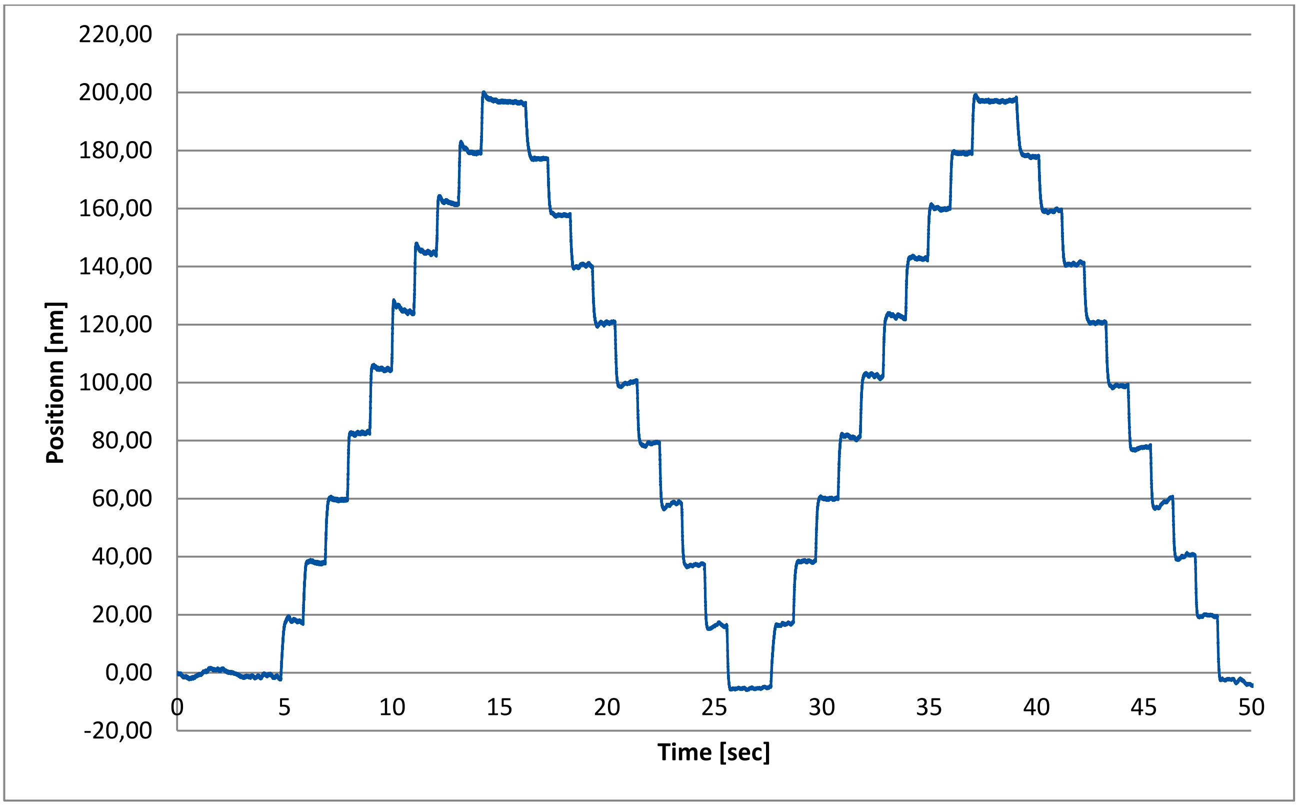
Performance of Stepper Motor Axes

Optimization of Precision, Stability, and Repeatability



1 Drive Technology Basics

Irrespective of the business sector or the market, a production process that is not based on moving components from one position to the other is inconceivable.

Positioning tasks of this type are increasingly being taken over by machines and automated procedures ensure safety and reproducibility. Reliable drives with the corresponding lifetime are essential for this purpose. At the same time, the demand on positioning precision in the industrial environment is also increasing.

On the following pages, it will be shown how positioning systems with a stepper motor drive can be used in precision positioning, and also what special properties they have.

Rotating electric motors are a typical and widespread solution for drive technology in the industrial sector. Stepper motors are usually preferred because they are considered to be particularly robust and have a long lifetime. The have a high torque even at low speed = velocity. They are also attractively priced and can be operated by affordable controllers. Stepper motors heat up during (continuous) operation and this must be taken into account when designing a system.

Stepper motors take discrete positions within one revolution. Because these steps have a constant distance, a position may be commanded using the number of steps without the need for a position sensor. Normally, there are 200 to 500 full steps in each revolution. The actual achievable step size is determined by the stepper motor control, which, depending on the version, electronically interpolates up to several thousand microsteps between the full steps.

When holding a position, stepper motors are very stable, particular the full steps. For this purpose, current must be continually applied to stepper motors without a self-locking gearhead.

PI uses smooth-running 2-phase stepper motors for the positioning axes in high-precision mechanics. A mechanical damper on the motor shaft, which also works as handwheel, supports smooth running. A combination of suitable linear measuring systems and high-resolution controllers increases the positioning repeatability.

Fig. 1 Examples of PI precision axes with stepper motor: L-509 linear axis (former PLS-85), L-511 linear axis (former LS-110), L-611 rotation stages (former PRS-110), L-310 Z-axis stage (former ES-100), MCS XY stage (from above)

2 Precision Positioning into the Nanometer Range

A stepper motor with 200 full steps per revolution rotates at an angle of 1.8° for each step. This results in a feed of 10 µm in conjunction with a drive screw with a pitch of 1 mm. The position resolution that could be theoretically achieved is calculated (without further mechanical gear reduction) from the number of microsteps in each full step, which the motor controller interpolates. A controller, with for example, 256 microsteps, achieves a design position resolution of 39 nm, which corresponds to 625 nm at 16 microsteps. The steps that are commanded in the mechatronic system and can be cleanly executed are limited to whole number multiples of this calculated resolution.

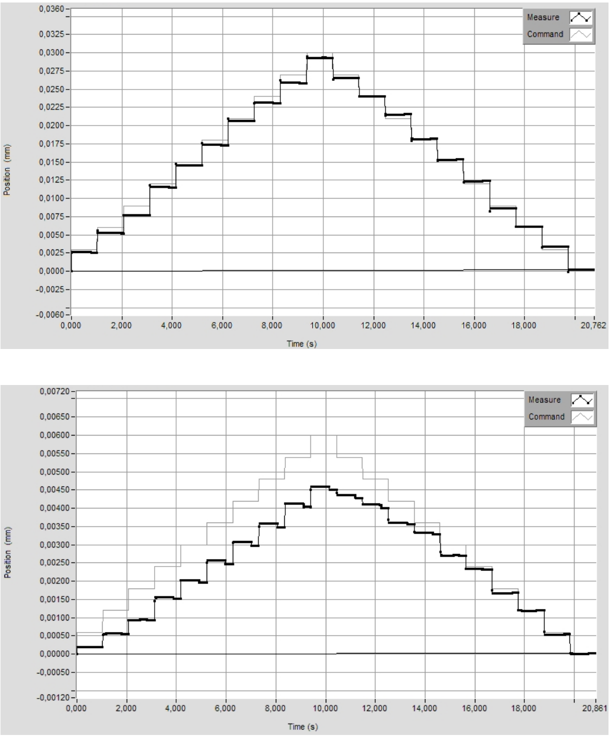


Fig. 2 Steps of an L-511 linear stage with 2-mm drive screw, which is controlled by a motor controller with 16 microsteps per full step. 3-µm steps (left), 0.6-µm steps (right)

Stepper motor controllers with more microsteps between the full steps such as for example, the SMC Hydra (3000 microsteps), achieve a corresponding finer division of the motor rotation angle. They allow virtually stepless position commanding, even in small and very small steps. This results in particularly smooth-running motors, a very high position resolution, uniform feed, and a higher dynamic velocity and acceleration range. The efficiency of these controllers is very high, which suppresses heating up of the motors.

Systems with these types of high-resolution stepper motor controllers are therefore theoretically able to achieve position resolutions into the nanometer range. This allows actual measured and typical step sizes in the range of a few nanometers, which are only limited by the mechanical characteristics of the positioning axis. Due to the high design resolution, virtually any step sizes are possible. Fig. 3 and 4 are examples of 100 nm and 25 nm steps of an L-509 axis with 1 mm spindle pitch.

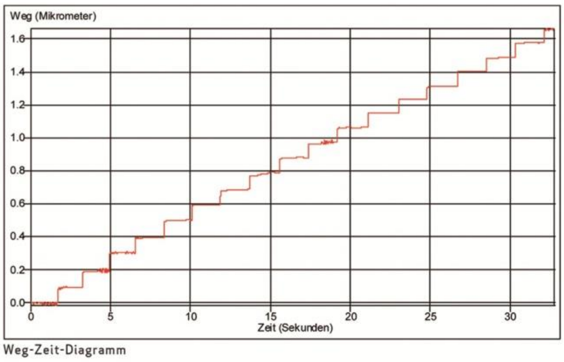


Fig. 3 100-nm steps of an L-509 linear stage with 2-phase stepper motor, and without position control

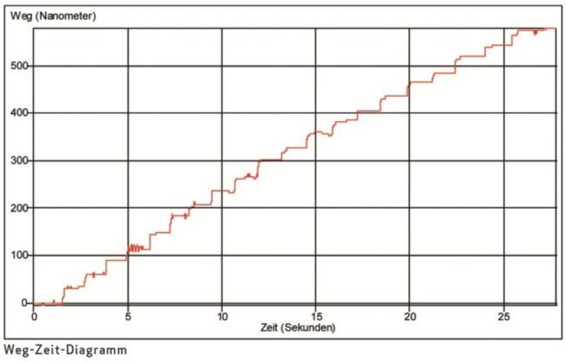


Fig. 4 25-nm steps of an L-509 linear stage with 2-phase stepper motor, and without position control

3 Optimizing the Repeatability with Position Control

A stepper motor executes uniform steps reliably with high-precision repeatability. The repeatability of a position that has been reached once in an overall mechatronic system also depends on the mechanical components and their interaction: The coupling and possibly the gearhead, drive screw, drive screw nut, and the guidings used, determine the mechanical play. These mechanical effects of the construction can never be completely eradicated.

The accuracy, with which a position is reached each time, can be improved by additional position feedback and evaluation in the controller. A direct-measuring linear or angle measuring system in the desired resolution effectively suppresses the mechanical backlash/play. At the same time, the linearity of a measuring system is normally higher than that of the motor so even here, there is room for improvement.

Fig. 5 to 9 show the step sizes of an L-511 axis with 2-mm spindle pitch, recorded during control. In this case, step sizes up to 20 nm are easily verifiable.

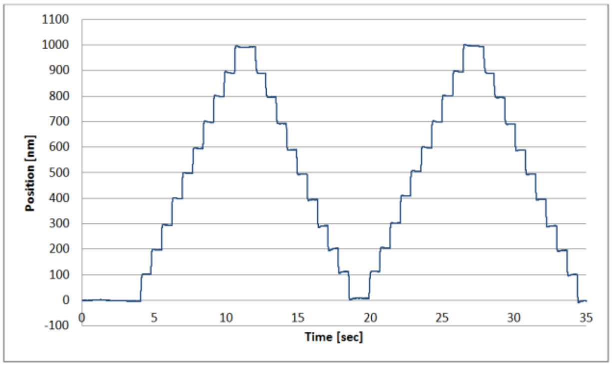


Fig. 5 100-nm steps of an L-511 linear stage with 2-phase stepper motor, and with position control (10 kHz sample frequency, unfiltered)

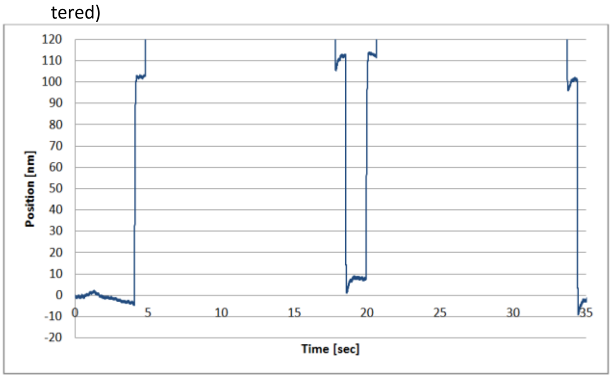


Fig. 6 Detail view of Fig. 5 (zoom)

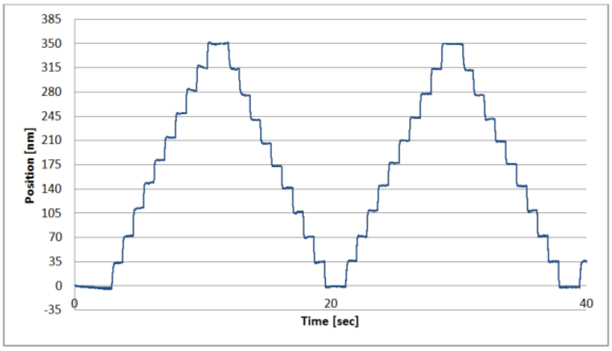


Fig. 7 35-nm steps of an L-511 linear stage with 2-phase stepper motor, and with position control

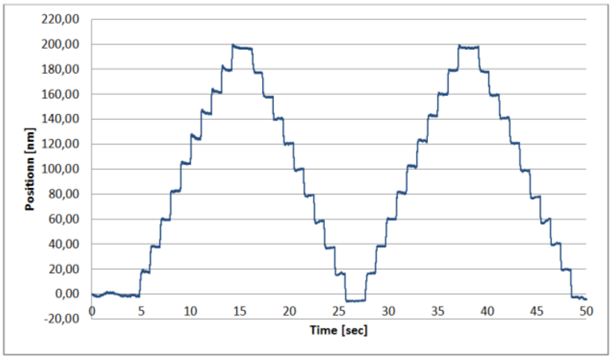


Fig. 8 20-nm steps of an L-511 linear stage with 2-phase stepper motor, and with position control

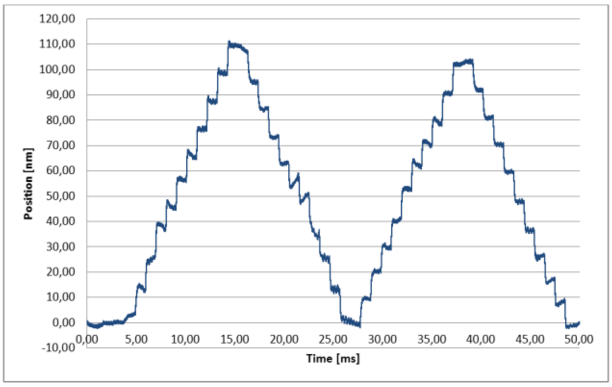


Fig. 9 10-nm steps of an L-511 linear stage with 2-phasen stepper motor, with position control. The 10-nm steps can still be differentiated, but are no longer executed cleanly

3.1 Stability and Resolution in Control

Position-controlled stepper motor axes are distinguished by an excellent position stability. Why is that the case?

Classical (DC) servo systems exhibit typical controller oscillation at amplitudes within the range of the resolution. Depending on the servo parameters, they can reach multiples of the resolution and even lead to the total instability of the system. These effects do not occur with stepper motors.

Initially a stepper motor does not need control for position stability. As soon as current is applied to the motor, it builds up a moment while it is at a standstill. In contrast to (DC) servo systems, it has an intrinsic velocity servo control ("velocity feedforward"). These are the ideal requirements for excellent stability. Common stepper motor controllers, with for example, 256 microsteps per full step, allow smooth control of discrete step sizes. The commandable positions are limited to whole number multiples of the theoretical resolution. Any step sizes within a range of a few tens of nanometers are however, not possible, and a disparity between the motor and the encoder resolution leads to a quantization of the achievable positions.

Stepper motor controllers with more microsteps allow virtually stepless position commanding, even in small and very small steps. The maximum accuracy is achieved when the position signals are transmitted as analog sine-cosine signals with 1 V_{pp} and then digitized in the controller with a high resolution. The position resolution of such a positioning system is only limited by the sensor.

3.2 Settling Behavior at the Position

The step-and-settle of an axis decisively affects the process execution times. Initially, the control algorithms in the controller influence the step-and-settle at the target position. SMC controllers suppress high frequencies and still allow dynamic positioning with only minimal overshoot. The axis therefore does not generate any oscillation that in return could be registered by the overall system.

In order to achieve the shortest possible settling times, the operating parameters must be optimized according to the specifications of the application. The mass of the payload, the resulting moments, and the orientation of the motion axis must definitely be taken into account. Further measures are not necessary; the system is stable, and optimized dynamically.

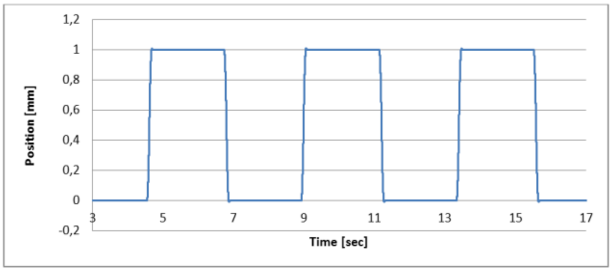


Fig. 10 1-mm steps, executed by an L-511 with position control (velocity 15 mm/s; acceleration 200 mm/s²)

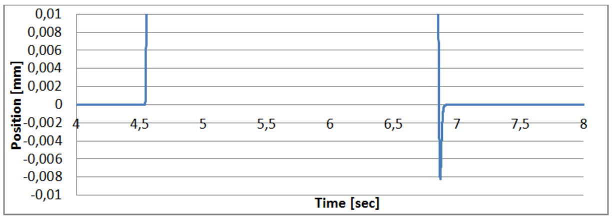


Fig. 11 The enlarged view from fig. 10 shows the very low oscillation of less than 10 µm

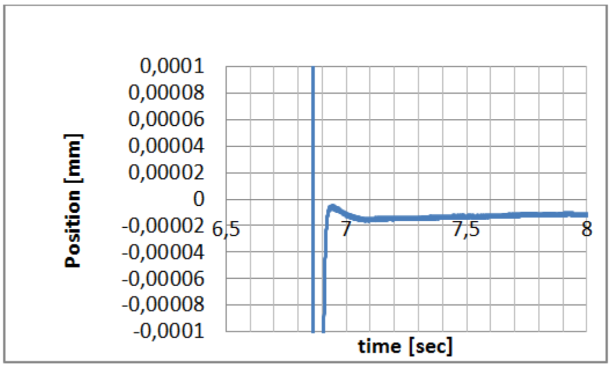


Fig. 12 Further enlargements: It is clear to see that only one single oscillation occurs. The target position was reached within a few tenths of a second within a window of less than 20 nm

4 Constant Velocity at Low Velocity

Velocity is a decisive parameter for selecting a positioning system. Often, the fastest possible motion and positioning are the most important factors. However, some applications require particularly slow and even feed motion. Particularly the velocity constancy presents a challenge.

The required velocities can range from a few 100 µm/s to considerably less than 100 nm/s. This corresponds to a feed of a few millimeters per day. For optimum and even motion, a positioning system is recommended with a high-resolution measuring system and with position resolutions of around a nanometer.

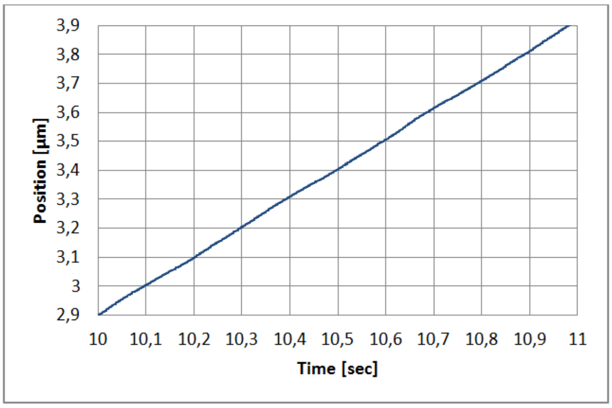


Fig. 13 Velocity constancy at 1 µm/s, measured using an L-511 with position control

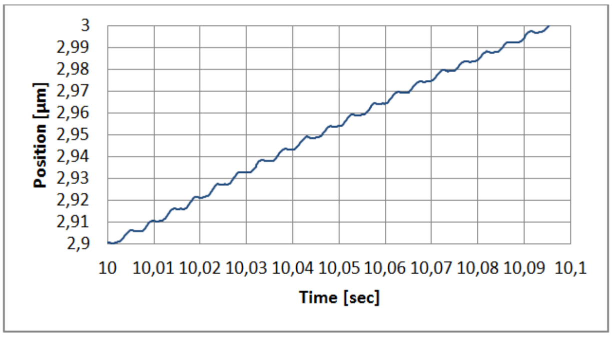


Fig. 14 The measurement from fig. 13 in an enlarged view. The periodic position deviation shown in the range of only a few nanometers can be attributed to the interferometer

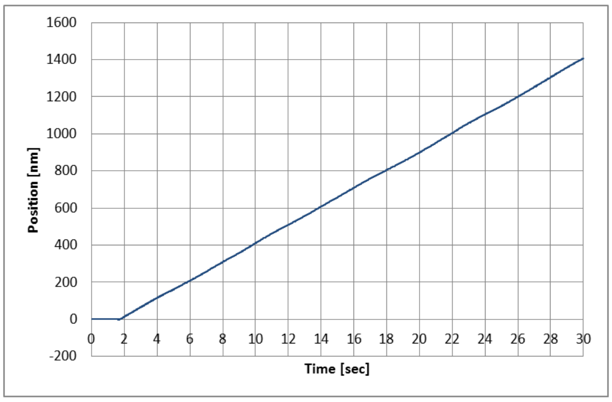


Fig. 15 Velocity constancy at 50 nm/s, measured using an L-511 with position control

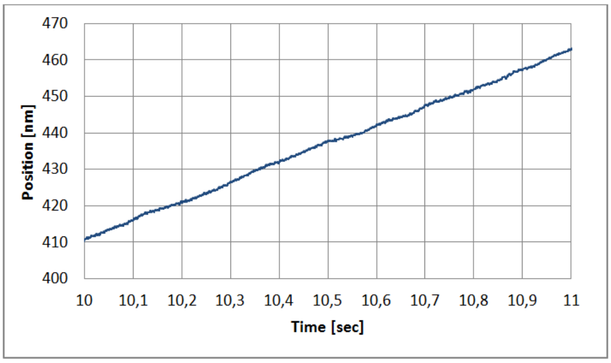


Fig. 16 Enlarged view of the measurement in fig. 15

Background: How does the number of microsteps influence the positioning characteristics of an axis?

Velocity constancy

With only a few microsteps per full step, each step is particularly noticeable at very slow velocities. This is illustrated initially in the path-time diagram, where steps are clearly visible when suitably enlarged (fig. 17 and 18).

Operating at 3000 microsteps per full step, the path-time diagram shows very smooth almost perfect straighten (fig. 19 and 20) and therefore a considerably improved velocity constancy.

If measuring is repeated with position control, almost perfect straightness is visible in the path-time diagram. Position deviation can be reduced to less than 100 nm by using the encoder (fig. 21 and 22)!

L-511 linear axis and C-663.11 Mercury Step motion controller (16 microsteps per full step). Velocity 5 µm/s

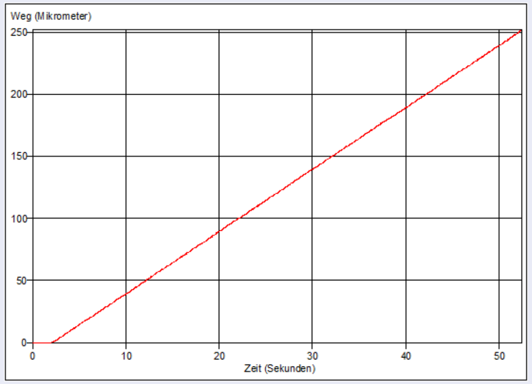


Fig. 17 Without position control (open-loop)

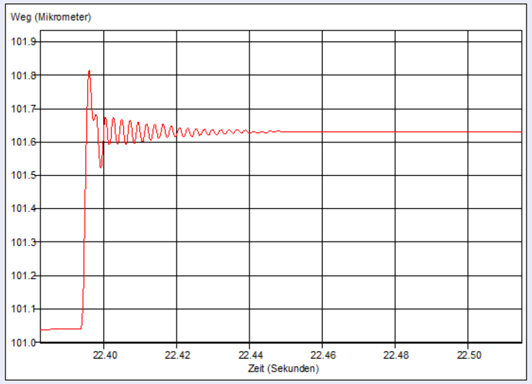


Fig. 18 Detailed view of Fig. 17 shows a distinct step

L-511 linear axis and SMC Hydra motion controller (3000 microsteps per full step). Velocity 5 µm/s

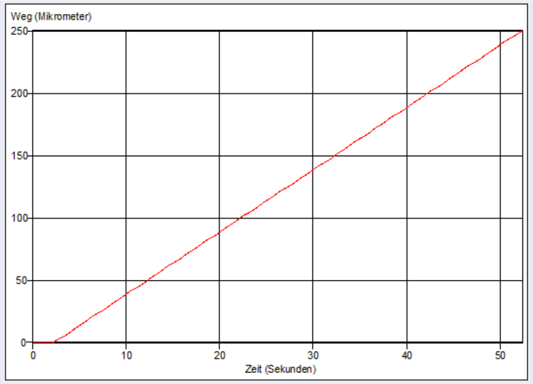


Fig. 19 Without position control (open-loop)

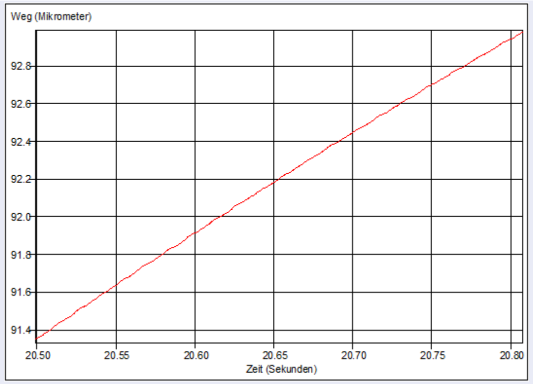


Fig. 20 Detailed view of Fig. 19

L-511 linear axis with measuring system (linear encoder) and SMC Hydra motion controller (3000 microsteps per full step). Velocity 5 µm/s

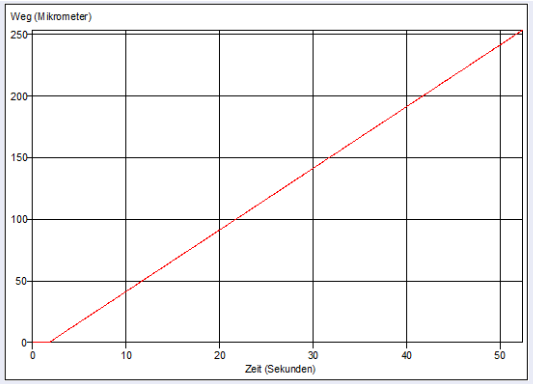


Fig. 21 With position control (closed-loop)

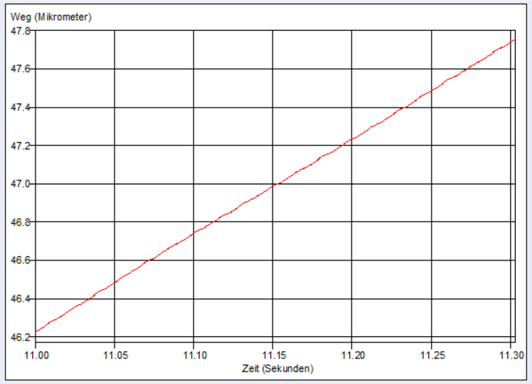


Fig. 22 Detailed view of Fig. 21

Background: How does the number of microsteps influence the positioning characteristics of an axis? (cont.)

Position deviation and frequency behavior

If an axis is operated by a controller with fewer microsteps per full step, a position deviation around 1 µm amplitude is shown (fig. 23).

Residual oscillation of the mechanics results in higher frequencies and therefore increased resonance (fig. 24).

L-511 linear axis and C-663.11 Mercury Step motion controller (16 microsteps per full step). Velocity 5 µm/s

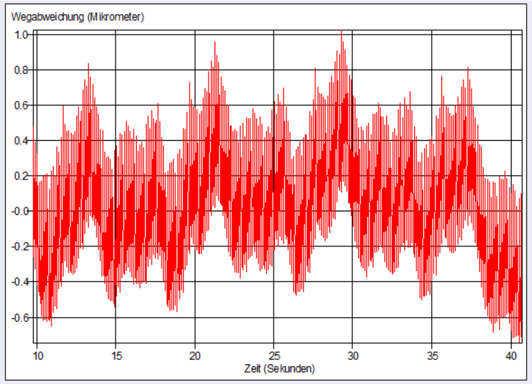


Fig. 23 Position deviation

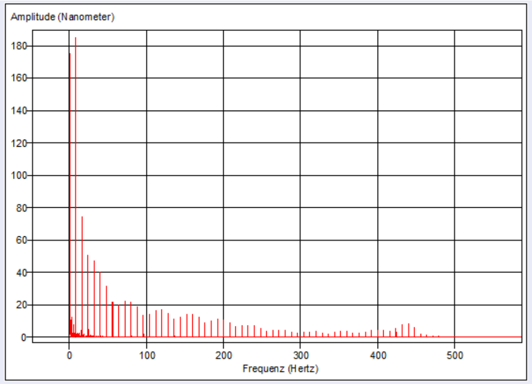


Fig. 24 Frequency spectrum

A controller with more microsteps per full step reduces both the absolute position deviation and the frequency spectrum considerably (fig. 25 and 26).

L-511 linear axis and SMC Hydra motion controller (3000 microsteps per full step). Velocity 5 µm/s

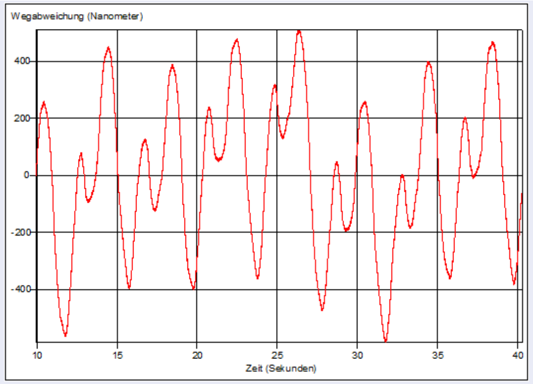


Fig. 25 Position deviation

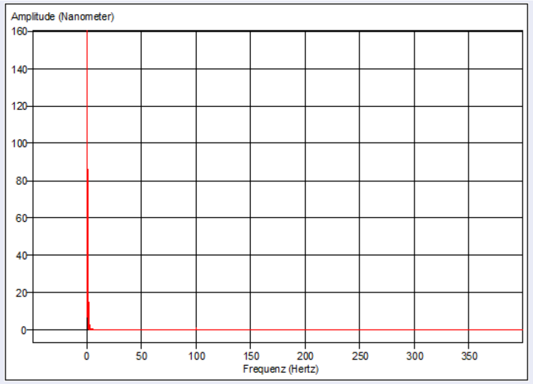


Fig. 26 Frequency spectrum

With the higher microstepping ratio, resonance now only occurs with 100 nanometer amplitude, a reduction to less than 10 % (fig. 27 and 28).

L-511 linear axis with measuring system (linear encoder) and SMC Hydra motion controller (3000 microsteps per full step). Velocity 5 µm/s

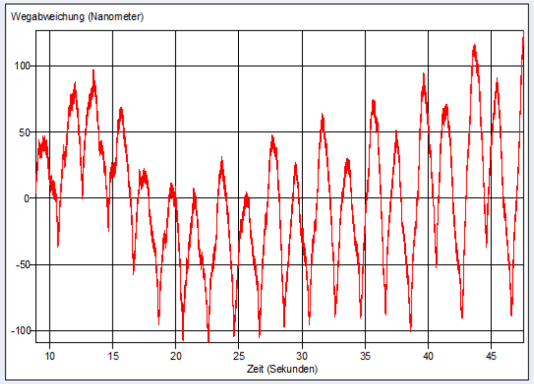


Fig. 27 Position deviation

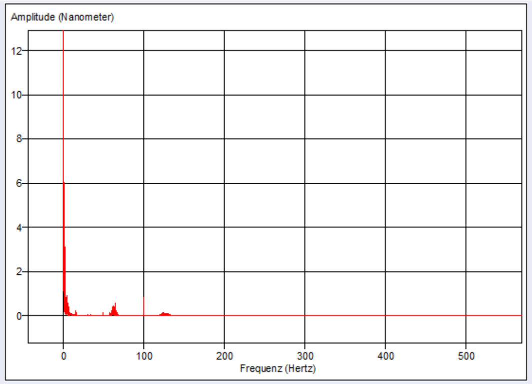


Fig. 28 Frequency spectrum

5 Dynamic Position Correction (Mapping)

Optimization of the overall accuracy of a positioning axis can be achieved by dynamic position correction. In particularly with rotary axes, it is possible to considerably improve the absolute accuracy, usually by a factor of 10.

For this purpose, the deviation from the target position at a predefined step size is initially determined with the help of a reference measuring system. A system with an accuracy of ±0.2 arcsec is available for this purpose at PI miCos. The measured deviations are stored in the controller (SMC Hydra) as a correction table.

Dynamic correction then takes place during operation because the values are already being used in the profile generator for calculation of the motion profile. That means all absolute errors are actually corrected during motion.

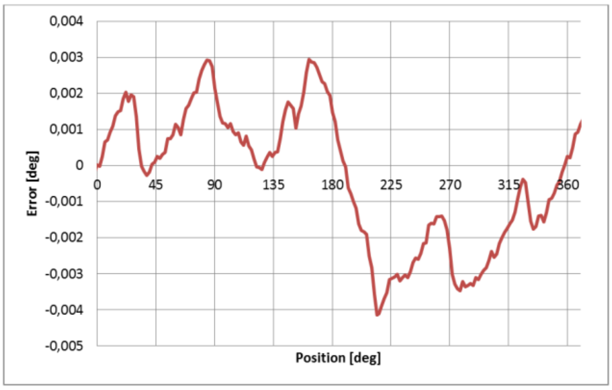


Fig. 29 The absolute accuracy of a PRS-110 (now L-611) rotation stage with stepper motor and angle-measuring system. The deviation from the target position is determined in steps of 1°. The angular error can be up to ±0.004°

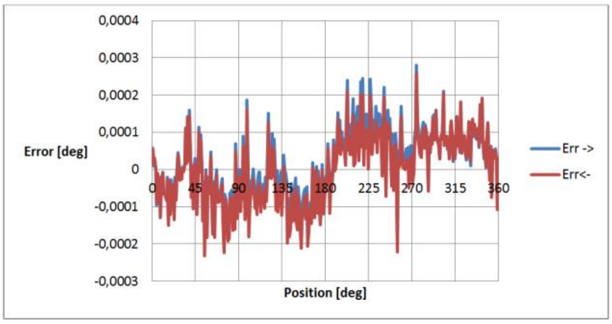


Fig. 30 The measured values from fig. 29 were stored in the controller (SMC Hydra) and used for dynamic position correction. The symmetrical behavior independent of the direction of rotation is clearly visible. It was possible to considerable reduce the position deviation and is maximum ±0.0003°

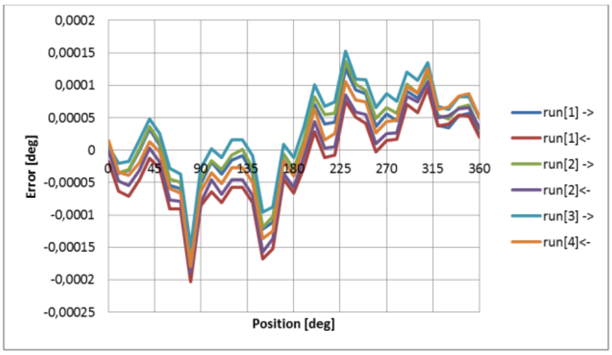


Fig. 31 The bidirectional repeatability is considerably and permanently improved by the stored error correction (mapping). The measurement shows several repetitions in steps of 10° in both the positive and negative direction of rotation

6 Measurement Set-Up

6.1 Ambient conditions, and resources

All measurements were performed in a measurement laboratory under standard laboratory conditions, i.e., clean surroundings without cleanroom classification, room temperature 22°C ±1°C, air humidity 43% ±3%. The measurement set-up is on a table isolated from vibration without further provision for isolation from thermal, acoustic or other external influences.

Measuring device, linear: Renishaw XL-80 interferometer

Measuring device, rotational: Heidenhain RON-905

Height of the reference mirror above the motion platform: 25 mm

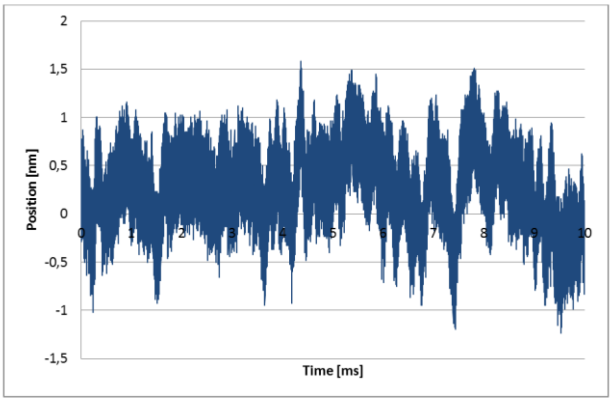


Fig. 32 Noise measurements from the SMC Hydra controller. Axis at rest, energized and controlled (sample frequency 10 kHz, unfiltered). The noise level is at approximately 3 nm (peak-peak), which can be attributed to the interferometer

Basically, the ambient conditions influence the achievable precision during positioning. A fluctuation of the ambient temperature of only 0.01 °C already has an effect of around 10 nm on the thermal expansion of a stage made of aluminum. Stabilization of the surroundings is therefore a basic requirement for precision and the repeatability of the results. If required, ultraprecision axes with special material pairing can be used, for example, on a granite base.

6.2 Positioning Systems and Motion Controllers

Measuring was performed on standard linear and rotation positioning systems, partly with additionally integrated measuring systems. Stages from series production were used.

The following positioning systems were tested:

L-511 (formerly LS-110)

L-509 (formerly PLS-85)

L-611 (formerly PRS-110)

The motor controllers or motion controllers are also from the PI portfolio.

Fig. 33 SMC Hydra with integrated DeltaStar Eco encoder interface module. 3000 microsteps per full step, evaluation from analog position signals (sin/cos, 1 V_{pp})

Fig. 34 C-663.11 Mercury Step; 16 microsteps per full step, without position control

Authors

Joachim Oberfell has been working for the former miCos Gmbh, now PI miCos GmbH, for more than 20 years

He is a specialist for complex positioning tasks and has frequently proved his particular talent for optimizing positioning systems and motion controllers. A sympathetic ear for customer requirements and his profound knowledge on motion control merge to produce the ideal solution for the respective application. Of course, it goes without saying that the precise knowledge of the operating conditions is an important requirement.

Joachim Oberfell attaches great importance to understanding the way a motor controller works in order to exploit all possibilities that a positioning system has to offer, whether it be a high-precision application in basic research such as coordination of several axes in Beamline experiments, or an ideal solution in the automation of production systems, where industry controllers with robust positioning axes are transformed to high-tech applications with future potential.

Birgit Schulze is product manager at Physik Instrumente (PI)

About PI

Over the past four decades, PI (Physik Instrumente) with headquarters in Karlsruhe, Germany, has become the leading manufacturer of positioning systems with accuracies in the nanometer range. The privately managed company is represented at four locations in Germany and internationally by fifteen sales and service subsidiaries. More than 850 highly qualified employees all over the world enable the PI Group to fulfill virtually any requirement in the field of innovative precision positioning technology. All key technologies are developed in-house. This allows the company to control every step of the process, from design to shipment: The precision mechanics and electronics as well as position sensors.

The required piezoceramic elements are manufactured by PI Ceramic, our subsidiary in Lederhose, Germany, one of the global leaders for piezo actuator and sensor products.

PI miCos GmbH in Eschbach near Freiburg, Germany, specializes in positioning systems for ultrahigh vacuum applications and parallel-kinematic positioning systems with six degrees of freedom as well as custom-made designs.