FROM WIDE-FORMAT PRINTERS TO ADVANCED STEERING MIRRORS

This year, the DSPE Conference on Precision Mechatronics on 23-24 September (see the impressions in the previous issue of *Mikroniek*) featured the theme 'SustAIning Precision'. It reflected the importance of sustaining the leading-edge position in precision engineering of our Dutch high-tech ecosystem, based on its ability to adopt and enable major innovations, such as AI, while harmonising these rapid evolutions with long-term goals. This article provides an overview of the conference, while the three AI keynotes are covered in a separate article, on page 14 ff.

JOS GUNSING

Introduction

The DSPE Conference was once again organised by and for technologists, designers and architects in precision mechatronics. Along with demonstrations and oral and poster presentations, there were ample opportunities for discussions, networking, sharing ideas and experiences, and, of course, socialising. Thus, the conference also contributed to sustaining knowledge exchange and networking (see Figure 1).

AUTHOR'S NOTE

Jos Gunsing is the founder/owner of MaromeTech, a technology & innovation support provider based in Nijmegen (NL), and a DSPE board member.

jos.gunsing@marometech.nl


1

Participants of this year's conference in front of conference hotel De Ruwenberg in Sint-Michielsgestel (NL). (Photo: Jos Gunsing)

This report covers a number of interesting contributions, including the award-winning presentation, poster and demonstration. What all of these contributions have in common is that they offer an extra boost to developments by way of innovative system approaches and also by thoroughly exploring, understanding and extending the properties of specific system functions.

The AI content of the contributions was not yet as prominent as the author had hoped for, apart from presentations on machine learning in control technology. In the reports on the Gas Bearing Workshop for the 2023 and 2025 editions (also written by the author), the combination of optimising the parameters of gas-bearing designs, including manufacturing tolerance insensitivity of the performance specifications, and the exploration to find efficient/effective algorithms/tools for facilitating this, was prominent. The author is curious what the next DSPE Conference will bring in this respect.

Precision-system approach

Starting on the system level, the presentation by Ivan Smits, mechatronic/control engineer at Canon Production Printing, discussed the development of very large mechatronic precision systems such as wide-format inkjet printers, where key drivers such as print quality and product cost are combined.

In his presentation "Follow the line – A system model approach", he described a new concept to compensate for motion errors in the Colorado XL printer (Figure 2).

In this printer, the medium/substrate is transported stepwise in order to have the surface inkjet printed. A carriage containing the printheads moves over the surface perpendicular to the media/substrate transport direction (each individual movement over the surface is called a swath).

The quality of the printed image is directly dependent on the accurate connection between the printed parts of the individual swaths, which is called registration. The human eye is particularly sensitive to recurring defects in the printed image; for example, we can detect line defects or mispositioning in the order of micrometers. It is a challenge to balance print quality (accuracy) and productivity (speed) in a cost-competitive printing market.

Canon has been working on a registration concept for wide format up to 3.4 m with compensation techniques under the codename 'Follow the line'. It will include the necessary equipment without increasing manufacturing complexity, due to excessively tight mechanical tolerances for the manufacturing of the inkjet printer.

The concept consists of:
- A camera system to accurately measure the media positioning errors (Figure 3).
- Accurate real-time positioning of the printheads (inner carriage) in two degrees of freedom (Figure 4).
- A media handling that allows a larger positioning error but can predict the current error and learn to improve the next media steps.

Naturally, this concept has an impact on the overall system and therefore a careful approach must be followed.
- System modelling approach:
  - architecture model;
  - function/feasibility models to be designed, built and tested;
  - system-level MIL (model in the loop);
  - integrated SIL (software in the loop);
  - printer engine verification on hardware.

- Remarks:
  - Regular reviews with the responsible stakeholders are necessary to have a complete picture of measures and consequences;
  - Several tools are available to test software and hardware:
    = Architecture model: System Composer/MathWorks;
    = Functional plant models: Simscape, Speedgoat, Morpf (proprietary Canon hardware for functional models/early prototypes).

2

Canon's Colorado XL wide-format printer (print width up to 3.4 m).

By following this way of working, Canon was able to develop and deploy the registration-error compensation in wide-format inkjet printers successfully, such that the balance between image quality, productivity and cost could be improved.

Research into specific precision-system element

Naturally, it is obvious that thorough knowledge is necessary to exploit the maximum performance of the individual system elements, such as elastic elements. The following presentation focused on in-depth knowledge of elastic elements in combination with the material properties and the manufacturing process, which have a big impact on the physical properties of an elastic element and thus on system behaviour. That's what Nico Tan, technical specialist at NTS Group, talked about in his presentation "Internal stresses in elastic elements".

Elastic elements are very commonly applied in precision mechanics. Tan dived deeper into the behaviour of leafsprings by following the manufacturing process of the elastic element from production out of a billet using electric discharge machining up to application. Due to the casting process of the billet, mechanical stresses build up in the material (e.g., compressive stress on the outside and tensile stress in the inside). In general, the (high-performance) elastic elements are thin/slender, monolithic and need a high yield stress to handle the load-elastic displacement combination.

3

Carriage with printhead and camera, taking pictures to check for registration errors.

4

Carriage with moveable inner carriage in two dimensions with printheads to compensate for registration errors.

The internal stresses (Figure 5) can lead to several effects after the elastic element has been manufactured:

- warping/spring back (Figure 6);
- deviations in perceived stiffness, including bistable/nonlinear behaviour (see Figure 7 for definition of normal direction and Figure 8 for resulting stiffness);
- deviations in eigenfrequencies;
- fatigue failure at unexpected (low) loads and number of cycles or at unexpected locations.

With respect to eigenfrequencies, Tan carried out a modal analysis and found a very significant lowering of the torsional mode frequency, whereas the bending mode frequency hardly changed due to the presence of internal stresses in the elastic element. Finite-element analysis also showed clearly that the points of the highest bending stress with respect to fatigue moved to different places in the elastic element and appeared to be significantly higher than the calculated bending stresses for an ideal situation without internal stresses.

Tan emphasised, based on his work, that internal/residual stresses in elastic elements are important factors to be taken into account and that their impact on performance can be very significant, so measures may have to be taken to keep the elastic element's performance in line with expectations.

Award-winning contributions

The best presentation, poster and demonstration award contributions gave very interesting insights into (sub-)system behaviour and their impact on overall system properties.

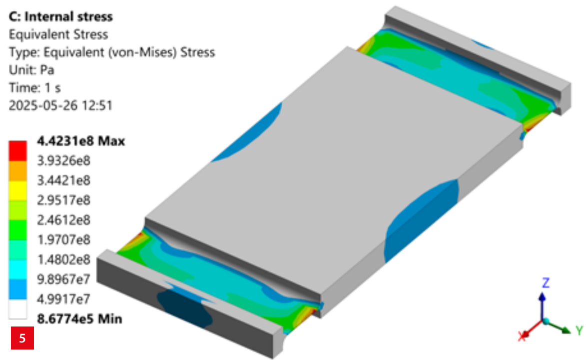
Reluctance-based steering mirror

The award for the best presentation went to Kevin Looman, Ph.D. candidate in the Control Systems Technology group at Eindhoven University of Technology (TU/e), working with Prodrive Technologies for "Reluctance based steering mirror with linear current-force relation and stiffness compensation: design and realisation".

His work deals with a beam-steering interferometer (Figure 9) with active tracking (using contrast-based extremum-seeking control) for accepting up to 20 times higher angular displacements of, for example, a wafer table without losing accuracy.

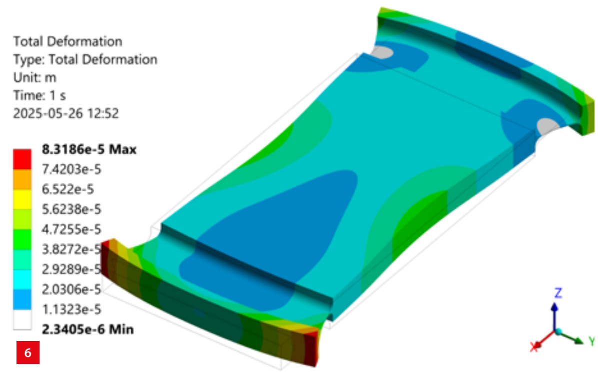
He started his steering-mirror project with the following requirements:

- mirror rotation +/–12.2 mrad (+/–0,7°);
- mirror modulation 10 µad @4 kHz, for contrast-based extremum-seeking control;
- power dissipation < 150 mW;
- volume within 40 mm x 40 mm x 40 mm;
- no angle-feedback sensors.



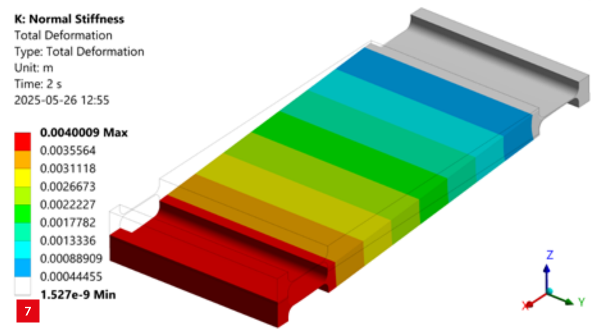
5

The new resulting stress distribution due to residual stress in the base material.



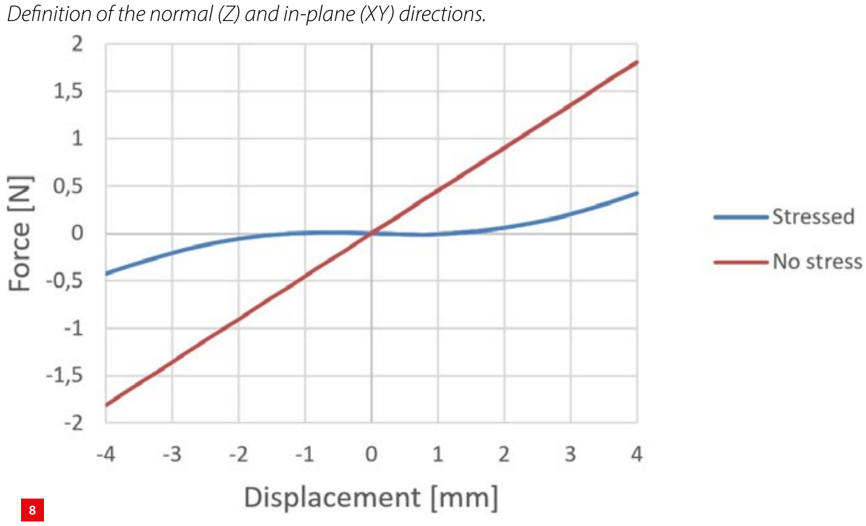
6

'Spring back' due to the new stress distribution.



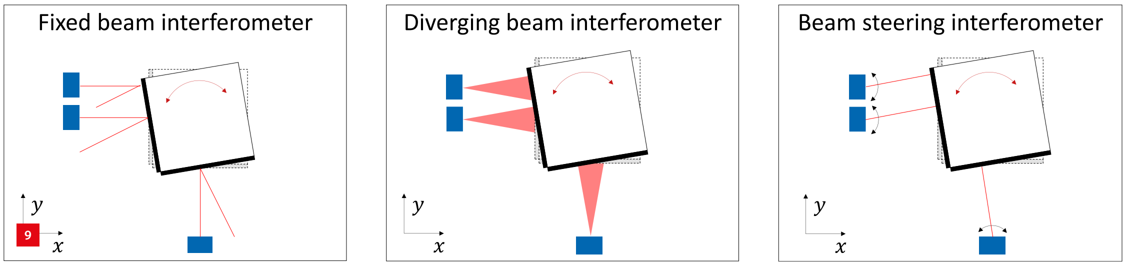
7

Definition of the normal (Z) and in-plane (XY) directions.



8

Stiffness graph in the normal direction around the neutral position.



Interferometer set-up concepts.

A search for off-the-shelf solutions discovered that the cost was too high and a piston axis was unavailable, while the delivery times were also excessively long. The solution direction that came up was a linearised hybrid reluctance actuator with the following features:

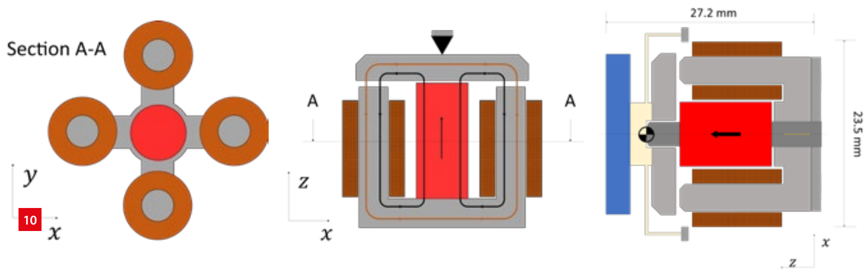
- A gap size of 5-7 times the stroke and an increase in permanent magnet size for linearisation (constant dynamics in working range).
- Piston axis that moves the mirror to create a virtual rotation point to cater for an optimal reflection of the laser beam with respect to the detector.
- High steepness-mass ratio for a high actuator force per Watt, thus giving a high enough acceleration to modulate at 4 kHz.
- Stiffness compensation for lower power dissipation.
- Simple tip/tilt architecture.

Although the concept itself appeared to be relatively simple, the manufacturing of components, especially the coil yoke, was still tricky due to its relatively small dimensions.

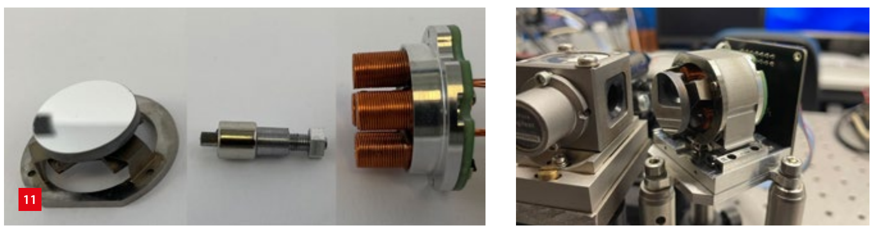
Figures 10 and 11 show the schematic design and the realisation, respectively, of the beam-steering mirror and a test rig.
Based on the results shown in Figure 12, a reluctance-actuator-based steering mirror that enables the implementation of beam-steering interferometry is possible. This can be concluded from the tests and optimisation:

- +/−20 mrad angle acceptance of plane-mirror interferometers possible using a beam-steering interferometer.
- Application of a hybrid reluctance actuator with increased gap size and stiffness compensation of 75%; power dissipation < 80 mW in total for both axes.
- Constant dynamics over the stroke due to linear behaviour.
- First (visible) parasitic eigenmode at 10 kHz.

Fast steering mirror
The award for best poster was given to "The Fast Steering Mirror, a small device that enables a big leap in EUV power in 1µm Source Systems", by Dieter Lambregts and Rob Waiboer of ASML and Jasper Winters and Bert Dekker of TNO. They developed a fast steering mirror that is applied in the pre-pulsing of tin droplets in the light source of an extreme-ultraviolet (EUV) lithography system.
The background to this technology is the continuous need to increase EUV power in order to improve productivity.



Schematic design of beam-steering mirror and test rig (on the right).



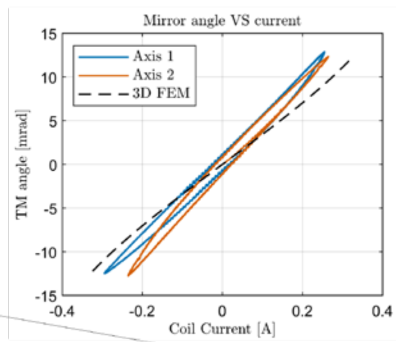
Physical realisation of the beam-steering mirror and the test rig (on the right).

Assembly without negative stiffness

Axis	Stiffness	Deviation from linear	Eigenfrequency
Horizontal	909 mNm/rad	0,06%	452 Hz
Vertical	998 mNm/rad	0,17%	473 Hz

Complete actuator assembly

Axis	Motor constant	Deviation from linear	Eigenfrequency
Axis 1	44 mrad/A	14.9%	232 Hz
Axis 2	48 mrad/A	13.1%	218 Hz
3D FEM	36 mrad/A	2.7%	



12 38 mW dissipation at end of stroke (per axis)

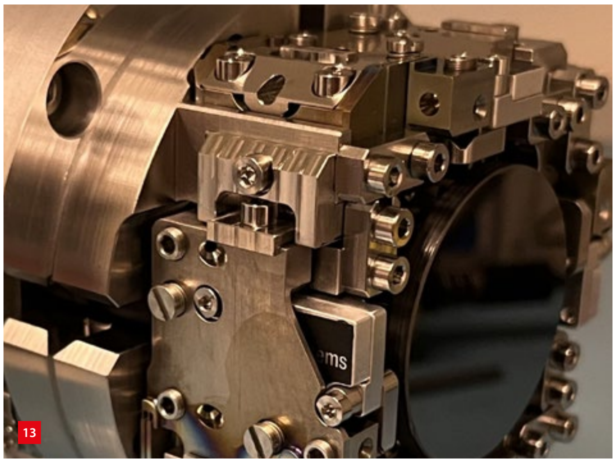
94% lower power dissipation

76% of positive stiffness is compensated

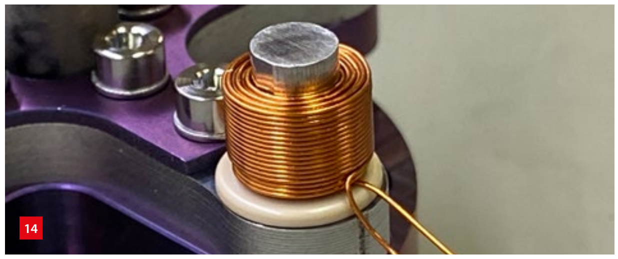
The results showing the main feasibility aspects: dissipation and stiffness compensation.

To suppress plasma disturbances, a minimum closed-loop bandwidth of 1,000 Hz is required. TNO had already developed a device for applications in the field of laser communication, but several enhancements had to be made to make it suitable for the ASML application:

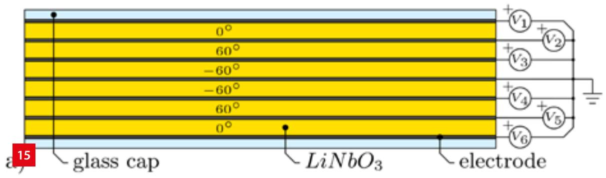
1. Larger SiSiC (silicon-infiltrated silicon carbide) mirror (Figure 13).
2. Increased angular resolution.
3. Reduced actuator delay.
4. Higher admissible optical power.



SiSiC mirror with four optical encoders placed on the edge of the mirror under 90° angles.



Laminated magnetic yoke.



Six stacked piezo wafer layers of 180 µm each between glass caps.

These enhancements were met by application of:

1. A lightweight SiSiC mirror:
   SiSiC is a high-performance material, featuring high hardness, thermal conductivity and temperature strength, and low corrosion, oxidation and thermal expansion.
2. Two pairs of high-precision optical encoders.
3. Visco-elastic passive damping of the bandwidth-limiting piston mode (perpendicular to mirror surface).
4. Lamination of the magnetic yokes to limit Eddy currents (Figure 14), together with compensation of the remaining delay in combination with application of a skewed notch filter in the control strategy.

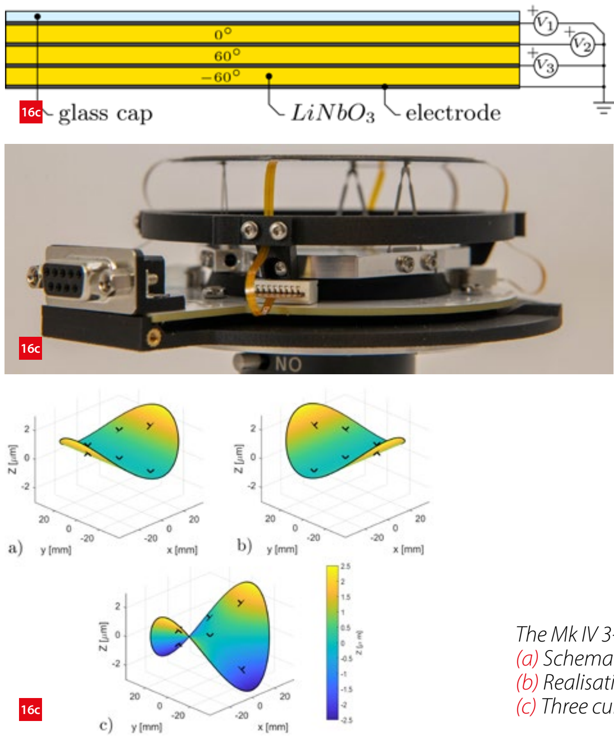
All of these measures, combined with the careful design of controls (including the application of a skewed notch filter), mode shapes and centre of gravity, led to a new fast-steering mirror system in the new 1-µm pre-pulse system that has already been shipped to a customer.

Deformable wafer table

Bas Huisman, Ph.D. candidate in the Control Systems Technology group at TU/e, received the award for his demonstration of "Prototype development of a Deformable Wafer Table". He also gave an oral presentation about his concept, which he had designed, built and tested. The need for a deformable wafer table comes from several directions. Experience has taught that even a Zerodur table suffers from edge wear. Also, the heating caused by the illumination of the wafer and internal wafer warping caused by the multiple layers deposited on it are likely to give deviations in focusing (out-of-plane) and overlay (in-plane), thus introducing potential inaccuracies and defects in the wafer layers.

Huisman designed a concept for a deformable wafer table using six stacked piezo layers for controlling six degrees of freedom (see Figure 15). His Mk I prototype did not show the expected results based on analytical calculations and Comsol simulations, and analysis revealed that the two-sided bonding tape between the layers might well have caused the measured effects. He therefore decided to build upon the experience more gradually, starting with a single active layer (Mk II and Mk III (improved bonding layer)), which led to the confirmation of the expected results. The various layers each require specific control settings due to their different height positions in the stack.

Meanwhile, Huisman has created Mk IV with three layers, which resulted in control over the various modes (see Figure 16). He concluded that the right direction to control of a wafer-table shape had been found and, more generally, that gradually building up complexity in a functional model/prototype may benefit the progress of development work and prevent premature conclusions about the feasibility of good ideas.



The Mk IV 3-layer prototype.
(a) Schematic design.
(b) Realisation.
(c) Three curvature modes.

Conclusion

The author wishes to underline that a lot of other high-quality presentations, posters and demonstrations were presented at the 2025 edition of the DSPE Conference. Many of those will hopefully appear as articles in forthcoming issues of *Mikroniek*. The organisers hope to present an equally inspiring programme at the next DSPE Conference in 2027, while the author is looking forward to future developments in precision engineering, particularly in relation to the application of AI both in new products and systems, and in smart design and engineering processes.