Novel Electrodynamic Feed Units for Small Machine Tools and Automation

Thomas Bödrich, Johannes Ziske, Markus Stock and Jens Lienig

Abstract Short travel ranges up to approx. 25 mm as in future small machine tools enable linear direct drives with simple single-phase design. Especially designs with moving magnet(s) and an iron core stator winding allow for large actuator constants, i.e. high forces at little losses and small volume. Different types of those compact, dynamic and cost-effective linear axes and tables as well as a novel planar direct drive have been developed, built and tested. They feature integrated ball or flexure guides, integrated incremental or absolute position sensors with resolutions from 0.16 to 1.25 μm, embedded flatness-based position control, sensorless force control and various control interfaces. Selected prototypes and their features are presented.
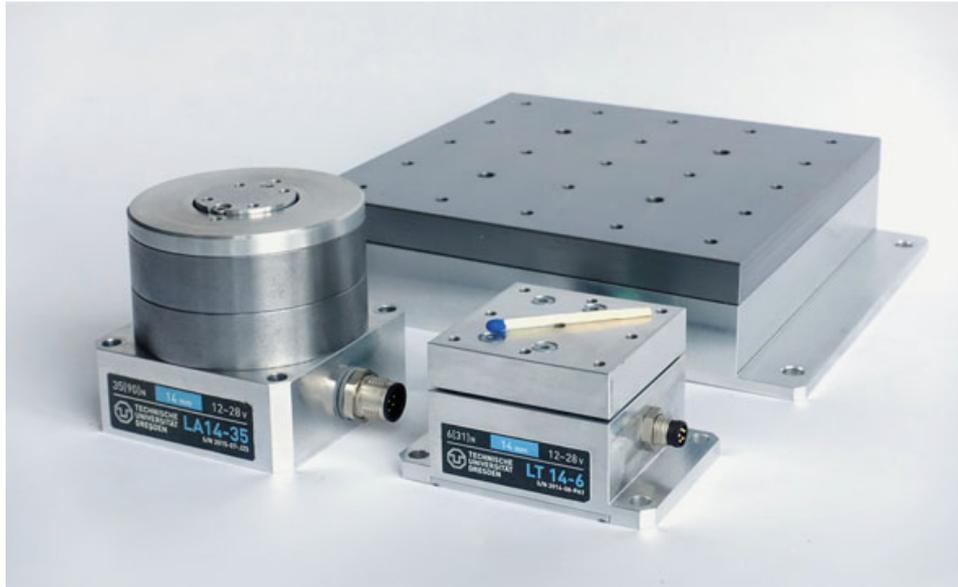
1 Introduction

Small feed motions in the mm and cm range today are often realised with miniaturised lead screw motor systems, allowing feed rates of only a few mm/s with typical reduction gears and screw pitches between 0.4 and 1 mm. Different types of piezo stages are available too for small feed motions, e.g. piezo stack actuators with forces in the kN range and limited strokes up to a few hundred μm [1] or piezo stepping motors with forces up to approx. 800 N and velocities of a few mm/s. For fast servo tools and diamond turning processes, voice-coil motors with strokes in the mm range are used [2]. All of the above-mentioned feed drives are either limited in stroke or in dynamics.

Small working spaces of future small machine tools of only a few cm³ enable unique technical solutions for dynamic feed drives that are not just derived by down-

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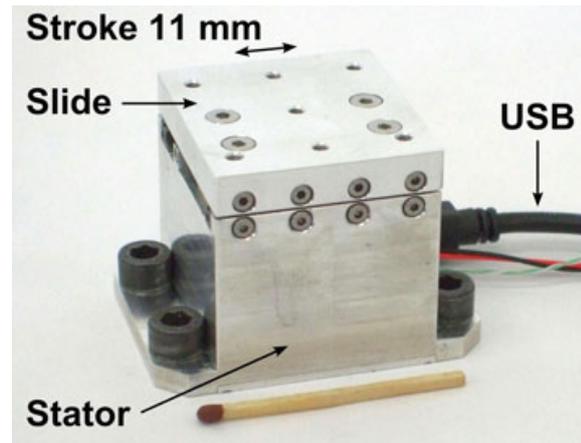e-mail: Thomas.Boedrich@tu-dresden.de

Fig. 1 Family of novel compact moving-magnet linear and planar direct drives for short strokes developed for small machine tools and automation
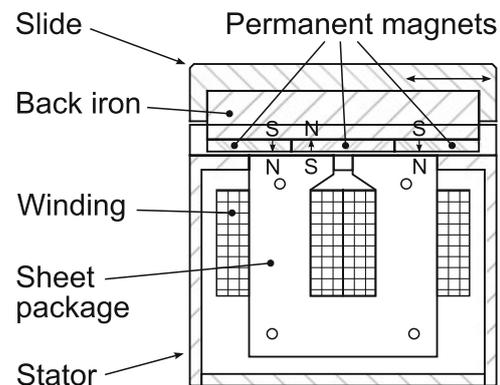
sizing of conventional machine tools [3, 4]. In large machine tools, three-phase linear motors are well-established as highly dynamic direct feed drives [5]. Small travel ranges up to approx. 25 mm in contrast allow for simple single-phase linear direct drives. Especially motor designs with moving permanent magnet(s) and a single-phase iron core winding in the stator offer high compactness, good dynamic behaviour and large volume-based actuator constants [6]. Despite those attractive properties, this motor concept is rarely used for precise positioning up to now. In addition to the single-phase design, the limited stroke allows for flexure guides that avoid stick-slip, backlash, wear and lubrication. Due to their simplicity all subsystems of those feed units, i.e. magnetic circuit, guide system, position sensor, control hardware and firmware can be combined to very compact modules. A variety of different prototypes of such translatory feed units and a novel planar direct drive have been developed within the Priority Programme SPP1476 "Small machine tools for small workpieces" (Fig. 1).

Beside compactness, design focus was on low to moderate costs for the complete feed units in order to foster their later utilisation. For that reason low-cost miniature position sensors with resolutions in the sub-µm range have been integrated into the drive units, resulting in positioning accuracies of a few µm. Higher accuracies can be achieved with different, but larger and more expensive position sensors, if needed.

Fig. 2 First prototype of a novel single-phase moving-magnet linear table with embedded control [8]

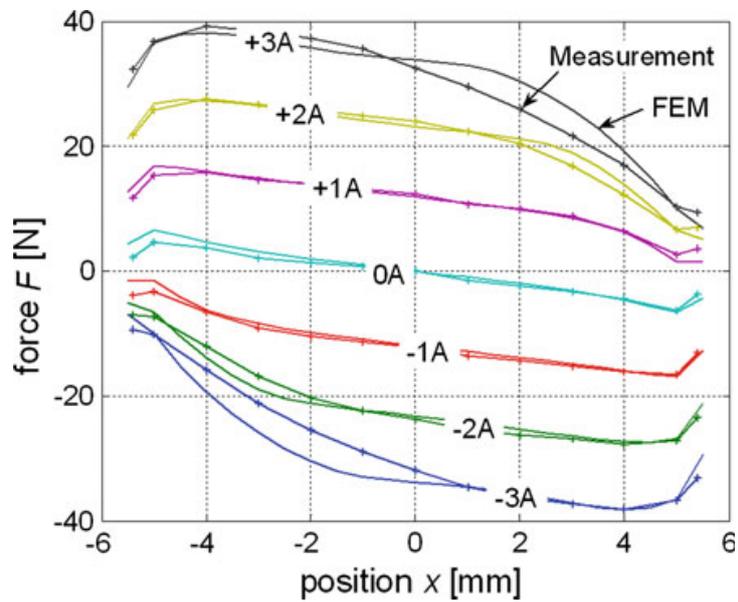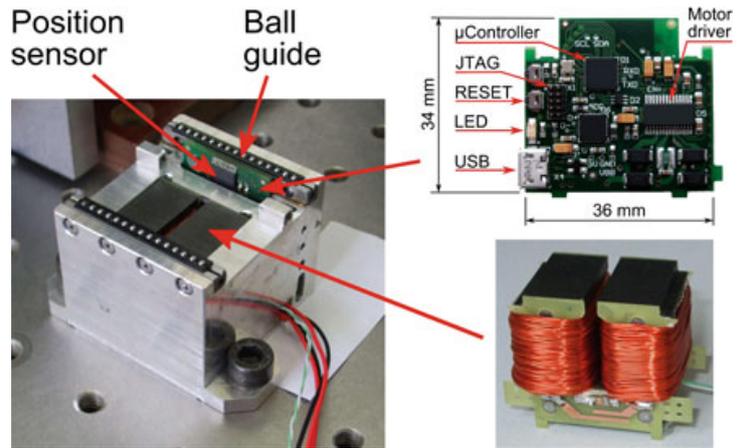**Fig. 3** Schematic cross-sectional view of the linear table shown in Fig. 2 [6]

2 Linear Tables

A first linear table that has been developed based on the above-mentioned single-phase moving-magnet concept is shown in Fig. 2 [6–8]. The stator contains a U-shaped, laminated sheet package with a single-phase winding (Fig. 3). Design of the magnetic circuit with magnetic network models and FEM is explained in [8]. The strong lateral magnetic attraction forces between mover and stator of approx. 180 N without current are utilised for a simple open ball guide that needs no adjustment during assembling (Fig. 4).
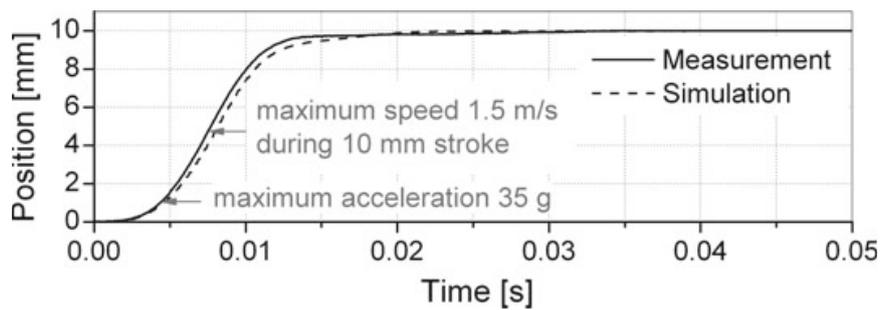
With a travel range of 11 mm, a peak force of 39 N (Fig. 5), an integrated low-cost position sensor (resolution $0.49\,\mu$m), embedded state space position control [9] and a USB interface, this miniature linear table features attractive properties. A two-sided repeatability of $3\,\mu$m, a positioning accuracy of $5\,\mu$m and accelerations up to 35 g during position controlled operation (Fig. 6) have been achieved with this module.

In a redesign process an improved prototype of a moving-magnet linear table has been realised (Fig. 7). Its integrated control electronics features an absolute magnetic position sensor with an interpolated resolution of $0.16\,\mu$m and CAN hardware for implementation of a CAN interface.

Fig. 4 Stator components of the linear table shown in Fig. 2 [6]

Fig. 5 Force position current characteristic of the linear table shown in Fig. 2 [6]

Fig. 6 Controlled response of the linear table to a 10 mm step of the set position [6]

Fig. 7 Redesigned moving-magnet linear table: travel range 14 mm, nominal/peak force $\pm 6/\pm 31$ N, integrated absolute position sensor with $0.16\,\mu$m resolution, intetrated control electronics with CAN hardware for implementation of CAN interface

Fig. 8 Prototype of a flexure-guided linear actuator [10]
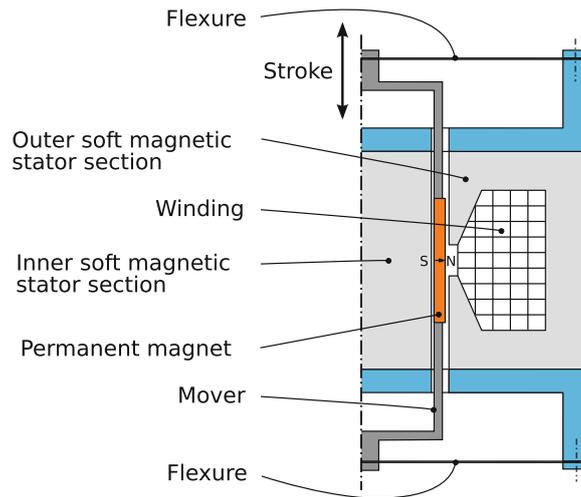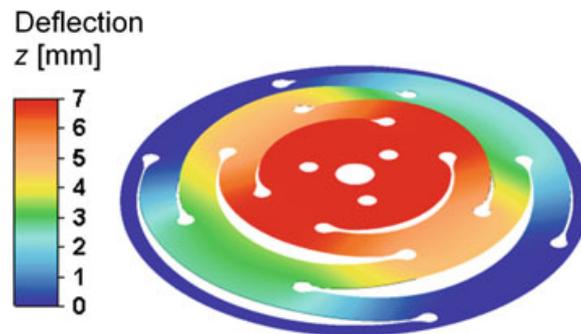
3 Cylindrical Linear Axes

In cylindrical linear actuators with axisymmetrical magnetic design lateral, i.e. radial magnetic forces as present in linear tables compensate along the circumference. This enables utilisation of flexures for guidance of the moving part.

3.1 Linear Actuator with Flexure Guide

Flexure guides operate without stick-slip, backlash and almost without wear and hence are well-suited for positioning in applications requiring high precision, long lifetime or lubricant-free operation (e.g. in cleanroom or vacuum). A developed prototype of a single-phase moving-magnet actuator with flexure guide is shown in Fig. 8 [6, 10, 11]. It consists of a tubular mover with radially polarised permanent magnets between two magnetically soft stator components (Fig. 9).
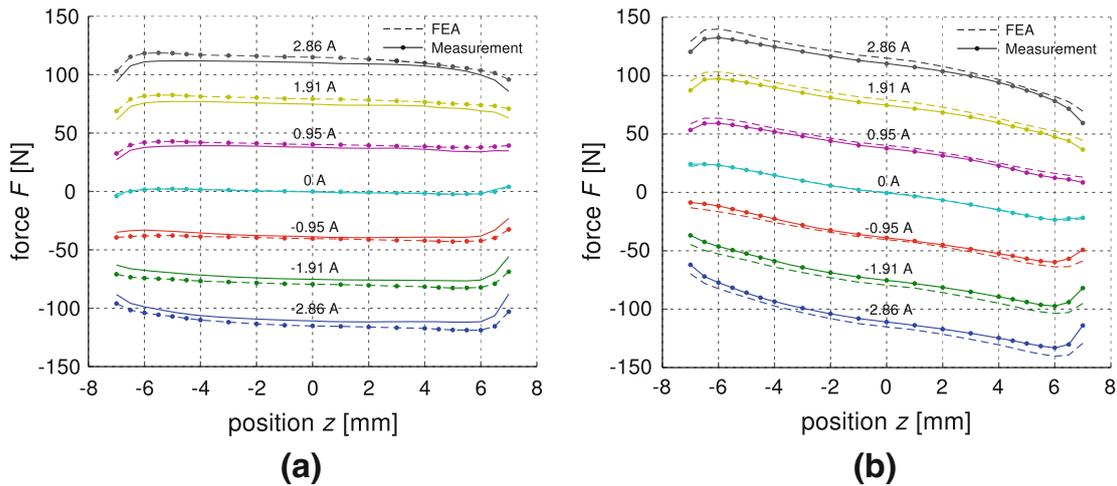
Fig. 9 Schematic half-section of the flexure-guided linear actuator [11]

Fig. 10 FE simulation of the designed flexure guide [11]

On each of its two ends the mover is guided with specifically designed flexures (Fig. 10). A large stroke of $\pm 7\,\text{mm} = 14\,\text{mm}$ has been realised with a small outer diameter of the flexures of only 59 mm. The total axial stiffness of the complete flexure guide is only 3.55 N/mm. This intentionally small value leads to small ohmic losses of 4.5 W only for holding the mover in either of its two end positions. Superposition of the magnetic force (Fig. 11a) and the restoring force of the flexure guide gives the net force of this actuator (Fig. 11b).

Lateral stiffness of a flexure guide depends on the cantilever length between the front flexure and the working element or tool center point. For the actuator shown in Fig. 8 radial stiffness has been measured [11]. With a cantilever length of 10 mm it is approx. $2\,\text{N}/\mu\text{m}$ in mid-position of the mover. With increasing mover deflection

Fig. 11 Force-position-current characteristic of the flexure-guided linear actuator **a** without and **b** with the restoring force of the flexure guide [11]

Fig. 12 Compact linear axis LA14-35 with integrated ball guide, position sensor and control electronics: travel range 14 mm, nominal/peak force $\pm 35/\pm 90$ N [12]
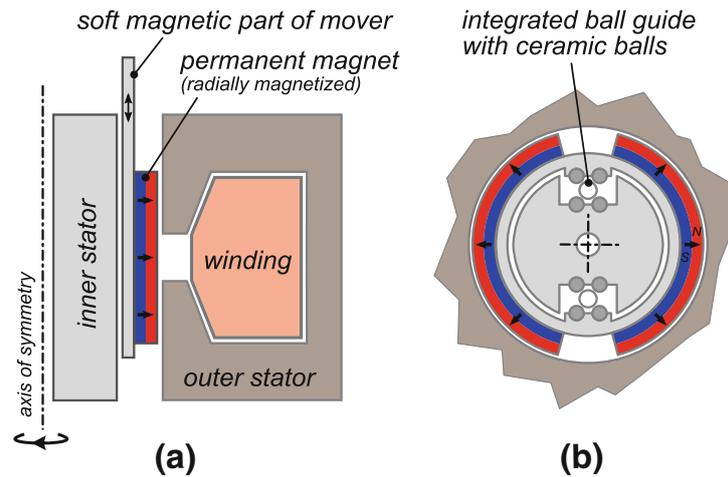

lateral stiffness decreases. At maximum mover deflection of ± 7 mm it is approx. 0.1 N/µm. Hence, flexure-guided actuators are suited for applications without or with moderate lateral forces, e.g. EDM or focusing and steering of optical beams.

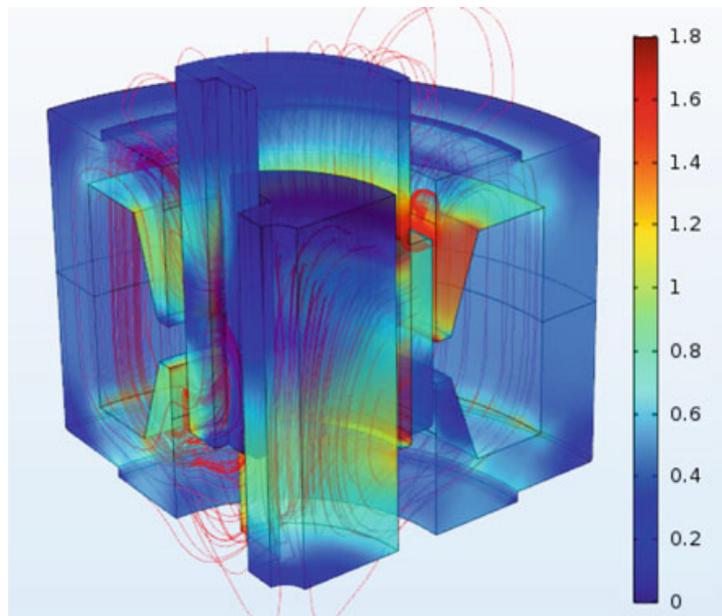## 3.2 Highly Integrated Linear Axis

In order to improve compactness and radial stiffness compared to the flexure-guided actuator described in the previous section, a linear axis with integrated ball guide and integrated servo controller has been developed, built and successfully tested Fig. 12 [12].

The back iron, which acts as return path for the magnetic flux, is split into a fixed and a moving part. This maintains an efficient magnetic circuit with small air gaps and minimizes the mass to be moved (Fig. 13a). Since the base body of the mover for

Fig. 13 Compact linear axis
LA14-35: Schematic
half-section of the magnetic
subsystem **a** and schematic
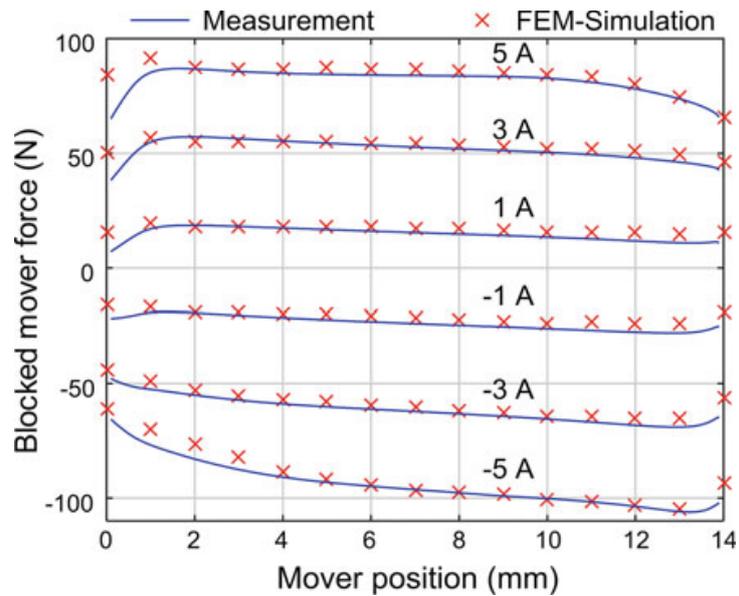top view on the integrated
ball guide **b** [12]

soft magnetic part of mover

permanent magnet
(radially magnetized)

integrated ball guide
with ceramic balls

axis of symmetry

inner stator

winding

outer stator

(a)

(b)

Fig. 14 3D FEM simulation
of the magnetic subsystem of
linear axis LA14-35
($x = 10$ mm, $I = 2$ A),
magnitude of flux density in
T [12]

high magnetic permeability is made of steel, it has a high stiffness and allows direct
integration of a ball guide as shown in Fig. 13b. This design leads to a particular
compact linear actuator with lightweight mover, high forces, good dynamics and
high stiffness in radial direction.

The magnetic circuit with integrated ball guide has been designed with 3D FEM
(Fig. 14). Simulated and measured actuator forces match very well (Fig. 15). Forces
are nearly constant along the entire travel range and proportional to the winding
current, which facilitates actuator control.

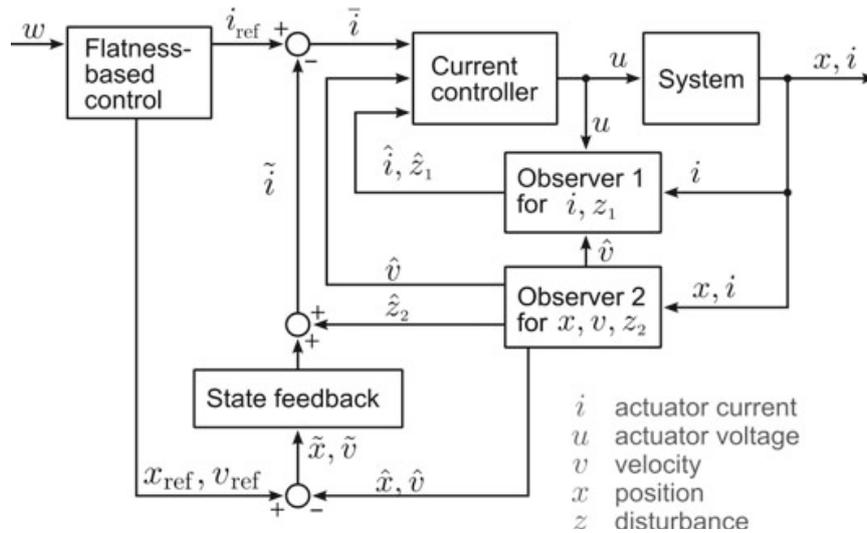**Fig. 15** Force-position-current characteristic of linear axis LA14-35 [12]

3.3 Integrated Position and Force Control

Flatness-based position control has been implemented and tested for the cylindrical linear actuators presented above on a specifically developed control electronics (Fig. 16). It enables fast and smooth positioning without overshoot (Fig. 17) and good disturbance rejection. A transient position deviation of 170 μm has been measured after a force step of -5 N, corresponding to a dynamic stiffness of 29 N/mm. This deviation is compensated by the position control within 22 ms.

Two observers have been designed to estimate the system states according to the system input u, the mover position x and the winding current i. The first observer estimates the actuator current $\hat{i}$ which is difficult to measure exactly due to sensor noise and PWM-driven winding current. In addition to the position $\hat{x}$, the second observer also estimates the velocity $\hat{v}$ of the mover, which is difficult to measure directly with a low-cost and compact sensor. Two disturbances are also estimated to further improve the control performance [12]. The controller parameters have been calculated using pole placement. Two observer configurations for low and high disturbance forces have been evaluated.
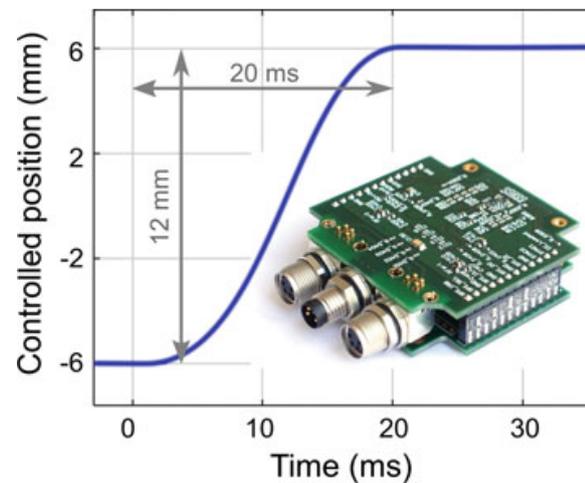
For the linear axis LA14-35 with integrated ball guide shown in Sect. 3.2, the control electronics (Fig. 17) has been integrated into the drive unit. With the integrated optical incremental position encoder with 1.25 μm resolution, a repeatability of 3.3 μm and a positioning accuracy of 8.8 μm has been measured. Alternative sensors with higher resolution in the sub-μm range are available, if higher accuracy is needed. In addition to position control, sensorless force control has been implemented, where the actuator force is determined from measured position and winding current.

The developed control electronics for linear axis LA14-35 has a simple serial RS-232 interface for transmission of set commands and status data. Additionally,

Fig. 16 Block diagram of the implemented flatness-based position control of the linear axes [12]

Fig. 17 Controlled response of linear axis LA14-35 to a 12 mm step of the set position and integrated control electronics [12]
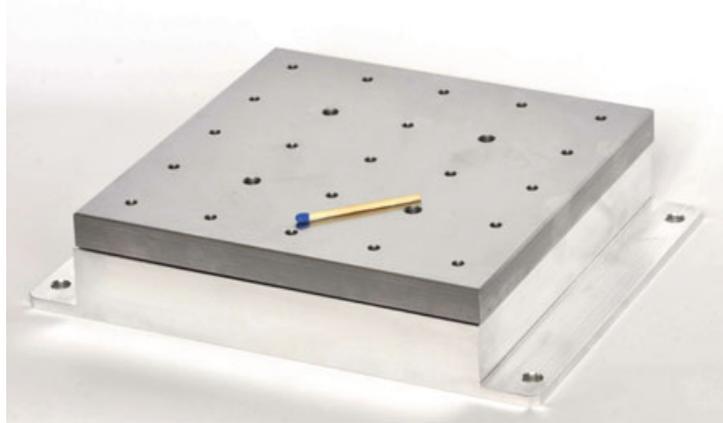

it is equipped with hardware for the fast EtherCAT fieldbus. Implementation of the CANopen drive profile CiA 402 for servo drives is work in progress.

Four linear axes LA14-35 have successfully been integrated into three sample machine tool configurations described in Sect. 1. These machine tools were exhibited at Hannover Messe 2016.

4 Novel Planar Direct Drive

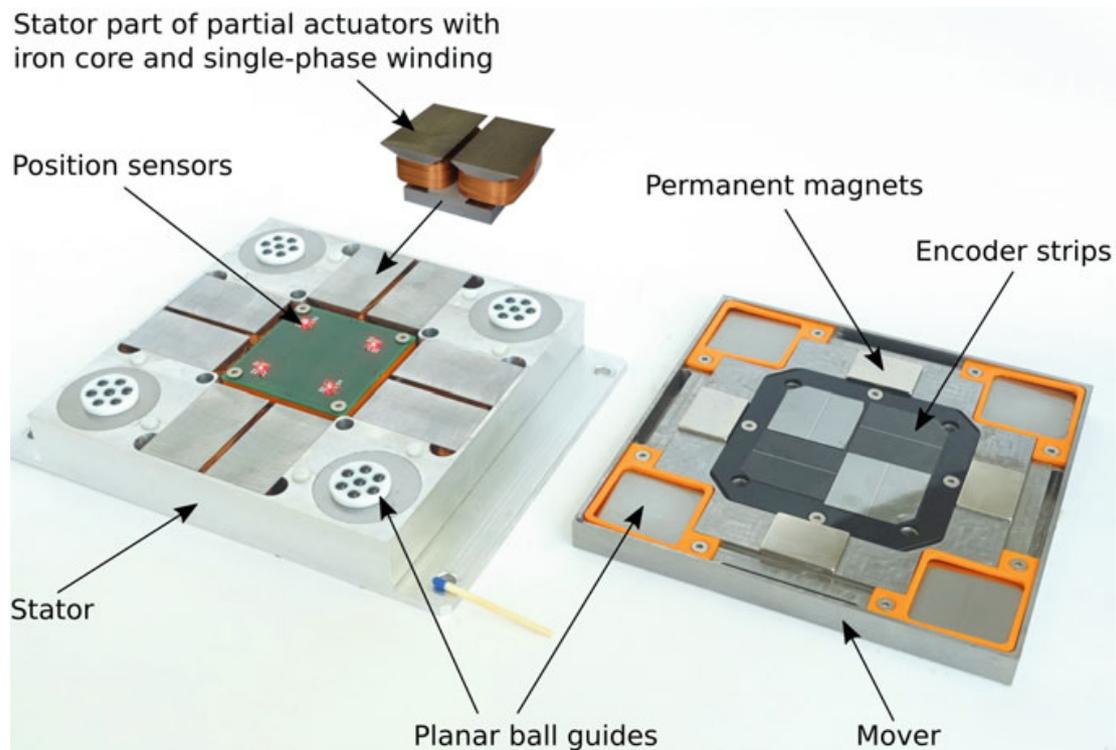In addition to the linear tables and axes described in the previous sections, a novel compact planar direct drive has been developed (Fig. 18) [13]. Unlike in many other direct drives with ironless multi-phase windings [14, 15] it utilises four partial actuators with U-shaped iron core and single-phase winding in the stator (Fig. 19). The magnetic design with iron core enables large forces at little losses (Fig. 20).

Fig. 18 Prototype of a
novel electrodynamic planar
direct drive: motion range
$20 \times 20\,\mathrm{mm}^2$, maximum
rotation $\pm 11°$, nominal/peak
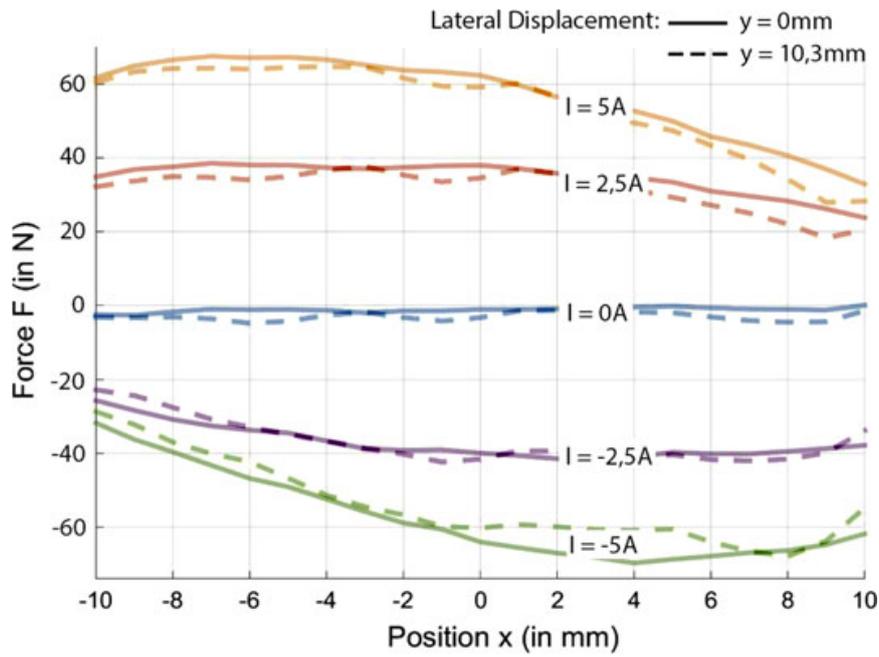force $\pm 25/\pm 72\,\mathrm{N}$ in x- and
y-direction [13]

The mover is guided by a simple low-cost planar ball guide that proved to be functional in first tests (Fig. 19). The x- and y-position and the orientation φ of the mover are measured with a maximum of four, at present three optical low-cost linear encoders with $1.25\,\mu\mathrm{m}$ resolution. Repeatability and positioning accuracy are yet to be measured, but an accuracy of approx. $10\,\mu\mathrm{m}$ is to be expected. Extraction of the orientation φ from the linear encoder signals works, but needs to be improved with future work [16].
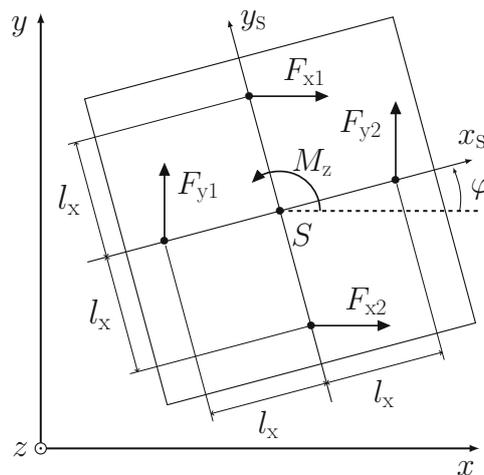
Constraint motion is achieved by proper control of all partial actuators of the drive. Overdeterminacy with four partial actuators (Fig. 21) and three DOF of the

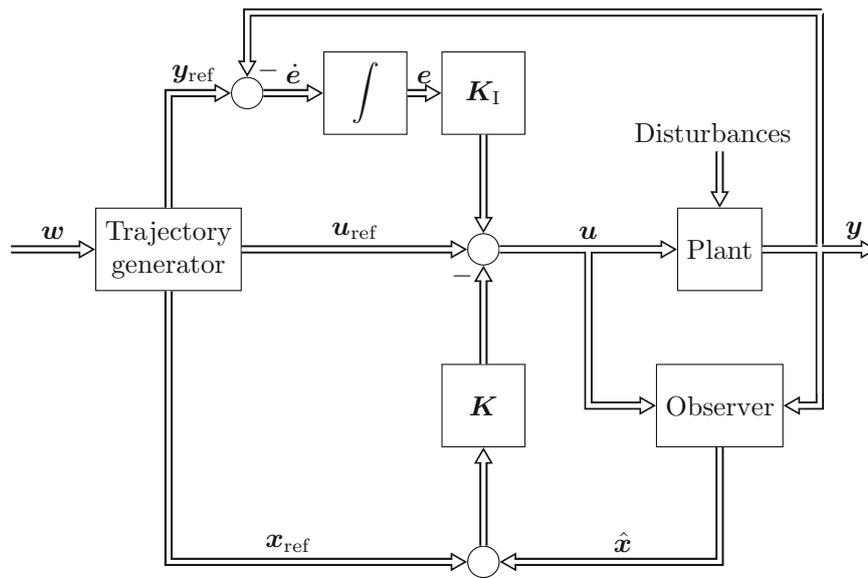**Fig. 19** Stator and mover of the planar direct drive [13]

Fig. 20 Measured force-position-current-characteristic of the planar direct drive in *x*-direction at two different *y*-positions of the mover (centred and maximum *y*-position), forces of both partial actuators for *x*-direction added [13]

Fig. 21 Thrust forces acting on the mover of the planar direct drive (*S*…center of mass) [16]

planar drive is avoided by introduction of three virtual inputs [16, 17]. Flatness-based position control of the planar direct drive has been implemented on a dedicated control electronics (Fig. 22). The underlying mathematical model of the planar drive and control design are described in detail in [16]. First tests of controlled drive operation showed the good dynamics of the planar drive (Fig. 23), but overshoot and settling time after a controlled position transition need to be reduced with future control optimisation.

Fig. 22 Block diagram of the flatness-based augmented state space controller of the planar direct drive [16]

Fig. 23 Controlled responses of the planar direct drive to steps of the set x position [16]

Selected components of the developed planar drive are currently redesigned. A weight-reduced mover is manufactured. A new miniaturised version of the control electronics has been developed and will be integrated into the planar drive. Low-cost components for the guide and the position sensors have been chosen intentionally for this first prototype, resulting in an accuracy of approx. $10\,\mu$m. If higher accuracy is needed, the linear encoders can be replaced by a 2D or 3D position sensor with higher resolution, resulting in higher cost. Also, the ball guide can be replaced by air bearings with little effort, if needed.

5 Summary and Outlook

Feed units for short strokes up to approx. 25 mm can advantageously be realised with simple single-phase electrodynamic direct drives. Commutation as required in larger multi-phase linear motors is not necessary. A family of such linear and planar direct

drives for short strokes has been developed, built and successfully tested at laboratory level. The chosen design concept *moving magnet* in conjunction with iron core single-phase stator windings leads to large volume-based actuator constants, i.e. to high forces at little losses and small actuator volume. Furthermore, this design yields nearly constant forces along the entire travel range, good dynamics and a simple and robust structure. Patents have been applied for on selected design features of the developed drives.

Various energy-efficient magnetic designs are at hand for cylindrical linear axes, linear tables and planar tables. Nominal forces up to several 100 N are possible with application-specific design. Different variants for the guide of the moving part have been developed and tested (integrated ball guide, flexure guide, slide bushing).

Most of the developed drive units have integrated optical or magnetic position sensors with incremental or absolute measurement and resolutions between 0.16 and 1.25 µm. Higher resolutions are possible with different, but larger and more expensive sensors. Integrated servo controllers have been developed for most of the built prototypes, allowing embedded position and force control. Flatness-based position control has been implemented and proved to be fast, stiff and precise. Sensorless force control has been realised in selected drives. Integration of an EtherCAT fieldbus interface in addition to RS-232 or USB is work in progress.

The developed drives can not only be used as compact and dynamic feed units in future small machine tools, but also in many additional fields of application such as automation, handling or optics. The performance achieved so far with the built prototypes is promising. Partners for tests and optimisation of the developed drives in practical applications and for joint development of application-specific drive units are highly welcome.

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