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).

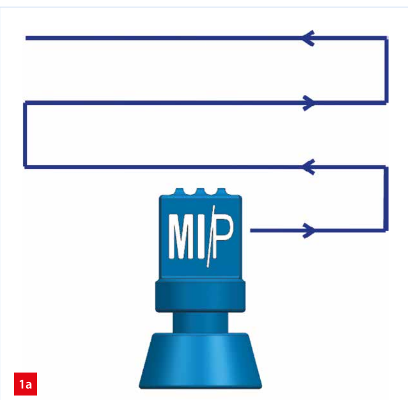
A stage has been realised that can perform both scanning strategies. All six DoFs are actively controlled by means of the electromagnetic actuator and measured by the metrology system, which enables nanometer-level positioning performance with high scanning accelerations and speeds, whilst being able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

System overview

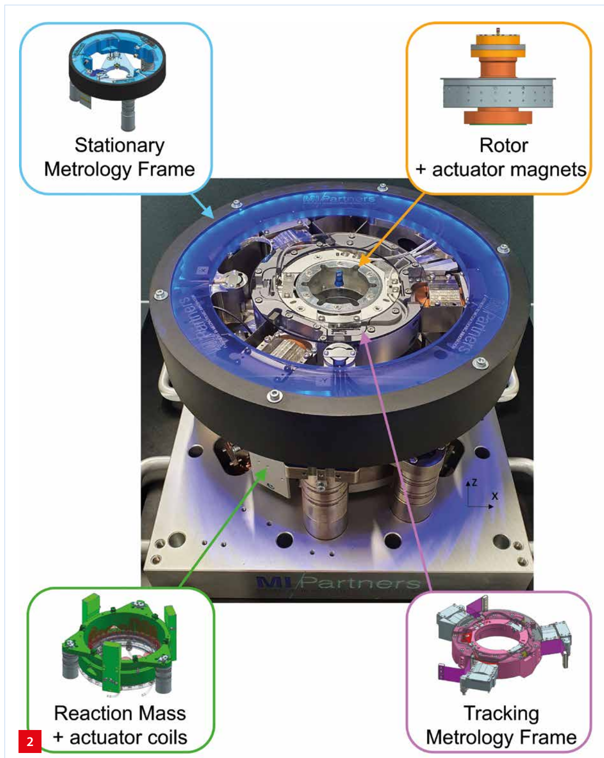
An overview of the main system components can be found in Figure 2. This article focuses on the mechatronic design of the actuator and the metrology system, and shows the positioning performance achieved so far. More details on the dynamics and control are presented in [1].

Mechatronic architecture

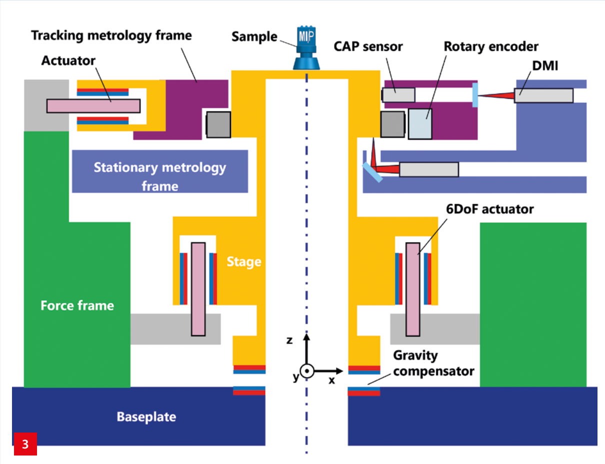
Figure 3 shows the schematic architecture of the sample manipulator. The sample is located on top of the rotor, which is actuated by the 6-DoF electromagnetic actuator. The stationary part of the actuator is connected to a reaction mass for filtering reaction path dynamics and enabling higher control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



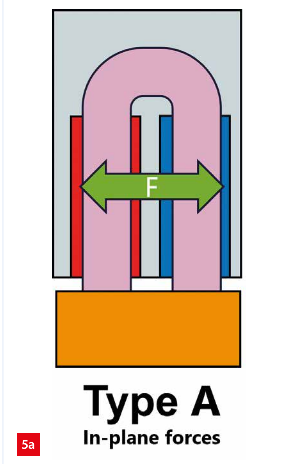
Impression of a beamline sample with possible scanning strategies.
(a) Scanning motion.
(b) (Eccentric) rotation.

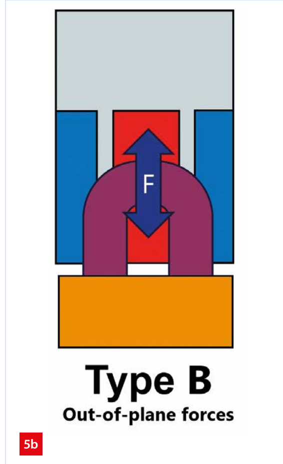


Main system components of the realised MagLev sample manipulator.



Schematic architecture design.



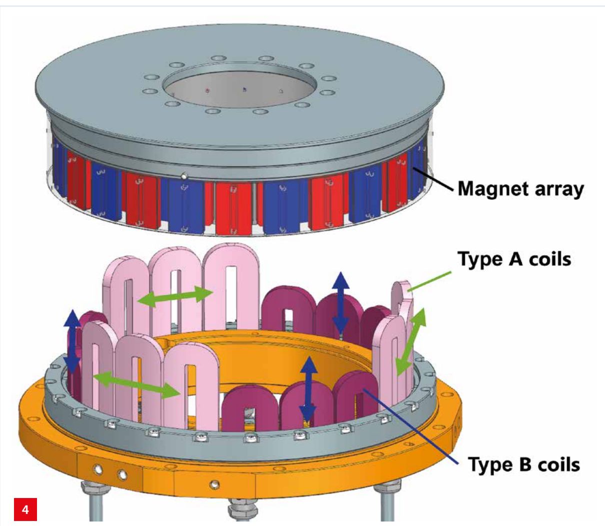


Actuator coil types.
(a) Type A: long coil.
(b) Type B: short coil.

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.

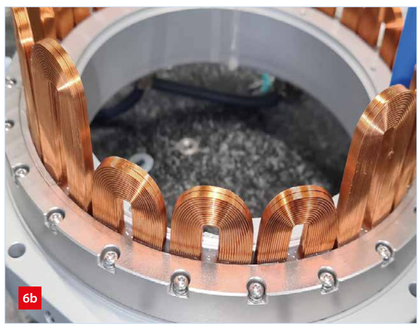


6-DoF Lorentz actuator components, with the in-plane (green) and out-of-plane (blue) forces displayed.

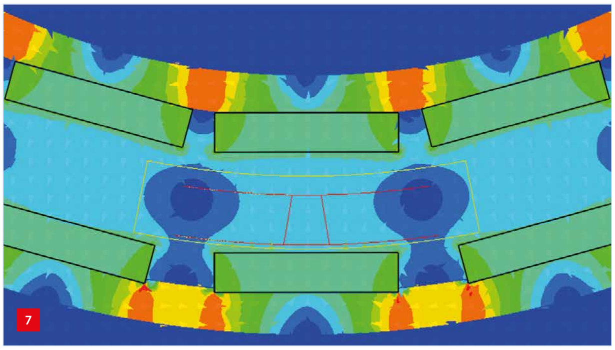
The type-A coils are more or less equal to a standard linear motor, but now in a curved configuration. The type-B coils are shorter, such that the horizontal part of the coils is in the magnet field to generate a net vertical force. See Figure 5 for both coil types. The magnet array is attached to the 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.



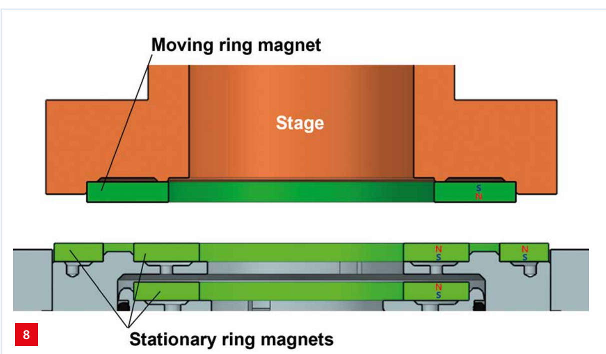
Simulated magnetic field in the actuator.

force. This allows for compensation of tolerances and ambient-temperature offsets, which affect the magnetic levitation force.

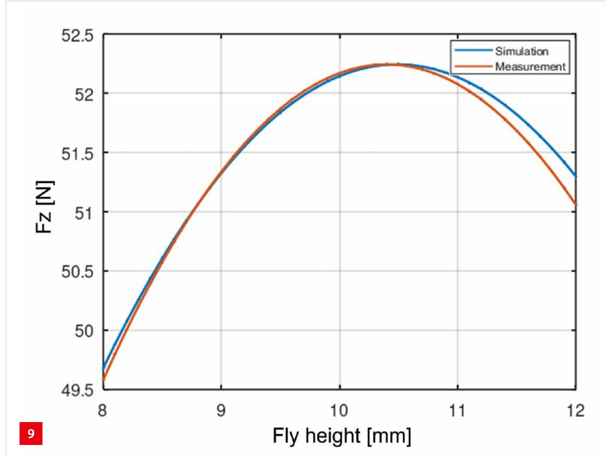
The magnetic field of the gravity compensator was simulated to determine the behaviour of the vertical force over the range of motion. Figure 9 shows the simulated and measured vertical force for 4 mm of *z*-stroke. The force is adjusted to match the stage weight in the centre position, over the required functional stroke (3 mm); the variation is < 1 N. The shape of the curve is very similar to the simulated force over the stroke.
Figure 10 shows the measured *z*-force in the *x,y*-range of the stage, which has a maximum variation of ~1.5 N over the full stroke. These measurements demonstrate that the *z*-force required from the actuator during levitation is reduced to < 5% of the stage weight (~5 kg).

Metrology

To enable a 3 mm stroke with nanometer positioning performance, the system has been equipped with distance measuring interferometers (DMIs). For the out-of-plane measurements, the DMIs measure on a highly reflective surface with a low flatness deviation, machined by diamond turning. The laser beam from the DMI is deflected by a 45° mirror onto this surface to measure the *z*-position in three locations; see Figure 11.
Due to the relatively large stroke, for the in-plane directions, a direct measurement towards the cylindrical surface by the DMI is not possible. At an offset, the inclination is too large and the reflected beam will not enter the DMI head anymore.



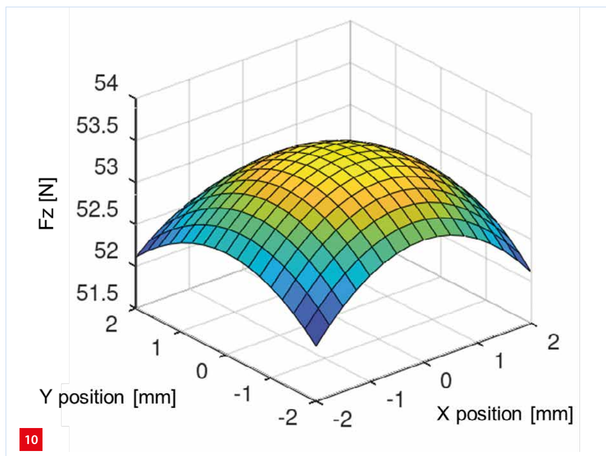
Gravity-compensator magnets.



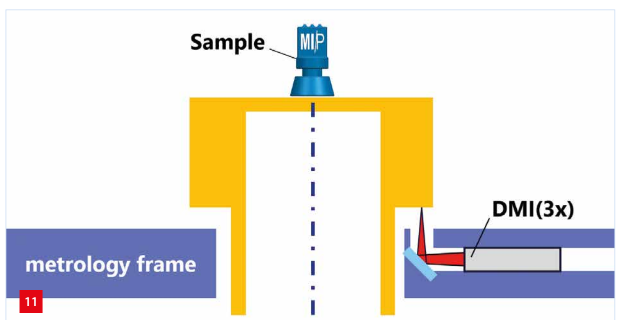
Measured z-force of the gravity compensator over the z-stroke.

Therefore, a stacked metrology principle has been developed where a tracking metrology frame (ring-shaped) is moving in the *x,y*-direction, along with the rotor. The rotation (*Rz*) of this tracking metrology frame is not changing, in order to hold the DMI mirrors perpendicular to the beam and ensure sufficient reflection of the beam; see Figure 12.

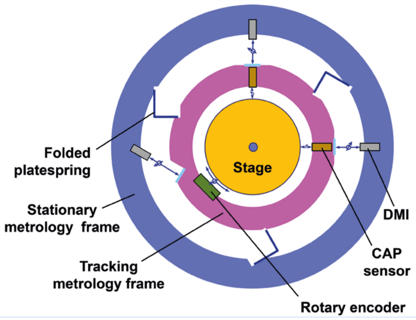
This tracking metrology frame has been equipped with two capacitive sensors measuring the *x,y*-position of the rotor relative to the tracking metrology frame. The *x,y*-position of the tracking metrology frame with respect to the stationary



Measured z-force of the gravity compensator over the x,y-stroke.

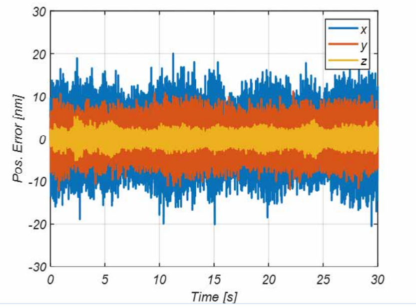


Out-of-plane measurement DMI with 45° mirrors.



12

In-plane stacked measurement.



14

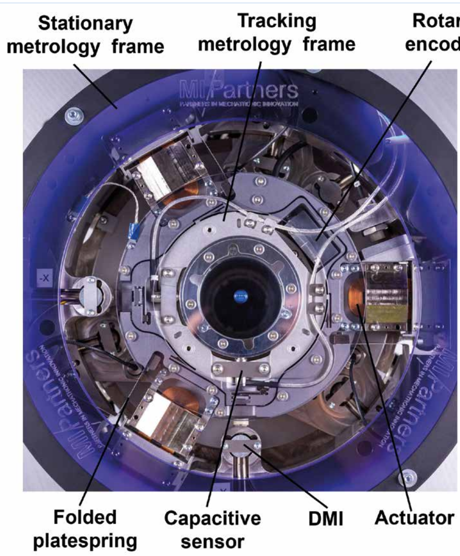
Standstill performance: x, y, z servo error.

metrology frame is again measured using DMIs.
So, the tracking metrology frame is not in contact with the rotor, but tracks the *x,y*-position of the rotor, based on the position measured by the two capacitive sensors. The actuation is achieved with three single-phase actuators, while three folded plate-spring flexures guide the tracking metrology frame in the out-of-plane direction.

A rotary encoder is also kept in range by the tracking metrology frame to measure the *Rz*-position of the rotor relative to the tracking metrology frame. A tangentially oriented DMI between the tracking and the stationary metrology frame finally enables the measurement of the *Rz*-position of the rotor relative to the stationary metrology frame. Figure 13 shows the components of the stacked metrology in more detail.

Performance

Currently, the performance of the system is being optimised. Firstly, feedback controllers have been implemented on the rotor and the moving frame. For the rotor, a controller bandwidth of about 150 Hz is achieved with 4 nm rms standstill performance.



13

Detailed overview of the in-plane stacked measurement.

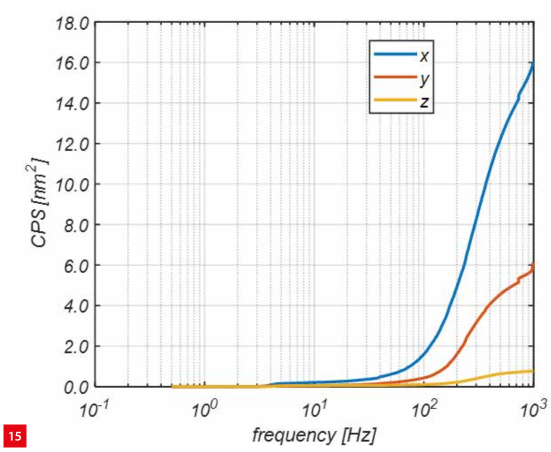
Figures 14 and 15 show the servo-error standstill performance in the *x*-, *y*- and *z*-direction with the current controllers. These are promising results, considering the fact that the tests were done in a non-ideal environment without further optimisation of the actuator decoupling model.

Future work

To achieve nanometer positioning performance during the described scanning motions, further activities are planned, such as:

- Implementation of an accurate actuator decoupling model; eventually with a strategy to calibrate some parameters.
- Feedforward correction of known error sources, such as:
  - disturbance forces from the gravity compensator;
  - disturbance forces from the actuator.
- Implementation of geometric calibrations, such as:
  - flatness and roundness deviations of the measurement surfaces;
  - perpendicularity of the sensors.
- Providing a thermally stable, vibration-isolated environment.

REFERENCE
[1] MI-Partners, "Extended abstract on rotating Maglev sample Manipulator", *NWC23-0188, Nafems World Conference*, 2023.



15

Cumulative power spectrum (CPS) of the servo error.