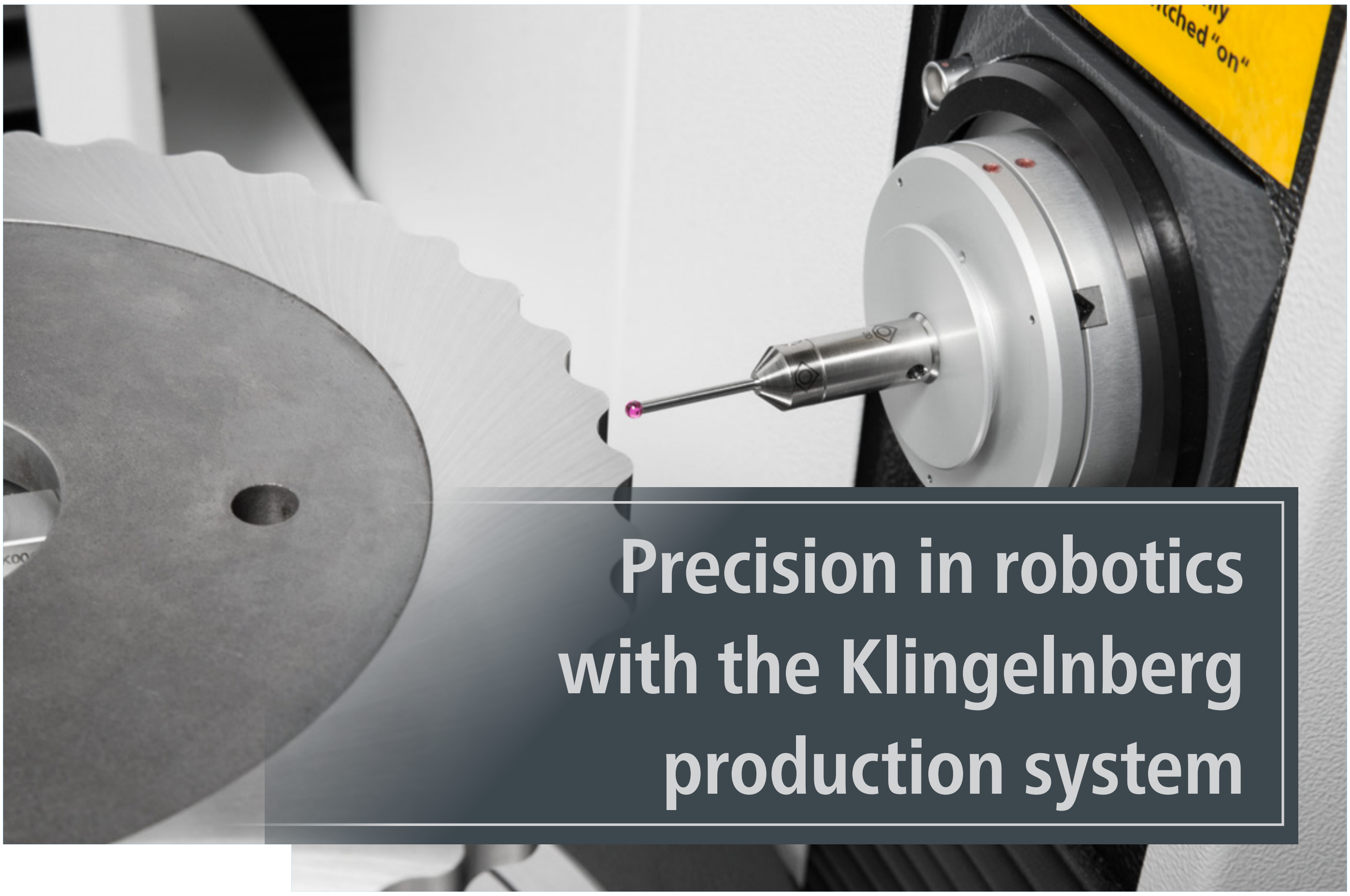

Precision in robotics with the Klingelnberg production system

Robots – an integral part of modern production and handling systems

Content:

Robot-based automation solutions are an integral part of industrial production sites today, and robots execute a broad range of complex tasks. For example, in the automotive industry, where robots are used in press plants, body shops and paint shops, the degree of automation now exceeds 90%. Robots are also being used increasingly in less automated areas of automotive manufacturing and production, such as vehicle final assembly. Thanks to assistance by robot systems and automation solutions, the physical stresses on workers performing repetitive, ergonomically critical activities and movements are significantly reduced. Moreover, compared with conventional manual and mechanized processing solutions, robot systems have the edge in terms of high availability and reliability, as well as positioning accuracy and reproducibility in motion sequences. For these reasons, robot systems are well established in many applications and sectors, not just industry: Highly precise and sensitive robot assistance systems also help doctors successfully perform minimally invasive interventions. They are also being used increasingly to care for disabled persons. In a price and quantity-driven market, the growing demand for robot systems in general results in the need for efficient and robust production of quality-critical components.

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A look at the market for industrial robots alone shows just how much the demand is increasing: Since 2010, the global market for industrial robots has grown steadily at an average rate of approximately 15% annually.

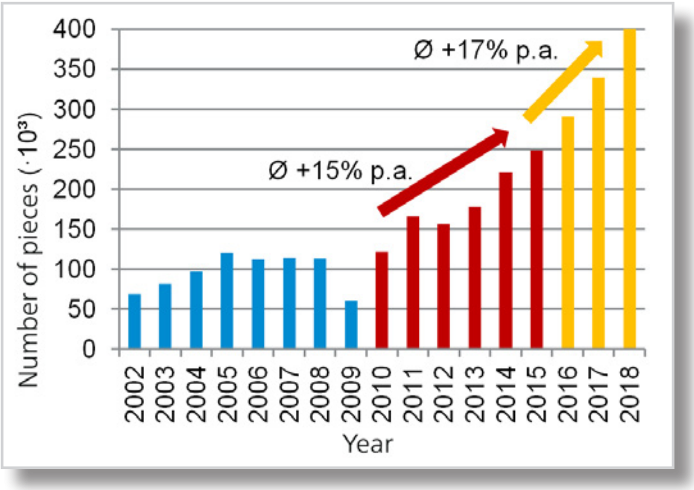

Figure 1: Global sales of industrial robots (Klingelnberg Management estimate)

Thus, between 2011 and 2015, approximately 200,000 industrial robots on average were introduced to the market (Klingelnberg Management estimate). This corresponds to an increase in industrial robots installed worldwide of approximately 80,000 units compared to the economically favorable years 2005 to 2008 (Klingelnberg Management estimate). With a market share of 66%, vertical articulated robots with five or six axes in particular account for a significant number of these.

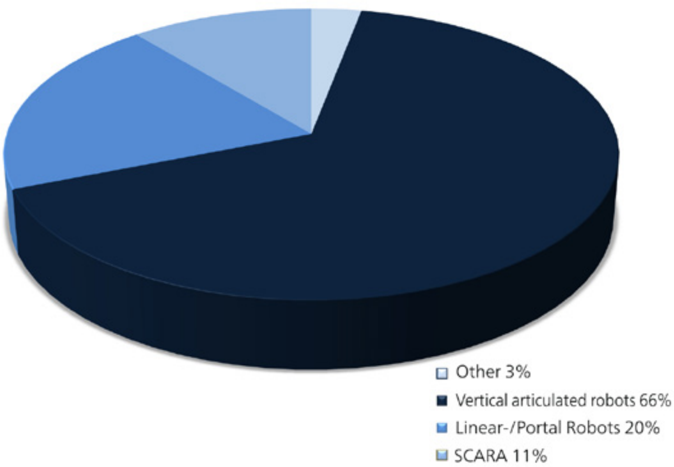

Figure 2: Market share by robot type (Klingelnberg Management estimate)

Looking ahead, a growth rate of approximately 17% per year seems likely in the coming years, due to the expected steady demand from the electronics sector as well as the automotive industry.

Structural design of robot systems

The kinematic design of robots is broken down into two basic structures: serial structure and parallel structure. In robots with a serial structure, motion and handling tasks are transmitted via rigid arms, which are connected in pairs by joints. SCARA and vertical articulated robots are examples of these. The joints in these robots generally have a planar design in the form of planetary or cycloidal gears. If two or more degrees of freedom are combined in a joint, as is the case for the joint in the end-of-arm tooling of a vertical articulated robot, bevel gears or hypoid gears are typically used. The serial structure is characterized by a high degree of flexibility.

By contrast, the drive axes in parallel kinematics exert a parallel action on the end-of-arm tooling. Parallel robot structures generally have one fixed and one moving plane, which are connected via multiple parallel arms. Due to their parallel design, these robot systems provide a high degree of accuracy. Such solutions, however, are always custom solutions for dedicated applications, making parallel-structure robots less versatile in terms of possible uses.

Mechanical gears at the root of precision and quiet running behavior

To execute motion and handling tasks as efficiently and cost-effectively as possible, robot systems must be highly mobile and highly dynamic in their traversing and positioning operations. At the same time, precise, uniform transmission of motion and torque is a major challenge for the gearboxes used in the joints and actuators in robot systems. This calls for minimal backlash and high torsional strength.

But how can the gearbox and gear requirements described be implemented and reliably attained on the production floor? What quality-critical variables must be taken into account for high-volume production of gear components? The Klingelnberg production system delivers solutions that make it possible for robot system manufacturers to produce high-precision drives in series.

Klingelnberg bevel gear systems for grippers and end-of-arm tooling

The precision of the bevel gear system in the end-of-arm tooling or in the “robot hand” is critical for positioning the tool center point (TCP). To ensure reliable quality, Klingelnberg offers a tried-and-tested, well-established solution: the Klingelnberg production system. This system, which received the “Industry 4.0 Award” from ROI, represents a complete closed loop production system for bevel gears. Closed loop control makes it possible to intervene proactively and take corrective action in quality-critical sections, leading to efficient, optimal results. Starting with the gear design, all of the requirements that the gear must meet are implemented to greatest advantage along the production chain. The corrections and adjustments required along a production chain that is subject to tolerances can be quantified using a closed loop production system.

A new production process starts off with the gear design. The macro- and micro-geometric flank forms of the gear set are first generated based on a simulation of the manufacturing process. A gear expert then optimizes the gear, striking a balance among the required properties and drawing on the tooth contact analysis under load for the critical operating conditions. High load-bearing capacity, low noise, optimal displacement properties under load and minimal circumferential backlash can be analyzed and adjusted for the best outcome as early as the design stage. In this case, the theoretical design of the gear set translates the requirements defined by the application into the information needed for production in the closed loop production system.

In this system, all of the information needed for every processing step along the production chain is pooled at a central location based on the designs: Essential elements for describing the precut gear in the closed loop production system include the geometry of the gear blank, the component-specific machine kinematics necessary for producing the gear, and the tool geometry for milling and deburring the precut gear. The processing data for grinding and the respective nominal values for measuring the gear geometry along the production chain round out Klingelnberg's Industry 4.0 strategy. All quality-critical production machines are linked via the Klingelnberg networking concept. Based on systematic, transparent information feedback along the production chain, the closed loop production system offers ideal conditions for optimal analysis and design of bevel and cylindrical gear sets.

When selecting a suitable gear cutting method for achieving superior gear quality, grinding is an optimal compromise between flexibility, performance, and productivity for bevel gears, cylindrical gears and hypoid gears. With the G 30 bevel gear grinding machine, Klingelnberg offers an economical, versatile complete package for series production of high-precision gears achieved through rigorous development of the vertical machine concept. The high rigidity and thermal stability of the reengineered vibration-damping machine bed guarantee optimal grinding results and highly productive machining processes. The axis arrangement, which has undergone further development since the predecessor machine generation, reduces the required traversing paths, resulting in a stiffer overall machine structure. The use of highly dynamic drives in this machine generation – combined with the newly developed touchscreen-based machine user interface and state-of-the-art control technology – result in minimal operating and auxiliary times in bevel gear machining. The software user interface, designed in every detail for intuitive handing, features a simple, structured navigation system throughout the machine setup process, as well as immediate feedback for invalid or incorrect input.

Thanks to continuous monitoring of the machine status and the machining process, the G 30 bevel gear grinding machine ensures maximum process reliability – even for high-output serial applications. An inspection of the initial component quality that includes monitoring of the workpiece locating surface and the stock allowance on the flank of the precut gear ensures a consistent quality of the component after grinding. Cycle time-optimized, automatic loading is the basis of every high-output serial process. Using the loading system, which is fully integrated in the machine and optimally coordinated on the NC side, workpiece changes can be performed on the G 30 in minimal time. The integrated tactile measurement system offers the possibility of a rapid quality assurance check directly in the machine during regular production. High precision and repetition accuracy of the measuring results generated on the G 30, combined with automatically generated corrections of the machine kinematics and tool profile, lead to fewer component rejects and greater efficiency in production.

Klingelnberg cylindrical gears for robot joints

Planetary gears being primarily used in the joints of articulated robots, call for high transmission precision and minimal circumferential backlash. A wide range of gear forms are used: In Asia cycloidal gears are more or less a standard as in Europe and America planetary gears with an involute tooth profile are common. All robot gears show a compact design and a very large transmission ratio.

The tight tolerances require production technologies that enable maximum gear quality. That is why the main active surfaces of the machine elements used in robot gears are ground. A gear grinding machine is therefore always part of the production chain. Since robot gears have external as well as internal teeth, the gear grinding machine should be able to process internal and external gears – with minimal setup times. In many applications, external gears in mid-sized to large lots are ground by generating grinding, thus a gear grinding machine for the robot industry ideally combines all essential gear grinding technologies. The VIPER 500 W, which provides an ideal machine base for machining robot gears, does just this. Figure 3 shows components being machined in an eccentric gearbox on a VIPER 500.

The internal gear is machined with the V5 internal grinding arm. The use of dressable tools enables point-by-point correction of the profile and tooth thickness. With a non-involute tooth profile – such as in cycloidal gears – the tooth form is edited via the "free profiles" function in GearPro. This function is available for external and internal gears.

Robot gears should have as little backlash as possible. The eccentric gears must meet minimal geometric tolerances in order to function. On drawings of the cam disks, tolerances are therefore indicated for the position of the web bores

Figure 3: Cycloidal gear grinding on a VIPER 500

Distance zero point to workpiece center in Y-direction: 0,0000 mm

Left flank: No	X [mm]	Y [mm]	Radius [mm]	Right flank: No	X [mm]	Y [mm]	Radius [mm]
1	0,0000	110,8000	0,0000	1	0,0000	110,8000	0,0000
2	0,1388	110,8015	0,0000	2	-0,1388	110,8015	0,0000
3	0,2772	110,8061	0,0000	3	-0,2772	110,8061	0,0000
4	0,4152	110,8137	0,0000	4	-0,4152	110,8137	0,0000
5	0,5523	110,8243	0,0000	5	-0,5523	110,8243	0,0000
6	0,6884	110,8378	0,0000	6	-0,6884	110,8378	0,0000
7	0,8231	110,8541	0,0000	7	-0,8231	110,8541	0,0000
8	0,9563	110,8732	0,0000	8	-0,9563	110,8732	0,0000
9	1,0877	110,8948	0,0000	9	-1,0877	110,8948	0,0000
10	1,2171	110,9189	0,0000	10	-1,2171	110,9189	0,0000
11	1,3444	110,9454	0,0000	11	-1,3444	110,9454	0,0000
12	1,4693	110,9741	0,0000	12	-1,4693	110,9741	0,0000
13	1,5918	111,0047	0,0000	13	-1,5918	111,0047	0,0000
14	1,7116	111,0373	0,0000	14	-1,7116	111,0373	0,0000
15	1,8287	111,0716	0,0000	15	-1,8287	111,0716	0,0000
16	1,9430	111,1074	0,0000	16	-1,9430	111,1074	0,0000
17	2,0544	111,1446	0,0000	17	-2,0544	111,1446	0,0000
18	2,1628	111,1831	0,0000	18	-2,1628	111,1831	0,0000
19	2,2682	111,2226	0,0000	19	-2,2682	111,2226	0,0000
20	2,3706	111,2630	0,0000	20	-2,3706	111,2630	0,0000
21	2,4700	111,3042	0,0000	21	-2,4700	111,3042	0,0000
22	2,5664	111,3460	0,0000	22	-2,5664	111,3460	0,0000
23	2,6597	111,3883	0,0000	23	-2,6597	111,3883	0,0000
24	2,7501	111,4310	0,0000	24	-2,7501	111,4310	0,0000
25	2,8375	111,4739	0,0000	25	-2,8375	111,4739	0,0000

for the gear. The quality of the cam disk depends on the gear geometry itself and the position of the gear with respect to the web bore. Figure 4 shows an example of dimensioning for a cam disk pair.

Cam disk machining entails certain requirements for the alignment of the cam disks on a machine. There are two possible production sequences, each of which has advantages and disadvantages. The web bores can be machined either before or after gear grinding. If the cycloidal gear is machined after the bores, the component must be clamped with reference to the web bores. The gear is then always ground relative to the table. This requires measuring the gear teeth on a component during the process setup, and the relative position of the web bores to the gear teeth must be corrected in this case. If the fixture cannot be removed, the gear can be ground again. Alternatively, the gear can be ground first, and the web bores can be machined relative to the gear afterward. In this case, the clamping device used to machine the gear on the VIPER 500 has a less complex design. The web bores must still be positioned relative to the gear teeth, although with larger tolerances.

Complete measurement on one precision measuring center – directly on the shop floor

In addition to gear measurement, a Klingelnberg precision measuring center performs a host of other measurement tasks. It is possible, for example, to efficiently execute all the measurement tasks required on a cycloidal gear in a single setup. The previous paragraphs presented typical cycloidal gears, including several geometrical elements besides the gear teeth. Those elements are absolutely relevant for the function and must therefore be measured. Other options include the integration of roughness measurement, eliminating the need to invest in additional devices for the inspection room.

As digitization on the shop floor progresses, machine tools are being networked with measuring machines, enabling

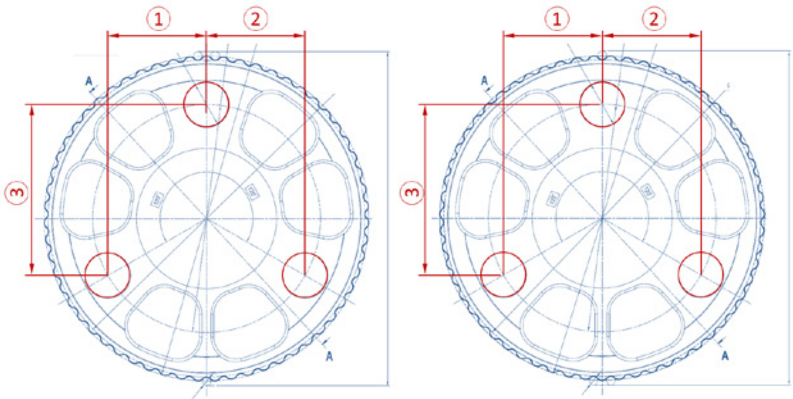

Figure 4: Drawing of a cycloidal gear

a closed loop for cycloidal gears. In the first step, the machine tool produces against the nominal gear data. The measuring machine measures against the nominal data and reports the actual data and deviations back to the machine tool in a digital format. This way the machining process can be optimized in order to minimize deviations from the nominal geometry, significantly increasing the accuracy and quality of the cycloidal gears.

Klingelnberg precision measurement centers are designed for use on the shop floor. To achieve this, Klingelnberg has drawn on its experience in developing machine tools, combined with its expertise in precision measuring technology. The key factors in its success are the machine's rugged design in combination with the precise temperature compensation. This is called the Klingelnberg Ambience Neutral Technology.

The production environment is rife with dirt and vibrations from production machines and transport systems. The rotary table bearing in Klingelnberg precision measuring centers has a roller bearing design, making it extremely insensitive to dirt compared with air-bearing systems. The measurement systems are therefore well protected – while at the same time easily accessible for cleaning during maintenance if necessary. Overall, this produces an extremely rugged system for the production environment. The machines can also be fitted with vibration insulation. This ensures that shocks and vibrations coming from the surrounding environment do not affect the measuring result.

Temperature fluctuations are another feature of the production environment. Every Klingelnberg precision measuring center has a machine bed made of precise cast steel. This ensures that all machine components and the steel component to be measured have an identical coefficient of thermal expansion. Sensors measure the temperatures of the workpiece, the machine, and the environment. These influences can be compensated directly using a temperature model. The temperature model is tested regularly in a temperature laboratory at Klingelnberg. Real temperature curves measured on shop floors are specified during the testing to ensure the practical viability of the system.

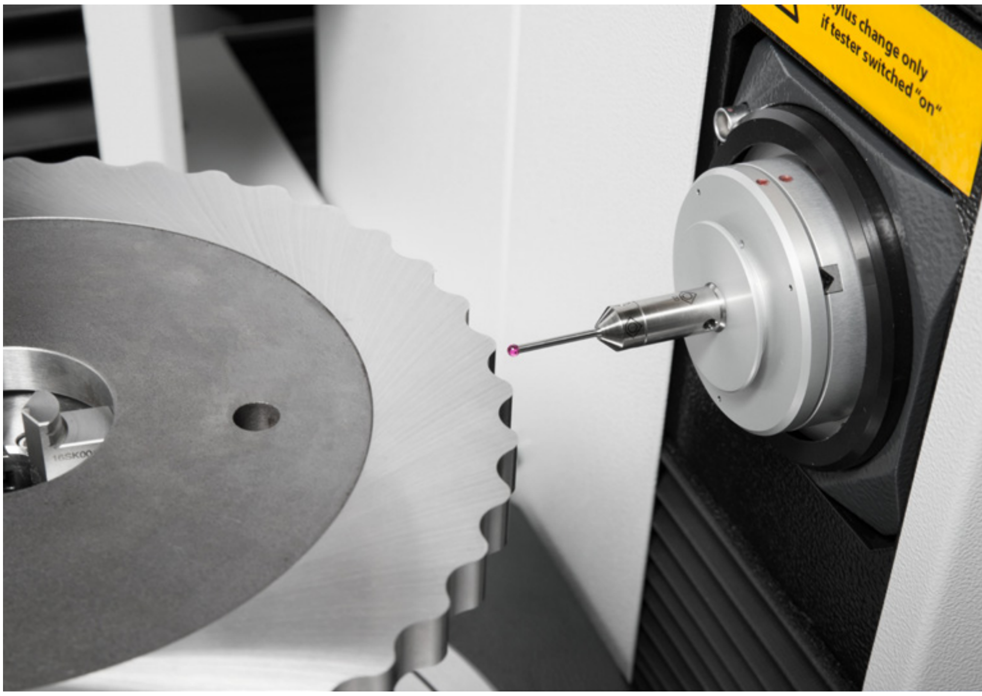

Figure 5: Measuring a cycloidal gear on a Klingelnberg P 40

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