Kemro X Robotics
Robot accuracy

White paper

KEBA®

Automation by innovation.

„It is the mark of an educated man to look for precision in each class of things just so far as the nature of the subject admits.“

Aristoteles

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Robot accuracy

The use of industrial robots in different industries has increased significantly since their introduction in the 1950s. Initially, their main benefit was performing repetitive and dangerous tasks, but the precision of their movements was limited.

Advances in disciplines such as lightweight mechanical design, electric servo drives, precision gears, closed loop control, and improved motion planning have led to significant improvements in achievable precision. Nowadays, a path deviation below 1 mm is no longer unusual for a medium-sized precision robot.

Due to the many advantages of robots, more and more fields with significantly higher precision requirements have started to investigate solutions based on robotics. Typical target accuracies are in the order of 0.1 mm.

Examples for such fields are:

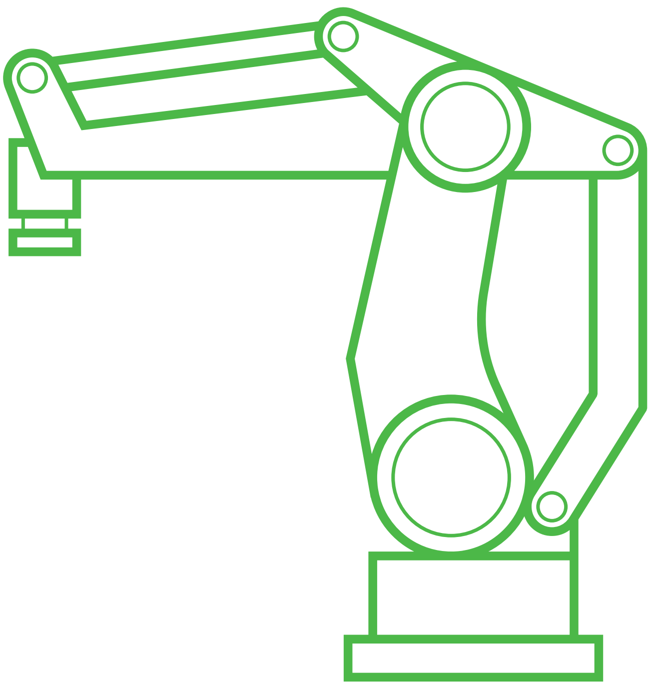
// laser welding and cutting

// precision painting and ink-jet technologies

// 3D printing

// assembling of miniature electronics or also aeroplanes

With the right means and know-how, accuracy levels of better than 0.1 mm are well within reach. ■



Improving robot accuracy

Robot accuracy is a field of continuous improvement. For a long time, the standard approach for high-precision robots was to improve precision in the manufacturing of the mechanical components of the robot, especially the gearboxes – to get closer and closer to the design model.

But enhanced processing power and measurement technologies allow considering a dynamic model of the robot's behavior in the controller – capturing the real characteristics of the mechanics and extending the model with the deviations from the ideal, purely geometry-based model.

Moreover, the pressure to lower prices supports this development. For the serial production of robots, it may be more efficient to reduce classic manufacturing costs (parts and labor) and spend the effort on calibration and compensation functions.

There is quite a number of effects that can influence and degrade robot accuracy, especially if we consider dynamic errors when moving along a path. The relative importance of these factors is different for each type of robot. »

The most important factors are:

// robot geometry

- dimensions
- angular deviations in axis alignment

// gear effects:

- gear ratio & gear ripple
- elasticity, backlash, hysteresis

// limited stiffness: link elasticity, bearing errors (tumbling motion, cross elasticity)

// servo errors

// vibrations

// factors of lower importance:

- encoder accuracy
- temperature effects of elongation

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Leonardo Da Vinci developed the first robot.

In other words, there is a significant number of different factors causing path deviations, and most of them can be modeled more or less accurately. However, a complex compensation model with many parameters has the drawback of potentially becoming unreliable. Each additional parameter opens up a new dimension of variations. The measurements must contain independent variations of all these dimensions to reliably identify the influence of each parameter. This is by no means an easy task. Combining a set of too complex compensation functions with too weak measurements may lead to severe degradation of accuracy in situations not covered by the measurements.

If we have, for example, a dependency on weight and position and vary weight and position together in a fixed ratio, we are unable to identify the influence of each of the two individually. If we do not vary this ratio during the measurement, but later in the application, we enter uncharted territory.

Optimizing robot accuracy requires a precise identification of the dominant factors. This is the only way to acquire a reliable compensation model. The more effects are considered, the more effort has to be spent on calibration and validation of the compensation functions, which will potentially decrease the robustness of the solutions. ■

Accuracy factors

Robot geometry is defined by angles and distances between robot joints. For serial kinematics, the errors of all links add up to the total error of the TCP (Tool Center Point).

Robot geometry

This is why robot accuracy is very sensitive to the exact geometric parameters. Errors in distances directly translate to TCP errors. Errors in angles affect the TCP via the respective lever from the rotation center.

Improving the geometric model of the robot is the field of classic robot calibration. »

SPOTLIGHT

Kemro X Robotics robot calibration

KEBA robot control software has functions for the calibration of robots using laser trackers or other external measurement devices.

This includes the automated generation of robot programs required for the measurement process.

Calibration results can be directly imported into the robot configuration, thus avoiding problems of parameter conventions and conversions.

Advanced Kemro X Robotics robotic calibration not only considers geometric parameters, but also gear elasticity.

The picture shows the difference between uncalibrated robot, classic geometric calibration and additional calibration of gear effects.

Gear effects

Most robots have their position encoders for their joints mounted on the motor shaft. This is essential for obtaining a robust and stable drive speed loop. However, errors in the gearbox add to the total position error of the robot.

Gear ratio

Of course the transmission ratio is known by design. But it must also be considered with a sufficient precision. This is especially important for linear axes with large travel ranges.

Gear elasticity

An industrial robot controller usually works with a stiff body model of the robot. In reality, however, the entire robot and most importantly the gears are not perfectly stiff, so the joint position and the TCP position will be slightly altered, depending on the load.

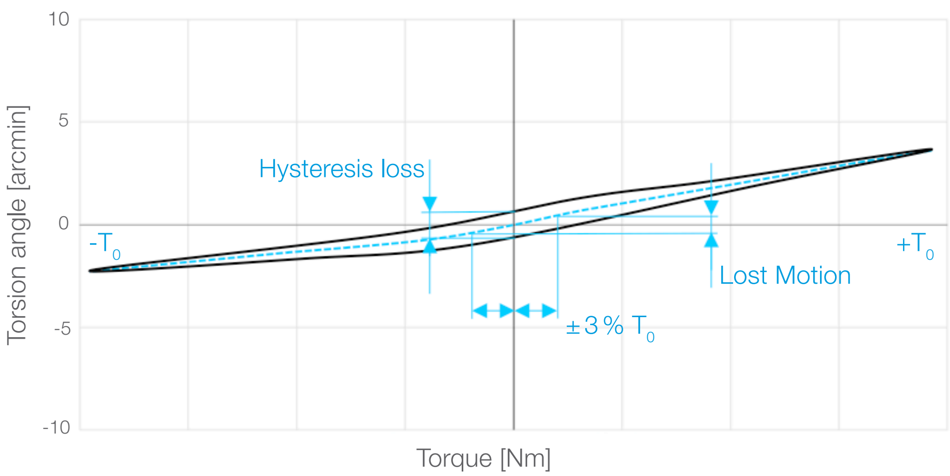
Some numbers

For a linear rail with **10-meter** range 0,01 mm accuracy translates to a relative resolution of 1:1 000 000. This requires a precision of more than **6 digits.**

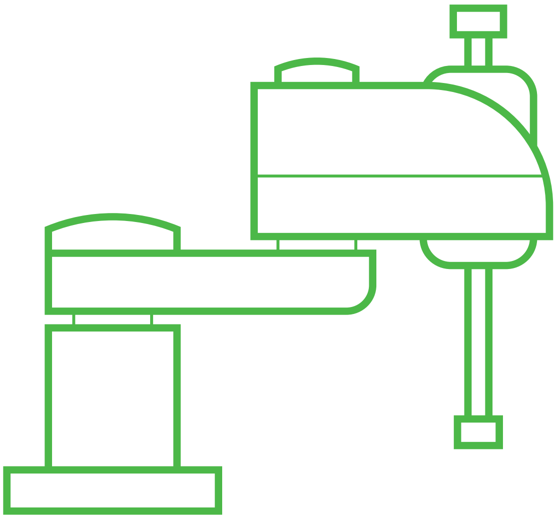
Gear elasticity at full load results in a deviation of some arcmins **(1/60 degrees).**

The thermal expansion of aluminium of a length of 2 meters over a temperature range of 20 K is about **1 mm.**

At a closer look, the gear elasticity is not even constant across the range of loads. Typically, gears are softer at zero load and become stiffer as loads increase. »



The stiffness characteristics of a gear show mainly two effects: a nonlinear elasticity, which can be compensated with the right model, and a hysteresis, which adds a factor not controllable by compensation models. Photo credit: Nabtesco Precision Europe GmbH



Given the gear elasticity characteristics and a correct dynamic robot model, the deviation can be calculated from the torque load and compensated for in the controller.

Compensation of gear elasticity does not play an important role when the robot load is quite constant, the working range is small, and the dynamics are low. In these cases, the gear elasticity has the same effect as a constant joint position offset and can be modeled in that manner.

Gear hysteresis and hysteresis loss ("backlash")

As stated above, the angular precision and hence the joint angles are critical for robot accuracy. This also means that any backlash of the gear will compromise robot precision. While the gear effects explained above can be considered in an extended robot model, backlash is a lot harder to tackle.

Backlash in fact means that there is an uncertainty about the real joint position. In slow movements around zero it is impossible to know at which position within the hysteresis window the joint will settle at standstill. Therefore, backlash is a severe limiting factor for robot accuracy.

Basic backlash models, like the ones often used for CNC machines with linear axes, simply add a hysteresis depending on the direction of movement. An improved compensation model might add the hysteresis depending on the sign of the gear torque.

In many cases, backlash is a rough simplification of the real behavior of the drive train. Most of the behavior is not really of a bang-bang characteristic, but a combination of elasticity and friction. When a gear is deformed elastically by a torque load and the load is reduced back to zero, the gear output will not return to the zero position. Elasticity in combination with friction will result in a small offset. When the procedure is repeated with the inverted direction of the torque load, the final deviation will also have changed direction. When the torque resulting from a certain deformation is below the stiction value of the gear output at standstill, the gear output will stay at its position without relaxing the deformation. The correct term for this behavior is hysteresis loss.

In general, there is a complex interplay of elasticity, friction and inertia of the parts in a dynamic case. It is nearly impossible to precisely predict at which position the gear output will come to rest. This is why the change of torque load direction of an axis is so critical for robot precision and thus remains a key factor for the mechanical design of the robot.

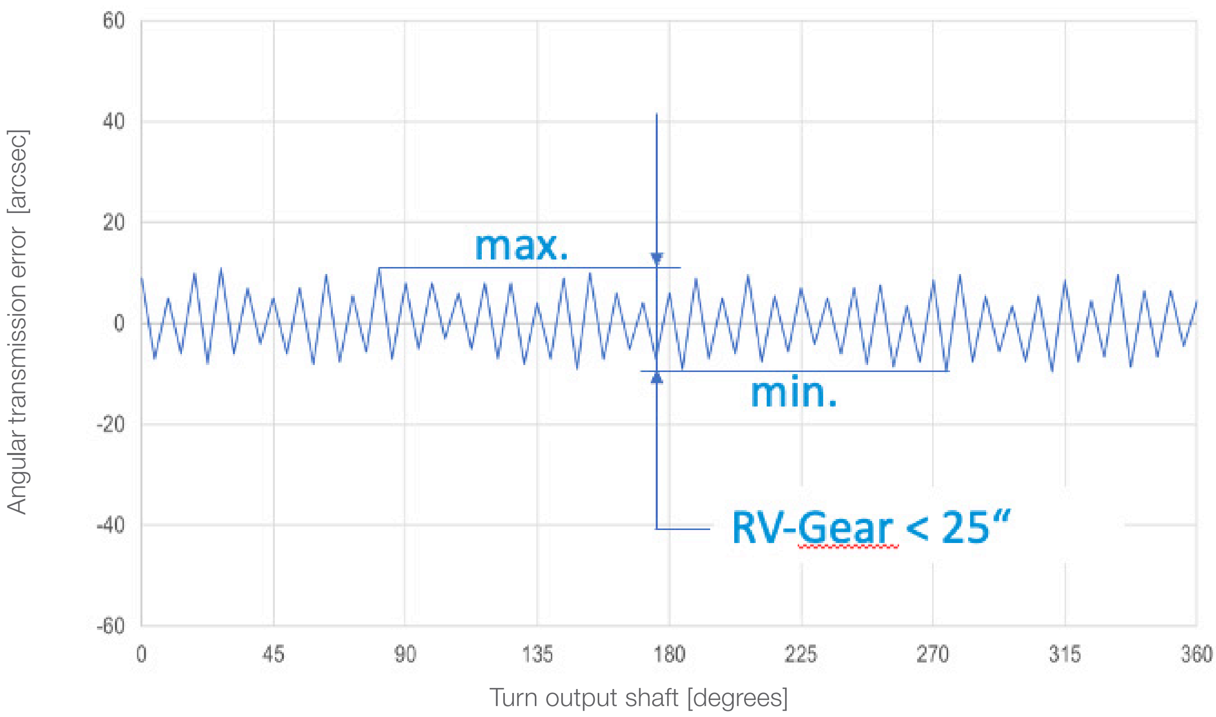
Wherever possible, backlash is to be avoided. This is not only true for the gear itself but for all elements in the drive trains (belt transmission, coupling gears, …). »

Gear transmission error (“ripple”)

An important gear characteristic is the transmission error – the so-called gear ripple. As most gears are designed with toothed wheels or similar geometries, the gear ratio is not perfectly constant. The effective radius of two wheels in contact – i. e. the gear ratio – is slightly modulated by the depth of the teeth and the ratio of radii at the current contact point. Production tolerances for the elements add up to these effects resulting in the full transmission error of a gear. This results in a variation of the gear ratio depending on the gear position. For typical robot gears, this effect leads to TCP deviations for a medium sized robot of about 0.1 mm or more.

Dual encoder system

Gear effects can be eliminated by a dual encoder system. In such a setting, there is a second encoder mounted on the output shaft of the gear, which exactly measures the joint angle. If this second encoder is used for the position control loop, gear effects will have no influence on the robot’s accuracy. Also, a second encoder can improve the backlash/friction behavior significantly, as the motion controller can take these disturbances into account. »



Gear transmission errors are an important quality feature of a gear. They not only add to a static deviation but the periodic characteristic may be the reason for vibrations at certain speeds. Photo credit: Nabtesco Precision Europe GmbH

3,3 million industrial robots are estimated to be in use worldwide.

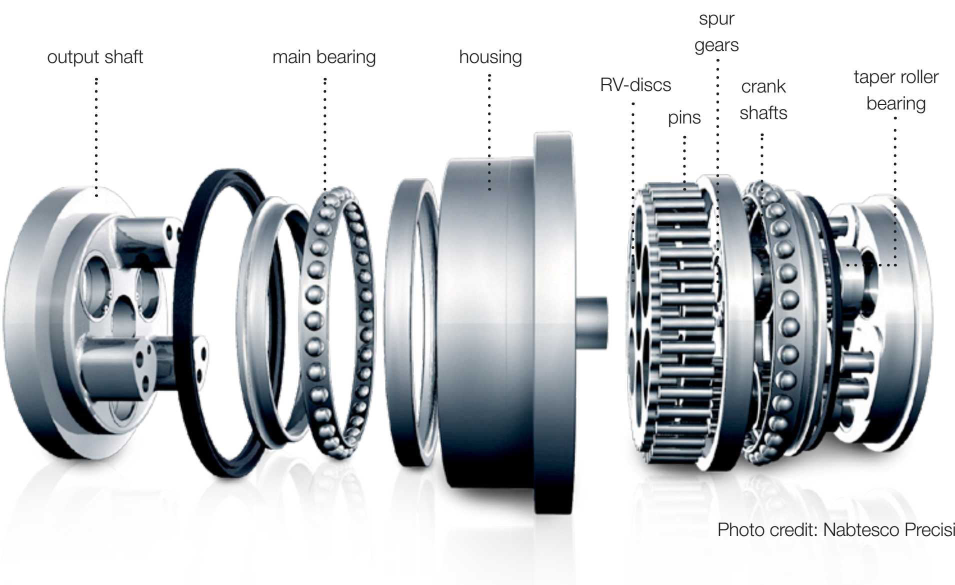


Photo credit: Nabtesco Precision Europe GmbH

Nabtesco & KEBA cooperation

Nabtesco

Cycloidal gear specialist Nabtesco and controller expert KEBA are among the technology leaders in their industries. The two robotics experts have bundled their expertise, experience and know-how.

Robot precision

The purpose of this cooperation is to improve robot precision. KEBA controllers are prepared to integrate transmission-specific data and characteristics from Nabtesco gears in order to increase robot precision. Gear data can either be type-specific or based on the individual characteristics of a gear measured at the Nabtesco plant.

The goal: Industrial robots with the highest precision available on the market.

Condition monitoring & predictive maintenance

Know-how is not only shared for precision, but also for the gear life cycle. Functions are added to KEBA controllers that indicate the current load in an application. This way, excessive loads above the specified range can be detected and unexpected premature failure can be avoided. With this information, new business models such as improved service offerings or preventive maintenance can be offered by the robot manufacturer.

Robot dimensioning

The simulation capabilities of KEBA controllers together with the data and characteristics from Nabtesco gears can be used for dimensioning the robot mechanics.

Limited robot stiffness

The gear elasticity is one example of a load-dependent deformation of the robot. The bearings of the joint and the robot links also have some elasticity. The bearings may deflect due to moments perpendicular to the joint axis. Even the links that make up the elements of an arm may be flexible. The critical points of every arm are the fixtures where the elements are connected, mostly by screws.

On a robot with a balanced design the contribution of all these factors – gears, bearings and links – are of the same order of magnitude. Accounting for all these effects in a compensation model is a complex task, and the effort needed to determine all necessary parameters often does not pay off.

Some of the elasticity effects of the links may be compensated by measuring the complete robot and adapting the gear elasticity parameters, so that they contain some amount of link elasticity ("lumped elasticity model").

Servo errors

At standstill the servo loop usually is able to track the actual motor position to the set value. The position control loop in the drives typically contains an integrator that will drive the position error to zero. But when the robot is moved along a path, there will be a deviation of actual motor positions and set values. Moreover, when the robot load is changing or some external force is applied, there will be a servo following error. Therefore, the servo following error has to be considered in order to validate the overall precision of a robot during motion.

Dynamic robot model

For a robot operating in free space without contact, the servo error can be significantly reduced by using a dynamic robot model, which is used to calculate the required motor torques for a desired trajectory. With a perfect model the robot could be held on its path just via computed torques without any feedback. However, the robot model will not be perfect. Therefore, feedback control is still necessary, but the feedback only needs to compensate model errors and disturbances. »

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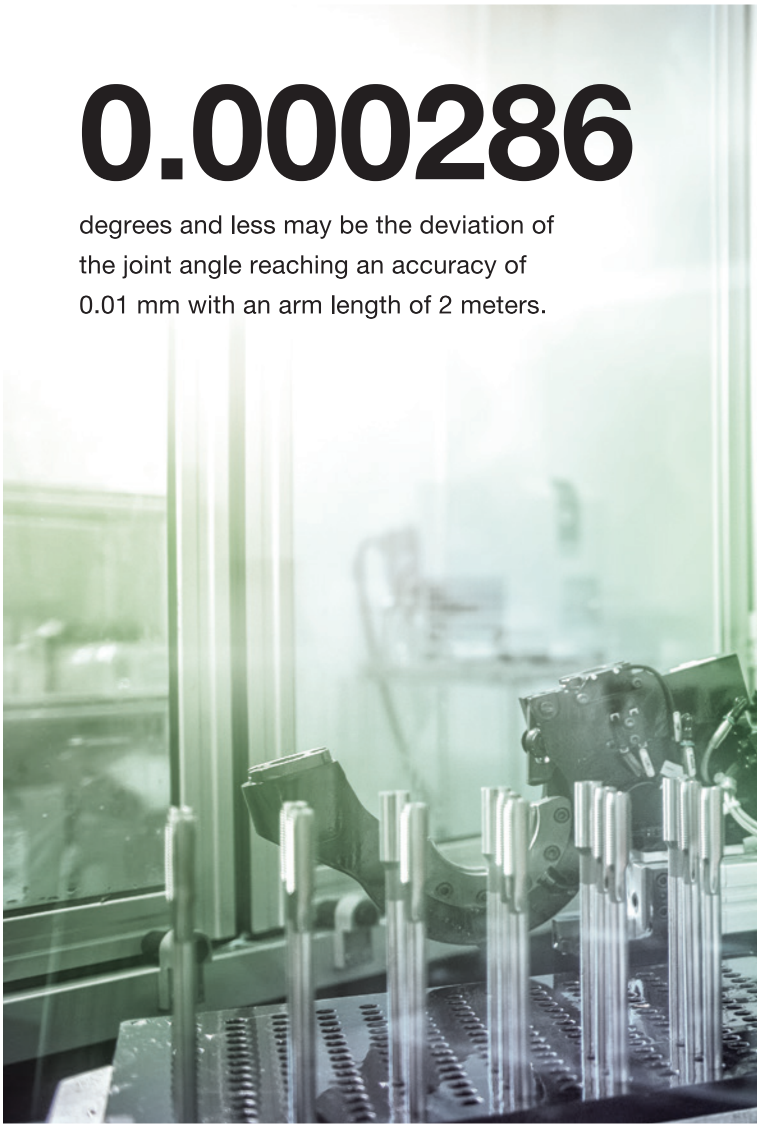
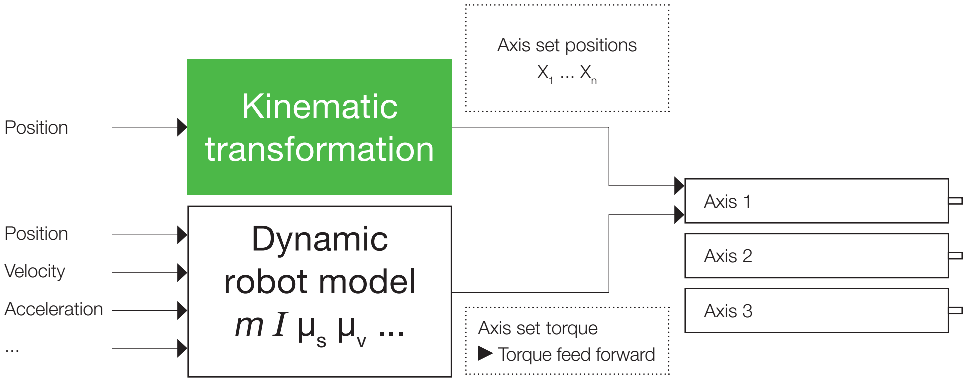
degrees and less may be the deviation of the joint angle reaching an accuracy of 0.01 mm with an arm length of 2 meters.



Interpolator

A dynamic robot model can be used to calculate the required torques for the motors and to reduce the servo following errors significantly, especially at very low and very high speed.
Photo credit: KEBA



Stiff body model

A common simplification is to neglect all the elasticities and use a stiff body model for the computed torque. The precision of such a model will degrade as soon as dynamic effects from elasticities increase. This applies to movements at very high dynamics or with disturbances close to the resonant frequencies of the system.

Friction at low speed

Another major difficulty in dynamic robot modeling is friction at very low speeds or at points where the direction is reversed. Friction in this area is a complex phenomenon. A good friction model can significantly reduce servo following errors at the velocity zero crossing, which represents a severe problem in continuous path applications with high precision requirements.

Elastic dynamic model

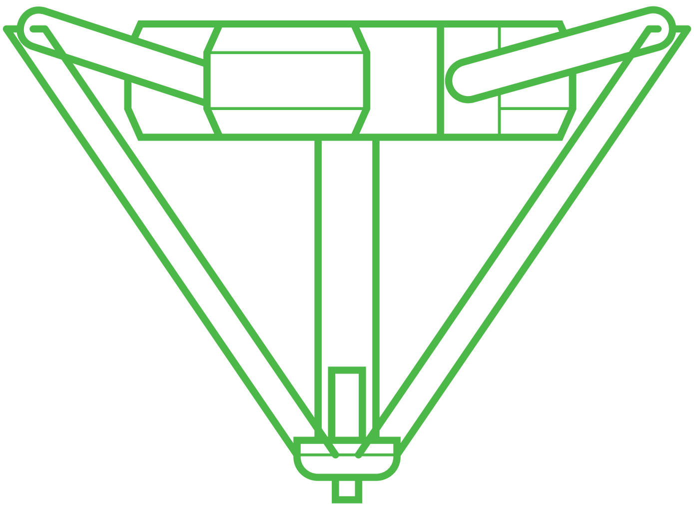
Sophisticated dynamic models may also include the effects of elastic coupling between motor and robot arm. »

SPOTLIGHT

Kemro X Robotics dynamic model

KEBA robot controllers provide a dynamic model for serial and parallel robots. Parameters can be gained from design data. Moreover, parameter identification from robot measurements is available.

The dynamic model contains precise friction models, delivering high accuracy both at low speeds and in situations of reversing speed direction. Parameter identification for variable load contributions like tool or workpiece and also friction can be performed online on the controller.



Vibration

For motions at low dynamics the elastic effects can be accounted for in a quasi-static approach leading to small geometric deflections. But the robot's inertia – the motors and the robot links – together with the elasticities form a resonant system. The resonant frequencies can either be stimulated by the trajectory signals generated by path planning or by disturbances and external forces. While stimulation emerging from path planning can be avoided with the help of motion profiles or filters, disturbances from inside the mechanical system or external forces cannot be removed.

Disturbances of the latter kind are e. g. periodic errors of the gear ratio (gear ripple). At a certain drive velocity, the pattern of this ripple will match some resonant frequency of the robot and stimulate vibrations in the drive train, which cannot be compensated by the drive feedback. The dynamic deflections due to the elasticities will lead to errors at the TCP that are greater than the stiff body errors plus the servo errors. »

High-order errors

There are a number of factors influencing robot accuracy not mentioned so far.

Movable or soft parts mounted on the robot arm may degrade accuracy, especially if they contain additional links of the tool or the robot arm to the base, like cables or hoses. These forces transmitted to the robot arm can outweigh all other efforts to increase accuracy.

Higher-order errors are mostly controlled by avoiding rather than compensating them, or by simple lump approaches in the dynamic model.

In addition, temperature elongation or deformation of mechanical parts may degrade robot accuracy. Depending on the kind of lubrication of the gears, temperature may also have a strong influence on friction. Temperature effects may be compensated if the effort for – quite elaborate – measurements is made. ■

Robot validation

For any application requiring high accuracy, the validation of the accuracy plays a key role – whether in the commissioning phase for obtaining information on initial accuracy, or during an optimization process for judging the effectiveness of the measures taken. Characterizing a robot's accuracy can be quite complex if all the requirements from all the different applications are taken into account.

ISO 9283

The ISO 9283 standard defines measurement methods as well as calculation criteria for different accuracy aspects that allow a comparison of characterization results between different robots and/or robot manufacturers. It contains both static and dynamic characteristics.

The validation procedure is defined as well as the exact calculation of accuracy criteria.

Application-specific validation

The standard provides a good basis for comparing robots and gives a rough indication about accuracy, but it is not always the appropriate characterization for the reachable level for a certain application.

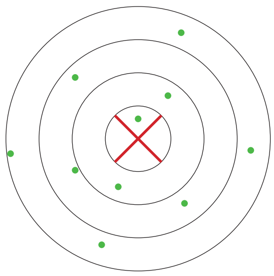
Robot accuracy depends on many factors like working range, speed, shape of the required movement, etc. Therefore, it is recommended to validate the accuracy in an application-specific setting.

Accuracy analysis

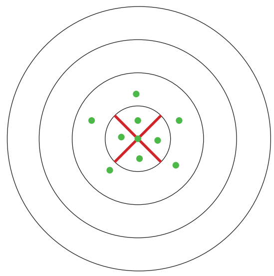
After a robot has been validated there is often the need to know about the limiting factors of accuracy. One first has to find the areas of the workspace with maximum deviation and then identify the reason for the deviation. Identifying the main contributing factor to the deviation is the pre-condition for improving the system – be it a better fit of the calibration model or model parameters, optimization of the drive control, or an improvement of the robot mechanics.

A detailed, well-founded analysis of a certain effect often requires a special robot trajectory and corresponding measurements. ■

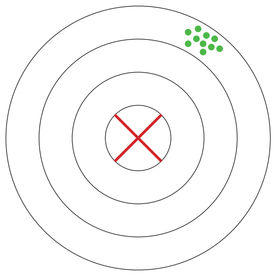
Repeatability and accuracy over 10 measurements



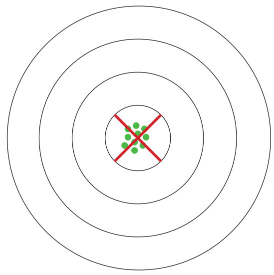
Bad repeatability and bad accuracy



Bad repeatability and good accuracy



Good repeatability and bad accuracy



Good repeatability and good accuracy

Metrics defined in ISO 9283 define validation procedures for robots with defined calculation of characteristics. While the metrics make robots better comparable, the significance of the metrics for a specific application has to be considered In detail. Photo credit: KEBA

SPOTLIGHT

Kemro X Robotics robot validation

KEBA robot control software supports robot validation. Robot programs according to the ISO 9283 standard can be generated, the measurement with the robot is supported, and the calculation of criteria according to the standard is provided.
When using a laser tracker with a real-time interface, dynamic measurements and accuracy analyses are supported. This is especially important for applications requiring high accuracy along the entire motion path.

Analysis can be used to derive further steps of accuracy improvement, be it better calibration and compensation of mechanical characteristics, better servo control, or even pointers as to where the mechanics need to be improved.

Accuracy goals

The strategy of robot calibration and compensation may differ depending on the circumstances of the application. The accuracy required for a certain application often can be achieved with less effort when considering these circumstances.

The model for the robot will be incomplete in any case. The unmodeled effects result in the residual deviation after activating compensation. The goal of efficient accuracy optimization is to keep the deviations below a given limit with minimum effort. Therefore, it is important to know the influence of the different effects in order to select the minimum set of compensation functions.

Achieving high accuracy with a high variation of robot positions, speed and workpiece loads is very demanding in terms of measurement requirements and parameter tuning. But even then, the optimization will be a compromise for an overall minimization in the various different situations. If specializing with a view to selected, mission-critical situations, the compromise will be much easier to find.

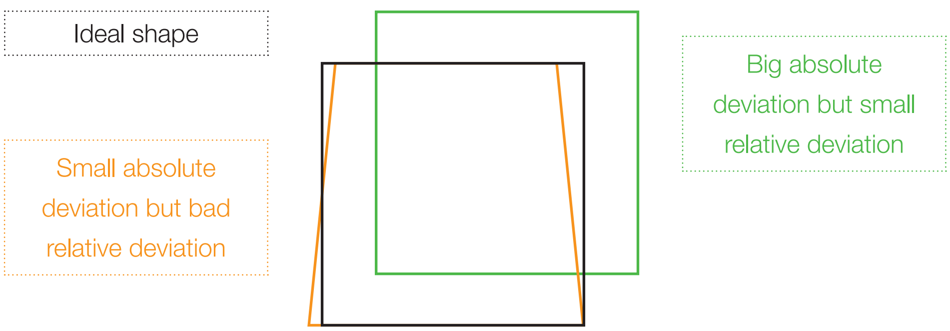
Absolute and relative accuracy

When talking about robot accuracy, one often talks about absolute accuracy, which is the deviation of the real TCP from an position programmed offline. The position usually refers to the robot base system or some defined object reference system.

Reference systems

The first difficulty arising here is knowing the exact position of the robot base system or the object reference system in the real world. This position is not always clearly defined and is often difficult to measure in a robot cell. »

Not only the position deviation is important but also the deviation from a geometrical shape. Pure position offsets can easily compensated. Photo credit: KEBA



Relative accuracy

For many tasks a more relaxed kind of accuracy is sufficient. Especially in high-precision applications, the working area of the robot is well defined. In this case, the robot does not need the high accuracy in the whole reachable working area.

For high-precision tasks, a constant offset between positions programmed offline and real-world positions is often eliminated by a sensor system. The deviation is measured e.g. by image processing systems, and the robot program is shifted correspondingly.

In such a setting a high geometrical precision in a restricted area relative to a defined reference position is required. This is relative accuracy, relative to a defined point, and significantly relaxes the effort necessary to reach a given accuracy level. »

SPOTLIGHT

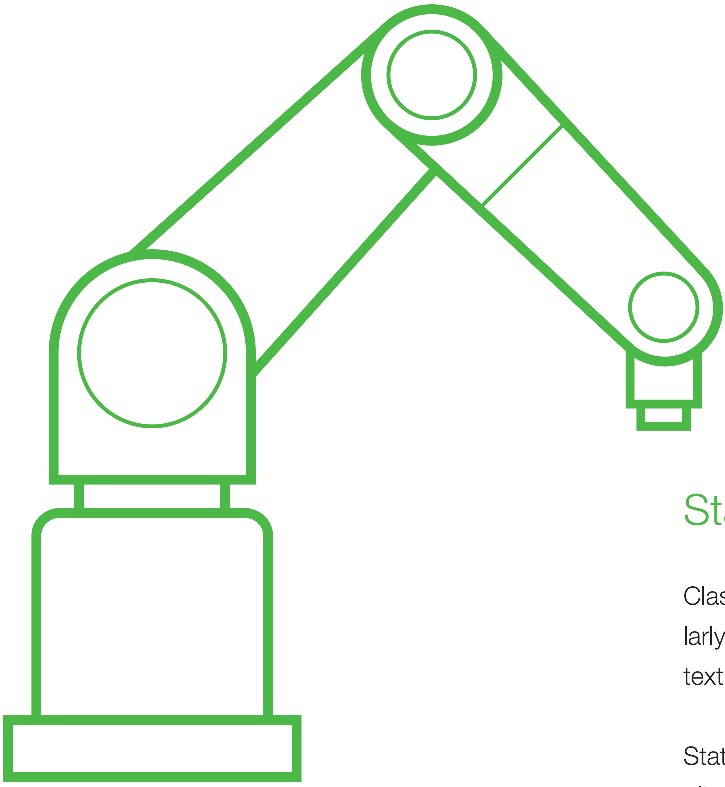
KEBA analysis services

Robot validation determines accuracy metrics, but for improving accuracy it is necessary to know the reasons for the deviations.

Isolating the dominant deviation effect leads to effective improvements.

This kind of analysis determines the key issue that requires changing, be it improving the calibration process or rede-signing mechanical components.

KEBA offers validation software and services that help robot builders gain these invaluable insights.



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and less must be the required relative resolution of a full rotation of a joint to achieve 0.01 mm with a 2-meter arm - which corresponds to a resolution of more than 18 bits

Static and dynamic accuracy

Classic robot calibration is performed at standstill. Similarly, robot repeatability – a term often found in the context of robot accuracy – is only a static characterization.

Static characteristics are important in point-oriented applications, like pick & place or spot welding, where it is sufficient to reach a certain accuracy at the end point. Many processes, however, need the accuracy during the movement on a pre-defined path. In dynamic situations there is a number of additional errors. They can be divided mainly into tracking errors of the servos and dynamic deflections of the mechanics.

Global vs. local model

When the workspace requiring high accuracy is well defined, compensation for the dominant deviations within this workspace is all that is needed. This means reduced calibration effort, but also a better fit for the compensation.

Furthermore, in this case parameters can be adjusted to compensate for unmodeled deviations. This is the reason why local optimization may lead to better results than global optimization.

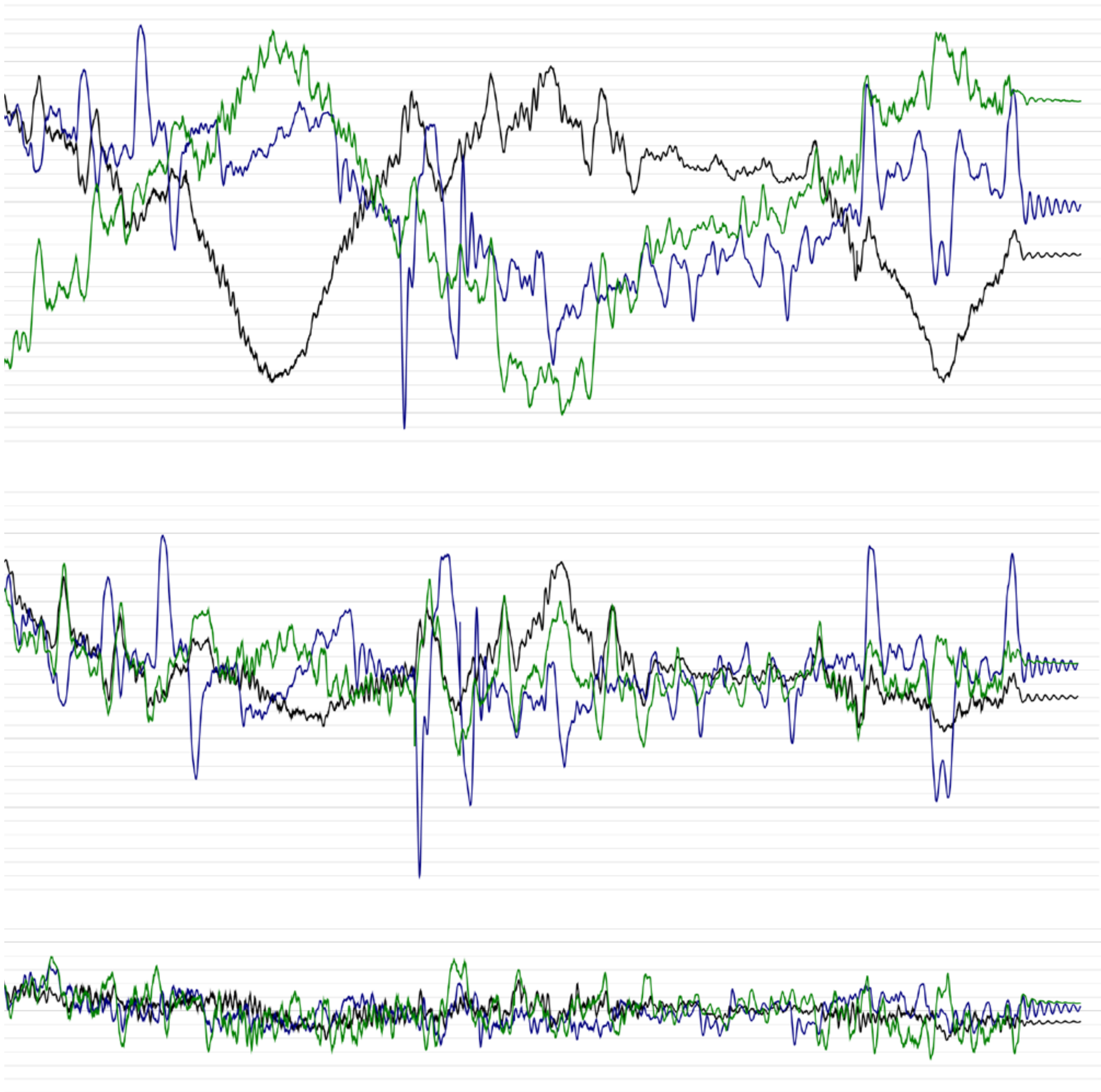
But local optimization has to be handled with care: The influence of unmodeled effects may lead to inappropriate parameters on a global level.

Limits of compensation

Some mechanical effects may evade any effort for accuracy improvements. In essence, these are effects that allow some movement without any sensor feedback or defined related force.

Obviously, any loose connection in the robot arm will prevent precise positioning of the tool. Gear hysteresis or backlash belong in this category, too. Loose parts like cable tracks or hoses may introduce variable forces to the robot tool and consequently degrade precision. ■

Compensation of gear elasticity can be done at different levels:



Static compensation or static and dynamic compensation. The picture shows Cartesian deviations of the TCP for a movement in a vertical plane without compensation (top), with compensation of static moments (center) or with compensation of static and dynamic moments. Photo credit: KEBA

Summary

Over the years robots have become more and more precise. On the one hand, static accuracy and repeatability are important for point-oriented tasks like pick&place applications. On the other hand, many processes require accuracy when moving along a predefined path.

The most important factors in regard to robot accuracy are:

// robot geometry

// gear effects

// limited stiffness

// servo errors

// vibrations

Applications that require high precision robotics:

// laser welding & cutting

// painting & Ink-jet technologies

// high-precision assembly

// 3D printing

For a long time, the standard approach to high-precision robotics was to perfect precision in manufacturing. Improved processing performance and measurement technologies offer the opportunity to evolve the robot model in control.

The goal of efficient accuracy optimization is to keep the deviations below a given limit with minimum effort. Pressure on price supports this development.

Robot validation plays an important role, and ISO 9283 defines measurement methods as well as calculation criteria for different accuracy aspects. It contains both static and dynamic characteristics.

Achieving the required precision for a robot or a specific application with minimum effort and costs requires a profound understanding of the accuracy factors. ■

Robot Effects Model

Limits

Vibration Servo

Static

Accuracy

Errors

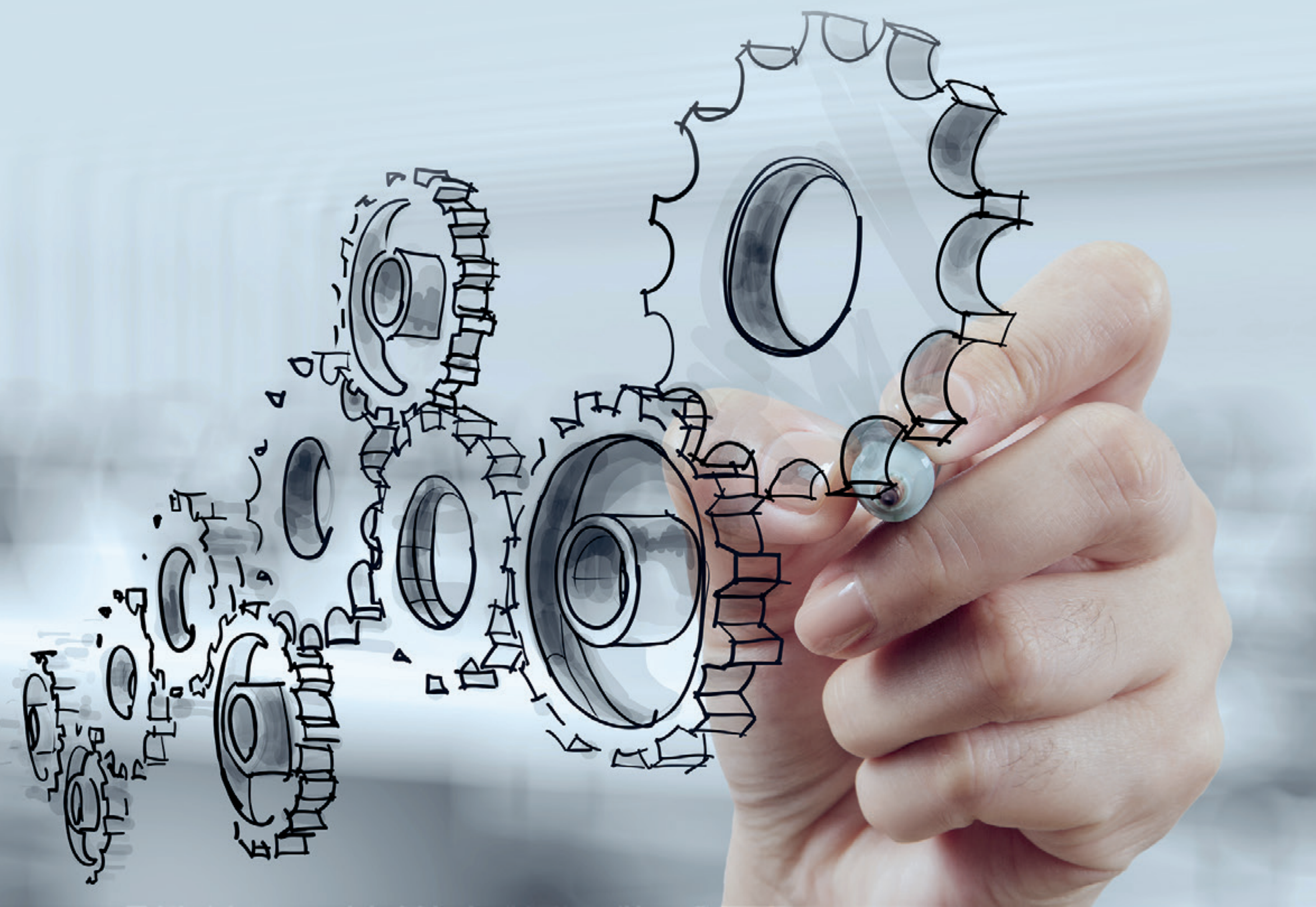
Gear

Validation Factors

Calibration Geometry

Dynamic

Stiffness Analysis



About KEBA AG

KEBA, founded in 1968, with headquarters in Linz (Austria) and subsidiaries worldwide, operates in three business areas: Industrial Automation, Handover Automation and Energy Automation. The product portfolio of the automation expert, which has a workforce of around 1,800, includes control and safety technology as well as drive technology for machines and robots, ATMs, parcel and transfer machines, power charging stations for electric cars and heating control systems.

In the area of industrial automation, KEBA develops and produces innovative and high-quality automation solutions for general machine and tool construction as well as for intralogistics, robotics, plastics, wind energy, turbo systems and sheet metal processing in accordance with the guiding principle „Automation by innovation“. Whether hardware or software, individual components or complete solutions - the Austrian technology expert offers powerful, modular and safe solutions for all industrial requirements.

KEBA Industrial Automation GmbH
Reindlstraße 51, 4040 Linz/Austria, Phone +43 732 7090-0, keba@keba.com

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Austria / China / Czech Republic / Germany / India / Italy / Japan / Netherlands
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