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DEVELOPMENT OF AN INTEGRATED GUIDING AND ACTUATION ELEMENT FOR HIGH DYNAMIC NANOPOSITIONING SYSTEMS

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ABSTRACT

In nano precision technology, actuating along the vertical axis is a special challenge because of the permanent gravitational force. In this paper, the development of an integrated guiding and actuation element for the vertical motion is presented.
A pneumatic-cylinder-like setup is used with its pressure being load controlled, to compensate the gravitational force of the load. An additional electromagnetic drive creates only dynamic forces for the precision motion, keeping the ohmic heat emission to a minimum. For the vertical guiding an aerostatic bushing is used. The whole setup sits on a planar aerostatic bearing pad. Therefore, translational friction can be neglected.
Initial testing results of such a unit are presented and an outlook for future research work is given.

Index Terms – nanopositioning, NPM-Machines, force compensation, voice coil

1. INTRODUCTION

In high precision machines special measures need to be taken to reach the required precision level. For nanopositioning and nanomeasurement machines (NPMMs) the Abbé-comparator principle is a key design concept. If the dimensional scale of a length measuring device is not in line with the measuring length, an imperfect guiding will result in an Abbé-error. To measure without the first order Abbé-error, the dimensional scale needs to be placed in line with the measurement axis.
For three-dimensional coordinate measurement machines (CMMs) this means, that all three measurement axis cross in a single point, the Abbé-point. In this point, the CMM interacts with the sample, as displayed in Figure 1. [1], [2]

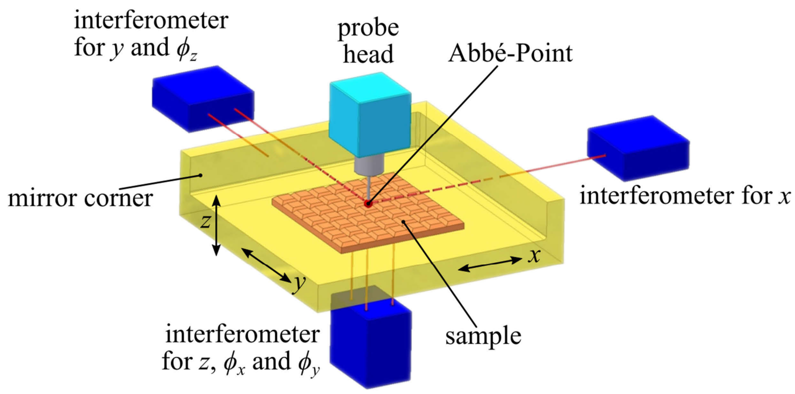

Figure 1: 3D Abbé-comparator principle of a NPMM [1]

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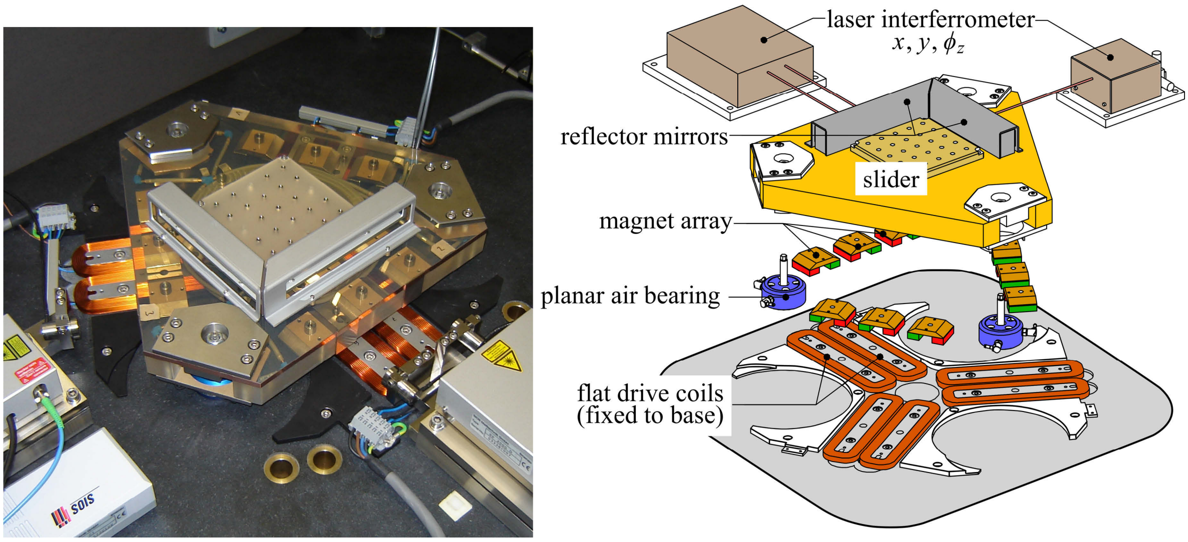

Figure 2: PPS100 photo and CAD explosion view

2. STATE OF THE ART – VERTICAL AXIS IN NANOPOSITIONING AND NANOMEASUREMENT MACHINES

Many companies and non-profit organizations are working on different approaches to further increase the precision while also increasing the travel range. Mainly three physical effects are used to lift the specified load, namely: Piezoelectric actuators, spring-preloaded stages and pneumatic piston setups.

For travel ranges of up to a few millimeters, piezoelectric actuators are commonly used. The drives are compact and lightweight and enable a high dynamic control. Since the lifted weight (sample mass and lifted mass of the drive) and the heat emission of these drives is very small, no special drive designs need to be realized. [3]

As in [2] and [4] springs are used to counterbalance the weight force of the z-stage with the sample, allowing for larger travels of 5 and 25 mm, respectively. Large efforts are made to create a constant spring force over the whole travel range. Additional actuators are needed to change the levering ratio between the spring and the output to adjust for different loads. The precision motion is realized by three voice coil drivers, supplying only dynamic forces.

The ISARA 400 [5] has an even larger vertical travel range of 100 mm. In this system, the sample rests on an x/y-stage but in contrast to the systems named before, here the whole metrology frame, including the measurement tool is moved vertically. For the z-guiding a large and a small air bushing sit on one rod. The space between the bushings is enclosed and used as an air chamber, sealed by the bushings. The rods cross-section change forms a piston area, which is pneumatically actuated. Additionally, for precision motion an electromagnetic linear direct drive is used. [5]

The PPS100 is a precision drive system (see Figure 2), which currently does not have a z-drive. It follows a parallel kinematic design approach, where three planar direct drives act on one air-suspended monolithic slider body. A single-beam and a double-beam laser interferometer (LIF) are used to achieve a measurement resolution in x and y of 0.02 nm. With this setup it is capable of a positioning resolution in the xy-plane of down to 0.5 nm in a circular travel area of Ø 100 mm. The rotation around the vertical axis (ϕ_z) is actuated as well (to keep ϕ_z constant), resulting in a Degree of Freedom (DOF) of 3 for the PPS100. [6]

Three air-bearing pads support the slider and allow for a virtually frictionless motion, but also introduce the flatness error of the corresponding surface as a guideway error. The tilting (ϕ_x, ϕ_y) and the vertical position (z) of the slider are subject to this error.

3. MOTIVATION AND GOALS

The flatness error of the air bearing counter surface (stator made of natural stone) is in the range of 1 µm. Setting the PPS100 slider at a worst case position results in a z-position error of up to 0.88 µm and a ϕ-tilting error of 4.3 µrad (= 0.9 arcsec).
A further reduction of the flatness error of the natural stone surface to reach the nanometer domain is technically and economically not feasible.
An alternative method to reduce the resulting guideway error at the slider is to introduce an active suspension system. These actuators can be placed in a lot of different combinations and locations in the kinematic chain. To preserve the parallel kinematic and monolithic approach of the PPS100, one actuator system should be integrated between the slider and each planar air bearing. Controlling these actuators independently will result in a DOF of 6 for the slider. To control the additional two rotational and one translational axis, the new freedoms need to be measured. A triple-beam LIF needs to be included below the slider. Further information about it can be found in [7].
The tilting range around the x- and y-axis should be only enough to compensate the error but the z-range should be 10 mm.

4. DEVELOPMENT

4.1 Functional Design

For larger vertical travels in precision drive systems often functional separation is carried out. As in [1], [4] and [5], two subsystems create independent forces in z-direction: One system creates a force to compensate the weight force of the lifted unit and another system creates a dynamic force to accelerate the lifted unit and counteract disturbances. This approach has also been realized in the development of a Lifting and Actuating Unit (LAU) for the PPS100. Every LAU consist of the following functional components (numbering see Figure 3):

1. (red) Quasi-static weight force compensation (WFC)
2. (yellow) z-guidance
3. (blue) Linear measurement system
4. (green) Dynamic drive
5. (purple) Planar bearing

As displayed in Figure 3, a pneumatic-cylinder-like setup has been chosen as weight force compensation. Via a controllable pressure in the chamber the necessary force can be created and adjusted to different load and lifting situations. Since the infrastructure for pressurized air is already present, this is the preferred solution.
The z-guidance is drawn as a prismatic guidance. A prismatic guidance is preferable, because a cylindrical guiding would leave the rotational motion undefined (it is not controlled via an actuator). The rotational locking is especially necessary for a lot of measurement systems, where a detector needs to be directly in front of a dimensional scale. Theoretically, when a 3-beam interferometer is used, a measurement system is not necessary. To have an absolute reference and a fallback system a measurement device is preferable.
The dynamic forces for accelerating, decelerating and compensating disturbances will be created with an electromagnetic voice-coil-like drive system. This type of drive has been used successfully in previous NPMMs and gives enough design freedom to customize it for the specific task. From a control point of view it is a very simple drive, since it needs only one current to be controlled (no commutation necessary). Furthermore, it can be designed rotationally symmetrical suiting very well to the pneumatic cylinder of the WFC.

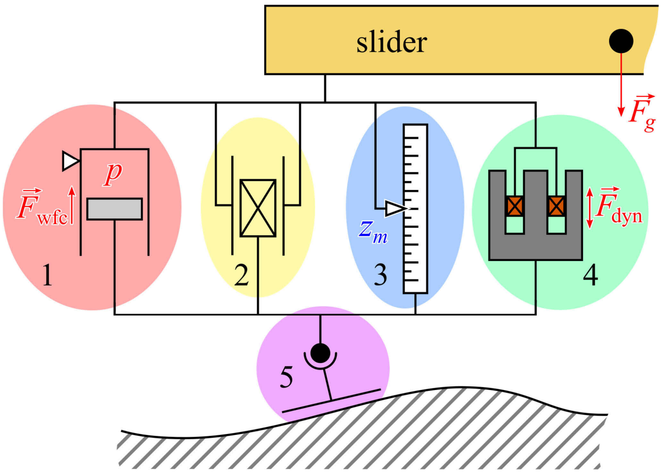

Figure 3: Technical principle of one LAU.

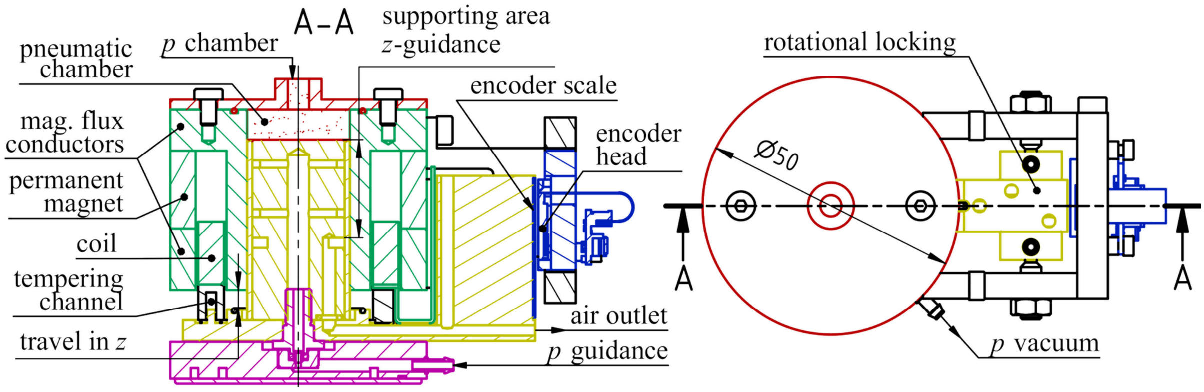

Figure 4: Cross-sectional and top view of one LAU (colors according to Figure 3).

As in the standard PPS100 setup, the vertical forces will be transmitted via a vacuum-preloaded planar air bearing pad to the base frame.

4.2 Development Outcome

Three different design variants have been drafted. The realized variant is shown in Figure 4 (the color scheme is preserved from Figure 3). In the cross-sectional view on the left the rotationally symmetric structure can be seen.

On the bottom the planar vacuum-preloaded air bearing is located (purple). The air is fed via a connector on the side of the bearing. Part of the fed air is directed upwards into a bushing-like setup (yellow). In this case the rod is the part where the air is emitted. The bushing is mechanically fixed to a block outside of the cylindrical unit. On two opposing sides of this block two small planar air bearings acting as the rotational locking are placed. Therefore, the prismatic joint is formed by combining the bushing setup with the rotational locking.

The bushing part itself serves not only as the z-guidance but also (since it is made of steel) as a conductor for the magnetic flux of the drive magnet. This permanent magnet is magnetized axially and creates the flux, which is channeled by the steel parts (magnetic flux conductors). Thereby, in the air gap (see

Figure **5**) between the parts a very homogeneous magnetic field is created. This is where the drive coil is placed. The coil sits on a part with an integrated cooling channel, which allows a tempering of the coil.

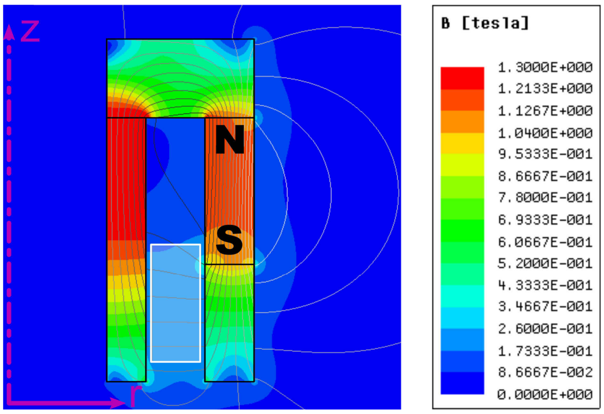

Figure 5: Simulation of the voice coil drive unit. The white frame is the cross-sectional area of the coil; the permanent magnet is marked with north and south pole.

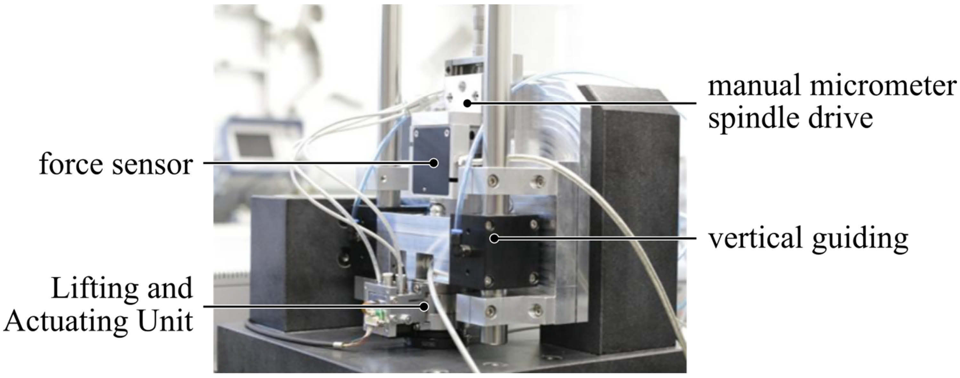

Figure 6: LAU mounted in the test stand.

Directly above the rod of the z-guidance is the pneumatic chamber. To allow a frictionless motion, there is no physical object sealing the chamber from the z-guidance. Therefore, air from the guidance will leak into the chamber. For controlling the pressure inside the chamber a commercial controller (AirCom PRE1-U02) was used. The complete control system was set up as a PID-controller, where the integral term is given to the pressure controller, whereas the P and D parts are fed to the amplifier of the voice coil.

On the block for the rotational locking the dimensional scale for the linear incremental encoder (blue) is attached. The encoder head (Numerik Jena Kit L4) is mounted onto the frame which holds the bearings for the rotational locking. Thereby a very good position of the head in front of the scale is assured.

5. PERFORMANCE EVALUATION

For the functional evaluation the designed LAU was fabricated, assembled and placed on a test stand (Figure 6). On this test stand a specific load can be put onto the LAU via a manual spindle drive and a force sensor. While controlling the electric current and the pressure the resulting force and position are recorded. Additionally, a laser interferometer measurement system (not displayed in the figure) is added for the nanoposition control.

First, the motor constant of the electromagnetic drive was recorded over the z-travel range.

Consecutively, the step response for the closed loop setup was measured. A z-step of $+1\ \mu m$ at $z = 5$ mm with a maximum velocity of $1\ mm/s$ was executed; Figure 7 shows this change in position. Additionally, the set point and the position filtered with a simple moving average (SMA) are displayed. The common overshoot of PID-controllers can be observed, as well as the small position noise. From the measured electric current the corresponding power output

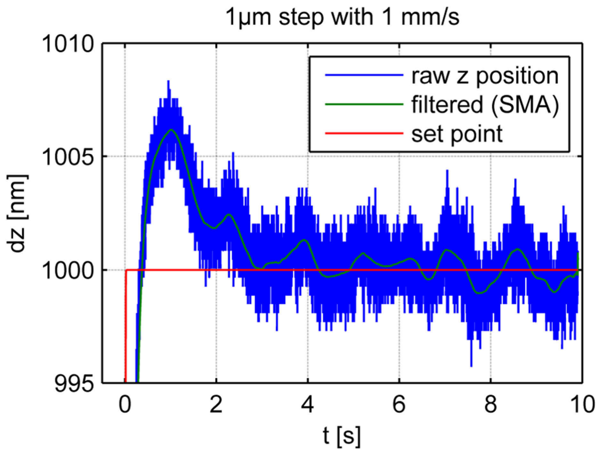

Figure 7: Closed Loop setpoint step response, measured with a laser interferometer.

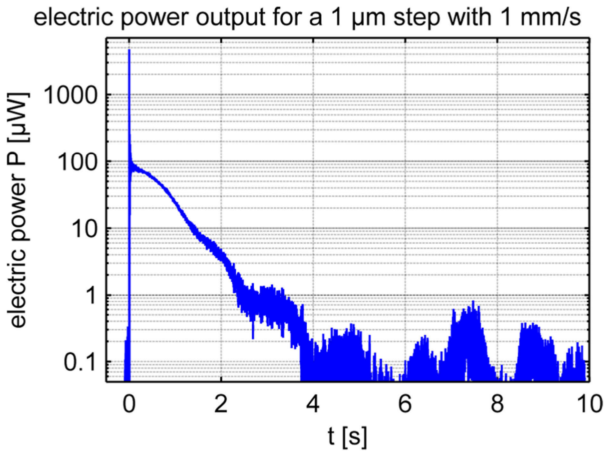

Figure 8: Dissipated power of the voice coil for the step shown in Figure 7.

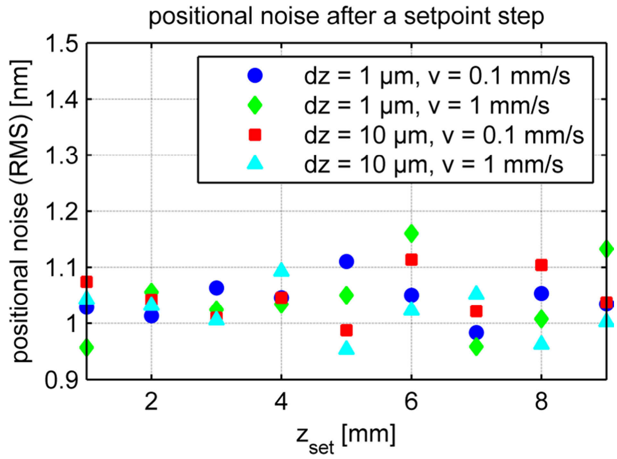

Figure 9: RMS-values of the positioning noise after a step at every millimeter of the *z*-travel.

of the voice coil is calculated and shown in Figure 8. The setvalue is reached after ≈ 3 s with a maximum power output of about 4.6 mW. It can be seen, that only a short current pulse (3 ms wide) is needed to accelerate the load. The chamber volume has now abruptly increased but the air-mass cannot be adjusted that fast. Therefore, there is still power needed to hold the load. The pressure controller starts to continuously feed air into the chamber, whereby the pressure rises, until the mass-pressure-equilibrium is reached again. During this process the power reduces from 0.8 mW to almost zero (1 µW) after 2.5 s. Now the voice coil only has to work against dynamic disturbances.

Subsequently, steps with four different parameter combinations have been executed at every millimeter of the *z*-travel. Figure 9 shows the root-mean-square (RMS) of the servo error after reaching the setpoint. It can be observed that the LAU holds the position very well over the whole travel range, with the RMS values slightly above 1 nm, independent from the previous step.

6. CONCLUSION AND OUTLOOK

In this paper the development of a vertical actuator system for NPMMs was presented. The development goals and the process were outlined and documented. A single actuator system was tested and the results were shown. In the performance evaluation it is demonstrated that the device is capable of nanometer precision over the whole travel range, while also having a minimal power output of less than a microwatt while holding the position.

In the future the system will be investigated regarding the lag of the pneumatic system (concerning tube length and pressure propagation). Currently, the control system is set very conservative. Further tuning and maybe a redesign of the controller structure is needed for a faster response. Additional analysis in the frequency domain may give a profound understanding of the system behavior, especially for the pressure controller.
In the future three of the presented LAUs shall be integrated into the PPS100. Therefore, the mechanical attachment and the connection of all tubes and power lines need to be laid out. A redesign is planned with the focus on improving the dynamics of the pneumatic subsystem. Additionally, the number of wires and tubes con connected to the slider should be reduced, since they might be the cause of a too high disruptive force on the slider.

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REFERENCES

[1] R. Füßl, R. Grünwald, I. Rahneberg and P. Kreutzer „Uncertainty Consideration of the Coordinate System in Nanopositioning- and Nanomeasuring Machines”, Technisches Messen 79, pp. 235–238, 2009.
[2] T. Hausotte, “Nanopositionier- und Nanomessmaschine”, dissertation, Ilmenau, 2002.
[3] B. A. Gozen and O. B. Ozdoganlar, “Design and evaluation of a mechanical nanomanufacturing system for nanomilling“, Precision Engineering 36, Elsevier, pp. 19–30, 2012.
[4] F. G. Balzer, “Entwicklung und Untersuchung zur 3-D-Nanopositioniertechnik in großen Bewegungsbereichen“, dissertation, Ilmenau, 2013.
[5] R. Donker, I. Widdershoven, D. Brouns and H. A. M. Spaan, “Realization Of ISARA 400: A large measurement volume ultra-precision CMM”, ASPE’s Annual Proceedings on Mechanical Metrology and Measurement Uncertainty, ASPE, Eindhoven, 2009.
[6] S. Zschäck, S. Hesse, A. Amthor, M. Katzschmann, C. Schäffel and C. Ament “Vergleich der Scan-Performance bei Nanopositioniersystemen mit großem Bewegungsbereich”, Technisches Messen 81, pp. 335–342, 2014.
[7] O. Dannberg, I. Ortlepp and E. Manske, “FPGA-based Signal Processing of a Heterodyne Interferometer “, 59th Ilmenau Scientific Colloquium, Ilmenau, 2017.

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