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.




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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

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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 Positioneringsnauwkeurigheid 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 eigenfrequency 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.

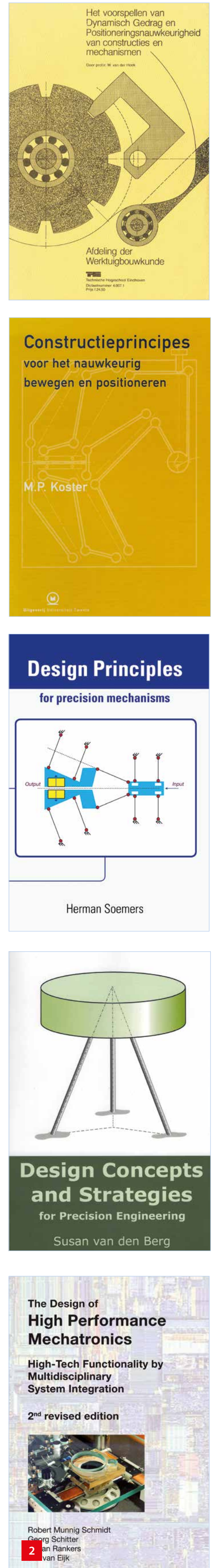
DPPM website

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.



2 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

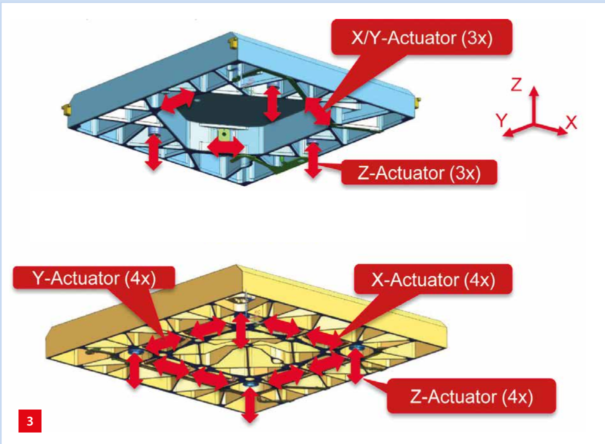
In semiconductor lithography stages, 6-DoF actuation was applied for a long time primarily to avoid unknown deformations of calibrated interferometer mirrors at the side edges of the so-called wafer chuck. Typically, three vertical and three horizontal actuators were applied in 120° symmetry (see Figure 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.

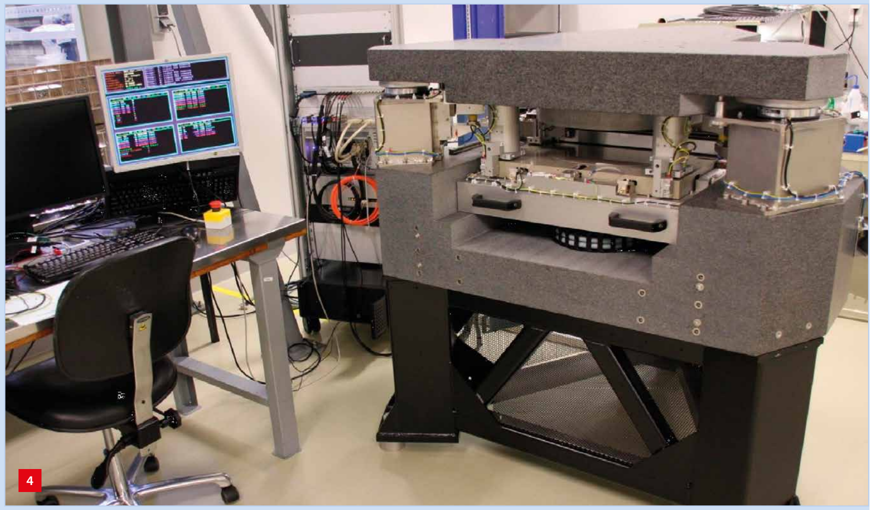
To mitigate this fundamental limitation, over-actuation (Figure 3b) was considered and first tested in an over-actuated test rig at ASML (see Figure 4). An aluminium chuck was provided with three vertical actuators for traditional control (see Figure 5a) and next, four vertical actuators were used (Figure 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.

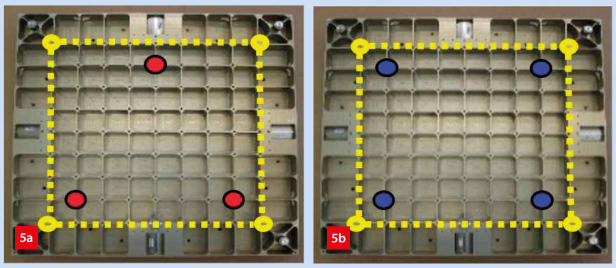
Development

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

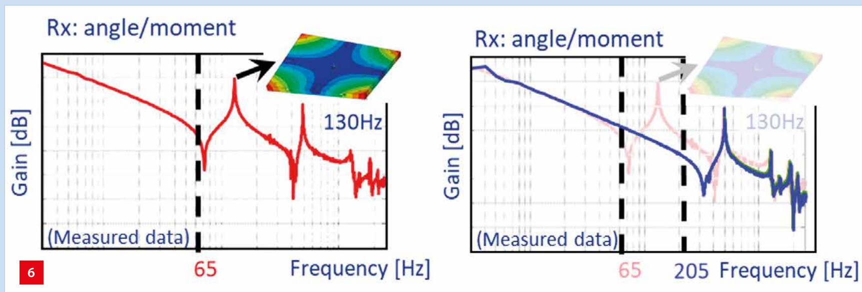




Over-actuated test rig at ASML Research.



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).



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.

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