Control of a Compact Electrodynamic Planar Actuator

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Abstract:
Planar motions for future small machine tools and for automation with strokes up to approximately 20 × 20 mm² can advantageously be realised with electrodynamic planar direct drives. Integration of the position control and power electronics thereby results in particularly compact devices. In this contribution, the design and characteristic of a built demonstrator of such a novel drive unit are shortly described in the beginning. It features a medium precision, low-cost position sensor system. A mathematical model for the planar direct drive is shown. A flatness based state space controller for transition between desired rest positions has been developed. Finally the achieved dynamics and accuracy are shown.

Keywords: Planar Direct Drive, 3 DOF Position Control, Flatness-based Control, Feedback Control

Introduction

Planar direct drives for two (x, y) or three (x, y, φ) DOF enable dynamic positioning of work elements or workpieces in handling, machining, assembling and additional fields of applications. With proper design, those direct drives can be compact, simple in structure, easy to manufacture and low-cost. In contrast to widespread x-y planar stages with serial arrangement of two stiff lead screw linear actuators however, the mover position must be actively controlled due to missing stiffness in de-energized state.

Within a research program on components for future small machine tools [1], a novel electrodynamic planar direct drive has been developed at Technische Universität Dresden (Fig. 1). It has a travel area of 20 × 20 mm², a maximum rotation of ± 11° and peak forces of ± 72 N. The aimed position accuracy is about 10 µm. It consists of four independent windings with iron core in a stator and permanent magnets with back iron in a mover. Low-cost linear position sensors for measurement of the positions x and y and the orientation φ of the mover are integrated into the actuator. Integration of a microcontroller board for embedded position control is work in progress. The overall design and the subsystems of that planar actuator are described in [2]. The following sections will focus on position control of the developed actuator.

Actuator Setup

Basically, the planar actuator consists of four independent single-phase moving-magnet actuators. Each of the four windings comprises a U-shaped iron core with two poles that interact with the belonging rare-earth permanent magnet in the mover [2]. This magnetic design enables for high thrust forces at little ohmic losses due to small air gaps and large winding cross-section areas. Nonlinearities in the force-position-current characteristic of each individual actuator are moderate (Fig. 2).

In most planar direct drives described in the literature [3-6], the mover is either guided by air bearings or magnetically levitated. In contrast to this, the first prototype of the novel planar drive has a simple, small and low-cost planar ball guide. It is biased by the permanent magnetic attraction forces between stator and mover.

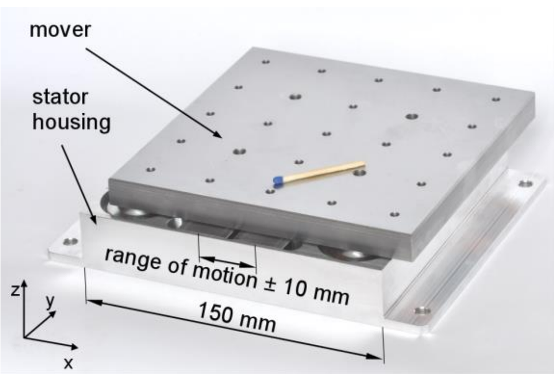

Fig. 1: *Prototype of a novel electrodynamic planar drive (maximum rotation of mover ± 11°)*

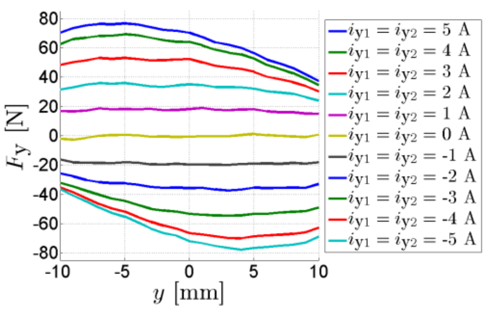

Fig. 2: *Measured force-position-current characteristic of the planar direct drive in y-direction at lateral mid position (x = 0 mm)*

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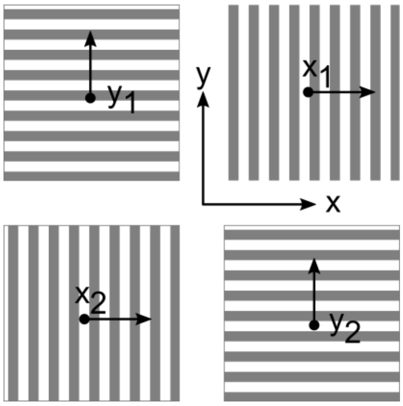

Fig. 3: *Schematic layout of the linear encoder strips and the position sensor setup*

Four optical incremental linear encoders, of which the minimum number of three at present is evaluated for determination of the positions x and y and the orientation φ of the mover, are integrated into the planar drive. The translational resolution is 1.25 µm. The orientation φ is computed from the difference of the positions of the two sensors for y direction:

$$\varphi = \arctan\left(\frac{y_2 - y_1}{b}\right) \quad , \ b = 30\,\mathrm{mm} \qquad (1)$$

where b is the distance between these two sensors. Additionally all four winding currents can be measured with a resolution of $\Delta i = 1{,}678$ mA. The velocities of in all three coordinates are computed numerically. The coil currents of max. ± 3 A are each set by a PWM-switched current amplifier with 20 kHz. Due to eddy currents the current ripple is far higher than anticipated which translates into a noisy current measurement.

The mover is made of a steel plate with overall dimensions of $150 \times 150 \ \times 15$ mm³. The total weight of the mover assembly is approximately 1.5 kg.

Mathematical Model of the Planar Drive

Fig. 4 shows the forces acting on the mover which are generated by the the four linear motors and named F_{x1}, F_{x2}, F_{y1} and F_{y2} respectively. φ denotes the rotation of the mover around the z-axis. Assume that φ is very small and the influence of the rotational motion on the electromagnetic characteristics of the planar direct drive can be neglected [7]. Under this assumption the thrust forces of F_{x1} and F_{x2} can be regarded as parallel with the direction x and the thrust forces of F_{y1} and F_{y2} parallel with the direction y. For that reason the simplified equations of motion for the mover can be expressed as follows:

$$m\ddot{x} = F_{\mathrm{x1}} + F_{\mathrm{x2}} - d\dot{x} - cx \qquad (2a)$$

$$m\ddot{y} = F_{\mathrm{y1}} + F_{\mathrm{y2}} - d\dot{y} - cy \qquad (2b)$$

$$J\ddot{\varphi} = \left(-F_{\mathrm{x1}} + F_{\mathrm{x2}} - F_{\mathrm{y1}} + F_{\mathrm{y2}}\right)l_{\mathrm{x}} - \bar{d}\dot{\varphi} - \bar{c}\varphi \qquad (2c)$$

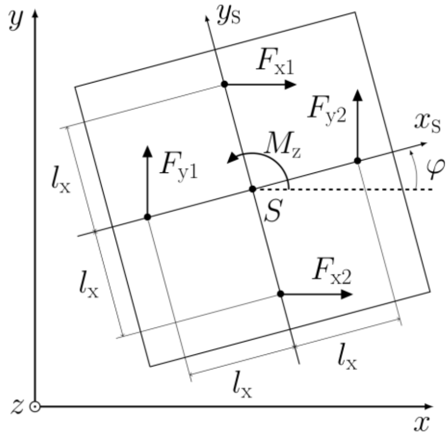

Fig. 4: *Thrust forces acting on the mover and coordinate system (S…center of mass)*

where m is the mass of the mover, J the moment of inertia, l_{x} the distance between the coils and the stage center, c and $\bar{c}$ the spring constants and d and $\bar{d}$ the damping coefficients for translation and rotation respectively.

The electrodynamic thrust force of each of the four independent actuators is roughly proportional to the current applied to it:

$$F_i = k_i \cdot i_i \ , i = \mathrm{x1, x2, y1, y2}\ , \qquad (1)$$

where k denotes the thrust constant and i the current.

Introduction of Virtual Inputs

The introduction of the virtual inputs i_{x}, i_{y} and i_{φ}

$$\begin{pmatrix} i_{\mathrm{x}} \\ i_{\mathrm{y}} \\ i_{\varphi} \end{pmatrix} = \begin{pmatrix} 1 & 1 & 0 & 0 \\ 0 & 0 & 1 & 1 \\ -1 & 1 & -1 & 1 \end{pmatrix} \begin{pmatrix} i_{\mathrm{x1}} \\ i_{\mathrm{x2}} \\ i_{\mathrm{y1}} \\ i_{\mathrm{y2}} \end{pmatrix} \qquad (3)$$

allows the decoupling of a planar stage. Intuitively the planar direct drive can be regarded as three independent linear motors each described by the following state space representation

$$\frac{\mathrm{d}}{\mathrm{d}t}\begin{pmatrix} x \\ \dot{x} \\ i \end{pmatrix} = \begin{pmatrix} 0 & 1 & 0 \\ -\frac{c}{m} & -\frac{d}{m} & \frac{k}{m} \\ 0 & -\frac{k}{L} & -\frac{R}{L} \end{pmatrix} \begin{pmatrix} x \\ \dot{x} \\ i \end{pmatrix} + \begin{pmatrix} 0 \\ 0 \\ \frac{1}{L} \end{pmatrix} u \qquad (4a)$$

$$y = \begin{pmatrix} 1 & 0 & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} x \\ \dot{x} \\ i \end{pmatrix} \qquad (4b)$$

as discussed in multiple publications e.g. [3-6].

Flatness Based Position Control

Differential flatness has been introduced in [8] as a property of nonlinear systems. For linear systems flatness is also an interesting characteristic because flatness equals controllability of linear systems. It can easily be demonstrated that the flat output for the planar drive is $\mathrm{y} = (\mathrm{x} \quad \mathrm{y} \quad \varphi)^{\mathrm{T}}$. With the help of a flat input and a plant model one can generate flat reference trajectories for a transition between two rest positions. For the developed planar actuator polynomials are used as shape function since they are computationally simple and are able to approximate any given function on a bounded interval. Furthermore the trajectories for the components of the flat output, i. e. for each of the three directions, can be designed individually [9].

Assuming that at time $t = 0$ with $x(t = 0) = x_0$ a new trajectory planning starts and the desired end position is $x(t = \tau) = x_\tau$ the boundary constraints

$$\begin{array}{ll} y_1(0) = x_0 & y_1(\tau) = x_\tau \\ \dot{y}_1(0) = \ 0 & \dot{y}_1(\tau) = \ 0 \\ \ddot{y}_1(0) = \ 0 & \ddot{y}_1(\tau) = \ 0 \\ \dddot{y}_1(0) = \ 0 & \dddot{y}_1(\tau) = \ 0 \end{array} \tag{5}$$

can be applied to the trajectory y_1 which describes the movement in x-direction. For simplicity a seventh order polynomial has been chosen which can meet all of these requirements.

State Space Controller

Flatness based feed forward control provides set point values for position, velocity, acceleration, current and voltage along the desired trajectory. A state space controller

$$\boldsymbol{u} = -\boldsymbol{K} \cdot \boldsymbol{x} \tag{6}$$

with the constant gain matrix K is used to diminish the error between the measured outputs and the references. It compensates for model indeterminacies and disturbances. By augmenting the system model with an integrator it is possible to compute the augmented state feedback

$$\boldsymbol{u} = -(\boldsymbol{K} \quad \boldsymbol{K}_{\mathrm{I}}) \cdot \begin{pmatrix} \boldsymbol{x} \\ \boldsymbol{x}_{\mathrm{I}} \end{pmatrix} \tag{7}$$

using established design techniques like pole placement or optimal control. These methods yield the constant gain matrix K and the integral gain KI. Fig. 5 shows the block diagram of the developed control structure.

Several parameterizations of the augmented state space controller have been tested. The optimal control design with the cost function

$$J = \int_0^\infty (\boldsymbol{x}^{\mathrm{T}}\boldsymbol{Q}\boldsymbol{x} + \boldsymbol{u}^{\mathrm{T}}\boldsymbol{R}\boldsymbol{u})\mathrm{d}t \tag{6}$$

tends to be more robust and attenuates better the natural frequency of the plant. As a starting point Brysons Rule [10] was used which makes the matrices $\boldsymbol{Q}$ and $\boldsymbol{R}$ diagonal. The diagonal entries are selected that a fixed percentage change of each variable makes an equal contribution to the cost J. After that the weightings of the positions and velocities were increased until the desired transient response was achieved. Fig. 6 displays the exemplary position transition in x-direction. The achieved dynamics are good, however, the average settling time for a position accuracy of 10 µm of 3.5 s is too high. Moreover the mover tends to oscillate.

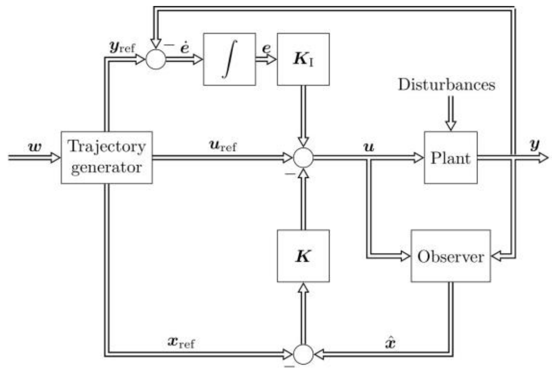

Fig. 5: *Block diagram of the flatness based augmented state space controller*

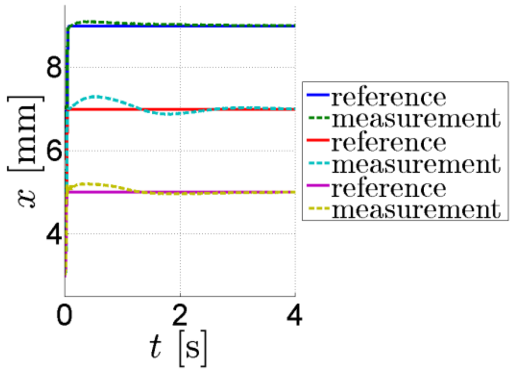

Fig. 6: *Position transition in x-direction using a LQ-regulator and feed forward control, center position for lateral direction y=0 mm*

Preliminary Technical Data

The main features of the presented actuator are:

- stroke ± 10 mm = 20 mm,
- continuous force ± 20 N, related continuous current 1.2 A,
- peak forces ± 72 N , related peak current 5 A,
- winding resistance 5 Ω,
- winding inductance 40 mH,
- electrical time constant 6,7 ms,
- mechanical time constant 444 ms
- mover weight 1.5 kg.

Summary and Future Work

Flatness based position control has been implemented and successfully tested with a specifically developed microcontroller and PWM driver hardware. Reference trajectories for the three coordinates x, y and φ can be designed individually. The presented planar direct drive exhibits good dynamics though the settling time until the steady state error is compensated is still high. Characterisation and optimisation of the different controller variants have not yet been completed but the performance achieved so far is promising.

The absolute accuracy has not been quantified so far but those measurements are planned for future work. Minor improvements on the prototype are to be expected with a redesign. A weight-reduced mover with a total weight of 1.2 kg is currently manufactured. Reluctance forces of a few Newtons observed with the present mover made completely of steel will be eliminated with the re-designed mover.

The implementation of the control methods on a 32-bit microcontroller has been proven difficult due to limited computing performance. Further optimization aims for a shorter control cycle to diminish quantization effects. For the same reason observer designs tested so far have not delivered proper state estimations. Nonlinear control schemes are subject to current investigations.

Future work will also focus on reduction of overshoot and settling time. Furthermore the angular measurement needs to be improved due to drift problems. Different or additional position sensors could enhance measurement and positioning accuracy.

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