6D Planar Magnetic Levitation System - Mag6D

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***Abstract* – The paper describes the structure, the performance and a set of model based design steps of a novel 6 DOF planar magnetic drive system with nanometer positioning accuracy. The movable platform of the system is free of any wiring connection and the upper surface is freely accessible.**

I. INTRODUCTION

The paper describes the structure of a novel 6 DOF planar magnetic drive system with nanometer accuracy. Some details of the model based design are described and a few qualification results are given.

A main advantage of the system is that it uses only six, i.e. the minimum number of sensors and coils to control all six DOFs what keeps the system simple and makes it very effective. Furthermore the measurement system and the actors are completely located below the slider, hence the platform is freely accessible from above.

II. STRUCTURE OF THE SYSTEM

The new developed, magnetically levitated motion system with six degrees of freedom allows a motion of the slider-platform of 100 x 100 mm^2 in x-y-direction and 100 µm in z-direction. Rotation around z-axis is limited by the measurement system to ±0.25°, rotation around x- and y-axis is limited by the geometry of the system to ±100 µrad.

The system is actuated by 3 coil pairs mounted at the stator which interact with 3 Halbach arrays in the moving platform. Using only 3 arrays instead of 4 (see e.g. [4]) minimizes the required components of the system. Furthermore a system with only 3 arrays is smaller and lighter what decreases the power losses and hence the thermal load of the system. The more elaborate commutation can easily be done by the controller. The use of efficient Halbach arrays gives high magnetic field components below the slider reducing the power consumption of the coils and hence the heat generation in the system. Temperature stability is an important requirement for high accurate positioning technology.

The measurement system consist of a compact 6D-measuring head, placed between the coil pairs and a moving grid plate mounted on the bottom side of the slider platform. The planar degrees of freedom (x, y, r_z) are measured by 3 optical sensors which scan the grid. The vertical degrees of freedom (z, r_x, r_y) are determined by 3 pairs of capacitive sensors, which measure the vertical distance to the grid plate. The sensor resolution is in the nanometer and tenth of micro radiant range. A main advantage is the grid plate inside the movable platform. Therefore the sensor system allows the access to all sides of the platform, a requirement in inspection systems. Furthermore the moving platform is completely passive. No cables or other connections between slider and stator which can introduce disturbance forces are needed.

To avoid disturbances on the capacitive sensor values the frequencies of the PWM amplifiers and the measurement frequency of the sensors have to be synchronized.

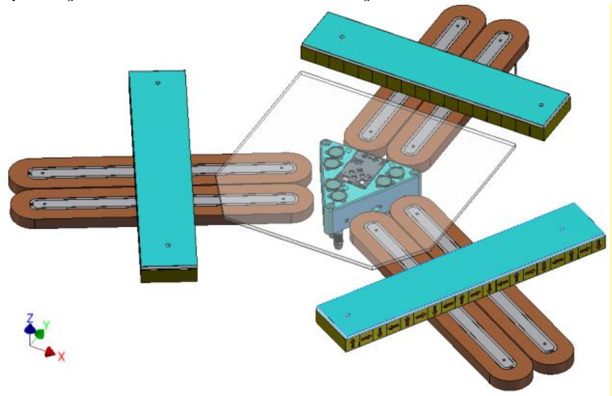

Figure 1. Schematic structure of the Prototype System

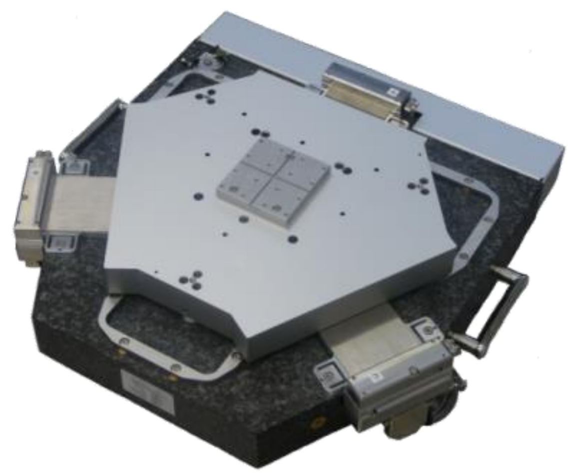

Figure 2. Setup of the Prototype System

III. HALBACH ARRAY CONFIGURATION AND COMMUTATION

Halbach array configurations are known for their high flux density on one side and small stray fields on the opposite side. The high field components below the magnets minimize the power consumption of the coils. Due to that characteristic they were chosen for the setup. The Sm_2Co_{17}-magnets with medium magnetization grade generate a flux density of about 0.5 T below the array. This material is also ultra-high vacuum compatible and can be used in applications that require a strong hydrogen atmosphere. Hence these magnets were used in a first prototype.

Figure 3 shows a schematic of an array with a FEM result. Depending on the coil position with respect to the magnets coil currents generate horizontal and vertical forces. Additional a torsional momentum around an axis perpendicular to the image plane of Figure 3 is generated.

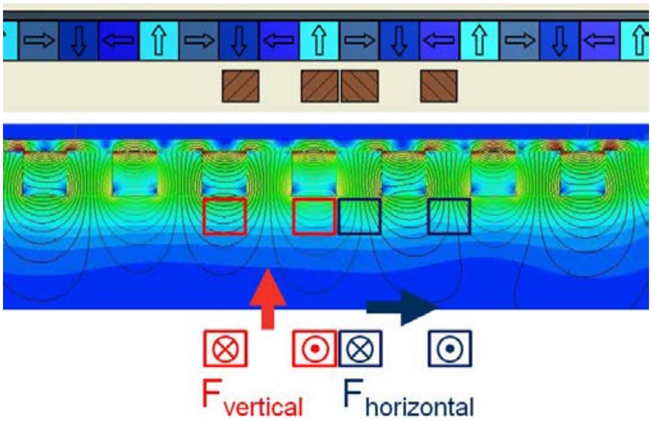

Figure 3. Model of a Halbach array (above) and flux distribution calculated by FEM (below), the sketch shows, how vertical and horizontal forces can be generated by a coil pair

Because no iron material is used in the actuator system no nonlinear effects like hysteresis or saturation occur. Hence the generated forces and momentums depend linear on the coil currents and superposition can be assumed. Figure 4 shows the almost sin/cos-like proportionality factors calculated by FEM.

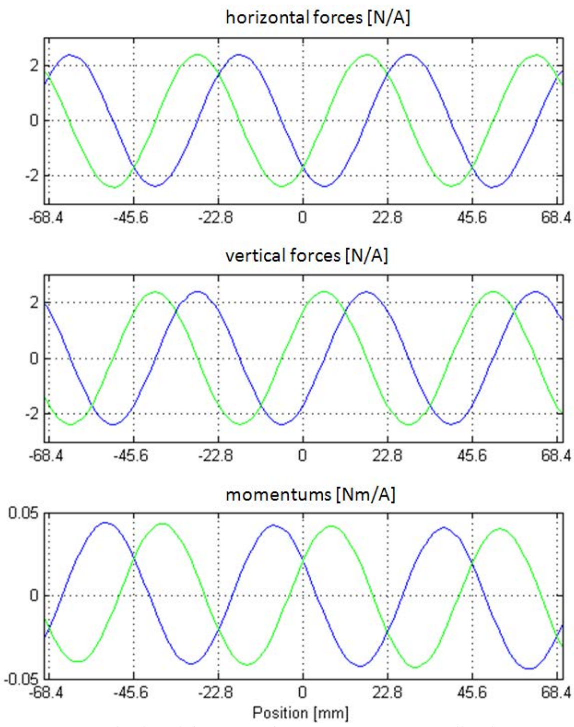

Figure 4. FEM-Calculated forces and momentums at a Halbach array, caused by the left (blue curves) and the right (green curves) coil

Depending on the slider platform position this generated forces and momentums can be transferred into a platform fixed Cartesian coordinate system. Thus the position depending relation K(x,y) between the 6 coil currents $i_1 \ldots i_6$ and the forces F_x, F_y, F_z as well as the momentums M_x, M_y, M_z can be determined.

$$\begin{pmatrix} F_x \\ F_y \\ F_z \\ M_x \\ M_y \\ M_z \end{pmatrix} = K(x,y) \cdot \begin{pmatrix} i_1 \\ i_2 \\ i_3 \\ i_4 \\ i_5 \\ i_6 \end{pmatrix} \tag{1}$$

The (6x6)-Matrix K(x,y) is invertible in the whole travel range and thus forms the basis for the commutation of the coils. With the inverse Matrix $K(x,y)^{-1}$ the force set points, calculated by a controller, can be converted into the set points for coil currents.

These simulation based results were checked by measuring of the magnetic flux density below the Halbach arrays. The horizontal flux component, which generates vertical forces, is shown in Figure 5 and Figure 6. The measured flux densities match well with the simulation results. Close to the Halbach array the horizontal component of the magnetic field shows harmonics of 5th and 9th order. But the coil geometry that is exposed to the magnetic field works like a filter function. Finally the forces are almost sinusoidal as shown in Figure 4.

The final test for simulation accuracy was done by measuring the required coil currents in closed loop mode when the slider levitates at a fixed position. The maximum deviation from the predicted coil currents was less than 2.5 percent. This can be explained by simulation errors, variations of the magnetic properties and unexpected variations of the geometry or mounting of the Halbach arrays. The blue curves in Figure 10 show the errors, caused by these deviations when moving with constant velocity. A system specific correction of the matrix $K(x,y)^{-1}$ can be derived from the deviation between predicted and measured coil currents which minimizes the position errors. The red curves in Figure 10 show the result.

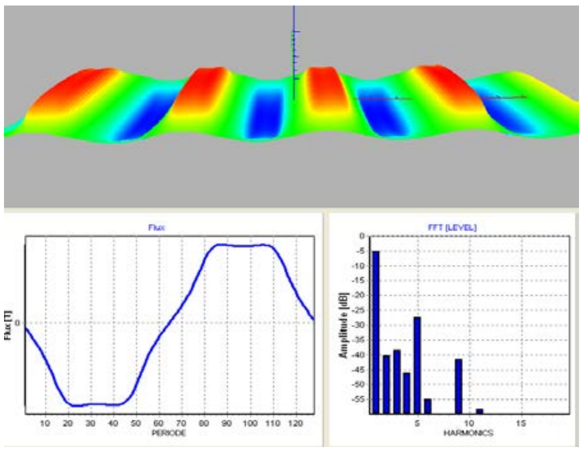

Figure 5. Measured horizontal flux component X, 1 mm below the Halbach array, harmonic distortion of 5th and 9th order

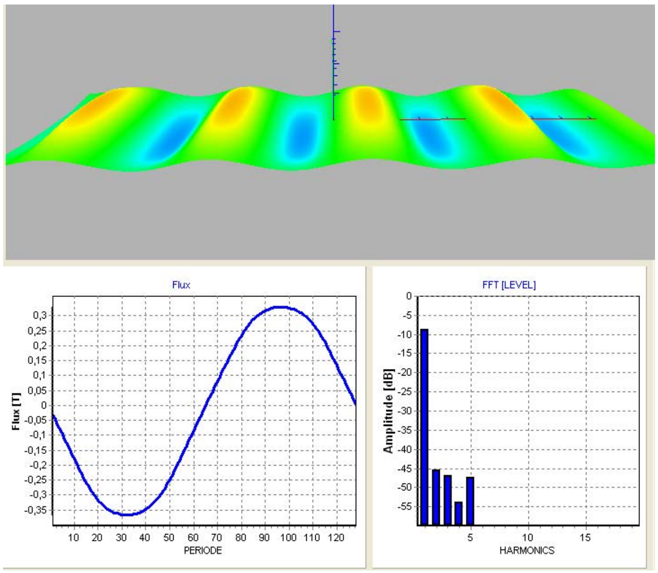

Figure 6. Measured horizontal flux component X, small distortions in 4 mm distance

IV. Thermal Management

Applying forces and momentums generated by the slider platform weight to equation (1) the power losses caused by gravitation can be calculated from the necessary coil currents. Figure 7 shows the result for the first prototype.

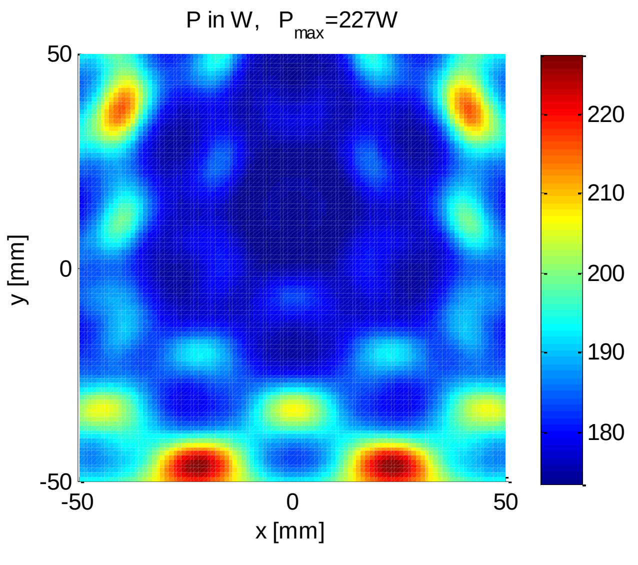

Figure 7. Sum of power losses in all coils to carry the load of 5.3 kg with arrays of SmCo-magnets versus the slider position

For a second prototype with a lighter slider platform and with NdFeB-magnets Figure 8 shows, that the power losses can be considerably reduced to less than 100 W.

Because temperature stability is an important issue for highly accurate positioning technology the coils are equipped with very flat cooling sandwiches based on efficient liquid pipe technology. Thereby the temperature rise on the top of the coil housing remains less than 1.5 K for the first prototype and less than 0.3 K for the second prototype.

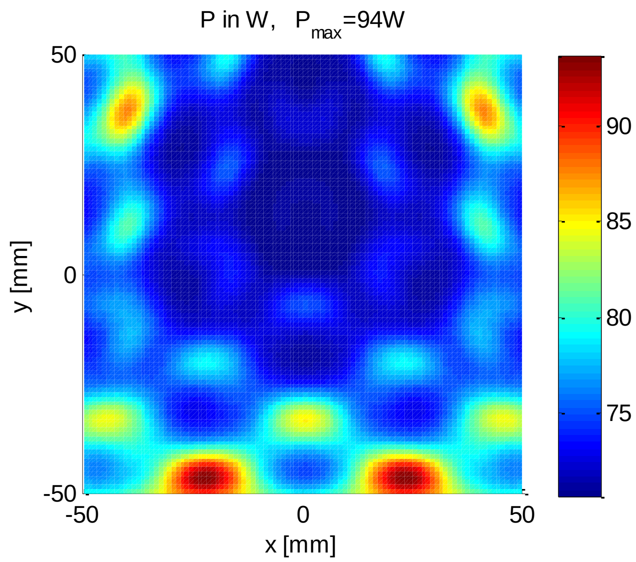

Figure 8. Sum of power losses in all coils to carry the load of 4.2 kg with arrays of NdFeB-magnets versus the slider position

V. Digital Controller

The control for all DOF of the platform is based on PI's digital industrial modular controller concept. The position controller uses six independent servo loops. The position inputs of the servo loops are calculated by a coordinate transformation which transforms the measured sensor values to the DOF-positions. The current set points for the six amplifiers are calculated from the output of the servo loops, using the position dependent commutation matrix $K(x,y)^{-1}$. These set points are input of six PWM current amplifiers.

The real time operating system of the CPU is synchronized by a FPGA interrupt mechanism. The controller runs with a PC-ETX processing module with a servo cycle time of 200 µs. Trajectory generation, simple to use command set and PI's real time interface is implemented. The necessary initialization and shutdown procedures are developed to drive the system in a well-defined starting position or switch it off at the parking position.

An algorithm, which measures the necessary data and calculates the correction for the commutating matrix $K(x,y)^{-1}$ is developed. Hence the correction can be adjusted specifically to every system.

VI. Results

The prototypes show position stability in the resolution of the sensor system. Also for fast dynamic motion sequences tracking errors are in the nm range when using correction matrices to compensate the difference between the FEM based commutation matrix $K(x,y)^{-1}$ and the true relation between forces/momentums and coil currents.

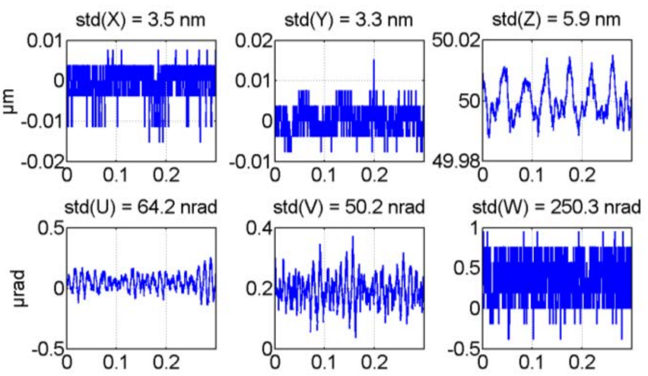

Figure 9. Position stability at position x = y = 0, z = 50 µm; u = v = w = 0

Horizontal movements with 50 mm/s and 2 m/s² are done with a vertical deviation (z) of less than 0.25 µm (see Figure 10 red curves). The difference between the blue and the red curves shows the strong influence of the correction matrices.

The z-curve in Figure 10 still shows a systematic error motion which will be compensated in an updated controller version.

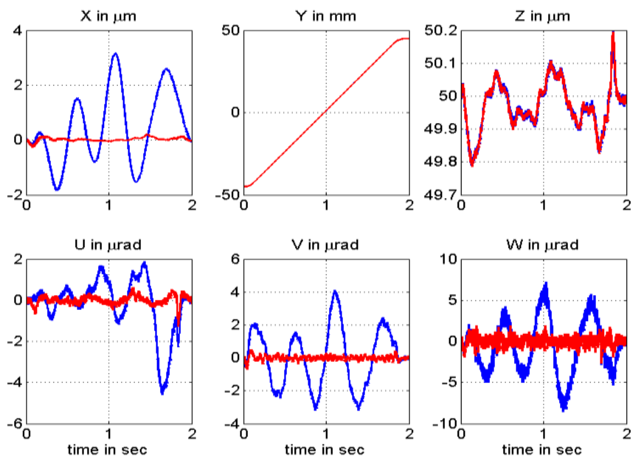

Figure 10 Horizontal movement with 50 mm/s without (blue curves) and with correction matrices (red curves)

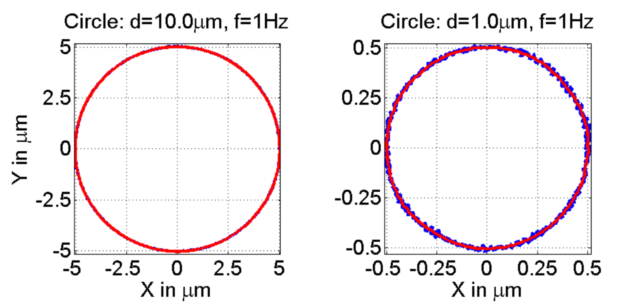

Figure 11. Circular motion in x-y-plane with diameters of d = 10 µm and d = 1 µm, blue curve: measured positions, red curve: low passed positions (f_{Pass} = 50 Hz, f_{Stop} = 100 Hz, Stopband: -40 dB)

Figure 11 shows circular motions of 2 different diameters. There are no hysteresis effects observed. The accuracy is in nanometer level. Due to the z-travel of 100 µm also Helix movements can be performed with some nm-resolution (Figure 12).

The controller setup in the prototype limits the maximum velocity to 100 mm/s at the moment but there are no physical limits caused by the structure.

The high eigenfrequency of the platform assembly of more than 500 Hz allows high control bandwidth. The small noise level of all axes shown in Figure 9 opens the way for further improvements with new high resolution sensor systems in the servo loops.

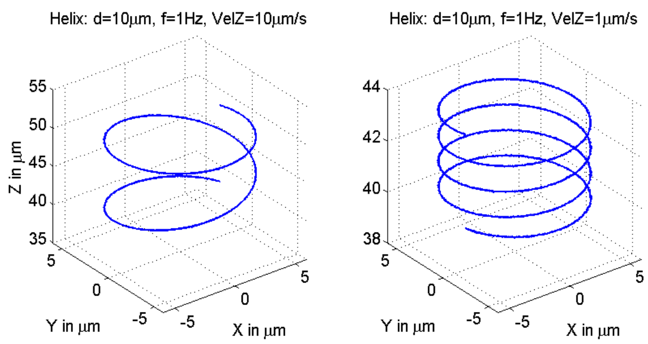

Figure 12. Helix movements with a diameter of 10 µm and a z-velocity of 10 µm/s and 1 µm/s

VII. Conclusion

A prototype of a 6 DOF planar magnetic levitation system with nanometer positioning capability as shown in Figure 2 has been constructed. It comprises an integrated compact 6D sensor and is controlled by PI's modular E-712 digital nanopositioning controller, using precalculated commutation functions for the three coil pairs realizing a smooth path control.

ACKNOWLEDGEMENT

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