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EXPERIMENTAL VERIFICATION OF LOOK-UP TABLE BASED REAL-TIME COMMUTATION OF 6-DOF PLANAR ACTUATORS

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ABSTRACT
The control of contactless magnetically levitated planar actuators with stationary coils, moving magnets and 6-DOF is very complicated. In contradiction to normal synchronous AC machines the forces and torques cannot be decoupled using a sinusoidal commutation scheme. Instead, a feedback linearization law has to be applied as commutation scheme that decouples the forces and torques and calculates the required currents to realize the desired forces and torques of the magnetic suspension.

This feedback linearization law is based on the coupling matrix that links the current in each coil to the force and torque vector on the actuator. The accurate calculation of this coupling matrix in real-time is critical for controlling the planar actuator. In this paper a look-up table based method is used to apply feedback linearization and the performance of the algorithm is verified with measurements.

INTRODUCTION
Usually, high-precision positioning systems with multiple DOF consist of a long-stroke stage with an additional short-stroke stage to achieve submicron accuracy in a large workspace. Cross-talk between the actuators in the system, friction in bearings and cable slabs to the moving parts limit the accuracy of such machines.

Six degree-of-freedom (DOF) synchronous planar actuators with an active magnetic suspension have the potential to combine long-stroke movement and submicron accuracy in one stage. These types of actuators are currently being developed as an alternative for these positioning stages [1-3].

A cable slab to the mover can be made obsolete, if a topology is used with moving magnets and stationary coils as shown in Figure 1, since no power is necessary at the mover. Finally, the mechanical design of such an actuator is much simpler since long and short stroke movements are integrated in a single displacement device.

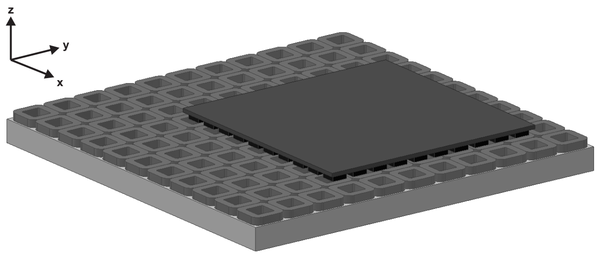

FIGURE 1: Magnetically levitated planar actuator with moving magnets and stationary coils.

The control of such a planar actuator is complicated [4-7] due to the non-linear relationship between the current in each coil and force-torque vector on the moving platform [4,6,7-9]. Another complexity is the over-actuated nature of the system, since there are over eighty coils and only six degrees of freedom, where each coil acts as a single Lorentz actuator. This requires additional constraints in the control law to get a unique solution for the currents in the coils to obtain a certain desired force-torque vector [4,6,7]. Finally, the control currents have to be recalculated every sample time so the commutation algorithm must be accurate but also fast enough to be calculated at closed-loop rates of several kHz [8,9].

By choosing an appropriate mapping between the control currents and the force-torque vector on the magnet array, the first two problems can be addressed [6,7]. Such a mapping needs an accurate calculation of the matrix that couples the currents in the coils to the force-torque vector on the platform. The calculation of the coupling matrix can be done by using simplified models of the real system [8,9].

Another way of calculating the coupling matrix is to use a look-up table. While some effects are hard to include in a simple model (e.g. end-effects), they can be easily included using look-up tables. Since all model calculations are done offline, a very accurate and time consuming model can de used, while accessing a look-up table in real-time is very fast. However, the amount of memory that a look-up table can use is limited. For fast access times to the data in the look-up table, all data should be stored on the onchip cache of the DSP.

Since the planar actuator has a large number of coils, long stroke and multiple DOF, the use of one look-up table is prohibited, due to its extremely large size for a DSP. In addition, the offline computational effort for such a look-up table is enormous, even with the computational power available nowadays. However, look-up tables can be used for the control of such a system if a smart approach is used [11] which keeps the advantages of a look-up table, while keeping its size small enough for DSP-based real-time control.

FORCE AND TORQUE CALCULATION

All forces calculations are based on the Lorentz force, since the planar actuator does not contain any ferromagnetic materials. This is due to the fact that the moving magnet planar actuator is based on repulsive forces between the stationary coils and the moving magnets.

The Lorentz force $\mathbf{F}_c$ on a coil exerted by an external magnetic flux density generated by the magnet array $\mathbf{B}_m$ can be written as:

$$\mathbf{F}_c = \int_{V_c} \mathbf{J} \times \mathbf{B}_m dV_c, \tag{1}$$

where $\mathbf{J}$ is the current density in the coil and V_c is the volume of the coil. The force $\mathbf{F}_m$ and torque $\mathbf{T}_m$ on the magnet array is given by:

$$\mathbf{F}_m = -\int_{V_c} \mathbf{J} \times \mathbf{B}_m dV_c, \tag{2}$$

$$\mathbf{T}_m = -\int_{V_c} \mathbf{r}_{mc} \times \mathbf{J} \times \mathbf{B}_m dV_c, \tag{3}$$

For every volume element dV_c, the torque arm $\mathbf{r}_{mc}$ from the magnet array to the element is different. It is not possible to find an analytical expression for the Lorentz force and Lorentz torque integrals in case of a three-dimensional coil. Nevertheless, it is possible to obtain an analytical solution of the force and torque for a coil is some simplifying assumptions are done. First, the magnetic flux density of the planar actuator can be represented as a sum of spatial harmonics as it is discussed in [8] and [10]. Second, the coil can be modeled as a number of filaments or surfaces, for which it is possible to find an analytical solution for the Lorentz force and Lorentz torque [8].

As can be concluded from the expressions derived in [8], the torque acting on the magnet array depends on two components. The first component can be expressed as the cross-product between a constant torque arm and the force vector, where the torque arm is defined as the vector between the center of mass of the planar actuator and the geometrical center of the coil. The other component does not depend on an arm, but is the result of the force distribution over the coil and the different arm to each coil volume element dV_c.

The analytical expressions provide a good insight in the mechanisms that determine the forces and torques on the planar actuator. However, the simplifying assumptions compromise the accuracy of the model. First of all, only the first spatial harmonic of the planar actuator magnet array can be included if real-time calculation is required. Second, it is not possible to include end-effects, thereby constraining the use of coils on the perimeter of the magnet array. The current in these coils must be forced to zero [7] by using an additional window function in the calculation of the coupling matrix. If the end-effects are included, the coils on the perimeter can be used to control the planar actuator. These coils have the largest arm with respect to the center of the platform, so they can contribute significantly to the applied torque vector.

DERIVATION OF LOOK-UP TABLES FOR THE EXPERIMENTAL SETUP

Using this approach a commutation scheme is derived for a prototype of a planar actuator. The coil and magnet array are shown in Figure 2 and Figure 3, respectively. The magnet array consists of 10 x 10 poles and interacts with a maximum of 81 coils of the 105 coils in the setup at any time. The dimensions of the magnet array and the coils are listed in Table 1.

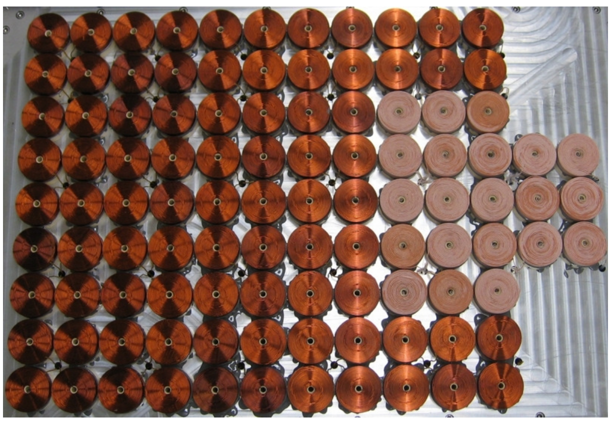

FIGURE 2: Photo of the coil array assembly.

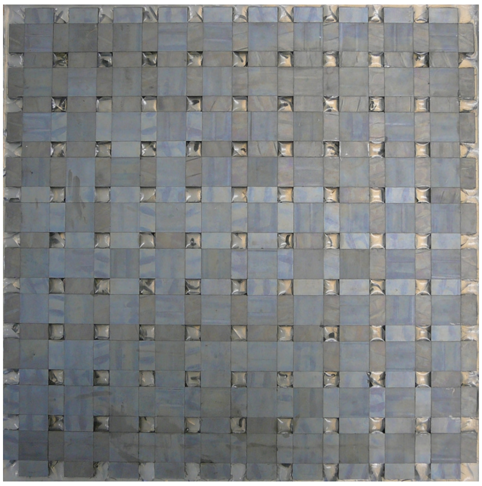

FIGURE 3: Photo of the Halbach magnet array assembly.

TABLE 1: Dimensions of magnet and coil array

Parameter	Symbol	Value	Dimension
Pole pitch	τ	40.0	[mm]
HB magnet width	d	14.0	[mm]
Magnet height	m_h	10.0	[mm]
Coil width	c_w	51.0	[mm]
Coil bundle width	c_{bw}	21.1	[mm]
Coil bundle height	c_{bh}	11.4	[mm]
Airgap	g	2.0	[mm]

The look-up table method [11] is based on symmetries in the magnetic field density underneath the magnet array. To show the symmetry, the forces K_F and torques K_T per Ampere-turn for a single coil are calculated. The torque look-up table term K_T is the part of the torque vector that depends on the volume integral and is defined as:

$$K_T = K_{T_{real}} - \mathbf{r} \times K_F, \tag{4}$$

The coil is moved over a distance of 2τ in the plane underneath the magnet array, where the initial position is shown in Figure 4 and the movement directions are indicated by the two arrows. The center of the top-left magnet is defined as the origin of the coordinate-system. The values of K_F and K_T are shown in Figure 5 and from this figure it is very clear that the values are repeating itself every pole pitch. It is also visible that the round coils do not have any volume dependent term for K_{Tz}, which means that the torque around the z-axis only depends on the cross product of a fixed arm and the force vector. As described in [11], similar plots can be drawn for the end-effects at the sides and at the corners.

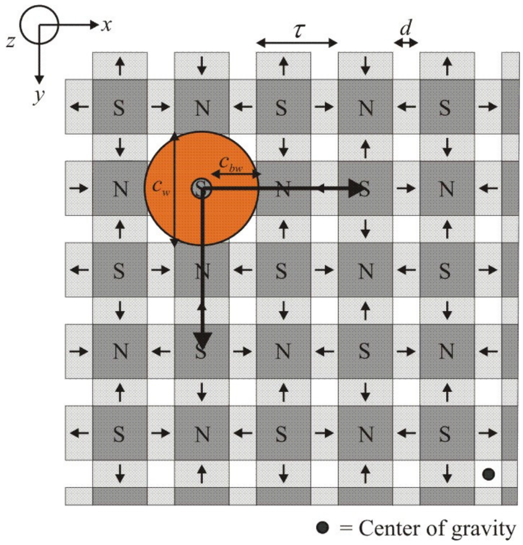

FIGURE 4: Halbach magnet array with a single coil

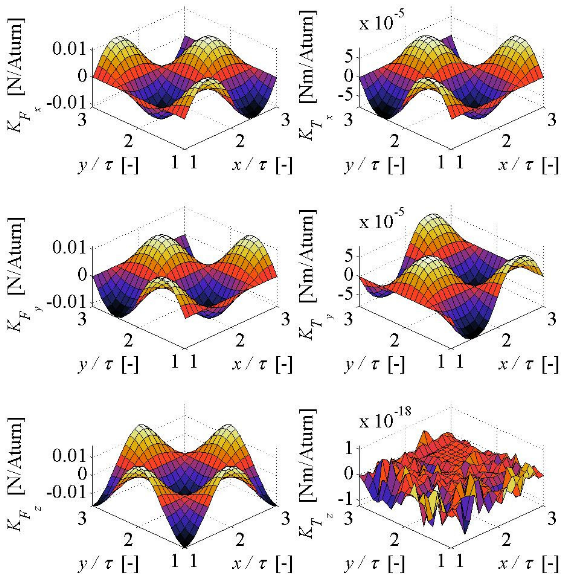

FIGURE 5: Plot of the x-, y- and z-components of K_F and K_T for different positions underneath the Halbach array.

The behavior of all coils can be deduced from three sets of look-up tables. There is one set for coils completely underneath the magnet array (${}^{c}K_{F,T}$), a set for coils at the side (${}^{t}K_{F,T}$) and finally a set for coils at the corner (${}^{tl}K_{F,T}$). The area at which the values are calculated is shown in Figure 6, as well as the areas where the sets are used. The look-up tables have a resolution of 0.5 mm in the x- and y-direction and are 2D. The z-dependency is included using a polynomial fit of the field strength as function of the airgap. Since the variation in height is only 2 mm this method does not introduce significant errors [11].

The commutation scheme includes all end-effects and can calculate the currents for all 81 coils within 104 µs, according to a dSpace benchmark test using a DS1005 1 GHz processor.

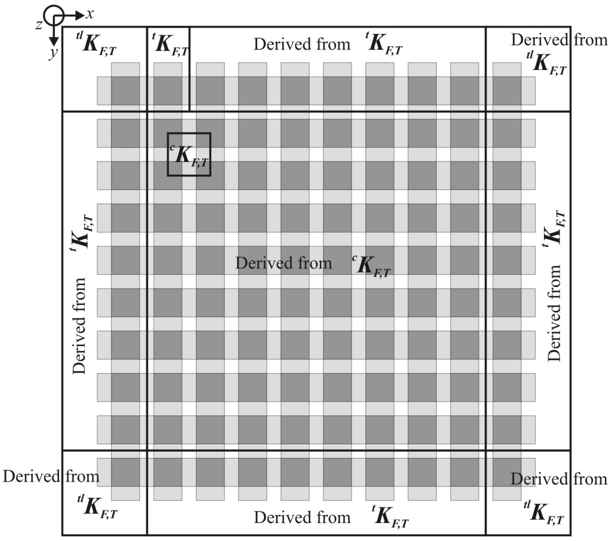

FIGURE 6: Look-up table sections

EXPERIMENTAL VERIFICATION

The commutation is verified by mounting the magnet array on a 6-DOF Force/Torque (FT) sensor that is fixed in a *x*-*y* robot. The robot moves the magnet array over the coil array while the commutation algorithm calculates the currents that are necessary to realize the desired forces and torques. The measured forces and torques at different positions above the coil array are compared with the desired values to verify the performance of the commutation algorithm.

In Figure 7, a photo of the experimental setup is shown with the relevant parts. All coils are embedded in resin to create a smooth surface, so they are not visible as in Figure 2, which was made before casting.

The magnet plate is moved within the workspace (200 x 80 mm) to 1071 grid points that are spaced 4 mm apart. At every position two measurements are done. First, a zero measurement is done, i.e. the reading of the 6-DOF FT sensor is measured with a zero current setpoint to all coil amplifiers. Second, the current setpoints are sent to the amplifiers to create 50 N in all three directions and zero torque around the three axes. Both the zero measurement and the load measurement are done for half a second with a sample time of 330 microseconds and then the mean of each period is used as the measured value. The magnet plate is kept at the same position by the *x*-*y* robot during this process. Then the robot moves the magnet plate to the next grid point, where the process is repeated. The measured forces and torques by the 6-DOF FT sensor are shown in Figure 8 and Figure 9, respectively.

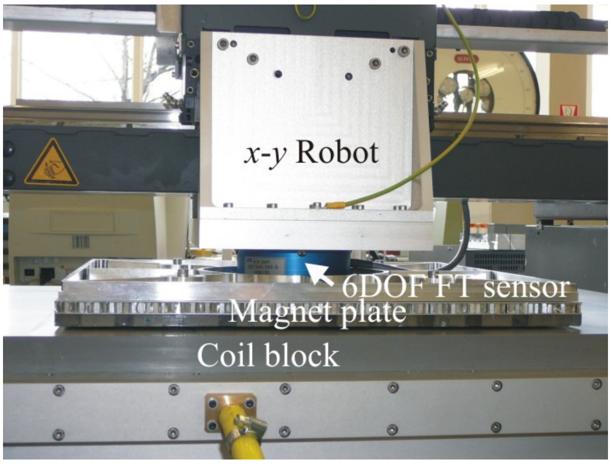

FIGURE 7: Experimental setup.

DISCUSSION

As is clear from Figures 8 and 9, the commutation algorithm is capable of calculating the currents necessary to realize the desired forces and torques on the magnet array with an accuracy of ca. 3%. In addition, some variation is visible in the surfaces that are fitted through the measurement points. These variations show some periodicity, which is related to the spacing of the coils. Both in *x*- and *y*-direction, the coils are space 53.33 mm apart and the variation of the errors is related to this distance.

The errors have several causes, which are:

1. Mechanical tolerances of the coils. The standard deviations of the coil height, coil inner diameter and coil outer diameter are 52 µm, 12 µm and 409 µm, respectively.
2. Mechanical tolerances of the magnet plate. The magnets are 50 µm accurate and the plate is about 100 µm deformed due to the gravity and forces between the magnets.
3. The magnetization of the magnets is not perfectly uniform and the magnetization vector is not completely perpendicular to the magnet surface.
4. The alignment of the coordinate systems of the robot, the magnet plate, the coil block and the 6-DOF FT sensor is not perfect.

All these factors contribute to the errors, so it is hard to distinguish which effect is dominant.

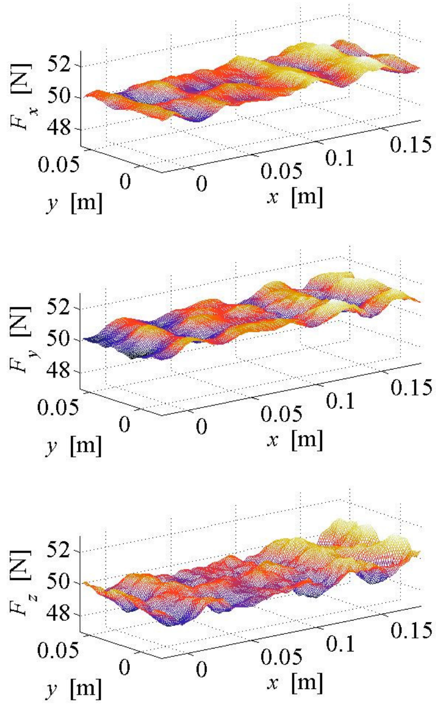

FIGURE 8: Measured forces on the magnet plate.

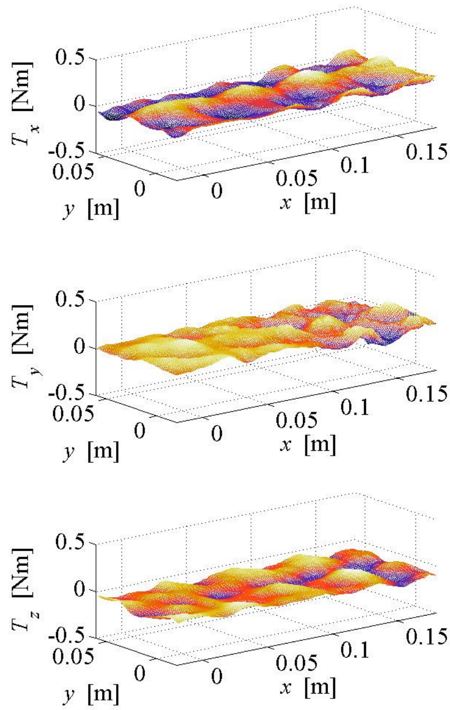

FIGURE 9: Measured torques on the magnet plate.

CLOSED LOOP CONTROL

Now the commutation has been verified the planar actuator can be put in a closed loop control system. The position and orientation of the magnet array is measured using eddy-current sensors. The mass of the planar actuator is 13.7 kg, of which 11.7 kg are magnets. The other 2 kg is aluminum honeycomb material that is used to provide mechanical support.

Six SISO PD position controllers with a 10 Hz bandwidth are applied for each DOF of the planar actuator. A MIMO control is not required since the commutation algorithm provides feedback linearization. To investigate the accuracy and quality of the decoupling, a step of 0.1 mm is applied in the x-direction, while the errors and controller outputs for all six DOF are monitored. In Figure 10 the response in x-direction is shown and the errors of all other DOF. The corresponding force and torque outputs of the controllers are shown in Figure 11.

The errors show that there is cross-coupling between the degrees of freedom but it is limited. In addition, it is visible that there is a position dependent force ripple, since the static errors depend on the x-position, which is clearly visible for z and the rotation around the x-axis, θ.

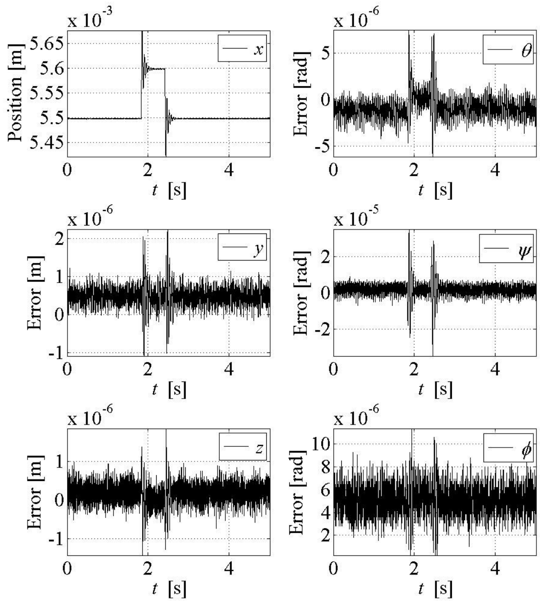

FIGURE 10: System response of the planar actuator on a 0.1 mm step in x-direction.

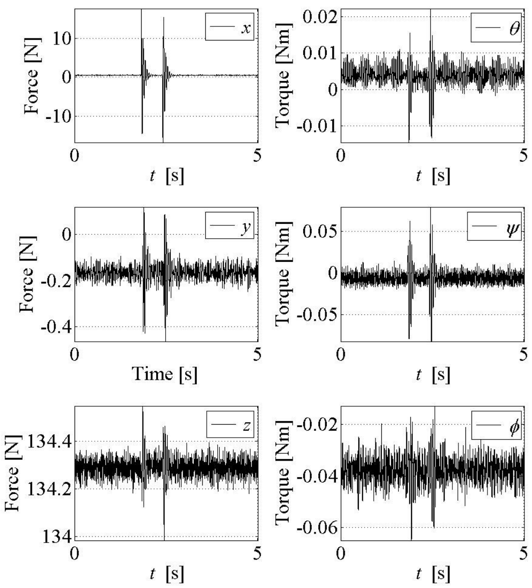

FIGURE 11: Controller output for each DOF of the planar actuator during a 0.1 mm step in *x*-direction.

The errors are nevertheless in the sensor noise, which is less than 1 μm RMS and several μrad RMS.

The *x*-controller outputs a peak force of almost 20 N, but the reaction in *y*- and *z*-direction are about 0.2 N, which shows that the cross-coupling is about 1%. The torques are small, considering that the planar actuator measures 425 x 425 mm and has a mass of 13.7 kg.

CONCLUSION

A look-up table based commutation algorithm for the decoupling of forces and torques on a 6-DOF magnetically levitated contactless planar actuator with moving magnets is presented that includes end-effects. The method is verified with measurements and can realize the desired forces and torques within an accuracy of 3%. Finally, the behavior of the planar actuator with this commutation algorithm is demonstrated in closed loop control.

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