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- THEME: PROGRESS IN ACTUATOR TECHNOLOGY
- ROTATING MAGLEV SAMPLE MANIPULATOR
- HYBRID VARIABLE-RELUCTANCE ACTUATOR TECHNOLOGY ON-SKY
- HIGH-VELOCITY INNOVATION THROUGH RAPID LEARNING CYCLES

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Publisher
DSPE
Julie van Stiphout
High Tech Campus 1, 5656 AE Eindhoven
PO Box 80036, 5600 JW Eindhoven
info@dspe.nl, www.dspe.nl

Editor
Hans van Eerden, hans.vaneerden@dspe.nl

Advertising canvasser
Gerrit Kulsdom, Sales & Services
+31 (0)229 – 211 211, gerrit@salesandservices.nl

Design and realisation
Drukkerij Snep, Eindhoven
+31 (0)40 – 251 99 29, info@snep.nl

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The cover image (featuring a rotating MagLev sample manipulator) is courtesy of MI-Partners. Read the article on page 5 ff.

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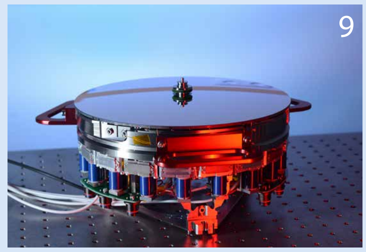

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PROGRESS IN ACTUATOR TECHNOLOGY

Precision engineering requires having a great deal of knowledge concerning many disciplines and components. As there is so much knowledge available, the best approach is to get to know who the experts are in a subject, as you cannot know everything and everybody personally. Our society DSPE can help you in making acquaintances in the community of precision engineers.

This issue of Mikroniek is about actuators, in particular their technological progress. It is just one subject among the plethora of technical subjects, but it is a crucial one for the performance of a high-tech system. Actuators are vital components in a wide variety of mechatronic systems, as they are responsible for converting energy into physical movement or force. They also enable precise control over the movement of the system, which is essential for the system's ability to function.

Accuracy, force, cleanliness, operation in vacuum or cryogenic conditions, high temperature, lifetime, size, maintenance, costs, standardisation and other requirements can be part of the actuator specification in a design.

When ASML was just starting up, one of its most important modules was the X-Y stage for wafer positioning. These earliest systems used the high-accuracy hydraulically actuated H-drive. However, when oil was banned from semiconductor cleanrooms, ASML turned to the linear electromagnetic motors. For years, the sustained development of these actuators has helped ASML to increase performance (overlay) and speed (productivity). One could say that the development of actuator technology contributed to the success of ASML substantially.

Fundamental research on actuation definitely has had an impact on our high-tech industry and will continue to do so in the future, as is demonstrated in this issue.

To conclude, talking of ASML, Martin van den Brink, who is the technological genius behind ASML's overwhelming success in the lithography market, recently retired as co-president and CTO of ASML. In acknowledgement of his merits, DSPE decided to appoint him an honorary member. In this Mikroniek, more about Martin.

Hans Krikhaar
President of DSPE and program manager Fontys Engineering Master System Design
hans.krikhaar@dspe.nl

ADVANCES IN STANDSTILL PERFORMANCE

In synchrotron beamlines, samples are analysed, while precisely positioned in the X-ray beam. Current systems typically use a set of stacked stages based on piezo or stepper motors. To enable higher throughput and performance, MI-Partners has developed a magnetically levitated sample stage. The stage can be controlled in six degrees of freedom (6-DoF), with an infinite rotation around the vertical axis (z-axis) and a stroke of 3 mm along the x-, y- and z-axis. The stage is based on a novel electromagnetic actuator and positioning metrology system.

MARYN WIJNHOVEN, RONALD FAASSEN, LUCAS KOORNEEF, DICK LARO, MARTIJN PRINCEN AND THEO RUIJL

AUTHORS' NOTE

Maryn Wijnhoven (mechatronic system designer), Ronald Faassen (dynamics and control architect), Lucas Koorneef (senior mechatronic system designer), Dick Laro (system architect), Martijn Princen (mechatronic system designer) and Theo Ruijl (CTO / senior mechatronic system architect) are all associated with MI-Partners, mechatronic innovation specialists located in Veldhoven (NL).
Part of the work described in this article was presented at the 38th ASPE Annual Meeting, November 2023, in Boston (MA, USA).
m.wijnhoven@mi-partners.nl
www.mi-partners.nl

Introduction

For tomography in a synchrotron beamline, two typical sample scanning strategies exist:

- Fast 2D planar scanning while intermittently changing the rotation position (*Rz*). Hereto, the stage should hold the *Rz*-position fixed while performing a 2D planar scan perpendicular to the X-ray beam. This is called raster scanning (Figure 1a).
- Fast continuous rotation scanning while intermittently changing the axis of rotation. Hence the stage should perform rotations around the centre axis (*z*-axis) but also off-centre (Figure 1b).

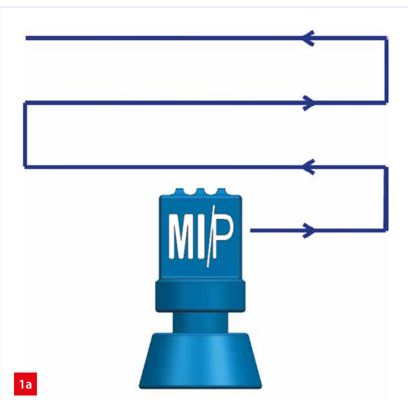
A stage has been realised that can perform both scanning strategies. All six DoFs are actively controlled by means of the electromagnetic actuator and measured by the metrology system, which enables nanometer-level positioning performance with high scanning accelerations and speeds, whilst being able to operate in vacuum.

System overview

An overview of the main system components can be found in Figure 2. This article focuses on the mechatronic design of the actuator and the metrology system, and shows the positioning performance achieved so far. More details on the dynamics and control are presented in [1].

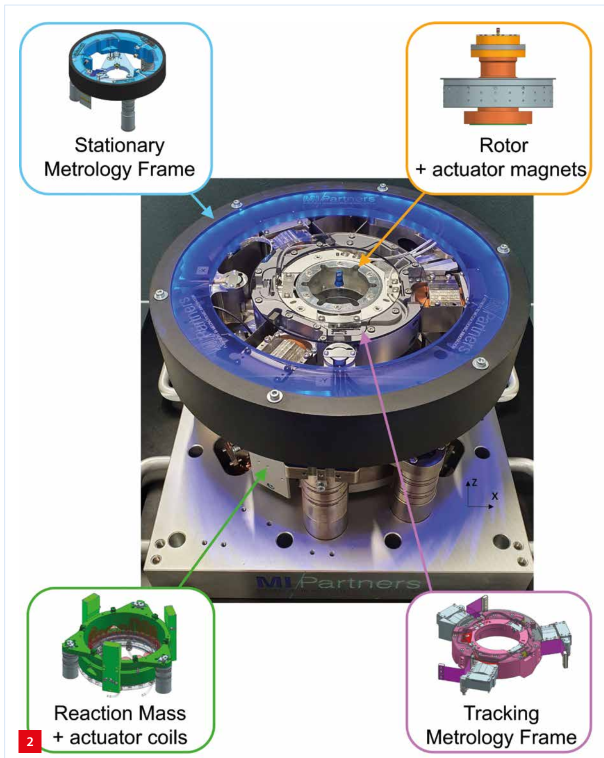
Mechatronic architecture

Figure 3 shows the schematic architecture of the sample manipulator. The sample is located on top of the rotor, which is actuated by the 6-DoF electromagnetic actuator. The stationary part of the actuator is connected to a reaction mass for filtering reaction path dynamics and enabling higher control bandwidths. A magnetic gravity


1a

1b

Impression of a beamline sample with possible scanning strategies.
(a) Scanning motion.
(b) (Eccentric) rotation.



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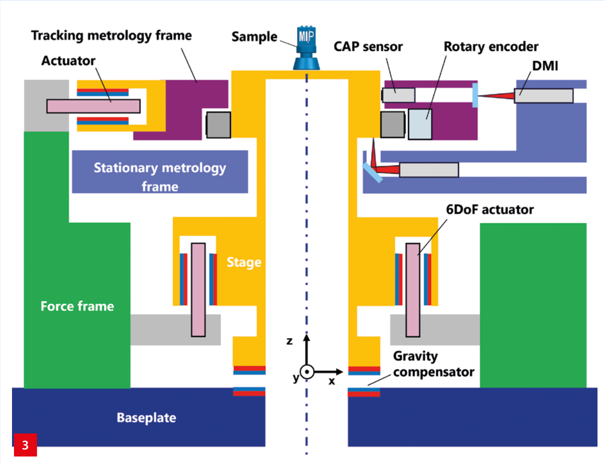
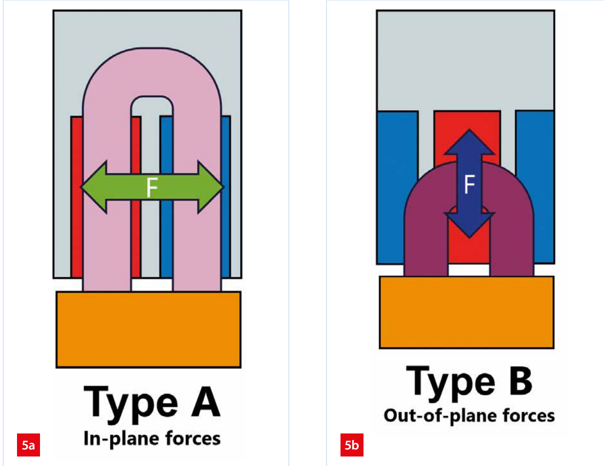
Main system components of the realised MagLev sample manipulator.



Schematic architecture design.

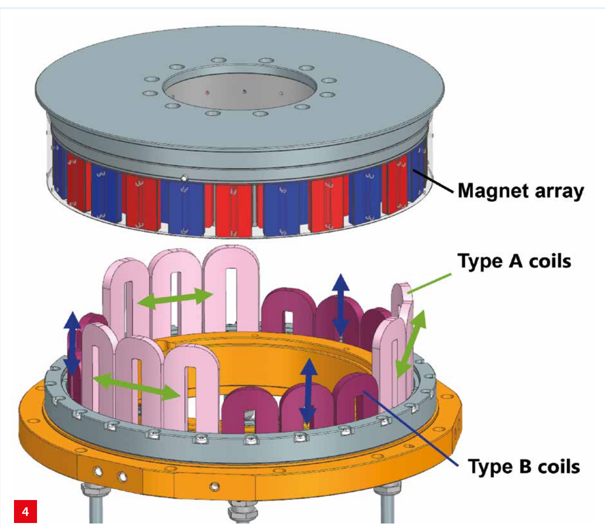


Actuator coil types.
(a) Type A: long coil.
(b) Type B: short coil.

compensator has been implemented to reduce power dissipation in the actuator during levitation of the rotor. The position of the rotor is measured close to the sample, via sensors connected to a metrology frame. This metrology frame is suspended and damped with respect to the baseplate in order to reduce the influence of floor vibrations. The metrology principle and main components are explained below.

Actuator

A 6-DoF Lorentz actuator was developed with translation strokes of 3 mm along the *x*-, *y*- and *z*-axis, and infinite rotation. Figure 4 shows the main components of the actuator. Nine coils (type-A coils: three sets of three coils) are used to achieve in-plane forces (F_x, F_y, M_{rz}) and nine coils (type-B coils: three sets of three coils) achieve out-of-plane (vertical) forces (F_z, M_{rx}, M_{ry}). Each set of three coils forms a 3-phase motor. The coils are all stationary and connected to a reaction mass to filter reaction path dynamics in order to enable higher control bandwidths.



6-DoF Lorentz actuator components, with the in-plane (green) and out-of-plane (blue) forces displayed.

The type-A coils are more or less equal to a standard linear motor, but now in a curved configuration. The type-B coils are shorter, such that the horizontal part of the coils is in the magnet field to generate a net vertical force. See Figure 5 for both coil types. The magnet array is attached to the rotor and with this motor configuration all six DoFs can be actuated. Figure 6 shows the curved magnet track and the curved coil configuration.
To determine the properties of the actuator over the full range of motion, a magnetic model was used; see Figure 7.

Gravity compensator

The purpose of the gravity compensator is to deliver a constant *z*-force over the full range of motion, without introducing disturbance forces and moments. This reduces the power dissipation in the actuator when the rotor is levitated. The gravity compensator consists of one ring-shaped magnet at the moving side and three ring-shaped magnets with opposing magnetic orientation at the stationary side; see Figure 8.
With this configuration, attractive forces counteract repulsive forces, resulting in a defined net force equal to the weight of the stage and small moments when moving off-centre (*x*, *y*).
The bottom stationary ring magnet can be manually manipulated in the vertical direction to fine-adjust the vertical

6-DoF Lorentz-actuator components.
(a) Magnet track.
(b) Curved coil segment.

IMPROVING SYSTEM PERFORMANCE AND ROBUSTNESS

High-tech positioning systems require high controller bandwidths and the decoupling of the various degrees of freedom (DoFs) to obtain the best system performance. Typically, one actuator is needed per actively controlled DoF, but practical design considerations often lead to an over-actuated system. It is shown here, however, that the freedom provided by over-actuation can be used to not only decouple rigid-body modes, but also to isolate non-rigid-body resonance modes. Thus the performance and/or robustness of the controlled system is improved without actually having to add an additional control loop.

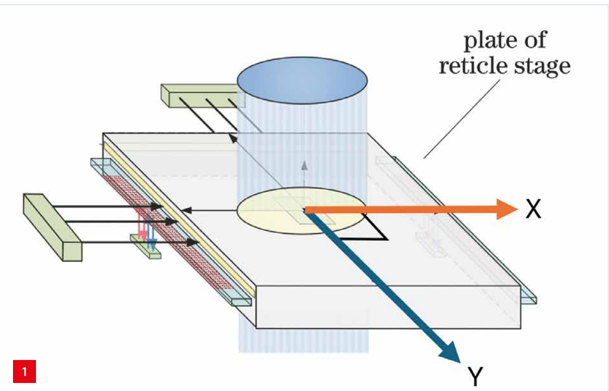
MATHIJS SCHOUTEN, GEORGO ANGELIS AND FRANK SPERLING

Introduction

High-tech positioning systems aim to position a system very accurately. This often goes hand in hand with high velocities and accelerations. High controller bandwidths and mutual decoupling of the various degrees of freedom (DoFs) are desirable for obtaining the best system performance.

Typically, one actuator is needed per actively controlled DoF. Volume conflicts, design choices (such as symmetry for centre-of-gravity positioning) or actuator force limitations often lead to an over-actuated system. In these systems there are more actuators than actively controlled DoFs (and sometimes even more actuators than observable DoFs); see Figure 1.

In motion control, the goal is usually to control the rigid-body movements, i.e. the actively controlled DoFs. This is done by decoupling the MIMO (multiple input, multiple output) system into logical directions through combining physical actuator forces in such a way that a resultant force is applied in only one specific logical direction.

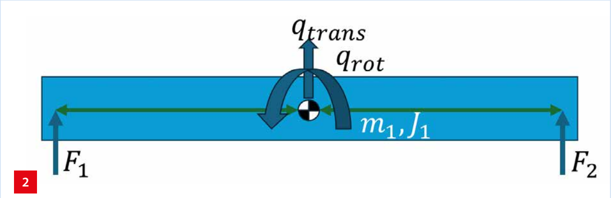


1 If a system contains more actuators than controlled DoFs, it is called an over-actuated system. (Source: [1])

AUTHORS' NOTE

Mathijs Schouten (mechatronics engineer) and Frank Sperling (director Technology) work at Nobleo Technology in Eindhoven (NL), an engineering firm specialising in autonomous intelligent systems. Georgo Angelis is a dynamics expert for Nobleo Technology and CEO of Sensing360 in Utrecht (NL).

frank.sperling@nobleo.nl
www.nobleo-technology.nl
www.sensing360.com



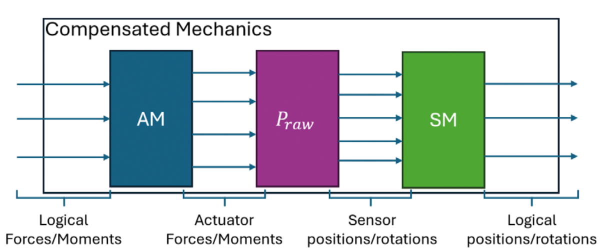
2 Example of a symmetrical beam with forces F_1 and F_2 on the left and right ends, respectively.

As an example, consider a symmetrical beam with two DoFs, a translation and a rotation, and actuators on the left and right ends of the beam; see Figure 2. Typically, the sum of the actuators drives a translation and their difference the rotation, i.e., for translation, the two forces have the same direction and, for rotation, the opposite direction. This mapping can be captured in a distribution matrix, which is referred to as actuator matrix. This decoupling matrix is often based on geometry, mass and inertia properties of the system and decouples to the principal axes of inertia.

In a similar way, the sensor matrix converts sensor readings to logical coordinates. The mathematically obtained decoupled system is referred to as compensated mechanics (see Figure 3). The term 'compensated' is used to distinguish between 'raw', i.e. physical, inputs/outputs and a system with ***AM*** and ***SM*** that works in logical (control-oriented) inputs/outputs:

$$\boldsymbol{P}_{\mathrm{CM}} = \boldsymbol{SM} \cdot \boldsymbol{P}_{\mathrm{raw}} \cdot \boldsymbol{AM}$$

Here, $\boldsymbol{P}_{\mathrm{CM}}$ is the compensated mechanics plant, ***SM*** is the sensor matrix, $\boldsymbol{P}_{\mathrm{raw}}$ is the 'raw' plant, and ***AM*** is the actuator matrix. Thus, using an actuator matrix and a sensor matrix



3
The compensated mechanics give a logical-to-logical transfer function. Note that the number of sensors/actuators does not have to be equal to the number of controlled DoFs.

together with the 'raw' plant, the compensated mechanics are obtained. This transfer function describes the system in logical/functional DoFs. If the DoFs are along inertial axes this can also result in decoupled system behaviour, which then turns the control problem into a series of (decoupled) SISO (single input, single output) control tuning problems. Typically, this is the preferred route for the control design of high-performance mechatronic motion systems.

The actuator matrix maps the input signals to the physical actuators in such a way that only one functional input direction is actuated. All other specified directions should not be affected. Consider the beam shown in Figure 2; when this system is decoupled correctly, rotations can be made without making a translation and vice versa.

A practical method to derive the actuator matrix $\boldsymbol{AM}$ (for rigid-body-mode decoupling) is to use a measured transfer function from physical actuator inputs to logical outputs $\boldsymbol{TF}_{raw}(\boldsymbol{\omega}) = \boldsymbol{SM} \cdot \boldsymbol{P}_{raw}(\boldsymbol{\omega})$ and define a frequency point at which the transfer function is mass-dominated (typically a low-frequency point), $\boldsymbol{\omega}_{mass}$, in a high-coherence (> 0.9) area, then:

$$\boldsymbol{M}_{\text{inv-meas}} = \boldsymbol{TF}_{\text{raw}}(\omega_{\text{mass}}) \cdot \omega_{\text{mass}}^2$$

Assume now an ideal transfer function (inverted mass matrix) in the functional direction, i.e. along inertial axes, $\boldsymbol{M}^{-1}$ (this matrix need not be exact, but it is always square and usually diagonal). To obtain the actuator matrix, the following equation can then be used:

$$\boldsymbol{M}_{inv-meas} \cdot \boldsymbol{AM} = \boldsymbol{M}^{-1} \quad (1)$$

From which follows:

$$\boldsymbol{AM} = \boldsymbol{M}_{\text{inv-meas}}^{-1} \cdot \boldsymbol{M}^{-1}$$

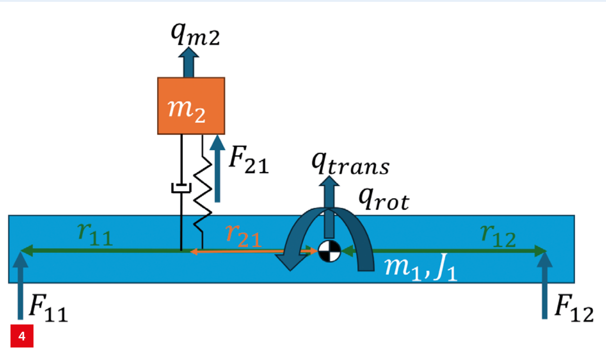
If a system contains as many actuators as controlled DoFs, the measured mass matrix $\boldsymbol{M}_{inv-meas}$ will, if all motions can be achieved, be a square, full-rank matrix. As a result, the actuator matrix $\boldsymbol{AM}$ will also be square and unique.

With an over-actuated system, there are more logical inputs (transfer function columns) than system outputs (rows). In such cases, the measured matrix $\boldsymbol{TF}_{raw}(\boldsymbol{\omega}_{mass})$ is not square and there is not one unique $\boldsymbol{AM}$ that can solve Equation 1. Here, the matrix inversion is often done using what is known as a pseudo-inverse. The pseudo-inverse calculates an optimal (minimum-energy) result, which is a solution $\boldsymbol{AM} = \boldsymbol{M}_{inv-meas}^{-1} \cdot \boldsymbol{M}_{inv}$, but not the only one! The solution space of all possible solutions to this equation can be calculated. In linear algebra, this is related to the null-space of $\boldsymbol{M}_{inv-meas}^{-1}$, which is then not empty.

Physically, this means that there are multiple actuator distribution combinations possible for obtaining the desired effect of diagonalisation, i.e. decoupling. In the case of the beam mentioned earlier (Figure 2), if there were a third actuator, then the system would be over-actuated. There would be multiple combinations possible for the distribution of the forces over the actuators such that only a rotation or a translation is obtained.

This article provides an opportunity to use this design space to not only decouple rigid-body modes, but also to isolate non-rigid-body resonance modes. It is shown here that the freedom provided by over-actuation can be used to improve the performance and/or robustness of the controlled system, without actually having to add an additional control loop. As an example, by isolating non-rigid body modes, a bandwidth-limiting resonance can become 'invisible' for the rigid-body input. It could also be that tracking performance and settling improve, as the disturbing non-rigid-body modes are either not or less excited.

To do this analysis, a simple and practical example is used, which will be presented first. Then the theory of this method is discussed and how it can be applied to the simple example. Following the theoretical approach, the practical approach will be applied to the example. After presenting the simple example, the results for an existing, more complex system will be discussed. Finally, this article will draw some conclusions.



4
Schematic overview of a simple example consisting of two bodies and three actuators.