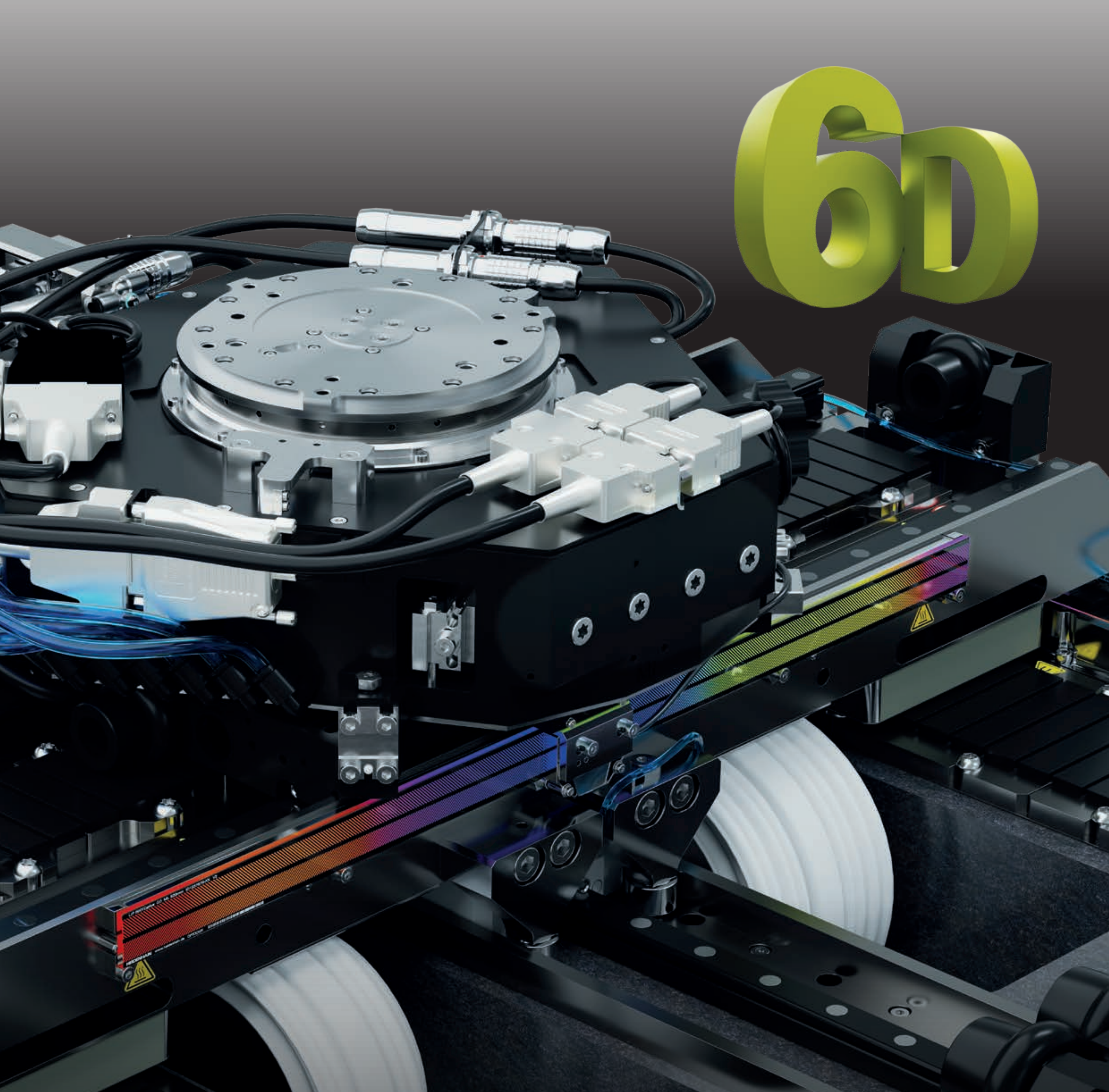


HEIDENHAIN

Breaking the Accuracy Barrier

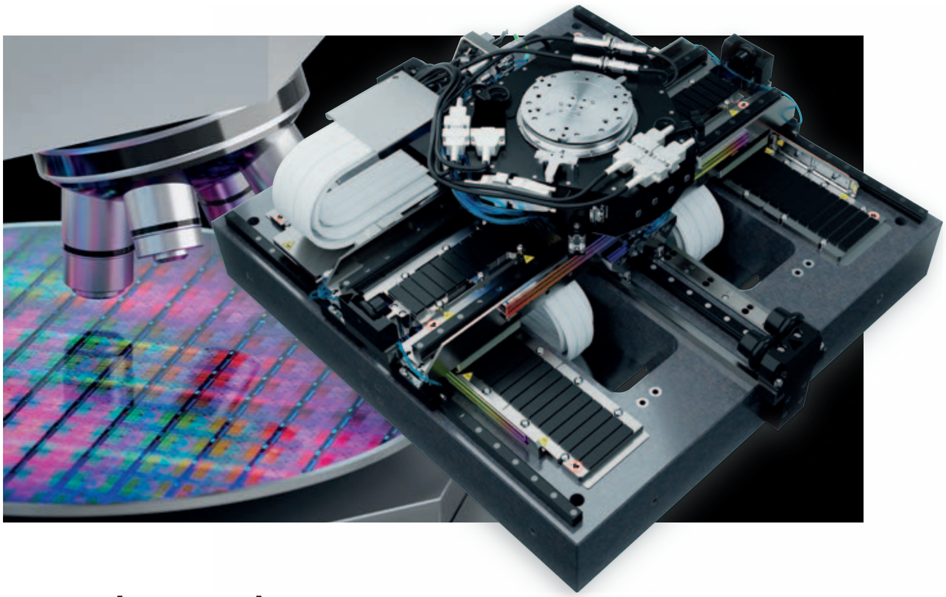
Achieve positioning accuracy better than 200 nm with MULTI-DOF TECHNOLOGY from HEIDENHAIN

TECHNOLOGY REPORT

New dimensions of accuracy for demanding applications

The accuracy of production equipment plays a vital role in the performance of the manufactured components, especially in the electronics and semiconductor manufacturing industry. The memory and computing capacity of today's computer chips depend on ever greater accuracy in front-end and downstream back-end production processes, including hybrid bonding and advanced packaging.

Sub-micron accuracy also plays a role in the subtractive manufacturing industry. Today's high-performance turbines, for example, achieve high efficiency, long service lives and minimal friction loss in no small part due to the perfect surfaces and exact dimensions produced by high-end machine tools featuring high-accuracy rotary and linear axes that enable precise motion control at the tool center point.



Measuring more degrees of freedom, correcting more inaccuracy

Until a few years ago, the micron was regarded as the limit of achievable accuracy. But this invisible barrier has since been demolished, not least through the development of MULTI-DOF TECHNOLOGY from HEIDENHAIN. By tracking in other degrees of freedom beyond their main axis of measurement, including in-plane and out-of-plane, encoders with this technology make it possible to detect and correct otherwise unavoidable system inaccuracy. Among the deviations that can be compensated for are linear guideway error, thermal expansion and the tolerances permitted during manufacturing or installation. But greater accuracy isn't the only benefit. Measuring additional degrees of freedom also improves a system's dynamic performance.

Factor-of-10 improvement in accuracy and dynamic performance

Even the simplest MULTI-DOF solution, the LIF 400 D*plus* linear encoder, which measures two degrees of freedom based on a single scale and two scanning heads, can attain sub-micron position accuracies. And this accuracy improves with every additional degree of freedom. When applied to the TELICA motion system from ETEL for hybrid bonding, for example, MULTI-DOF TECHNOLOGY from HEIDENHAIN increased the tool center point accuracy from 10 µm to the sub-micron level, with 500 nm possible in specially adapted motion systems. In addition to this accuracy improvement by more than a factor of 10, the motion system's dynamic performance also rose by a factor ranging from 8 to 10.

MULTI-DOF TECHNOLOGY is easy to implement

To take advantage of this accuracy and dynamic performance, machines only need to meet the standards required when using conventional LIP 6000 linear encoders from HEIDENHAIN. Encoders with MULTI-DOF TECHNOLOGY are installed and operated in much the same way. In fact, installation may be even more convenient because HEIDENHAIN can provide completed and calibrated assemblies that fully utilize the encoder's absolute accuracy within the larger application, a HEIDENHAIN concept known as TRANSFERABLE ACCURACY (see Page 18).

Even more convenience through the EnDat 3 interface

The EnDat 3 interface from HEIDENHAIN offers numerous benefits for MULTI-DOF applications. A scanning head for MULTI-DOF encoders features two scanning windows (see Page 9) whose data can be transmitted through just one cable by the EnDat 3 interface. The interface also provides EnDat system information about both the encoder and the overall system. This electronic ID label enables automatic setup of the encoder and even of the overall system if system data has been stored by the OEM. And by transmitting temperature-sensor data, or information for condition monitoring and predictive maintenance, to the production system's numerical control, EnDat 3 also offers many benefits for integrating external sensors and online diagnostics.

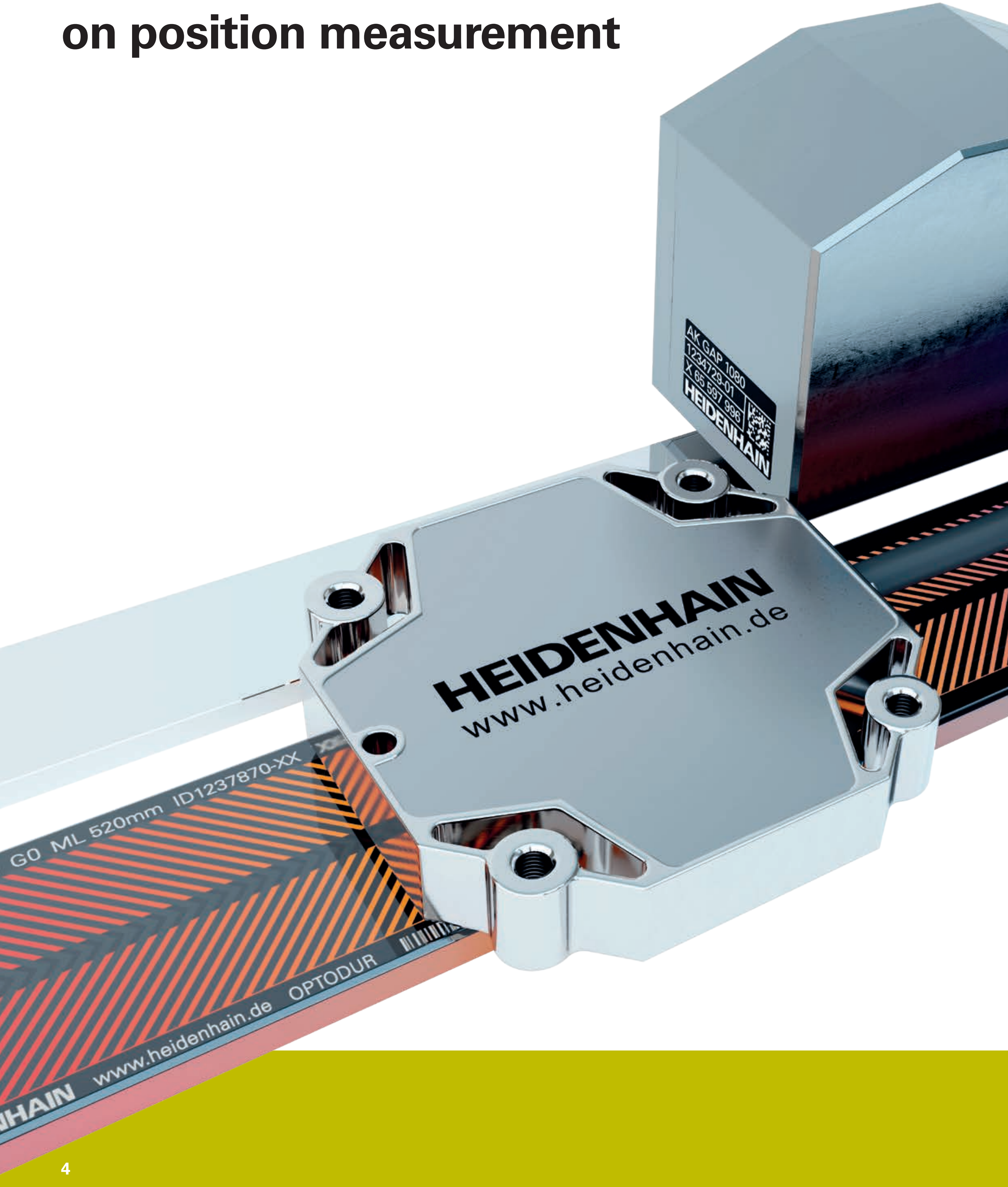
MULTI-DOF TECHNOLOGY for your application

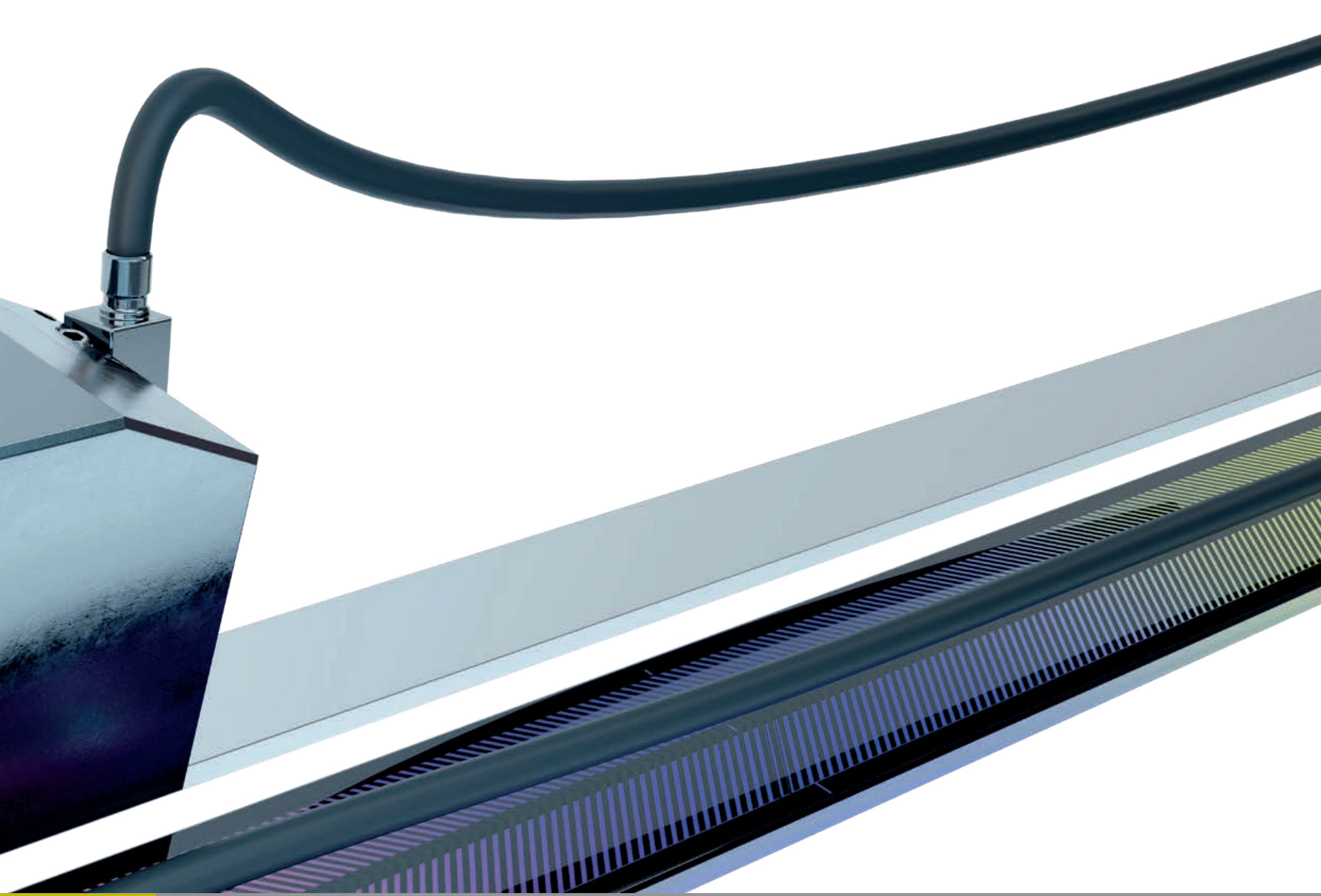
To handle the development of artificial-intelligence systems, semiconductor technology required a transition from monolithic chip structures to a chiplet approach. For example, in order to realize applications such as chips for humanoid robots and self-driving vehicles. But the chiplet approach isn't just about ever greater miniaturization: a significant increase in productivity is now back on the agenda of semiconductor manufacturers. HEIDENHAIN encoders with MULTI-DOF TECHNOLOGY unlock these new dimensions of higher accuracy and performance.

High-performance encoders from HEIDENHAIN are used in all areas of semiconductor and electronics production, encompassing front-end manufacturing, back-end production and the new mid-end processes needed for chiplet technology. Through this longtime experience, HEIDENHAIN has acquired strong expertise in the unique requirements and trends of electronics and semiconductor manufacturing.

To find out how your specific application can break the accuracy barrier, simply contact the HEIDENHAIN Sales team. Our multi-dimensional encoders can be acquired through normal HEIDENHAIN distribution channels and representatives. It's another reason why MULTI-DOF TECHNOLOGY is so easy to implement.

Degrees of freedom and their effects on position measurement





Three-dimensional space contains six degrees of freedom:

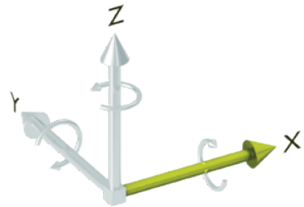
- Translational linear motion along the X, Y and Z axes
- Rotational motion about the R_X, R_Y and R_Z spatial axes

Any movement, even if occurring nominally along only one axis, is still subject to real-world deviations in all other degrees of freedom. These deviations are due to various factors such as imperfect guideway accuracy, temperature-induced changes and the role of motion dynamics (i.e., forces related to acceleration and deceleration).

Assuming the X-axis is the main axis of measurement, the following are some of the factors that diminish accuracy:

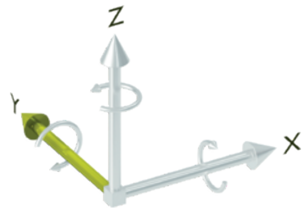
Deviations along the X-axis

- Linear expansion due to thermal effects
- Acceleration and deceleration forces due to motion dynamics
- Hysteresis within drive train



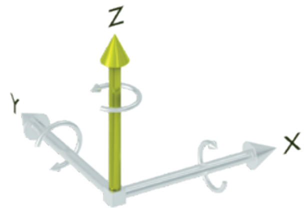
Deviations along the Y-axis

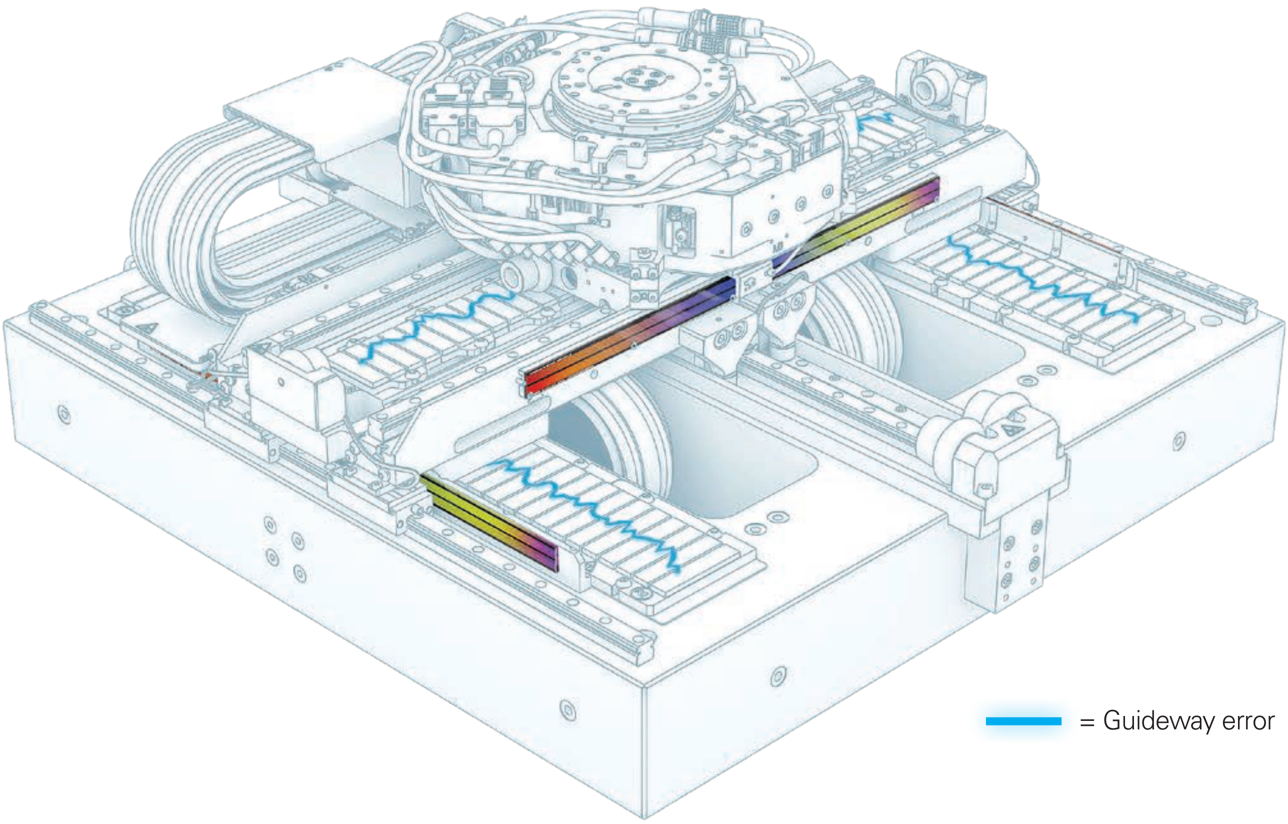
- Linear expansion due to thermal effects
- Horizontal guideway error, along with thermal and dynamics-based effects



Deviations along the Z-axis

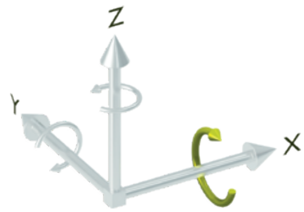
- Linear expansion due to thermal effects
- Vertical unevenness and waviness of machine bed
- Vertical guideway error





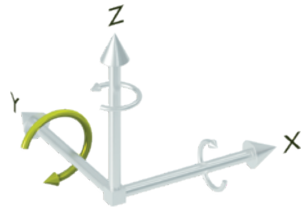
Deviations about the R_X-axis

- Roll motion about the longitudinal axis
- Tolerances of guideway components
- Mounting-induced parallelism error among guideways



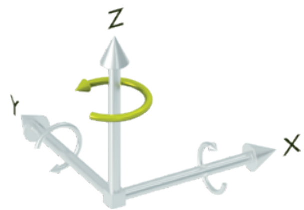
Deviations about the R_Y-axis

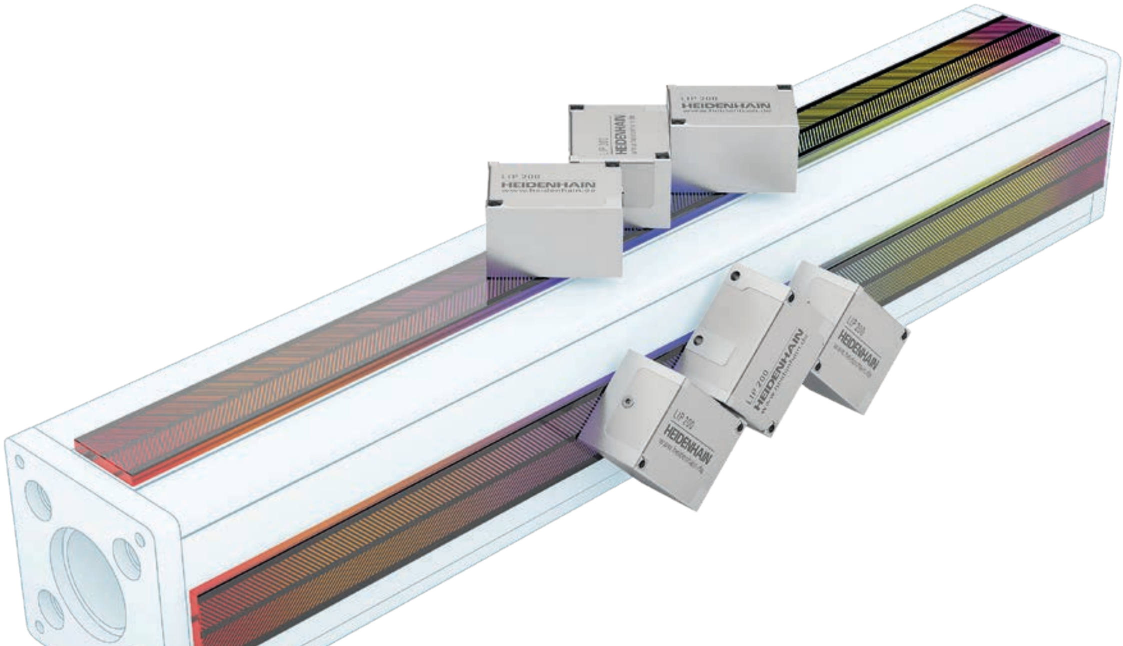
- Pitch about the lateral axis
- Acceleration and deceleration forces due to motion dynamics
- Tolerances of guideway components
- Mounting-induced parallelism error among guideways



Deviations about the R_Z-axis

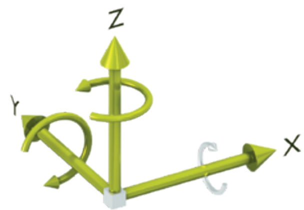
- Yaw about the vertical axis
- Acceleration-induced effects from motor
- Tolerances of guideway components





Degrees of freedom: X, Y, Z, R_Y, R_Z

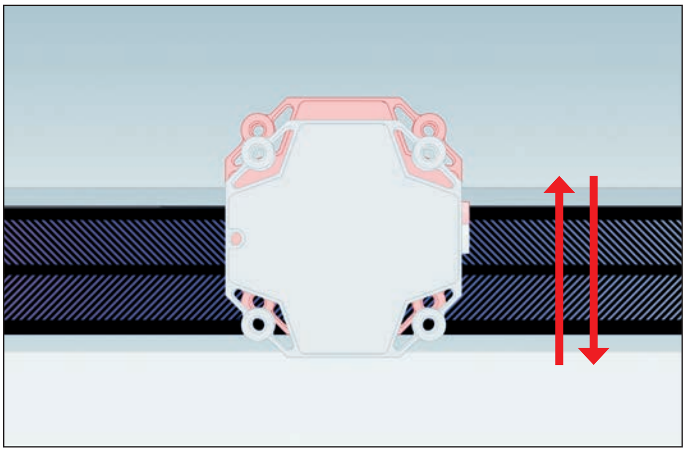
D*plus* measuring standards with three scanning heads each on two D*plus* scales that are mounted at right angles to each other in two mounting planes.



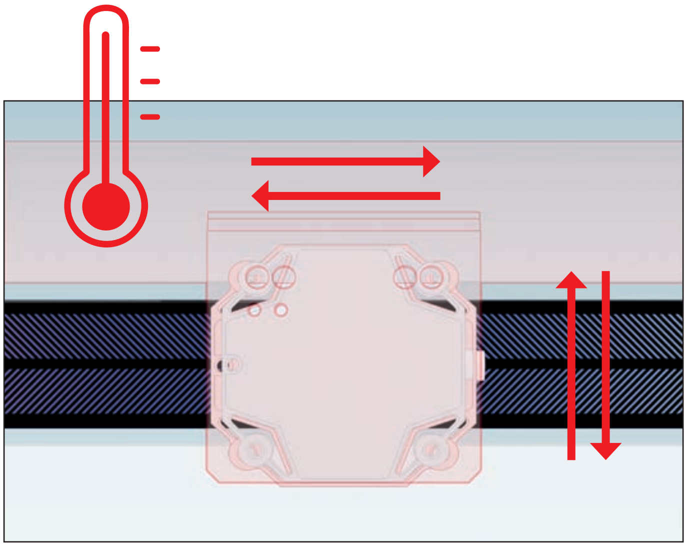
In-plane and out-of-plane measurements:
The right combination for every degree of freedom

A MULTI-DOF scale for linear measurement, with a proper arrangement of scanning heads, is sufficient to detect the following types of deviations through in-plane measurement:

- Thermal deviations
- Kinematic errors in the motion due to guideway errors, and yaw of the slide
- If applicable: hysteresis from the drive train



Linear guideway error



Thermal deviations

An additional GAP encoder installed parallel to the MULTI-DOF linear encoder, or a second MULTI-DOF linear encoder mounted in a different plane (e.g., with the encoders at right angles to each other), can detect the following types of deviations through out-of-plane measurement:

- Vertical unevenness of machine bed or guideway
- Vertical guideway errors of slide
- Pitch motion of slide

How MULTI-DOF TECHNOLOGY works

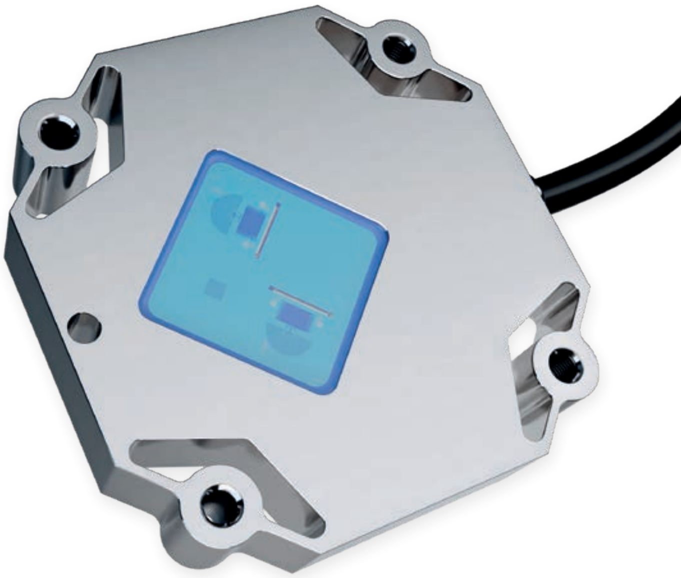
In-plane measurements with the LIP 6000 D*plus*

A D*plus* scale for a MULTI-DOF TECHNOLOGY encoder from HEIDENHAIN contains two graduation tracks with diagonally opposed 45° line structures. Scanning both tracks of the D*plus* scale provides feedback from the main axis of measurement and from a secondary axis. This data can be converted into linear position and axis straightness. If needed, additional referencing provides an absolute position.

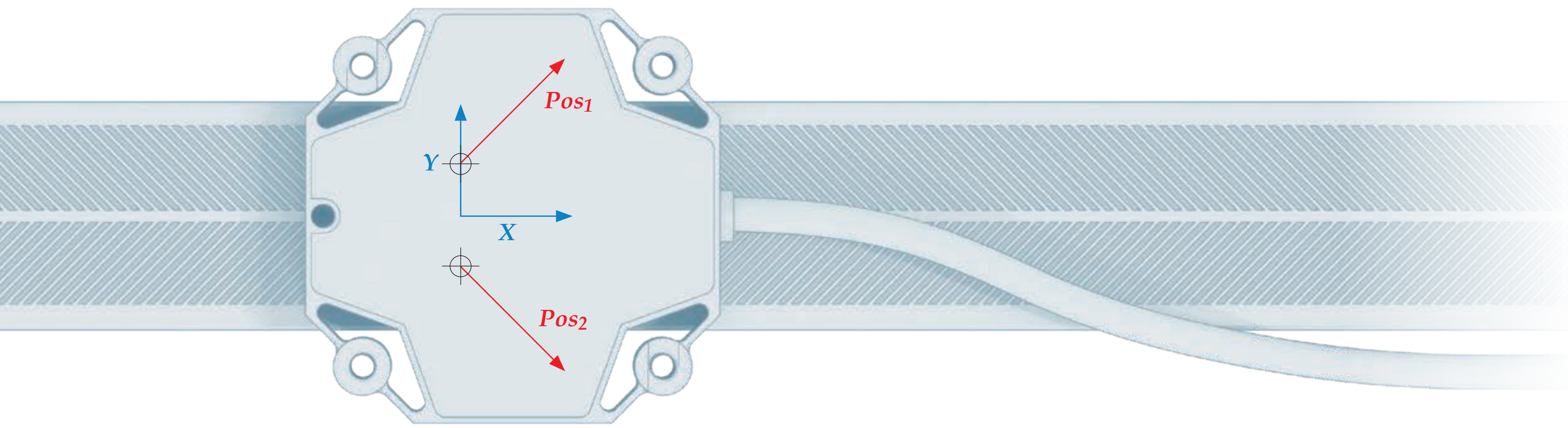
Watch our video about MULTI-DOF TECHNOLOGY

TECHNOLOGY REPORT

The encoder’s two-track scanning is remarkably convenient with a single D*plus* scanning head featuring two scanning windows. For its data transmission, this type of scanning head uses the HEIDENHAIN EnDat 3 interface. EnDat 3 allows the data from the two scanning windows to undergo mathematical processing in the scanning head. The resulting information is then transmitted over a single cable to the downstream electronics. MULTI-DOF TECHNOLOGY can also be used with other interfaces such as 1 V_{PP}, EnDat 2.2 or third-party interface electronics. In this case, however, the D*plus* scale must be read by two conventional scanning heads. Their position data is transmitted separately for mathematical processing downstream in the controller.



A grid encoder or a two-coordinate encoder that detects two directions of measurement at the same time can even measure the squareness error of two orthogonally arranged axes.



Calculation of position value

$$x = \frac{1}{\sqrt{2}} (Pos_1 + Pos_2)$$

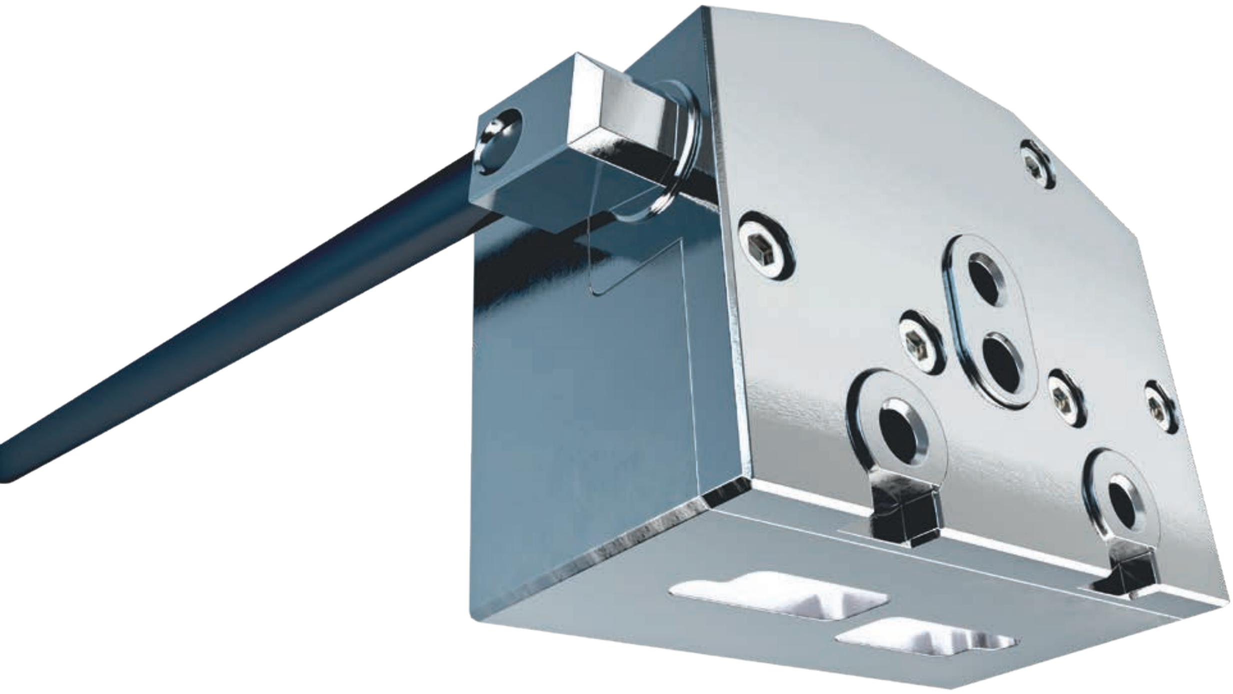
$$y = \frac{1}{\sqrt{2}} (Pos_1 - Pos_2)$$

For complex alignments of multiple scanning heads, the position data can be calculated by a multi-head processing unit from HEIDENHAIN.

Out-of-plane measurements with the GAP 1000

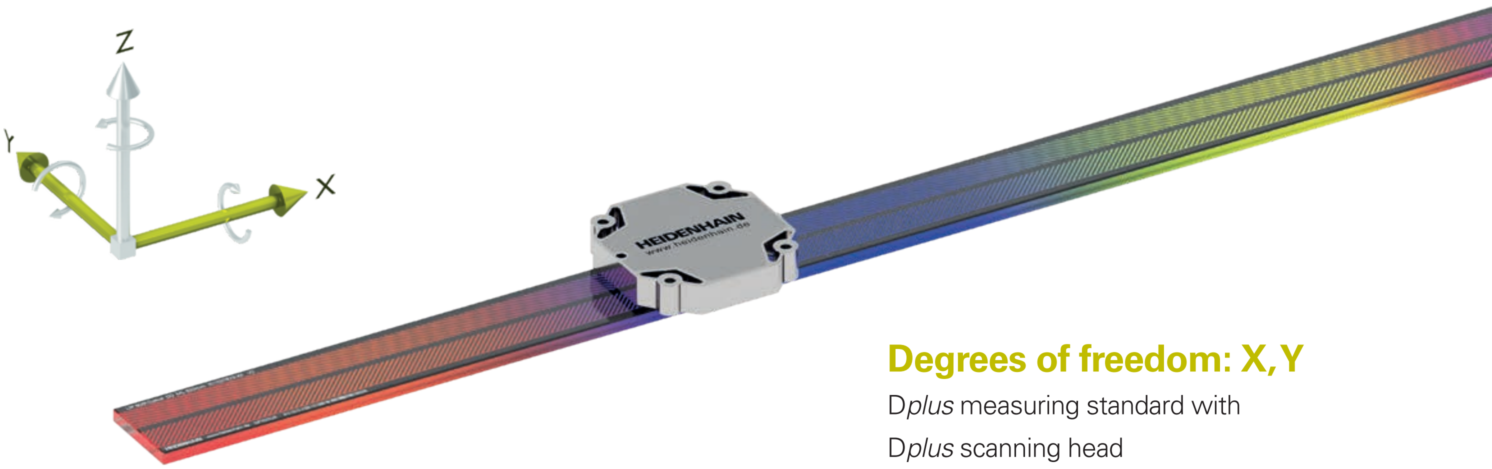
The GAP encoders are the first HEIDENHAIN solutions for measuring the gap between a measuring mirror and a scanning head. The GAP 1000 consists of a mirrored scale and a scanning head, and is suitable for vertical positioning tasks. When installed parallel to a D*plus* scale with 45° graduations, for example, the GAP can measure unevenness in the machine bed or in the table's guideway. And when two GAP scanning heads are installed over a single measuring mirror, errors arising from acceleration and braking events can be measured and corrected.

With sufficient space and suitable mounting surfaces, out-of-plane measurement can be implemented using two MULTI-DOF scales mounted onto orthogonal surfaces of a machine part.



In-plane measurement with MULTI-DOF TECHNOLOGY: The solution combinations are endless

Your imagination is the limit when configuring combinations of D*plus* scales, D*plus* scanning heads and conventional scanning heads. The amount of space for installing scales and scanning heads in your application may be the only limiting factor. Here are just a few of the possibilities!



Degrees of freedom: X, Y

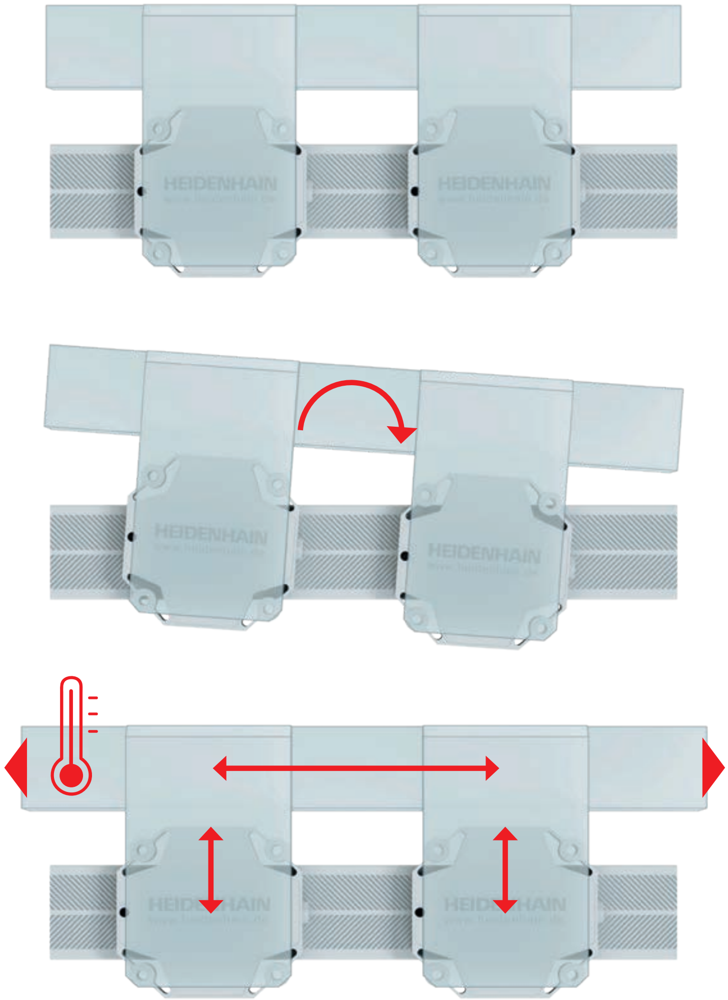
D*plus* measuring standard with
D*plus* scanning head

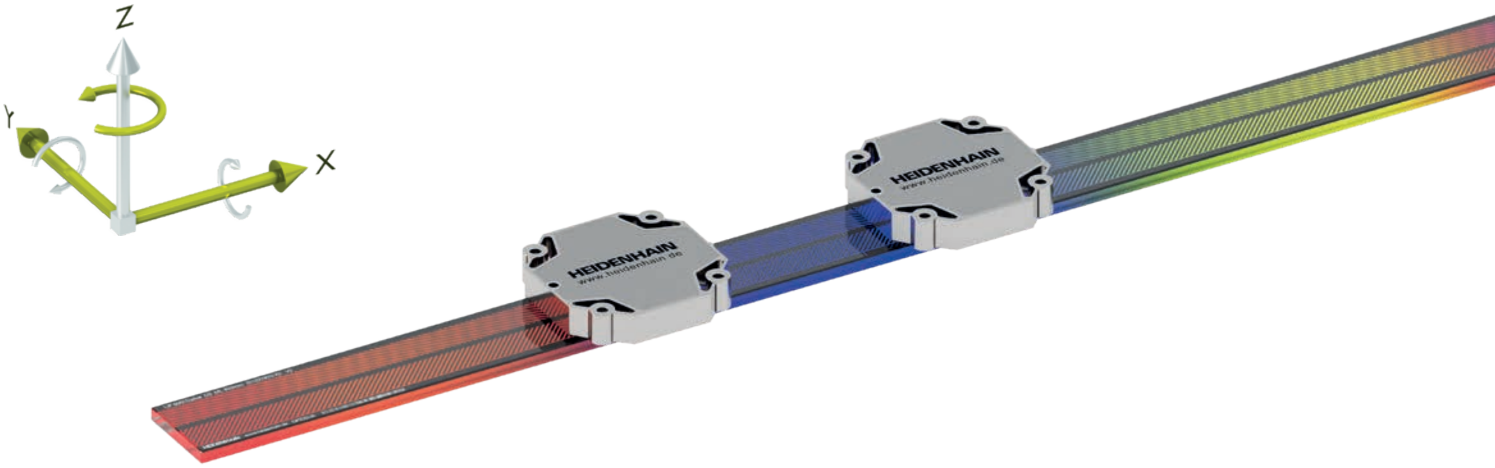
Simple but effective:
1 D*plus* scale + 1 D*plus* scanning head

An easy solution, because no additional space or installation work is required compared with conventional linear encoders, is to use MULTI-DOF TECHNOLOGY with one D*plus* scale and one D*plus* scanning head, as found in the LIP 6031 D*plus* encoder. Even this simple configuration provides feedback for both a main axis of measurement and a secondary axis, thereby correcting linear and straightness deviations.

Slightly more elaborate, but a lot more information: 1 D*plus* scale + 2 D*plus* scanning heads

A second D*plus* scanning head on a D*plus* scale requires virtually no additional space but dramatically expands the error correction potential. Along with linear and straightness deviations, this configuration also measures the amount of yaw about R_Z and other factors such as thermal expansion.



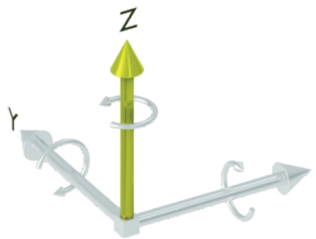


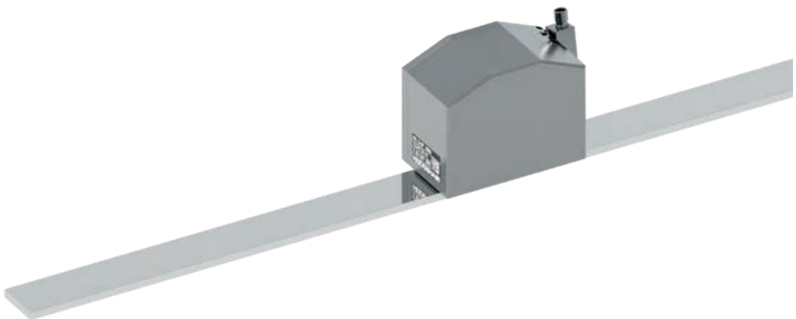
In-plane and out-of-plane measurement with MULTI-DOF TECHNOLOGY: measure all degrees of freedom

Developing the GAP 1000 gap encoder has allowed HEIDENHAIN to accommodate high-accuracy vertical position measurement relative to a measuring mirror. This significantly expands the range of multi-dimensional position measurement in tight machine spaces.

Gap measurement alone:
1 GAP measuring mirror + 1 GAP scanning head

The GAP encoder can measure the gap between any components within a system, even without a guideway. It delivers low position noise and high resolution, two characteristics that conventional solutions can usually only achieve through considerably more expensive and complex gap sensors. The encoder's feedback data is transmitted via the standard 1 V_{PP} interface, allowing for easy integration of GAP encoders into most systems.

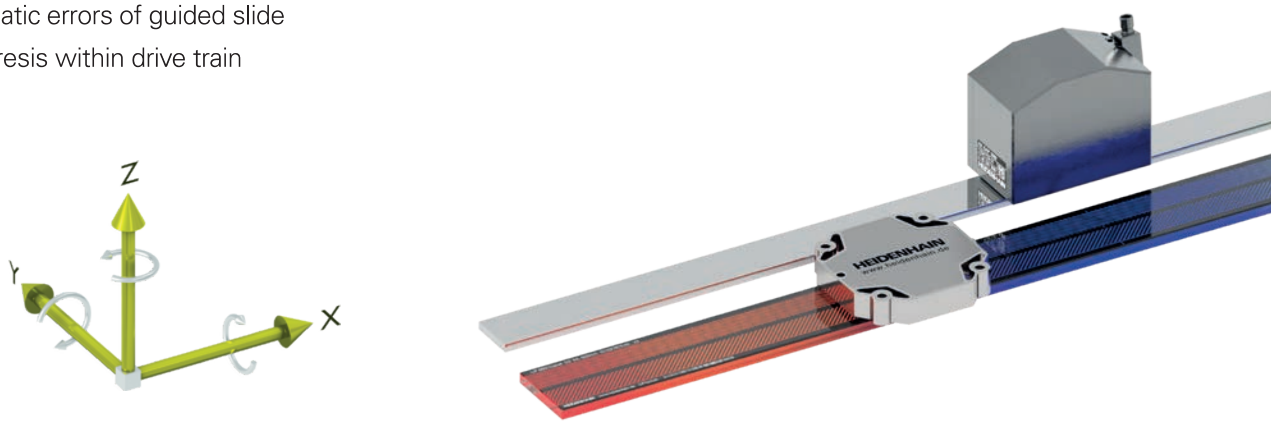




Measuring the most critical deviations:
1 D*plus* scale and 1 GAP measuring mirror + 1 D*plus* and 1 GAP scanning head

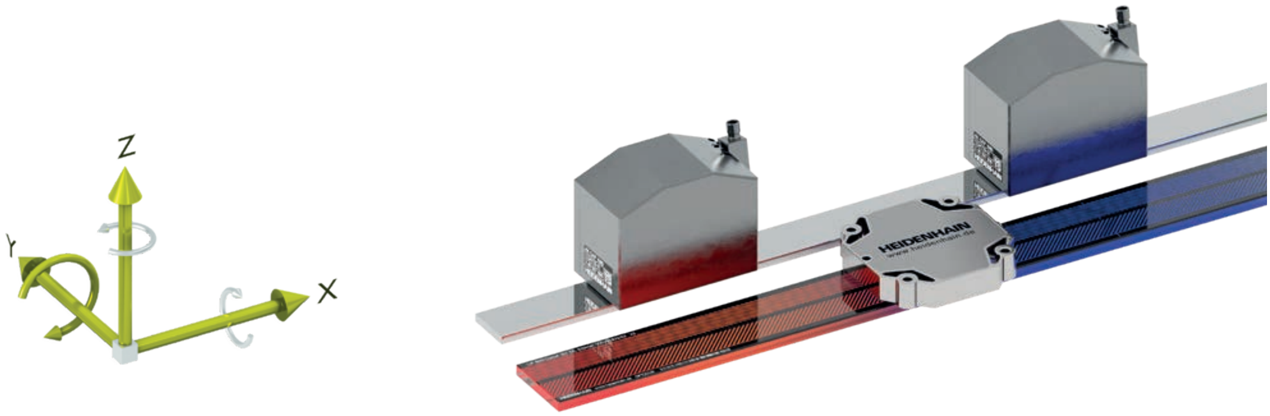
This space-saving configuration measures the three translational axes X, Y and Z using a GAP measuring mirror parallel to a D*plus* scale along with a single GAP scanning head coupled to a D*plus* scanning head. This layout can be used to correct the most critical deviations arising from installation and operation:

- Thermal deviations
- Kinematic errors of guided slide
- Hysteresis within drive train



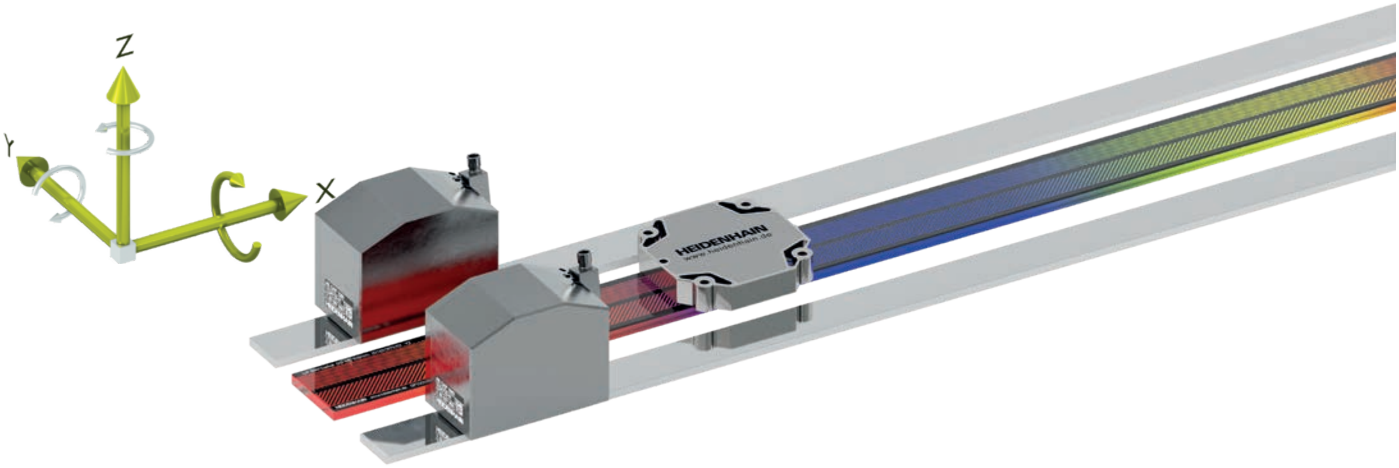
Measuring pitch motion:
1 D*plus* scale and 1 GAP measuring mirror + 1 D*plus* and 2 GAP scanning heads

Pitch deviations about the Y axis can be measured by adding a second GAP scanning head for gap measurement to the configuration of one D*plus* encoder and one GAP encoder. This solution is easy to implement in terms of space and installation effort.



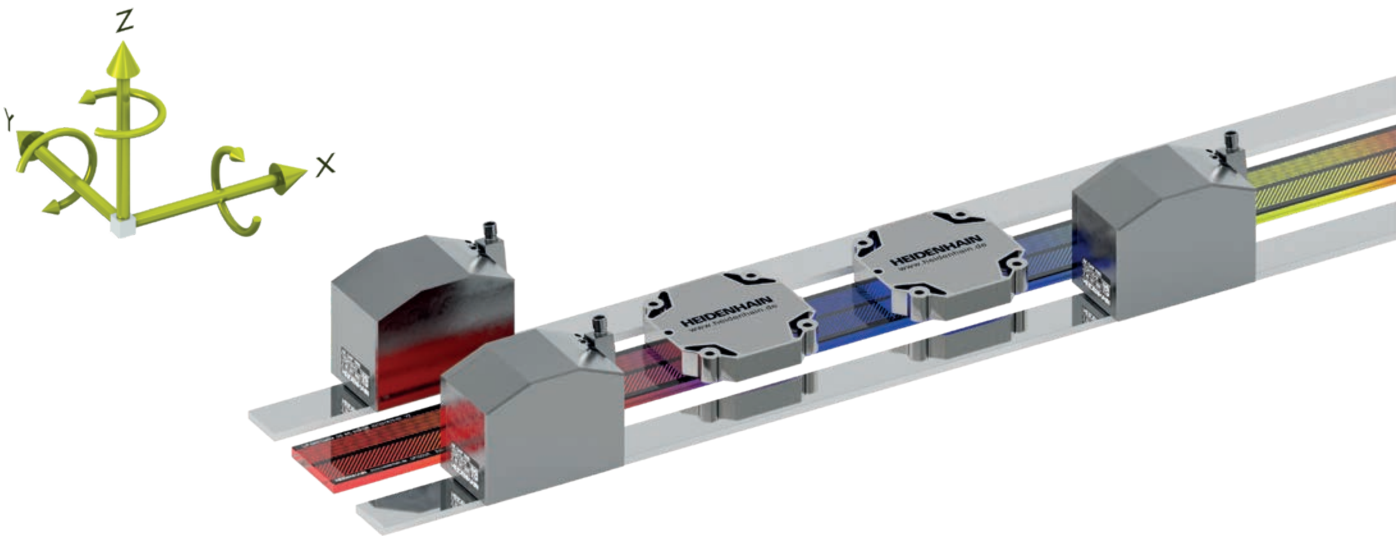
Measuring roll motion:
1 D*plus* scale and 2 GAP measuring mirrors + 1 D*plus* and 2 GAP scanning heads

Measuring the amount of roll about the X axis is somewhat more involved. Two GAP measuring mirrors must be installed parallel to a D*plus* scale, with one GAP scanning head for each mirror. The space requirement in the machine changes accordingly.



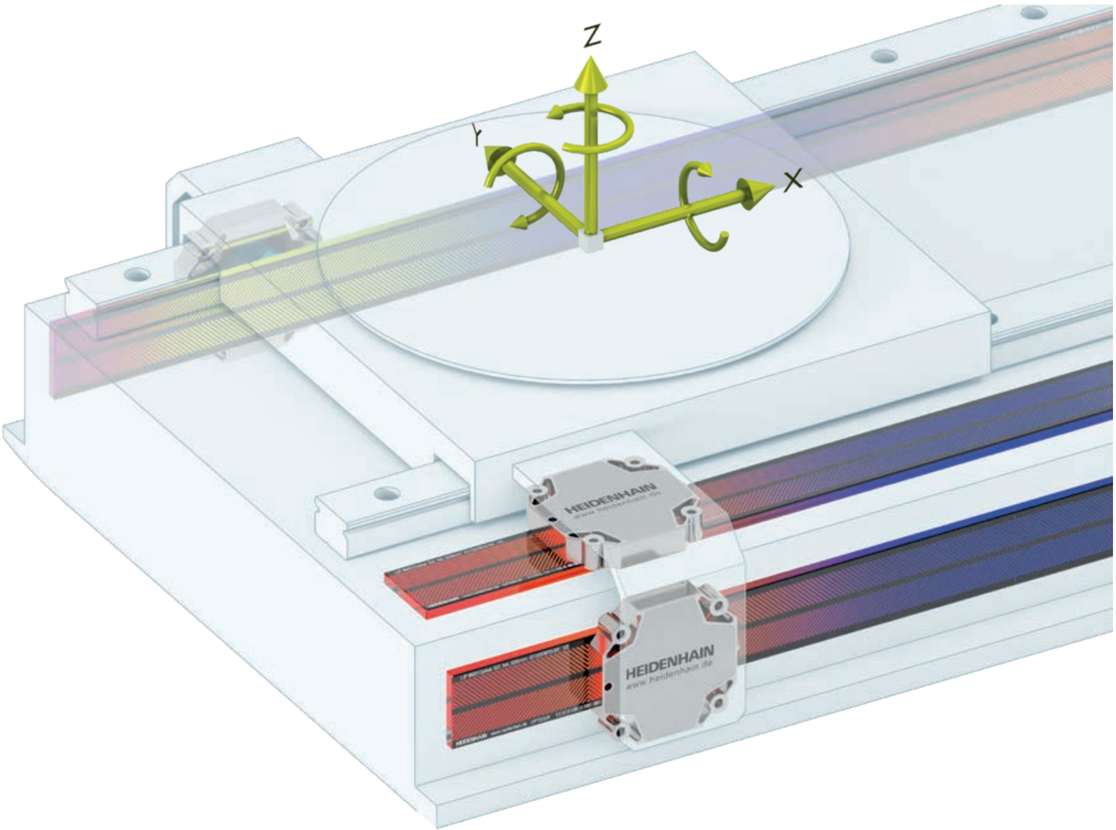
Measuring all degrees of freedom in one mounting plane
1 D*plus* scale and 2 GAP measuring mirrors + 2 D*plus* and 3 GAP scanning heads

Building on the configuration with one D*plus* scale alongside two parallel GAP measuring mirrors, implementing a solution that measures all degrees of freedom is relatively simple. In this case, the D*plus* scale must be scanned by two D*plus* scanning heads. And an additional GAP scanning head must be added to one of the GAP measuring mirrors. These scanning heads also deliver added information, such as about thermally induced deviations.



Measuring all degrees of freedom in two mounting planes
3 D*plus* scales + 3 D*plus* scanning heads in orthogonal planes

Through resourceful arrangement of the scales and adequate space in the machine, all degrees of freedom can also be measured by three D*plus* scales, each with one D*plus* scanning head. The orthogonal and opposing placement of the scales ensures perfect interplay between the primary and secondary axes of measurement . The pitch measurement can be optimized by adding a second D*plus* scanning head to a vertically oriented scale.



TRANSFERABLE ACCURACY: take full advantage of encoder accuracy in your application

What's the best way to get a MULIT-DOF encoder's specified accuracy into your application while keeping installation simple?

One option, of course, is to install the MULTI-DOF scales and scanning heads on your own. Through adhesive bonding or flexure bearings, the mounting process is similar in simplicity to installing conventional encoders. For both types of encoders, the scanning heads are easily attached via screws. Self-installation still yields the benefits of higher accuracy through multi-dimensional measurement and error correction. But to squeeze every last drop of accuracy out of your encoder, HEIDENHAIN offers completed, fully calibrated assemblies.

TRANSFERABLE ACCURACY: fully assembled and calibrated

Adapted to the mounting conditions of your specific application, HEIDENHAIN can deliver MULTI-DOF encoders as completed assemblies with certified accuracy. The TRANSFERABLE ACCURACY concept covers all preparatory work for deployment in your high-accuracy equipment, from the choice of material for the scale (e.g., Zerodur for zero thermal expansion) and carrier (e.g., ceramic) to providing the calibration data.

The scale's carrier is already equipped with decoupling elements for easy and accurate mounting to the machine bed. Thanks to a special measuring machine, the finished assembly is perfectly calibrated and adjusted at HEIDENHAIN. All that remains is for you to mount the carrier (already holding the scale), just as you would a conventional linear scale. There will be an unchanging parallelism error between the D*plus* scale and the guideway, but this systematic error is normal and easy to correct with a calibration run.

After successfully importing and processing the calibration data, you now have a machine axis with exceptional linear position accuracy and straightness and, depending on the quantity and placement of scanning windows, other degrees of freedom as well. This allows you to quickly and easily identify the position errors in your specific system, and to perform the necessary corrections.

LIP 201 D*plus* measuring standard assembly on a ceramic carrier

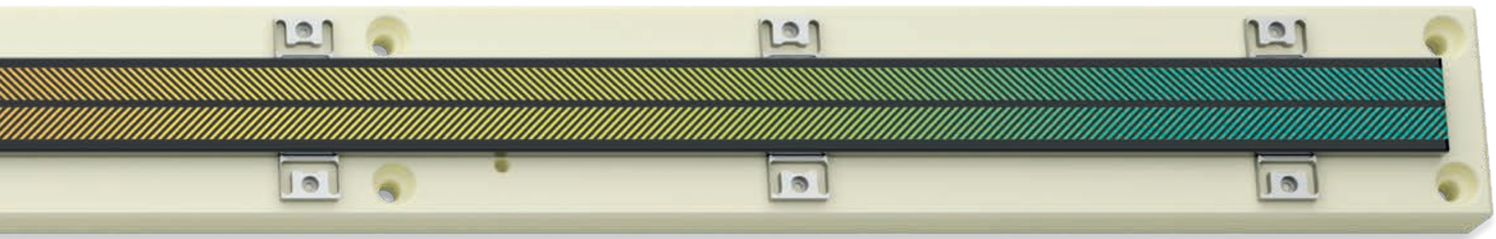
The effectiveness of TRANSFERABLE ACCURACY technology over long periods of machine operation has been measured with a special calibration tool in high-end semiconductor manufacturing operations. The results show that the HEIDENHAIN-certified accuracy (the reproducible linear position accuracy and straightness) for D*plus* encoders was maintained, not only immediately after installation and initial operation in the machine but also after intensive periods of productive use.

More to come:
The future of MULTI-DOF TECHNOLOGY and TRANSFERABLE ACCURACY

Adding to its already extensive range of multi-dimensional encoders and possible combinations, HEIDENHAIN is presently working on more solutions, applications and service offerings for its MULTI-DOF TECHNOLOGY and TRANSFERABLE ACCURACY:

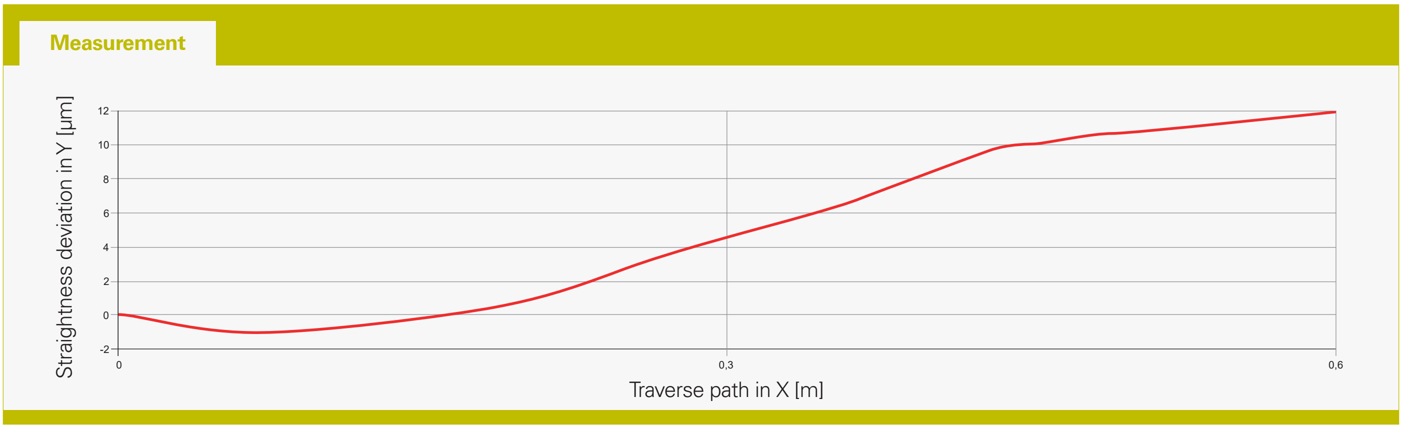
Chief among the upcoming products are rotary solutions, including new versions of the MRP 8000 angle encoder module. Its current design with two scanning heads already meets TRANSFERABLE ACCURACY requirements, making it a great solution for high-accuracy rotary axes and a viable alternative to air bearings. As a result, the MRP 8000 can attain an astounding system accuracy of ±0.1 arc seconds within the application, where it is unfazed by mounting conditions or external factors such as vibrations, shock loads, or temperature fluctuations. Future versions with more scanning heads will uplevel these angle encoder modules into true MULTI-DOF solutions, thus redefining the accuracy limits of rotary applications.

Future service offerings will include a machine calibration tool that can be loaned from HEIDENHAIN. Since machine calibration is not a daily activity, the high cost and continuous maintenance of one's own tool makes it an unattractive investment. A loan device lets you calibrate your systems with a certified tool precisely when needed.

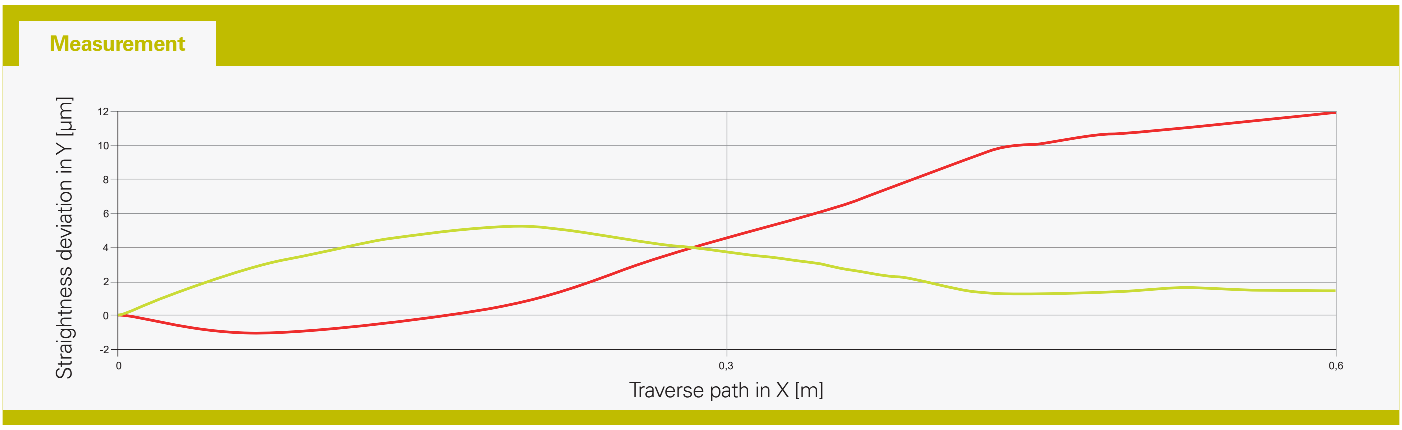


How it works: calibration with MULTI-DOF TECHNOLOGY and TRANSFERABLE ACCURACY

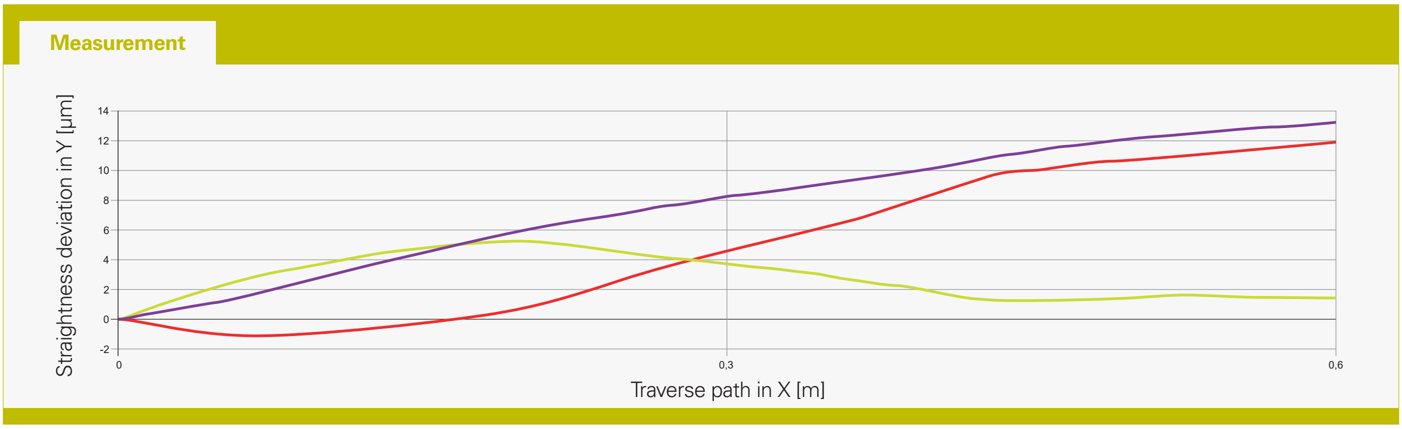
Using a calibrated D*plus* scale unit can improve the accuracy at the tool center point. This example explains the four simple steps for calibration. The individual curves show the deviations in the Y-axis from the absolute straightness in the X direction.



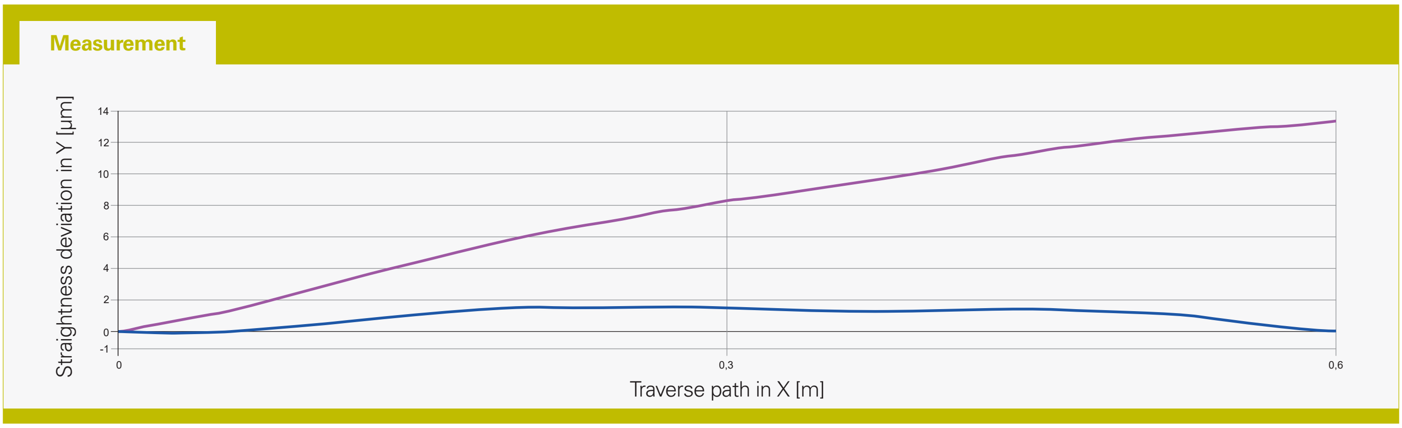
Initial measurement: the red curve shows the measured total position deviation regarding straightness without considering any calibration data.



Calibration data: the green curve shows the straightness deviation calibration data supplied by HEIDENHAIN with the scale assembly compared to the measured total position deviation (red).



Error analysis: in order to determine the actual deviation in the Y-axis, the total position deviation (red) is offset by the calibration data (green). The purple curve shows the measured straightness deviation after considering the calibration data.



Compensation: the blue curve shows the absolute straightness deviation remaining after the calculation compared to the measured straightness deviation (purple) after correction of the linear component. The deviation between the guideway and the D*plus* scale is eliminated mathematically by the 2-point compensation. In order to optimize accuracy at the tool center point, the controller of a motion system can actively compensate for this deviation in the process in another axis.

The EnDat 3 interface:

Less cabling, more options

Greater accuracy also means more data. And this data needs to be transmitted and processed as quickly, reliably and loss-free as possible. Digital interfaces are the obvious first choice. Of these, the purely serial EnDat 3 interface provides additional benefits, especially for encoders with MULTI-DOF TECHNOLOGY:

- **Transmission of all position data over a single cable with four wires**
- **Integration of external sensors**
- **Online diagnostic data for condition monitoring and predictive maintenance in your controller**

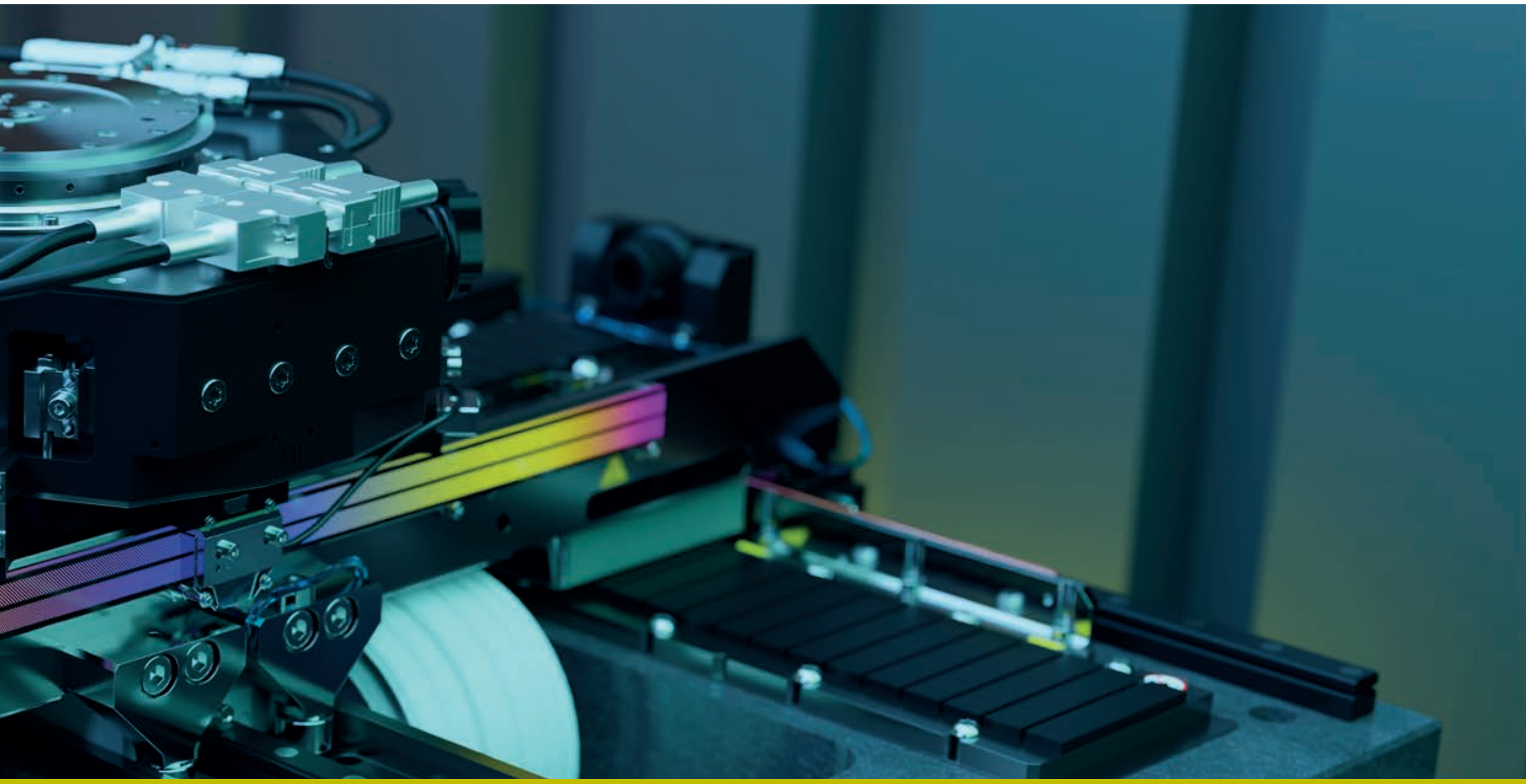
Greater simplicity for MULTI-DOF TECHNOLOGY: only one cable needed for each D*plus* scanning head

A D*plus* scanning head acquires position data from the two tracks of a D*plus* scale. Conventional interfaces cannot transmit this data over a single cable. Nor do they permit multi-scanning-window processing directly in the encoder. But thanks to its high data bandwidth, EnDat 3 is up to the task. And it can do more: EnDat 3 also permits the integration of sensor boxes for additional data about the entire machine, the stage, individual motors and specific axes, such as temperature data from external sensors. This significantly reduces cabling requirements, especially in complex systems with numerous axes and encoders. Less cabling saves space and lowers costs. Using fewer cables and connectors in motion systems also greatly increases process reliability and dynamic performance.

Functional safety and diagnostics: achieve peace of mind with EnDat 3

The EnDat 3 interface is designed for safety-related applications with up to SIL 3. The interface's black-channel principle, along with its separation of data for motion and safety controllers, makes implementation easy. Meanwhile, its online diagnostics for encoders and its easily integrated data from external sensors delivers an extensive data pool for dependable condition monitoring and predictive maintenance in your system controller. You can therefore allow highly dynamic processes to run automatically without worrying about machine damage. EnDat 3 keeps you informed about the status of your machines, enabling early maintenance planning.

Find out more about EnDat 3:
endat.heidenhain.com



Further information:

Discover the latest products and highlights on our microsite: semiconductor.heidenhain.com

Explore the MULTI-DOF TECHNOLOGY brochure with our current product range

Watch our video about MULTI-DOF TECHNOLOGY

Motion systems from ETEL

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1445106-20 · 09/2024 · H · Printed in Germany