusiastic audience for the lectures. I hear from people that they find it fun and accessible, joining the meeting for half an hour and then getting back to work with new inspiration."

In general, the lectures in Microsoft Teams go well technically. "They always start on the first Monday of the month at 12:02 PM (once the monthly air-raid siren test has stopped, ed.). We start testing everything half an hour before that and sometimes we still have to solve some minor problems, such as a video running too slowly, or the presentation of something on a green screen working differently in Teams than in Zoom. We haven't had any major 'showstoppers' yet. In the beginning we wanted to make it dynamic by pointing a camera at the presenter in front of a screen, but that caused some problems with interference. That is why we start with a short introduction of the presenter on camera, after which only their slides can be seen on the main screen, sometimes supplemented with a specific presentation."

For the time being, Bukkems still enjoys his task. "Approaching people, taking care of the announcements together with Julie van Stiphout and Erik Knol, facilitating the online meeting, that is fun to do. So, I'm happy to continue for some time, provided of course that the audience is still interested and that there is interaction with the audience during lectures. We do not record the sessions because we want to involve the audience live in the lecture and create interaction on the spot." After all, that's what the lunch lectures were meant for in the first place: exchanging knowledge and experience.

WWW.MI-PARTNERS.NL

MOTORCYCLING ENGINEERS

During last year's DSPE Conference on Precision Mechatronics, visiting a hangar with historical airplanes, the idea arose to organise a 'Hells Engineers' motorcycle ride. Last September, 11 motorcyclists associated with DSPE took a 150 km ride through rural parts of Noord-Brabant and Limburg. It was a successful first ride. Engineers who are interested in participating next year can contact Annemarie Schrauwen.

ANNEMARIE.SCHRAUWEN@DSPE.NL

BRONZE LAUREATE COMBINES LEARNING-ON-THE-JOB WITH FORMAL TRAINING COURSES

This summer, four people were awarded a Bronze certificate from ECP2, a European certified precision engineering course programme that is a collaboration between euspen and DSPE; see the previous issue of Mikroniek. Among them is Gijs Kramer, who studied Mechanical Engineering at the University of Twente, specialising in mechatronics design.

Euspen's ECP2 programme grew out of DSPE's Certified Precision Engineer programme, which was developed in the Netherlands in 2008 as a commercially available series of training courses. In 2015, euspen, DSPE's European counterpart, decided to take certification to a European level. The resulting ECP2 programme reflects industry demand for multidisciplinary system thinking and in-depth knowledge of the relevant disciplines.
A certificate scheme was instigated to promote participation. The Bronze certificate requires 25 points (one point equals roughly one course day), Silver requires 35 points and Gold 45 points, which qualifies a participant for the title 'Certified Precision Engineer'.

After his graduation, Gijs Kramer first worked at Exact Dynamics, where he had the opportunity to design a rehabilitation device from scratch to prototype, in a very small company. This process meant that he learned a lot from the experience of collaborating with his colleagues, covering areas such as service, manufacturing, sourcing, end-user contact, sales, and cooperation in a European project. "I am grateful for these great learning-on-the-job experiences, which still impact my engineering attitude."

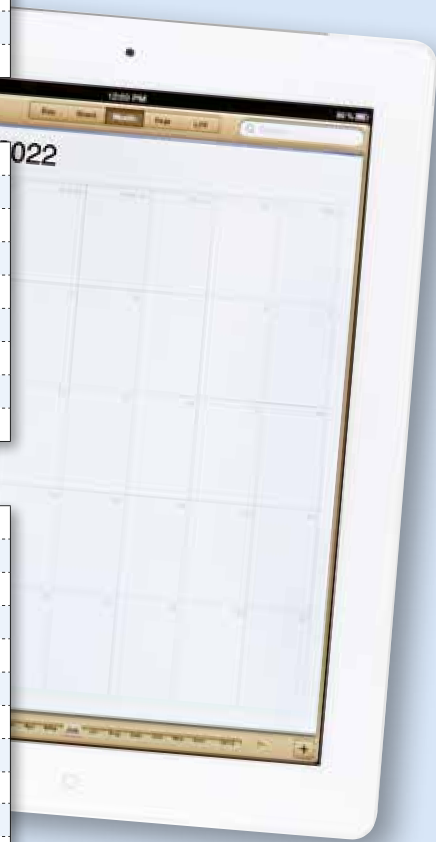
Since 2008, Kramer has worked as a design engineer at ASML, which also offers a great learning-on-the-job environment, albeit more in the areas of design & engineering and technology. In addition, he started following various formal (ECP2-certified) training courses. "For example, the Summer school Opto-Mechatronics, which introduced me to the teaching material of prof. Robert Munnig Schmidt, who was then still working on his textbook ("The Design of High Performance Mechatronics", Robert Munnig Schmidt, Georg Schitter, Jan van Eijk and (for the second edition in 2014) Adrian Rankers, ed.). It helped me to understand some neighbouring aspects, such as actuator design, of what I was usually working on at the time. Moreover, it got me enthused for new topics, such as op amp design, when I had never before considered trying to make one."

Other courses included Applied Optics, combining theory with practical exercises using real hardware, and Thermal Effects in Mechatronic Systems, "because understanding thermal limitations is everyday practice for me." The latest training Kramer especially enjoyed was Advanced Mechatronic System Design, Parts 1 and 2. "The experienced teachers highlighted system design aspects in a clear and relaxed manner, while we could demonstrate the lessons directly in a case study. The other benefits included getting to know more colleagues and really mimicking the on-the-job learning that I like so much."

Gijs Kramer (left) receiving the ECP2 Bronze certificate from the hands of Jan Willem Martens, founding father of the precursor DSPE certification programme.

WWW.ECP2.EU

ECP² COURSE CALENDAR



COURSE (content partner)	ECP² points	Provider	Starting date
FOUNDATION			
Mechatronics System Design - part 1 (MA)	5	HTI	5 June 2023
Mechatronics System Design - part 2 (MA)	5	HTI	30 October 2023
Fundamentals of Metrology	4	NPL	to be planned
Design Principles	3	MC	8 March 2023
System Architecting (S&SA)	5	HTI	13 March 2023
Design Principles for Precision Engineering (MA)	5	HTI	3 July 2023
Motion Control Tuning (MA)	5	HTI	to be planned (Q2 2023)
ADVANCED			
Metrology and Calibration of Mechatronic Systems (MA)	3	HTI	21 March 2023
Surface Metrology; Instrumentation and Characterisation	3	HUD	to be planned
Actuation and Power Electronics (MA)	3	HTI	to be planned
Thermal Effects in Mechatronic Systems (MA)	3	HTI	13 December 2022
Dynamics and Modelling (MA)	3	HTI	22 November 2022
Manufacturability	5	LiS	to be planned
Green Belt Design for Six Sigma	4	HI	29 March 2023
RF1 Life Data Analysis and Reliability Testing	3	HI	to be planned
Ultra-Precision Manufacturing and Metrology	5	CRANF	to be planned
SPECIFIC			
Applied Optics (T2Prof)	6.5	HTI	to be planned (Q1 2023)
Advanced Optics	6.5	MC	23 February 2023
Machine Vision for Mechatronic Systems (MA)	2	HTI	upon request
Electronics for Non-Electronic Engineers – Analog (T2Prof)	6	HTI	to be planned
Electronics for Non-Electronic Engineers – Digital (T2Prof)	4	HTI	to be planned
Modern Optics for Optical Designers (T2Prof) - part 1	7.5	HTI	to be planned (Q3 2023)
Modern Optics for Optical Designers (T2Prof) - part 2	7.5	HTI	20 January 2023
Tribology	4	MC	7 March 2023
Basics & Design Principles for Ultra-Clean Vacuum (MA)	4	HTI	to be planned
Experimental Techniques in Mechatronics (MA)	3	HTI	30 May 2023
Advanced Motion Control (MA)	5	HTI	to be planned (Q1/Q2 2023)
Advanced Feedforward & Learning Control (MA)	3	HTI	to be planned (Q2 2023)
Advanced Mechatronic System Design (MA)	6	HTI	to be planned
Passive Damping for High Tech Systems (MA)	3	HTI	29 November 2022
Finite Element Method	2	MC	9 March 2023
Design for Manufacturing (Schout DfM)	3	HTI	to be planned (Q2 2023)

ECP² program powered by euspen

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

WWW.ECP2.EU

Course providers

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

Content partners

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

Piet van Rens receives ASPE Lifetime Achievement Award

At the annual meeting of ASPE (American Society for Precision Engineering), last month in Bellevue, WA (USA), Piet van Rens received the 2022 Lifetime Achievement Award. Piet C.J. van Rens received an M.Sc. degree in Mechanical Engineering in 1980 from Eindhoven University of Technology, with professor Wim van der Hoek. For several years, he was Van der Hoek's assistant at Philips CFT. During this time, he worked at the Laboratory of Space Research in Utrecht for 3 years, and then for 24 years at Philips.

Van Rens has had a long history in the practice of precision engineering, working at the highest levels of precision in applications such as lithography and electron microscopy. He has also taught many generations of precision engineers both formally and informally, including six years at Delft University of Technology on a part-time basis, alongside 30 years of teaching for Mikrocentrum in Eindhoven. For the last ten years, Van Rens has been a practicing independent engineer, predominantly working for Settels Savenije and their customers, such as ASML, in all manner of high-precision technology applications.

His contributions stretch back over four decades, including those to the "The Devil's Picture Book" (*Des Duivels Prentenboek*), one of the foundational books in Dutch precision engineering. According to ASPE, "Van Rens is one of the pillars of the Dutch precision engineering community and an extremely gifted practitioner of the art of precision engineering. His contributions can be found in many ultra-high-precision machines in use today. He has had a long history with ASPE, where he has imparted much of his hard-earned knowledge and experience through extremely well-received tutorials in the ASPE tutorial programme."

Last year, the ASPE Lifetime Achievement Award went to Jan van Eijk, underlining the recognition that the Dutch school of precision engineering and mechatronics is receiving across the Atlantic.

Piet van Rens. (Photo: High Tech Institute)

WWW.ASPE.NET

SIOS displacement-angle differential interferometer

For measuring tolerances in the picometer range, SIOS Meßtechnik develops high-precision differential interferometers with ultra-stable thermal and physical properties: fluctuating parameters such as temperature, air pressure and humidity do not affect the very high measuring accuracy even over longer periods of time. SIOS' new and so far unique displacement-angle differential interferometer combines the advantages of the differential interferometer with those of the well-established triple-beam interferometer and makes it possible to record several degrees of freedom with long-term stability and synchronously.

A major problem here is that the measurements take place in production environments that cannot offer optimal laboratory conditions. The technology used must therefore be able to compensate for fluctuating environmental influences such as temperature, air pressure and humidity without falsifying its results, in order to also enable stable repeatability of multiple measurements. To do so, SIOS uses high-precision differential interferometers that achieve 25 times the stability of comparable measurement systems.

However, the increasing demand for suitable solutions, especially for xy-positioning, further challenged the know-how of the measurement technology specialists at SIOS. Long-term-stable measurements of several degrees of freedom were to be made possible simultaneously over longer distances. To achieve this, SIOS' high-precision SP 5000 TR triple-beam interferometer, which is designed for simultaneous displacement and angle measurements, was combined with the SP 5000 DI differential interferometer in order to benefit from its long-term stability.

With the SP 5000 TR-DI displacement-angle differential interferometer, SIOS claims to have developed the world's only system that uses two times tree laser beams to measure displacement and angle highly synchronously and – thanks to the compensation of environmental factors – with ultra-stability at the same time. The total of six laser beams are guided out of the sensor head in parallel and hit a flexible and a static reflector. In this way, a large part of the distance between the interferometer and the measurement location can be optically compensated.

The actual measurement concentrates on the difference in length between the measuring and reference beams, so that environmental influences that could affect the result can only have an effect on this small measuring range. In addition, all differential interferometers are equipped with long-term-stable sensors that have a temperature sensitivity of < 20 nm/K.
In the Netherlands, SIOS is represented by Te Lintelo Systems.

The newly developed displacement-angle differential interferometer combines the advantages of differential interferometers with those of triple-beam interferometers and makes it possible for the first time to measure several degrees of freedom with long-term stability and synchronously.

WWW.SIOS-PRECISION.COM
WWW.TLSBV.NL

New event: AM for Production

Mikrocentrum has launched a new event: AM for Production. Additive manufacturing (AM) is ready for the factory of the future, according to Mikrocentrum. "AM is in grande finale to break through in the high-tech and manufacturing industry. (...) Not only have great strides been made in terms of material use, accuracy, quality and standards, but the areas of application and possibilities for system integration have also grown enormously. Moreover, mass customisation is becoming a reality thanks to AM, offering new opportunities to stay ahead in a highly competitive (world) market."

The AM knowledge and networking event for high-tech and manufacturing companies will premiere on 29-30 March 2023 in the Brabanthallen in Den Bosch (NL). The event is targeted at specialised companies and organisations in the field of AM machines, peripherals, support services, software for AM implementation, and the delivery of high-quality end products, as well as standardisation, qualification, quality assurance and approvals for AM technology.

WWW.AMFORPRODUCTION.NL

HoT network to Tasker

The network of Eindhoven-based The House of Technology (HoT) for matching the supply and demand of technical expertise has found a new home at Tasker. From Eindhoven (NL), Tasker connects supply and demand of hardware engineering worldwide by matching profiles of engineers with projects ('tasks') of companies. Tasker combines flexibility and accessibility with the scalability of an automated platform.

The House of Technology will now focus on its platform of clubs in which managers of technology companies exchange knowledge and experience. There are two clubs for CTOs of OEMs (in the southern and the eastern part of the Netherlands) and clubs for CTOs of suppliers, COOs and product managers.

WWW.THEHOUSEOFTECHNOLOGY.NL
WWW.TASKERPLATFORM.COM

Hitting the bull's eye

Resolution, accuracy, repeatability and precision are critical requirements of motion systems. They fundamentally impact system complexity, cost, and development time. Understanding these terms will help to refine and optimise instrument requirements.

At a high level, New Scale Technologies, the developer and manufacturer of miniature motion systems located in Victor, NY (USA), uses the common dart board to visualise the meaning of accuracy, repeatability and resolution for the case of micropositioning.

- Accuracy: How close the actual position is to the target position. *The distance a dart is from the centre, or 'bull's eye' target.*
- Repeatability (often called precision): The variation of actual positions after several attempts to achieve the target position. *The grouping of darts after trying to hit the bull's eye.*
- Resolution: The smallest increment of motion a system can achieve. *The skill of the thrower to adjust their aim and incrementally place darts vertically or laterally on the board.*

With high resolution and repeatability, New Scale's M3 Motion Modules provide micropositioning of, for example, optics, probes and samples in precision instruments. Their position resolution in closed-loop operation is the smallest commanded movement the digital controller can achieve; in practice, it is the minimum movement detected by the position encoder, typically 500 nm. Position accuracy then is the variance between the stage position as achieved by the digital controller, and as measured by an independent measurement method. This variance is mapped over the range of motion. A significant component of the accuracy variance is repeatable and can be mapped, stored in memory, and corrected for by commanding offsets. This process, called calibration, improves accuracy up to the limits of system repeatability and resolution. Referring to the dart board (below), a person with a repeatable throw can improve their accuracy by adjusting their aim down and to the right.

One of the M3 Motion Modules from New Scale Technologies, which is represented by Te Lintelo Systems In the Netherlands.

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