FUTURE-PROOF DESIGN PRINCIPLES FOR PRECISION MECHATRONICS

An initiative to produce updated design principles for precision mechatronics has been developed by the professors of precision engineering and mechatronics at the three Dutch universities of technology in association with DSPE, and 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 was to collect over 100 cases that demonstrate the proper application of contemporary design principles. Many cases are already presented on a dedicated website and a broad selection will be collected in a new textbook, preceded by an extensive, in-depth introduction of the design principles.

The Dutch school of design principles for mechanical precision engineering originated in production mechanisation at Philips. 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 Wim van der Hoek to focus on the dynamic behaviour of cam mechanisms. He had started working at Philips in 1949 after having studied Mechanical Engineering in Delft (NL) and was appointed part-time professor of Design and Construction at Eindhoven University of Technology (NL) in 1961.

Through his work, Van der Hoek 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 and, in addition, started to collect examples of good and bad precision-engineering practices 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. Thus, Van der Hoek laid the foundations for the design principles for accuracy and repeatability. Table 1 gives an overview of these principles 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 has raised the bar. To meet their challenging specifications, thermal effects had to be addressed more extensively and new design concepts were introduced, such as 'virtual' servo stiffness, 'zero' stiffness, dual-stage configurations, and mass balancing.

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 became a new design paradigm to further improve performance.

Just as revolutionary was the embracing of 'forbidden' over-actuation, which was needed to avoid excitation of internal mode shapes. Thus, design for symmetry became key, which required, for example, additional force actuators on actuated

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

wafer chucks. This does not introduce significant uncertainty as long as the actuator stiffness remains 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. 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.

Update required

As well as an evolution of design principles, there was also a succession of textbooks published over the years, by Rien Koster, Herman Soemers and, recently, Susan van den Berg, who has brought design principles education in a didactically sound manner to the higher vocational education level.

In 2020, 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 – Delft, Eindhoven and Twente – 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 was to collect over 100 cases that demonstrate the proper application of contemporary design principles.

The cases could 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. A large number of cases is already presented on the dedicated website and more cases are welcomed. A broad selection of cases will be collected in a new textbook, preceded by an extensive, in-depth introduction of the design principles.

WWW.DSPE.NL/KNOWLEDGE/DPPM-CASES

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.

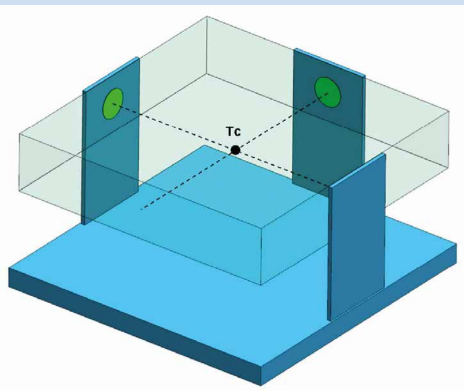
Illustrating the case for new design principles

On the DPPM website, the cases for the new design principles are presented divided in ten sections. Each case illustrates one or more of the new design principles and is thus featured in one or more sections. Reflecting the latest insights, some of the new design principles have been renamed/redefined. Here, one case is presented for each design principle.

1. Kinematic design

Ultra-stable iso-static bonded optical mount design

Optical components usually have a different coefficient of thermal expansion (CTE) compared to the mount. To prevent thermal problems, the mount design must be insensitive to a change in temperature (athermal design). One approach is to introduce elastic elements, such as leafsprings, in the mount. A leafspring in combination with a bond spot (low torsional stiffness) constrains only two translations. By arranging three leafsprings around the optical component, it is constrained once in each degree of freedom (DoF). The arrangement of the leafsprings determines the location of the thermal centre, which usually is located on the optical axis. Because of the flexures, the thermal expansion difference between component and mount can be large without significant effects.

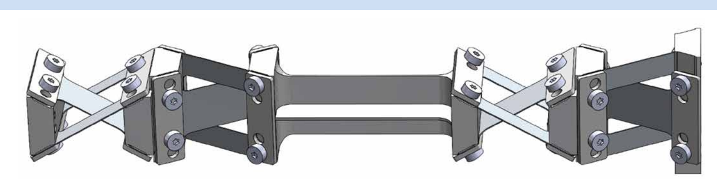


Case 1, developed at TNO Optomechatronics.

2. Design using flexures

Flexure-based 6-DoF parallel manipulator for fast adaptive optics

A demonstrator was developed for manipulating an optical element in at least five DoFs, while keeping the sixth DoF, a rotation around the optical axis, stationary. For practical reasons, a 6-DoF mechanism was developed with parallel kinematics and six linear actuators at the base. To exactly constrain the mechanism, the links between the actuators and the end-effector each constrain one DoF, equivalent to a wire-flexure. However, the range of motion, in particular of the rotations, and the critical load rendered a wire-flexure too risky. Therefore, each link consists of 2x2 serially stacked cross-flexure hinges and a torsion-compliant midpart.



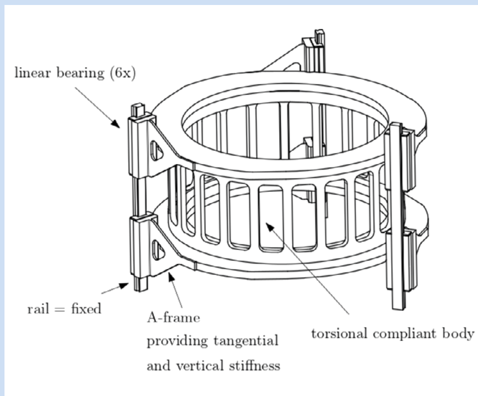
Case 2, developed at Demcon.

3. Design for static stiffness

Statically determined long-stroke linear guide

Creating a statically determined high-stiffness linear guiding over a long stroke, with high resonance frequencies, free of backlash or play, and with an axisymmetric thermal centre is not trivial. To ensure a sufficiently long service life without posing stringent manufacturing tolerances on the make parts, a statically determined design is desired avoiding uncontrollable high reaction forces. Therefore, the concept requires exactly five constraints to allow translation in one direction. The guiding must provide high stiffness in the constrained DoFs to achieve resonance frequencies above 300 Hz.

By combining multiple bearings, and distributing them at relatively large distances, the resulting stiffness obtained is significantly higher than the stiffness of an individual bearing, in particular for the rotational stiffnesses. Here, a total of six commercially available rolling element bearings are divided into two sets of three, an upper set and a lower set. Each set contains three bearings separated by 120° where the bearings are oriented tangentially to the moving object.



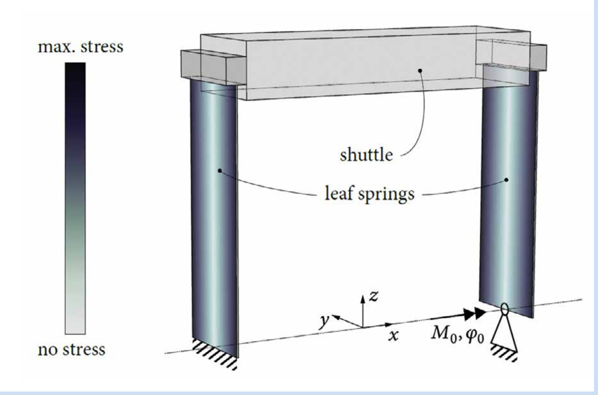
Case 3, developed at VDL ETG.

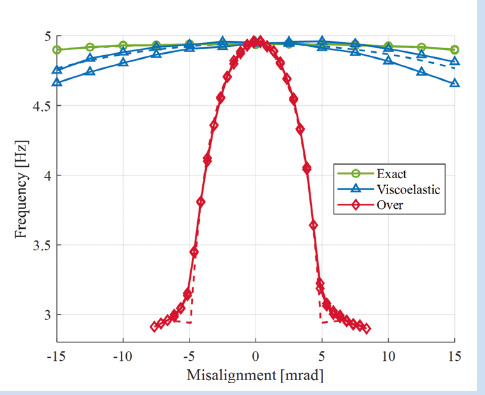
4. Design for dynamic stiffness

Improved dynamics by overconstraining using viscoelastic material

Flexure mechanisms are commonly designed to be exactly constrained to favour determinism, though at the expense of limitations on the maximum parasitic natural frequencies and support stiffness. The use of viscoelastic material was proposed for providing additional support stiffness in a certain frequency range without the indeterminism commonly associated with overconstraining. This design principle of dynamically stiffened exactly constrained design was exemplified by a parallelogram flexure mechanism.

Overconstraint and misalignment in a parallel leafspring mechanism cause stress and can change the stiffness of the mechanism. Experiments demonstrated that a custom synthesised elastomer compound can compensate for unintended misalignments without significant internal stress build-up, while improving the dynamic performance in terms of a higher first parasitic natural frequency.

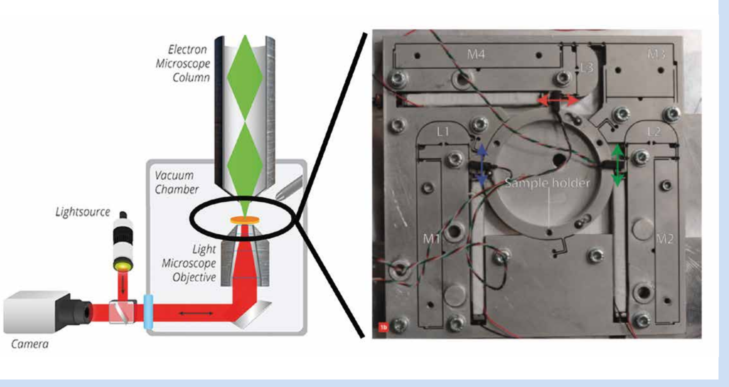




Case 4, developed at the University of Twente.

samples measuring a few square micrometers. The throughput of the system had to be increased by facilitating scanning over an area of 70 µm x 70 µm. To that end, a dedicated flexure-based scanning stage has been developed, with the flexures ensuring low friction and hysteresis. The application is in an ultra-high-vacuum environment with limited space. Feedforward model-based control of the stage achieves 10 nm accuracy at high scan speed, which is possible due to a very high overall stiffness.

The design consists of a flexure system: support of the sample holder in three DoFs is realised by a folded leafspring. Scanning is performed using two piezos, while a third piezo takes care of step actuation perpendicular to the scanning direction. To eliminate reaction forces, balance masses have been implemented, which are actuated by the same piezos but are moving in the opposite direction by means of flexure-based guiding and a lever.



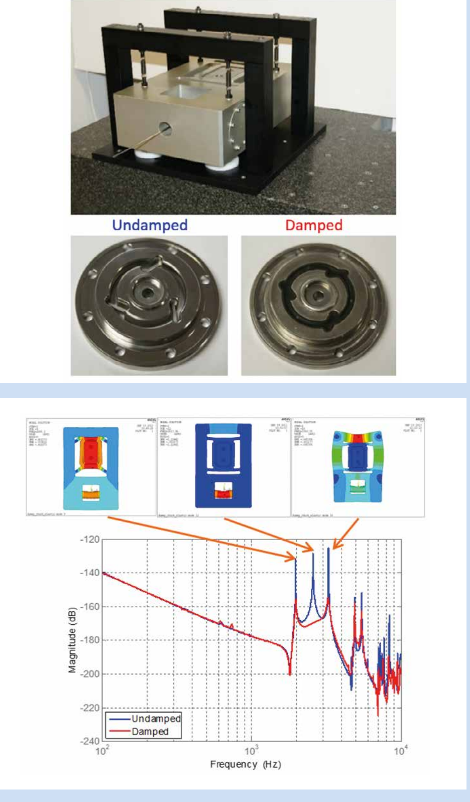
Case 6, developed by Hittech, Delft University of Technology and Delmic.

5. Design for damping

Passive damping in semiconductor wafer stages

For many years, high-tech systems have been designed as mass-spring systems with hardly any damping, primarily for reproducibility reasons. In the 2010s, passive damping became a new design paradigm with the goal of realising suppression of amplifications at resonances and, consequently, sufficient exponential decay of undesired vibrations in uncontrolled degrees of freedom.

Since mode shapes of traditionally designed motion stages are only lightly damped, further bandwidth increase is hampered. In the design of a 450-mm wafer chuck, it was observed that at about 3 kHz, a significant fraction of the chuck mass internally decouples due to two global horizontal bending modes resulting in the actuator interface, causing broad anti-resonance/resonance behaviour. The dynamic flexibility in the actuator interface was exploited to attenuate high-frequency amplifications at resonance through local implementation of broadband viscoelastic damping.



Case 5, developed at ASML Research.

6. Design for low friction and hysteresis

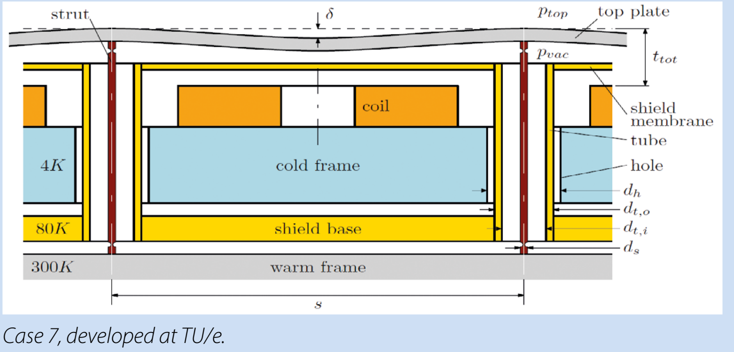
Balanced scan stage for an electron microscope

A confocal microscope in an electron microscope, developed by Delmic, makes combined electron-optical and optical images of biological

7. Design for stability

Superconducting magnet plate for planar motor application

To meet future demands for linear and planar actuators, superconducting motors are being investigated. To deal with limited cooling efficiency, a thin double shield isolation and a stiff motor fixation without significant heat flux are key. One option for the thin isolation



Case 7, developed at TU/e.

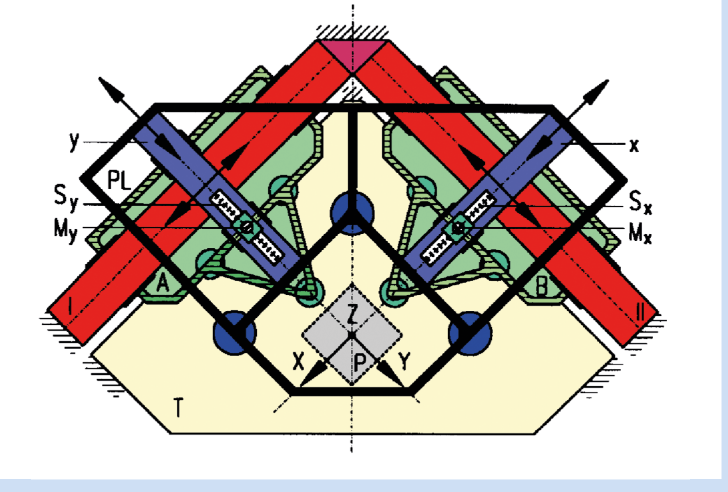
layer is the application of struts between top and bottom plate, which allows for non-contact isolation and minimum heat load. A first demonstrator of a compact superconducting motor 'tile' was designed as a building block for the stator in a superconducting planar motor of a wafer scanner.

8. Design for low sensitivity

High-precision 3D coordinate measuring machine according to Abbe and Bryan principle

To improve the precision of coordinate measuring machines (CMMs), an alternative high-precision 3D CMM was developed with measuring uncertainty beneath 0.1 µm in a measurement volume of 1 dm^3. The machine design was based on the Abbe and the Bryan principle, which are concerned with (preventing) measurement errors due to straightness errors in the system. Thus, smaller measuring errors are feasible with less effort on software compensation.

Application of a light and stiff construction, compensated air bearings and well-positioned linear motors resulted in high stiffness and favourable dynamic behaviour. A statically determined design, extensive use of aluminium and mechanical thermal length compensation made the machine less sensitive to temperature changes. To prevent mechanical disturbances an active vibration isolation system was designed.



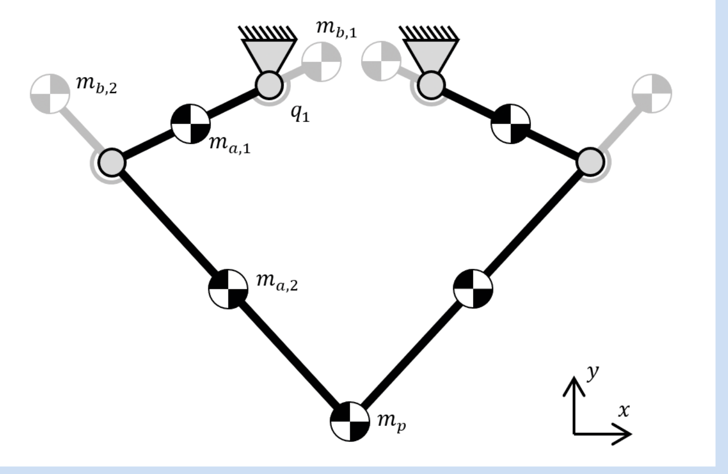
Case 8, developed at TU/e.

9. Design for load compensation

Low frequency benefits and high frequency drawbacks of shaking force balancing

Fast-moving robots induce large dynamic reaction forces and moments at the base, resulting in vibrations and a loss of accuracy at the end-effector. By adding counter-masses and counter-inertias these shaking forces and moments may be reduced or even eliminated. In practice, balancing leads to larger masses, increased motor torques and substantial bearing forces. The addition of mass lowers the natural frequencies of the mechanisms, leading to increased vibrations and a lowered controller bandwidth.

Traditional balancing approaches disregard the elasticity of the robot links, which leads to undesirable parasitic dynamics, unbalance and loss of controller performance. It was demonstrated that a partial balancing solution accomplishes 80% shaking-force reduction without the loss of controller bandwidth, while the fully force-balanced system has an approximate controller bandwidth loss of about 40%.



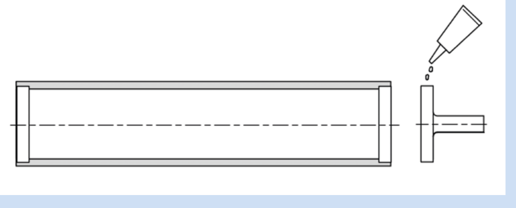
Case 9, developed at the University of Twente.

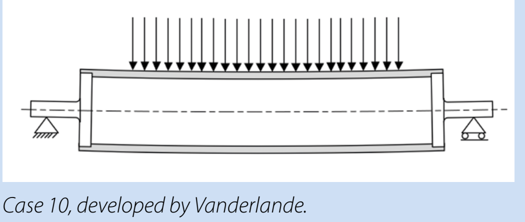
10. Design for manufacturability

Conveyor roller, joining shaft to roller

A conveyor roller is commonly supported by bearings with a smaller inner diameter than the roller diameter. There are, however, stiffness and fatigue issues with a typical welded roller assembly comprising a small diameter shaft that is assembled straight through the roller using two thin plates. Thicker plates would increase the stiffness, but also create unused extra mass and increase the cost.

A high bending stiffness combined with low mass and cost can be obtained using two small stiff end pieces adhesively bonded to the wide diameter of the roller. The problematic shaft-to-plate connection is eliminated by integrating it into a single stiff part. The stiffness is an order of magnitude higher than that of the welded roller assembly. As a result, reduced stress levels are attained without triggering any fatigue-related concerns.





Case 10, developed by Vanderlande.