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Magnetically levitated planar motion stage with atomic resolution for metrological high-speed scanning probe microscopy

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Abstract
Today, complex nanostructures are driving cutting-edge technologies such as photonics, semiconductor electronics, novel materials, and quantum research. Apart from the capability to manufacture such functional structures in the nanometre domain, appropriate means for their inspection are required. In this context, scanning probe microscopy provides diverse techniques to characterise the functional properties of nanostructures. However, today's high-tech industry promotes increasingly small feature size and high throughput so that even state-of-the-art measurement instruments struggle to satisfy the resulting requirements for sub nanometre accuracy over millimetres of travel in combination with scanning speeds of several millimetres per second.
This contribution proposes a novel electromagnetically levitated and driven planar motion stage with atomic resolution for sample positioning in metrological high-speed scanning probe microscopy. Key design objectives include a position resolution of 0.1 nm, a motion velocity of at least 10 mm/s and a scanning range of 12.7 mm by 12.7 mm with nano-positioning capabilities in the remaining four degrees of freedom. The focus is set on the first design phase of the stage, introducing the system architecture and the design choices made to achieve sub nanometre repeatability and long-term stability of position measurements in all six degrees of freedom. The concept is complemented by simulation results and preliminary component-level measurements to assess its feasibility.

Keywords: Magnetic levitation, nano-positioning, high-speed scanning probe microscopy

1. Introduction

More than ever before, technological progress in cutting-edge applications is driven by nanotechnology. The use of complex nanostructures enables a variety of contemporary technologies such as photonics, semiconductor electronics, novel materials, and quantum research. However, increasingly small feature size (in the single-digit nanometre range) and increasing throughput requirements present major challenges in the manufacturing of nanostructures on an industrial scale. High yield therefore requires comprehensive in-line inspection to identify defective structures across multi-stage production processes.

For this purpose, scanning probe microscopy (SPM) provides diverse inspection techniques for functional nanostructures [1]. While metrological SPM instruments provide high measurement accuracy in the nanometre domain, most of them are limited in terms of scan range (< 100 µm) and scan speed (< 10 µm/s). Commercial (non-metrological) SPM instruments offer slightly higher scan speeds (≈100 µm/s) and long-range options (up to 1 mm) but typically sacrifice metrological traceability. Video-rate SPM instruments achieve very high scan speeds over a very limited scan range (< 1 µm) but suffer from low precision and distorted images.

Addressing the conflicting goals of large range, high speed and high accuracy, this contribution proposes an electromagnetically levitated (MagLev) planar motion stage for sample positioning in traceable high-speed scanning probe microscopy. The challenge is to achieve sub nanometre precision over a planar travel range of several millimetres while considering the accessibility of the technology at the same time. In this case, accessibility refers to form factor, interfaces, control integration and costs. For this, Physik Instrumente (PI) GmbH & Co. KG can draw on more than 15 years of experience in the field of electromagnetic drives and electromagnetic levitation technology. Previous developments at PI include planar MagLev stages with nanometre stability over travel ranges of up to 100 mm [2, 3] which still present notable contributions to the state of the art in electromagnetic levitation technology for precision motion systems [4].

The development of the new MagLev stage is carried out as part of a funded research project which provides a specific use case within a prototype instrument. Section 2 provides a brief overview of the underlying project scope and the envisioned instrument. Section 3 introduces specification requirements and preliminary design considerations to enable sub nanometre resolution. Then, Section 4 outlines the state of development and selected component- and system-level studies to validate the feasibility of the design approach. Finally, Section 5 provides a summary and an outlook on future work.

2. Project framework and objectives

Development, construction, and characterisation of the MagLev stage are implemented within the framework of the research project 20IND08 MetExSPM (Metrological Express Scanning Probe Microscope). The overall research objective is to enable high-speed scanning probe microscopy for traceable measurements of localised functional properties of nano-structures with a measurement uncertainty of 1 nm. To this end, the project consortium investigates innovative technologies, components, and procedures, as well as their interactions in a total of four work packages:

1. Active self-sensing and self-actuating probes as high-speed nanometrology tools.
2. Long stroke high-speed scanning stages with a six degree of freedom (DoF) interferometric metrology system.

3. Data acquisition and processing procedures for high-speed scanning.
4. Metrological high-speed scanning probe microscope as a system demonstrator for active probes, scanning stages, reference metrology and data processing software.

The prototype instrument to be constructed in work package four incorporates the developments from the three previous work packages and provides a system-level proof of concept. The instrument will be initially set up for atomic force microscopy (AFM), however, it will also support other scanning probe types. The instrument design is based on a frame construction which holds positioning systems and metrology components as shown in Figure 1. The design is complemented by a vibration isolation system for the instrument frame and an enclosure for acoustic and thermal isolation.

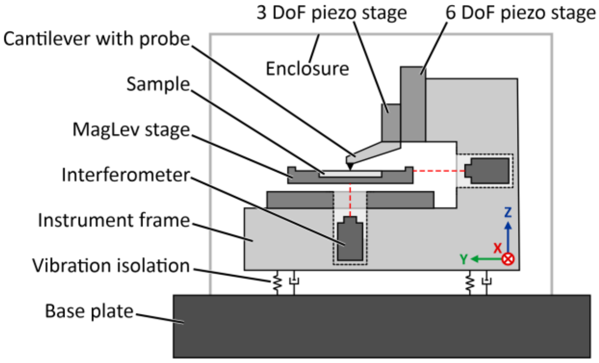

Figure 1. Schematic representation of the prototype instrument.

The MagLev stage supports sample positioning in the XY-plane but also allows for nano-positioning in the remaining four DoFs within a limited range. In addition to the integrated sensors for closed-loop control, the MagLev system is complemented by three multi-beam interferometers for reference measurements of the sample stage position. The reference interferometers are arranged according to the Abbe measurement principle with the intersection point of the primary beams at the cantilever tip (on the sample surface). The laser sources of the interferometers are calibrated to a metrological standard to ensure traceability of the measured position data.

The AFM scan head holding the active cantilever is mounted on a set of piezo stages, i.e., a long stroke stage driven by polycrystalline piezo actuators in six DoFs and a short stroke stage driven by monocrystalline piezo actuators in three DoFs. The long stroke stage features additional actuators for reaction force compensation to minimize vibration excitation of the instrument frame. The combination of MagLev and piezo stages allows for a hybrid scanning setup which supports both scanning operations via probe motion as well as sample motion.

3. Conceptual design for the planar MagLev stage

The following subsections compile main requirements for the planar MagLev stage and disclose preliminary considerations regarding key development challenges and design choices.

3.1. Specification requirements

Specification requirements for the MagLev stage are based on its function within the prototype instrument. Probe scanning operation requires precise sample positioning in the XY-plane with minimum deviations in the remaining four DoFs. Further requirements include minimum position noise (jitter) and drift during standstill. Sample scanning operation further introduces kinematic parameters (velocity and acceleration) and extends position noise and drift requirements from standstill to uniform movements.

The primary travel range in the XY-plane is defined as 12.7 mm by 12.7 mm (i.e., a quarter square inch). Secondary objectives include a motion range of 0.5 mm in Z-direction and up to 1° of rotation around all three main axes. The required scanning speed is 10 mm/s over at least 80 % of the primary travel in X- and Y-direction. Furthermore, a positioning bandwidth of at least 100 Hz in the small signal range (< 1 µm) is desired whereas peak acceleration with a payload of 100 g will be limited to 1 m/s^2.

The target position resolution of the internal feedback system is defined as 0.1 nm per translational DoF. The resulting position noise (at standstill or during motion) must be below 0.3 nm (1 σ) – assuming a thermal steady state, this will also represent the repeatability of the MagLev stage. Notably, the application favours repeatability and long-term stability over accuracy.

3.2. Preliminary considerations

3.2.1. Challenges

Major challenges in the development of the new MagLev stage revolve around the required precision in the sub nanometre domain. Thermo-mechanical effects are among the key issues regarding the accuracy and precision of mechatronic systems. Active components inevitably dissipate heat which leads to thermally induced deformation and affects overall precision of the system. Hence, a thermal management strategy is essential to ensure nanometre precision and long-term stability.

The internal displacement sensors of the magnetic levitation system present another critical issue. The sensor system must support contactless monitoring of all six DoFs of the levitating platform. The sensors for the long-stroke motions in X- and Y-direction must provide a consistent measurement performance over the full travel range. All sensors must also tolerate lateral motion and angular misalignment between the probe and the measurement target to utilise all six DoFs of the MagLev stage.

3.2.2. Design approach

The key measure to address the thermal issues in the MagLev stage is the integration of separate force and metrology loops. Both the base and the mover of the MagLev system feature metrology and force frames as depicted in Figure 2. On the side of the base, the frames are completely separated. Here, the metrology frame is attached to the isolated instrument frame; the force frame, on the other hand, is mounted on the base plate of the instrument. On the side of the mover, a full separation of force and metrology loops is not feasible. Thus, designated force and metrology frames are provided and coupled via flexure-based mechanisms which minimise the deformation of the metrology frame due to actuation forces and thermal effects.

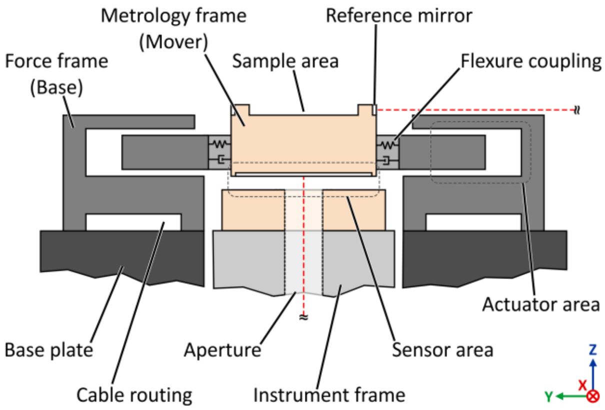

Figure 2. Schematic representation of the MagLev stage architecture.

All active components within the MagLev stage are potential heat sources – notably, this includes actuators as well as sensors. Removing heat via active cooling of sensor components may introduce noise to the metrology loop and is therefore avoided. Instead, the chosen approach to thermal management is to keep the thermo-mechanical system as inert as possible. This decision is further motivated by relatively low requirements regarding motion dynamics and the aim for low system complexity. Consequently, a combination of passive measures is considered:

- The metrology frame components are made from an ultra-low thermal expansion glass or glass ceramic material, e.g., Schott's Zerodur® or Corning's ULE 7973®.
- The mover of the motion stage is completely passive and as lightweight as possible.
- The Z-actuators are designed to support near-powerless levitation based on permanent magnets.
- The XY-actuators are oversized to counter the low efficiency of small direct drives.
- Thermo-symmetrical design is applied to force frame and metrology frame components.

Apart from thermal issues, the capability of the sensor system affects the overall precision of the MagLev stage. The sensor system for the application at hand features a combination of interferential encoders and interferometers as shown in Figure 3. A total of four encoders is used to monitor the X- and Y-motion and the rotation about Z. Here, two encoders are used for each translational DoF to account for Abbe errors, consistent noise levels per generalised DoF and thermo-symmetry. Note that the encoder heads are equipped with laser diodes which result in continuous heat dissipation. Similarly, a symmetrical layout with four interferometers is used to monitor the Z-motion as well as the rotations about X and Y. Although the used interferometer probes are completely passive, symmetry and redundance is still beneficial for the overall noise levels of the generalised DoFs.

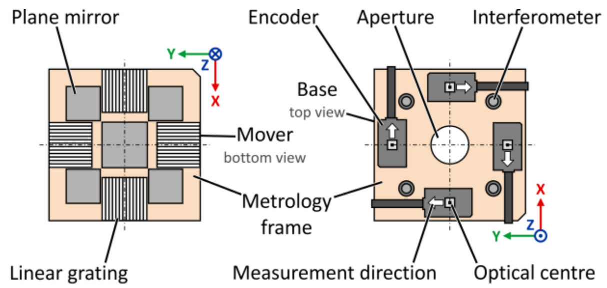

Figure 3. Metrology concept for the planar MagLev stage.

The selected sensor types achieve an interpolated resolution in the picometre range; however, this requires sufficiently precise alignment of probes and measurement targets. Interferential encoders typically provide installation tolerances regarding clearance and angular alignment of the scanning head and grating – dynamic changes of these parameters in operation affect signal quality and precision. Likewise, signal quality of interferometers decreases with inclination of the mirror surface. Since modifications of commercial sensors are unlikely to improve overall performance, the only viable measures include careful selection and comprehensive testing of potentially suitable sensors. Ultimately, the robustness of the selected sensors defines the spatial motion range of the MagLev stage.

4. State of development

Following the considerations from the previous subsection, a baseline design is established for the MagLev stage. Figure 4 shows a CAD model of the system, indicating overall dimensions, mass, and other distinct features. To assess the feasibility of the design, component- and system-level studies are conducted. The following subsections discuss selected findings on thermal management measures and sensor performance.

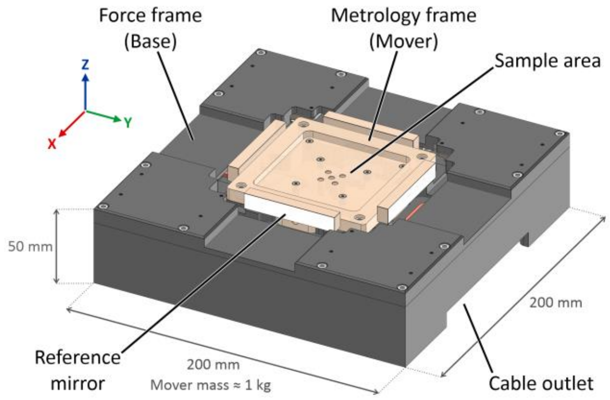

Figure 4. CAD concept for the planar MagLev stage.

4.1. Thermo-mechanical decoupling

The use of glass (or glass ceramic) materials with an ultra-low coefficient of thermal expansion (CTE) in combination with a separate force frame enables a purposeful and efficient design. Force frame components made from metal alloy allow for a highly flexible and cost-efficient integration of electromagnetic actuators. Therefore, metrology frame components made from low CTE materials can be reduced in size and complexity (to only accommodate sensors and samples) which enables a compact and rigid design to minimise gravity-induced warping. However, the combination of materials with distinctly different CTEs introduces other issues since thermal strain may cause excessive stress in contact areas. This is particularly crucial for brittle glass materials which may fail when a critical threshold for tensile stress is exceeded. Consequently, appropriate measures must be taken to account for thermally induced stresses at glass-metal-interfaces, which is relevant for the overall assembly (regarding interaction between force and metrology frames) as well as individual components (such as threaded inserts).

Accordingly, thermal decoupling of actuator and metrology frames via flexure guides is considered as a primary measure. The flexures are directly integrated in the force frame and permit specific deformation under thermal load. The flexure-based mechanisms are arranged to account for the dominant thermal elongation of the metal frame with minimum reaction forces at the glass component. Notably, flexure guides exhibit finite stiffnesses in the constrained DoFs which allow for more prominent structural-dynamic behaviour of the assembly. As a further measure, all inserts are made from Invar alloy. In this case, the magneto-strictive properties of Invar are neglectable since thermo-mechanical effects are much more pronounced.

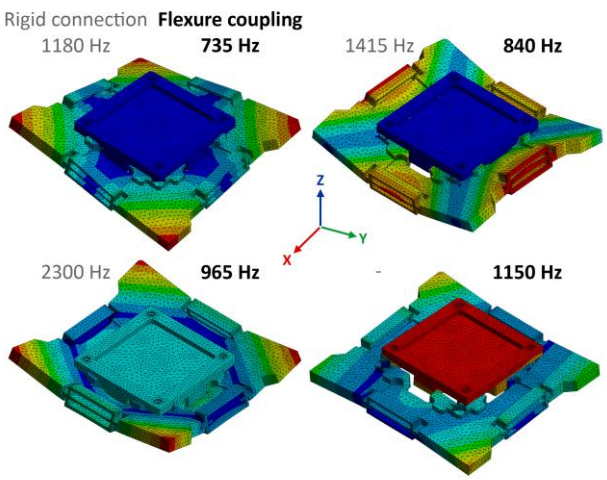

Figure 5. Mode shapes and critical frequencies of the mover (simplified geometry representation).

The feasibility of the thermal decoupling approach is assessed via finite element method (FEM) simulations. Initially, the mover assembly is modelled with rigid connections between actuator and metrology frames for baseline results. Subsequently, the model is extended with parametric bushing joints (each with a six DoF stiffness matrix) which represent flexure guides at the actuator frame. A preliminary stiffness matrix is chosen for the joints based on an established flexure design. The simulation results confirm the flexure-based decoupling mechanisms to be highly effective by reducing thermally induced stress in the glass component below 2 MPa for an excessive temperature increase of 10 K. However, the first resonance frequencies of the mover assembly are considerably lowered as documented in Figure 5. The inclusion of flexure-based coupling does not affect the first three mode shapes but introduces fourth and fifth eigenmodes with relative motion between the frames around 1150 Hz. In view of the desired control bandwidth of 100 Hz, the first resonance frequency at 735 Hz is still acceptable.

4.2. Sensor characterisation for XY-motion and Z-rotation

Since magnetic levitation systems rely on closed-loop control, their performance considerably depends on the sensor systems for position feedback. For this reason, individual test stands are set up to determine key performance figures of the selected sensor types. In the following, the focus is placed on the interferential encoders. All experiments are conducted under laboratory conditions (climate control, enclosure over test stand, setup on optical bench with vibration isolation system).

First, a linear test stand is set up to investigate the thermal behaviour and signal quality of the encoder. The test stand consists of a rigid aluminium frame holding the scanning head and a P-752 piezo stage from PI equipped with the grating. The signal chain includes custom-made interpolation electronics for the 1 V_{pp} signals connected to a PI C-702 controller via serial interface. The encoder is set up using the integrated gain adjustment without any further signal processing. The sample rate of the controller was set to 10 kHz.

The encoder shows a distinct thermal drift over the initial 150 minutes of operation. The temperature increase at the scanning head is measured to be approximately 3 K with this setup. The interpolated resolution is just above 6 pm per count, the noise levels are identified as 6 pm (1 σ) or 38 pm (peak to valley) respectively, see Figure 6.

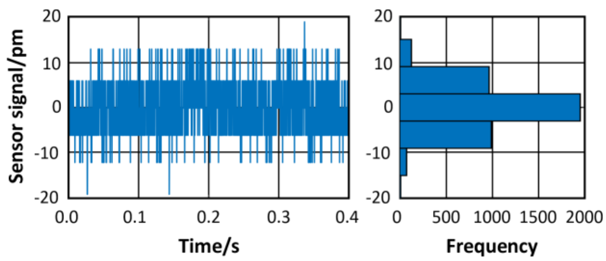

Figure 6. Signal noise of interferential encoder for XY-motion.

A second test stand is set up to determine the permissible misalignment between scanning head and grating. To this end, the P-752 piezo stage is mounted onto a PI F-206 hexapod. The hexapod is used to position the piezo stage with the grating relative to the scanning head. Then, the piezo stage provides a reference motion in measurement direction. A multifactorial approach is chosen for the experiment to determine the effect of simultaneous tilting about several axes in combination with clearance changes. Sine and cosine levels as well as phase errors are examined to evaluate the sensor performance.

The experiment generates comprehensive data sets which cannot be conveniently displayed in a single image due to the number of parameters. Hence, Figure 7 shows an extract from a measurement data set. Every subplot corresponds to a specific clearance value and illustrates the sine levels over combinations of roll (rotX) and pitch (rotY) angles for a set yaw (rotZ) angle. The data indicates a relatively high tolerance to misalignment within the investigated workspace with only few combinations of increased pitch angle and clearance offsets resulting in impermissible signal levels. Cosine levels are not shown here but behave in a similar manner. Phase errors are very consistent over the workspace (if sine and cosine levels are within 0.6 to 1.3 V_{pp}) and gradually change with clearance and roll angle within specified limits (±0.5 mm, ±1°).

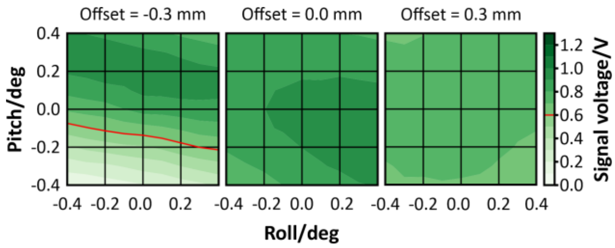

Figure 7. Partial workspace of interferential encoder for XY-motion.

In conclusion, the selected interferential encoders provide outstanding resolution and noise levels with sufficient tolerance to misalignment for use in the planar MagLev stage. While the experimental investigation indicates reliable operation within the specified workspace, it is still recommended to restrict the motion range of the MagLev system to ±0.25 mm in Z-direction and to ±0.25° for rotation about the X- and Y-axis

5. Summary and outlook

This contribution introduces a new planar MagLev stage for sample positioning in metrological high-speed scanning probe microscopy. Based on the intended use case within a prototype instrument, both specification requirements and development challenges are identified. A design concept for the MagLev stage is presented. Two critical issues of the development, the thermal management strategy and the sensor system, were focused.

The experimental study on the interferential encoders for monitoring of the XY-motion indicated an outstanding sensor performance with noise levels below 40 pm (peak to valley) and with sufficient tolerance to misalignment.

The simulation study on thermal decoupling mechanisms for brittle glass ceramic components confirmed an effective decrease of thermally induced reaction forces and stress to uncritical levels. However, the additional compliance in the actuator frame also decreased critical frequencies of the assembly below 1 kHz. While the simulated eigenfrequencies starting from 735 Hz are acceptable due to relatively low motion dynamics, further optimisation as well as component-level improvement of mechanical and electrical components are considered in future work packages.

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