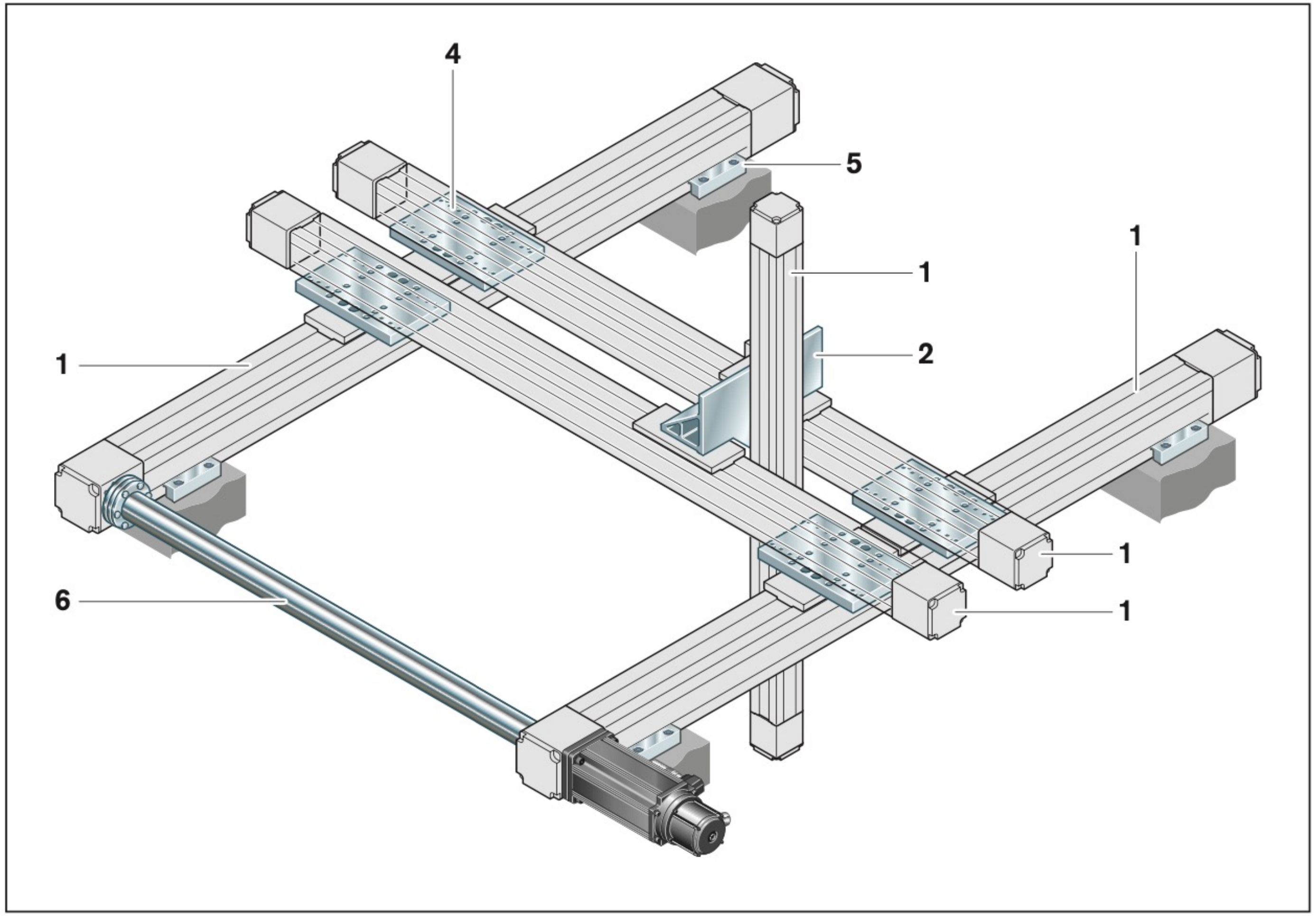
Lecture 05
Linear Motion Platform Design
第五章 直线运动平台设计

ME303 Introduction to Mechanical Design

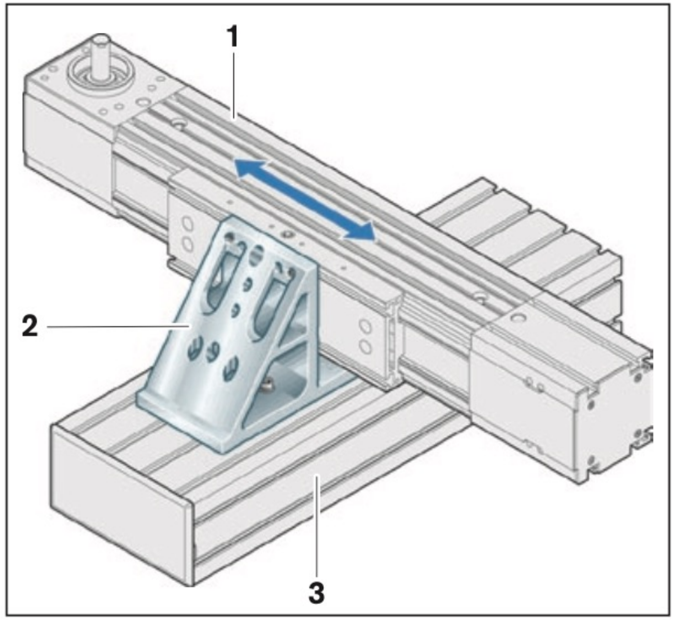
Adapted from https://www.icourse163.org/course/HUST-1206698847

Linear Motion and Assembly Technology

直线运动与装配技术

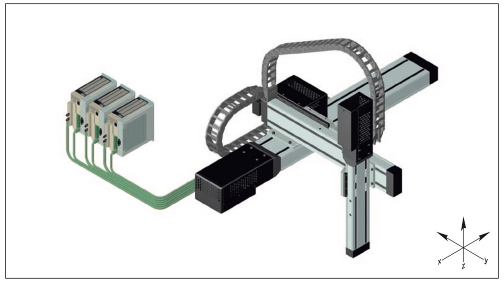


Linear module connection and combination possibilities



Linear module fixed to BME profile via a connection bracket; stationary carriage, moving frame

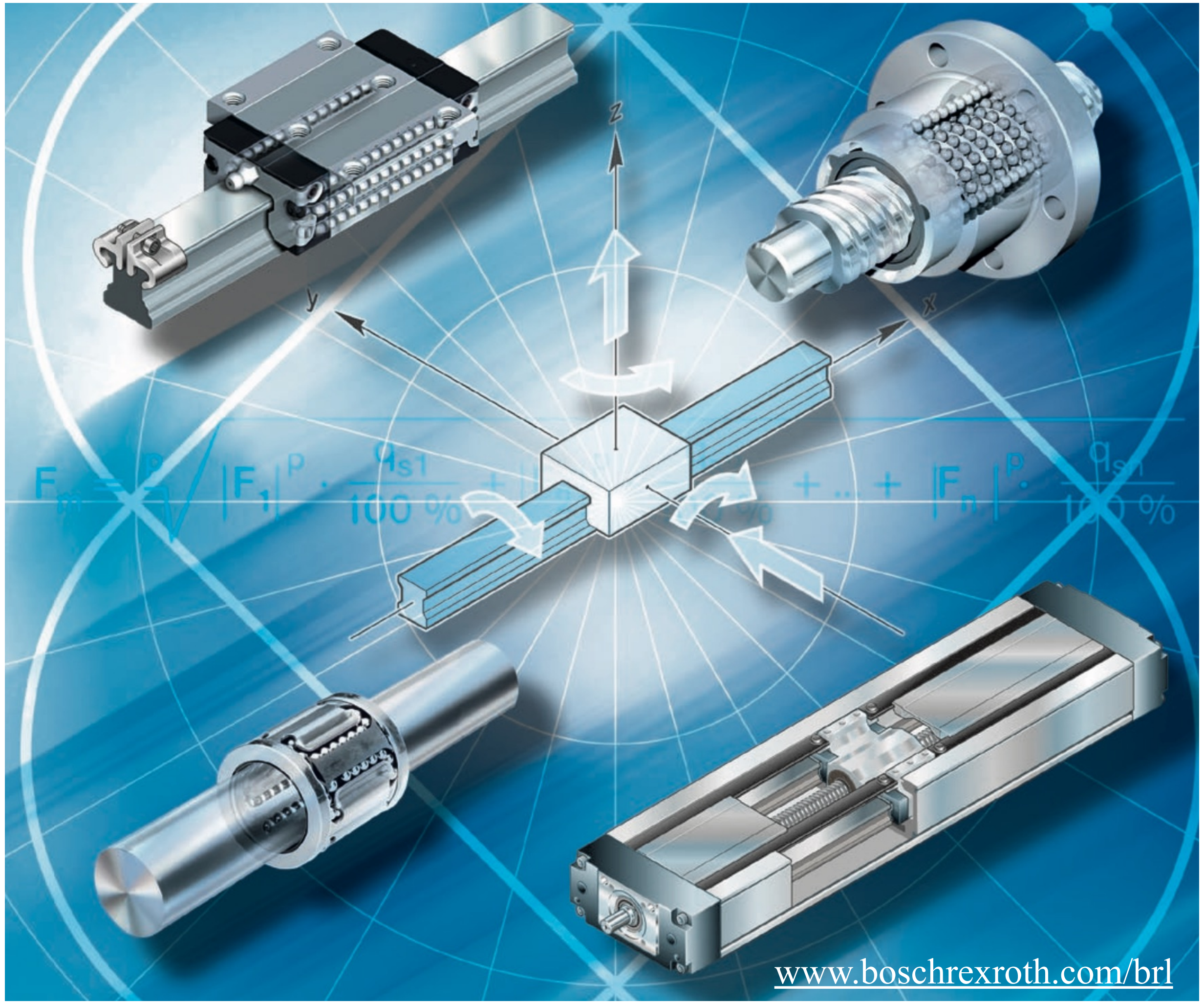
1 Linear module
2 Connection bracket
3 BME profile
4 Connection plate
5 Clamping fixture
6 Connecting shaft



3-axis system with servo controller for each axis

Linear Motion and Assembly Technology

直线运动与装配技术

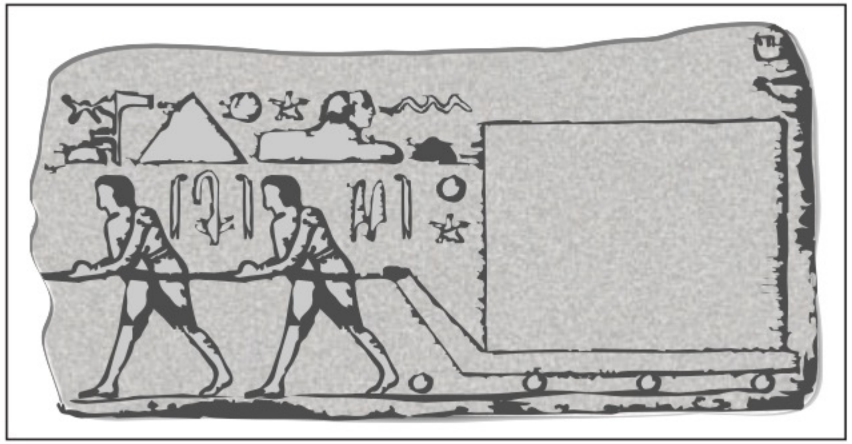


- Interface between static and moving machine elements. They significantly affect the machine characteristics.
- Comes into play whenever precision and high load-bearing capability are required, as is above all the case in machine construction and automation.

Historical Development

Linear motion

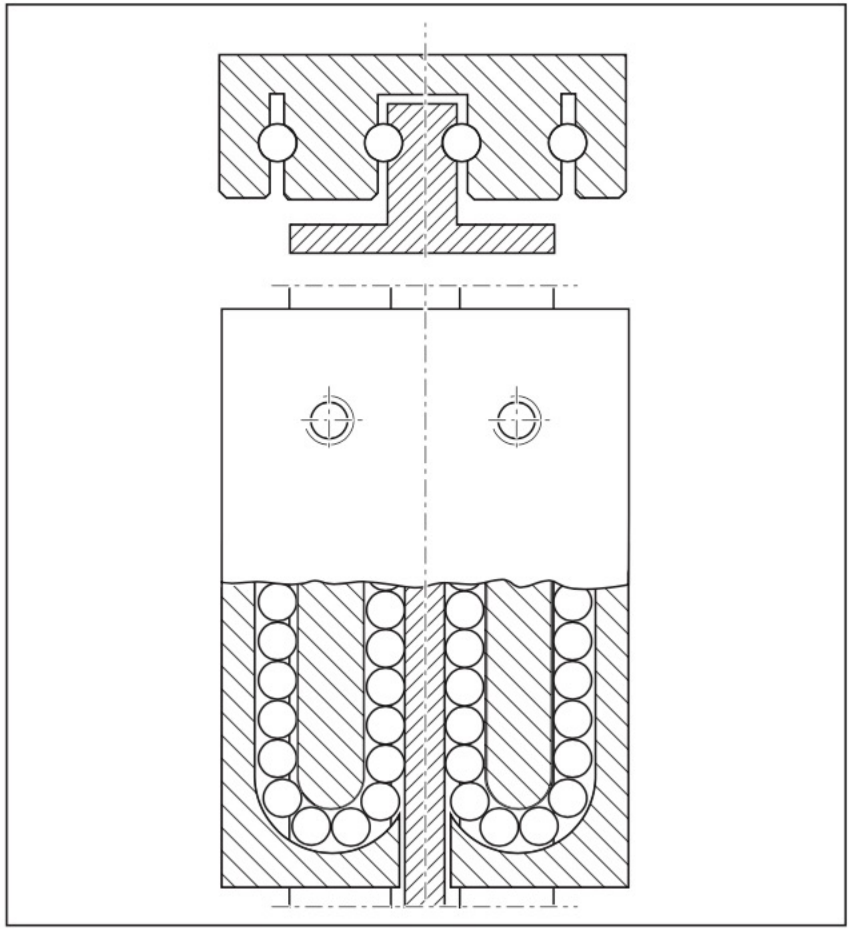
When building the pyramids, the Egyptians had already encountered the problem of how to move heavy loads. This was solved by using tree trunks laid under blocks of stone. Water was also applied as a lubricant to reduce friction.



Egyptian linear motion guide

Rolling contact profiled rail systems

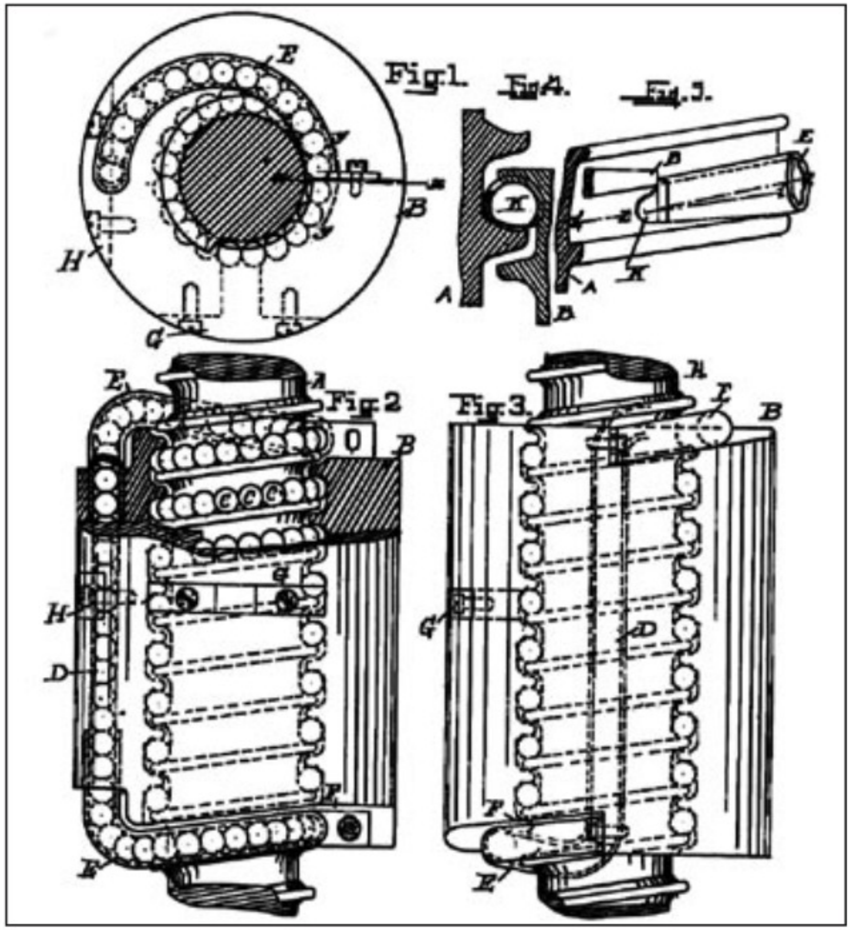
This basic principle is still used today in modern linear motion guides. The rolling elements nowadays, however, no longer have to be carried to the desired position by hand but instead recirculate within the guide system itself. The requirements regarding rigidity, load-bearing capacity and resistance to movement have also changed. Applications today place the highest demands on precision and economy.



Historical illustration of a ball rail system

Ball screw drive

Sliding screw drives were already used in Antiquity to convert rotary motion into linear motion. The ball screw drive was first mentioned in literature in the 19th century. It replaced sliding friction with rolling friction. It was first used industrially in the 1940s, when General Motors built ball screw drives into vehicle steering systems. Further industrial applications soon followed. Since then, the design and manufacturing processes have made enormous progress. Today, ball screw drives are found in a broad range of industries.

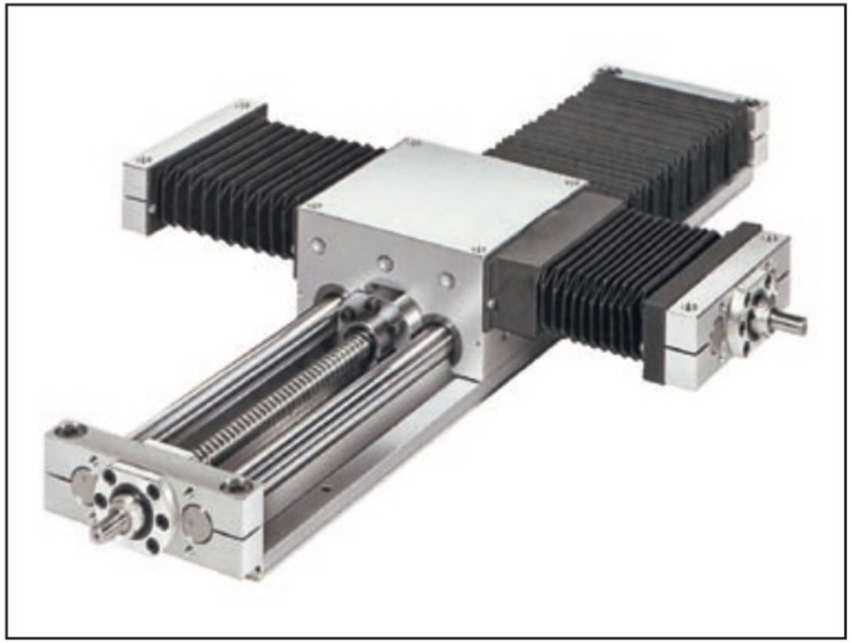


Ball screw drive from a historical patent

Linear motion systems

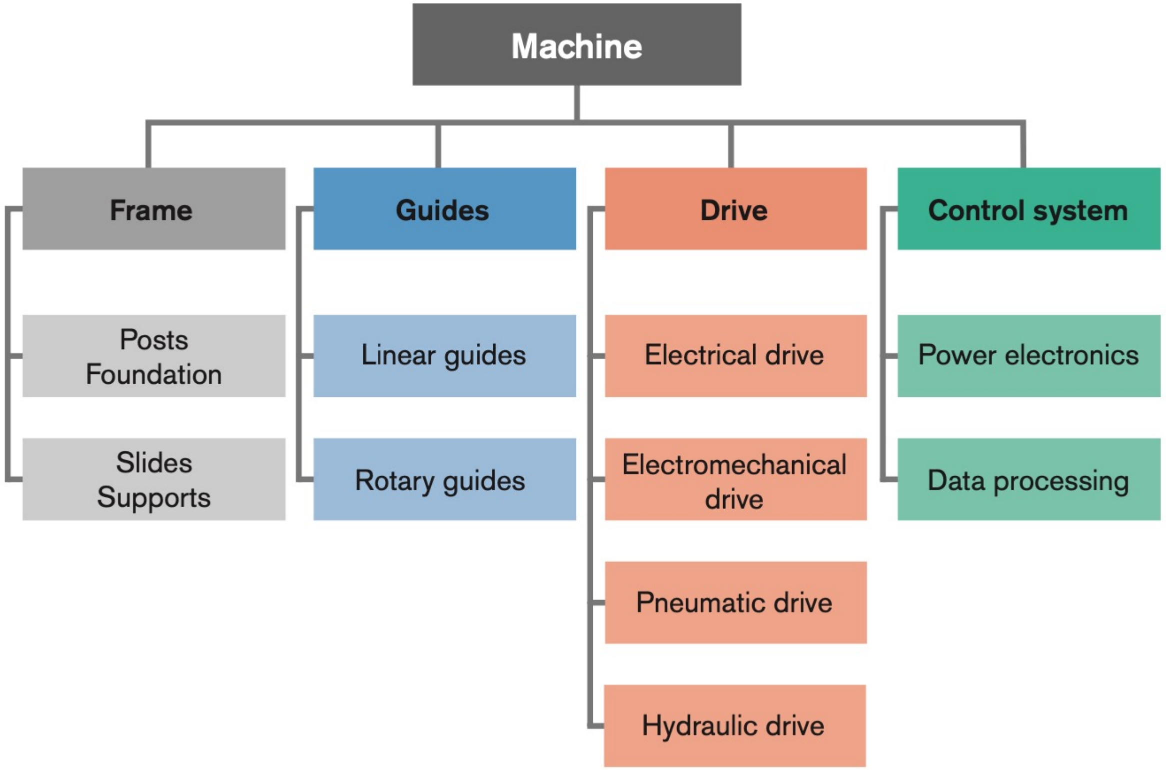
Linear motion systems are ready-to-install drive and guidance units. This makes it easier for users to design and assemble their applications. It is not necessary to calculate and dimension the individual components, since the linear motion systems are installed as complete units.

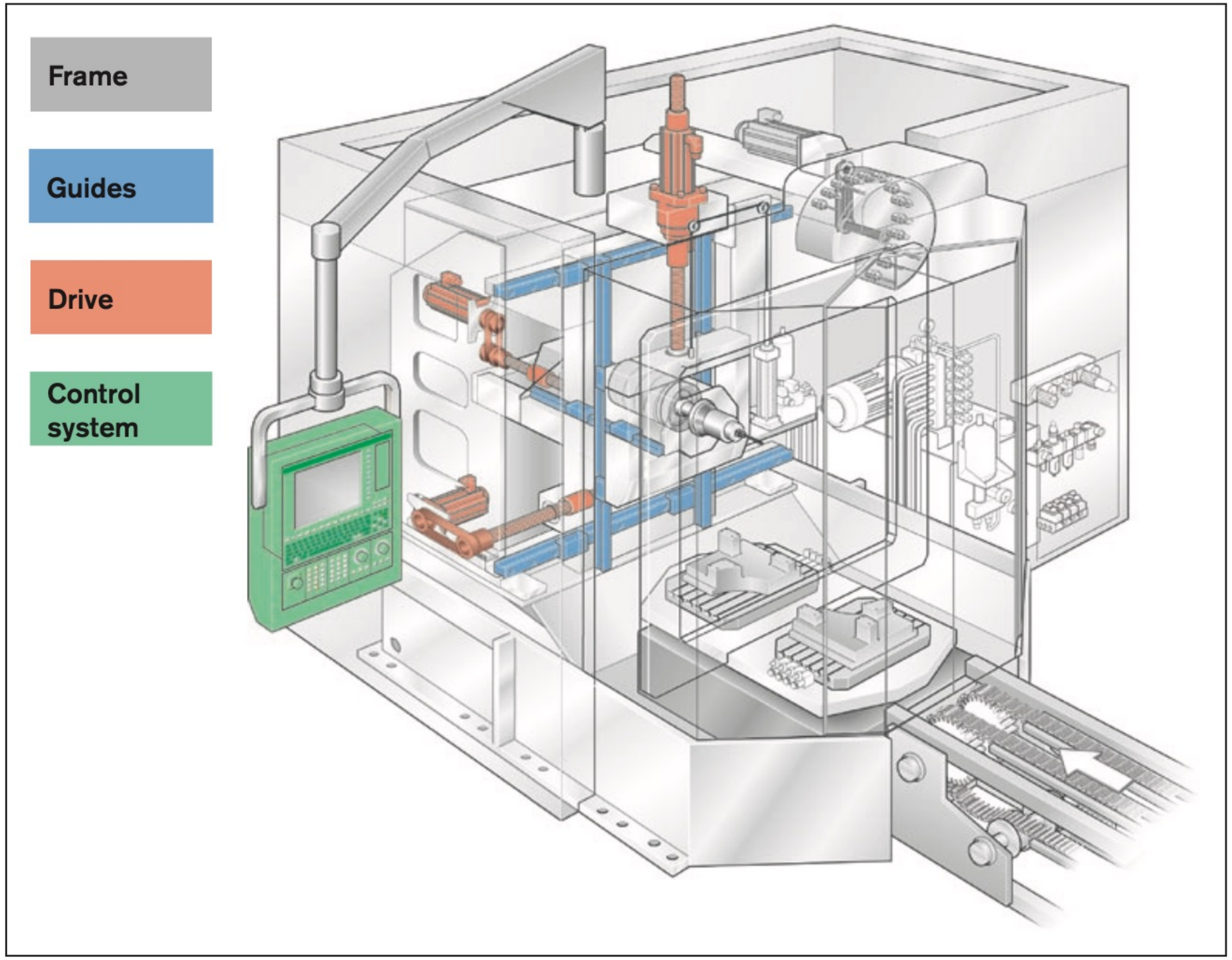
The first linear motion systems built by the former "Deutsche Star" consisted of linear bushings and shafts and a ball screw or pneumatic drive. These transfer tables were also offered as two-axis X-Y tables. Meanwhile, many different guide and drive unit variants have been incorporated into linear motion systems.



X-Y table from the "Deutsche Star" product range

Elements of a Machine

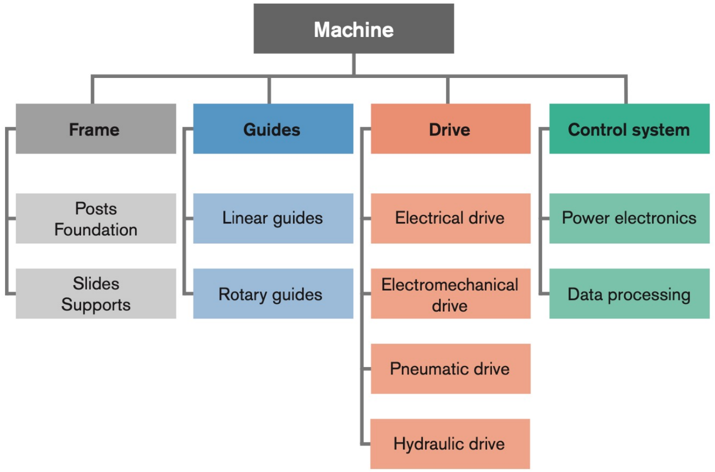


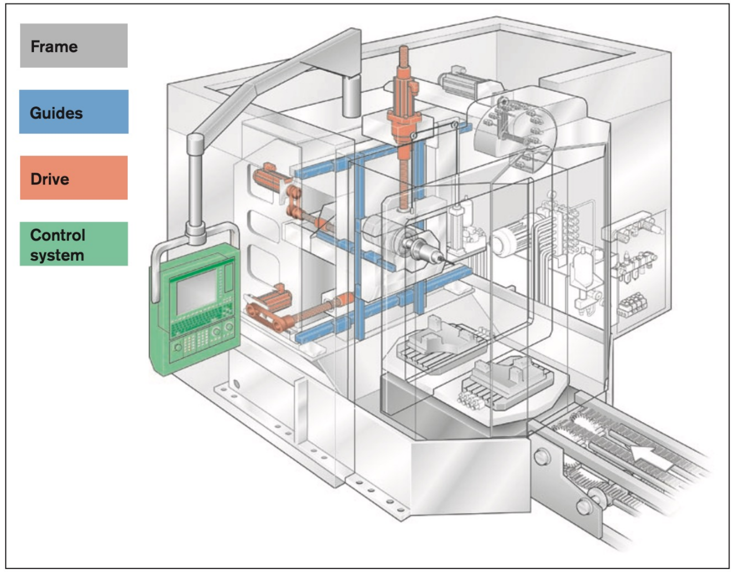


Machine with typical linear components shown in color

Basic Structure

Frame	A machine's frame consists of stationary components (posts, foundation) and moving components (slides, supports). There are various designs to suit the corresponding application (standard machine base, gantry design, etc.)	The frame's purpose is to anchor the machine and to transmit forces.
Guides	These are responsible for the guidance and power transmission of the moving machine components. The machine's accuracy is due in no small	measure to the accuracy of the guidance system. Based on the movement, a distinction is made between linear guidance and rotary guidance.
Drives	Drives convert electrical, hydraulic or pneumatic energy into mechanical energy. Electromechanical drives are a special form of drive incorporating transmission elements (e.g. ball screw drives). A distinction is made between main drives, which	execute relative movements (e.g. between a tool and a workpiece), and auxiliary drives, which execute positioning movements (e.g. workpiece transport or tool changing).
Control system	The control system coordinates the requisite movements of the machine, i.e. the moving parts' speed and acceleration. The power electronics serves the motors and high-powered actuators,	whereas the data processing system covers the limit switches, measuring systems, field bus systems and the safety circuits.



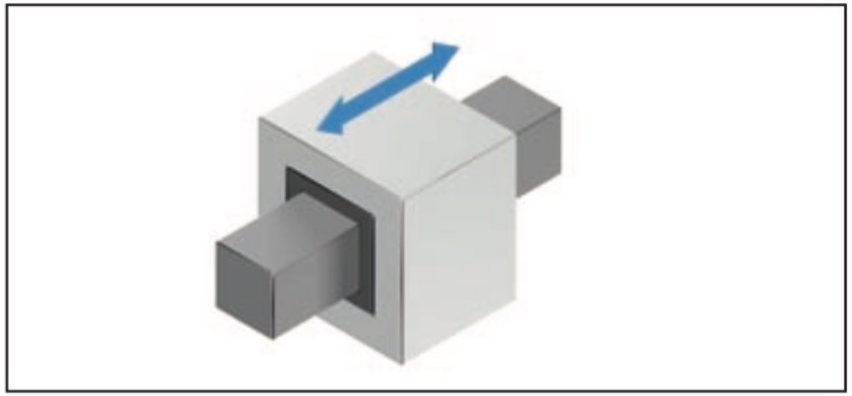


Machine with typical linear components shown in color

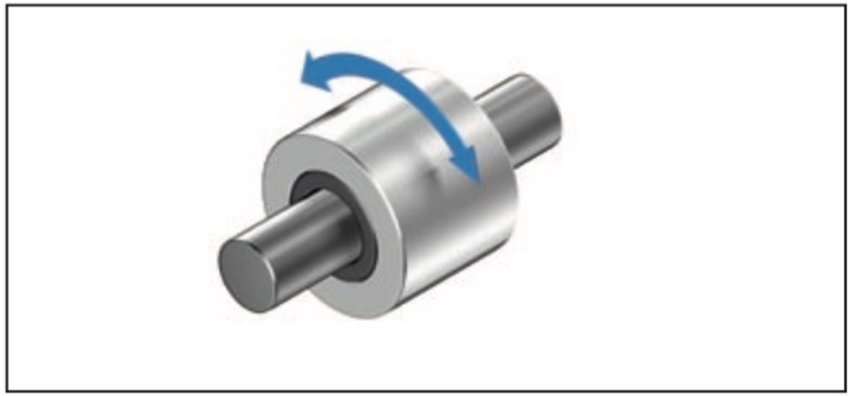
Guides

Guides with Different **Types of Motion**

Linear guides	Linear motion takes place along an axis. Examples: ball rail systems, dovetail sliders
Rotary guides	Rotary motion takes place about an axis. Examples: deep groove ball bearings, radial sliding bearings



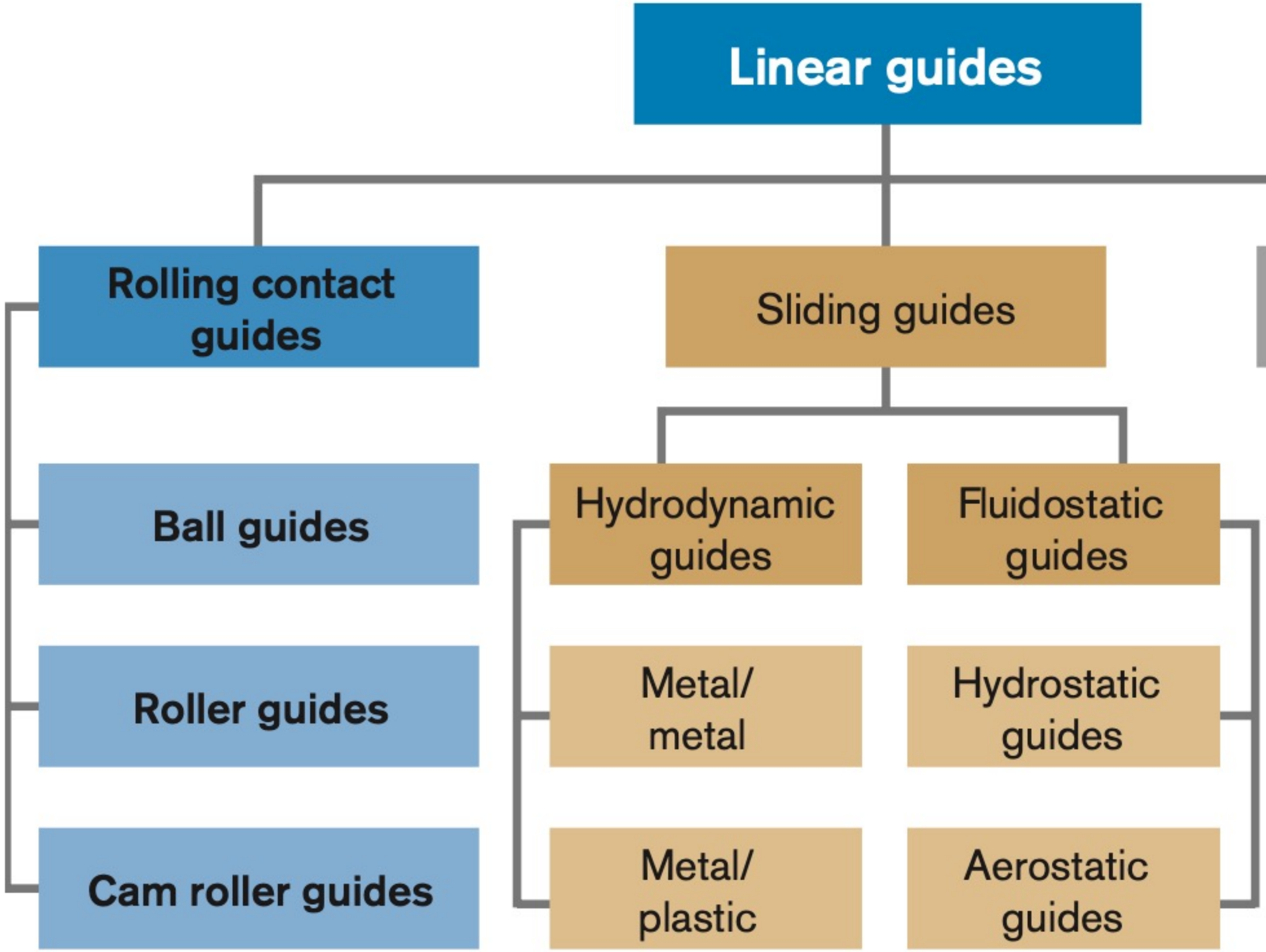
Linear guide



Rotary guide

Machines could not execute movements without guidance components. Depending on the guide's design, forces and moments can be transmitted in certain directions between moving and non-moving components. Guides can generally be differentiated according to their type of motion.

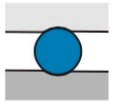
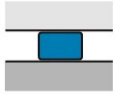
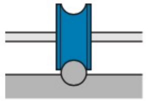
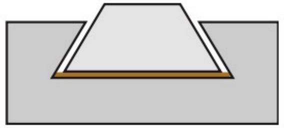
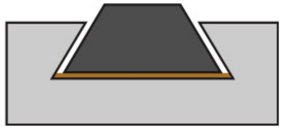
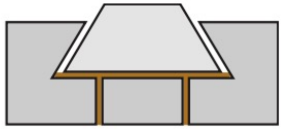
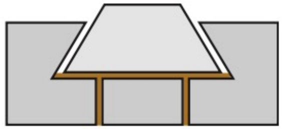
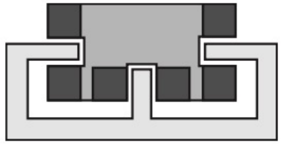
Guides with Different **Types of Contact Points**



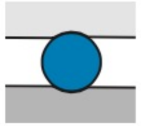
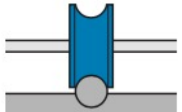
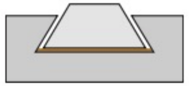
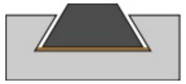
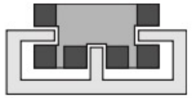
Linear guides can be differentiated according to the physical operating principle of the contact point

Guides

- Different operating principle of linear guides

Linear guides			Operating principle
Rolling contact guides	**Ball guide**		There are balls between the moving and fixed machine parts.
	Roller guide		There are rollers between the moving and fixed machine parts.
	Cam roller guide		There are cam rollers supported on ball bearings between the moving and fixed machine parts.
Hydrodynamic sliding guides	**Metal/metal**		Both machine parts are in contact during standstill. When movement starts, a lubricating film gradually forms between the moving and the fixed machine element. The lubricating film only separates the moving and the fixed element of the machine completely at higher sliding speeds.
	Metal/plastic		The operational principle is the same as for metal/metal. The metal/plastic material combination reduces friction when movement starts, until a complete lubricating film forms.
Fluidostatic sliding guides	**Hydrostatic guide**		A pump supplies liquid lubricant to the guide. The moving part rises. Between the moving and the fixed element there is a film of lubricant under pressure.
	Aerostatic guide		A compressor supplies compressed air to the guide. The moving and the fixed machine element are separated by the compressed air.
Magnetic guides			The moving and fixed machine elements are separated by magnetic force. The moving part "floats." The guide is therefore non-contacting.

Linear Guide Characteristics

Characteristics	Rolling contact guides			Hydrodynamic sliding guides		Fluidostatic sliding guides		Magnetic guide
+++ Very good ++ Good + Satisfactory o Adequate	Ball guide	Roller guide	Cam roller guide	Metal/ metal	Metal/ plastic	Hydrostatic guide	Aerostatic guide	Magnetic suspension
								
Load-bearing capability	+++	+++	++	+++	+++	+++	o	+++
Rigidity	++	+++	+	+++	++	+++	o	+
Accuracy	++	++	++	+	+	++	++	+++
Friction characteristics	++	++	++	+	+	+++	+++	+++
Speed	+++	+++	+++	+	+	+++	+++	+++
Damping characteristics	+	+	+	+++	+++	+++	+++	+++
Operating safety	+++	+++	+++	+++	+++	+	+	+
Standardization	+++	+++	+++	+	+	o	o	o
Service life	++	++	++	++	++	+++	+++	+++
Costs	++	++	++	+++	+++	+	+	o

The table shows that rolling contact guides score excellent ratings for the most commonly demanded characteristics.

When the price-performance ratio is considered, it is no surprise that rolling contact guides have replaced conventional sliding guides more and more in recent years and now represent the standard in machine components.

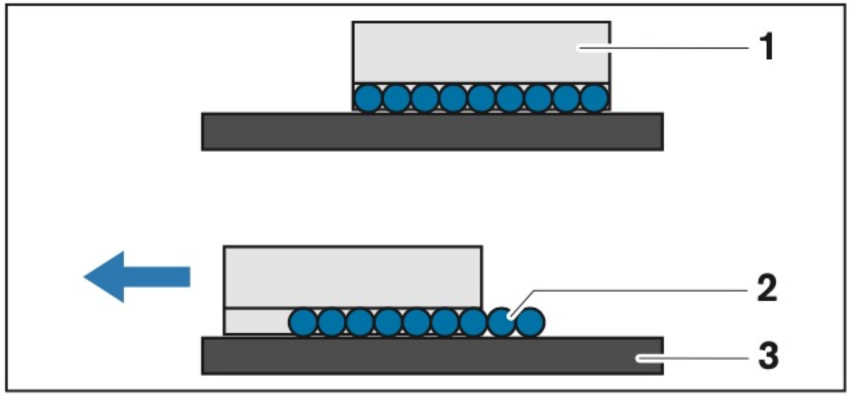
Guides with **Different Rolling Element Recirculation Principles**

Rolling element recirculation

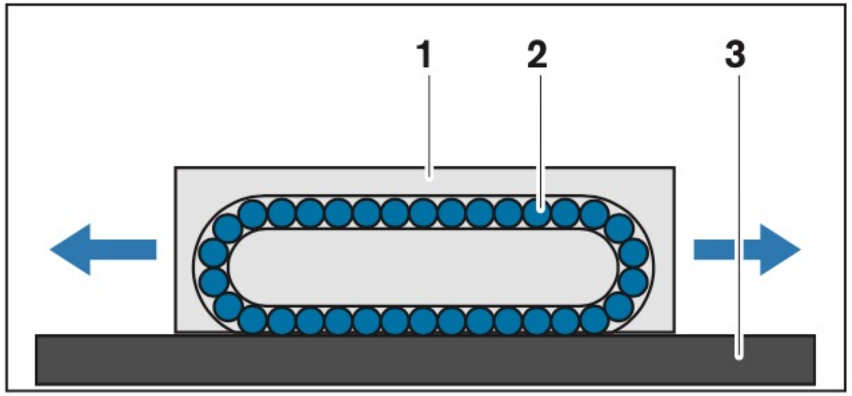
The type of contact point is not the only way to differentiate rolling contact guides. They also subdivide into guides with and guides without recirculation of the rolling elements.

In rolling contact guides without rolling element recirculation, the rolling elements (2) move at half the speed of the runner block (1) and therefore only cover half the distance. Rolling contact guides without rolling element recirculation therefore have only a limited stroke.

In rolling contact guides with rolling element recirculation, the rolling elements (2) recirculate within the runner block (1) and move together with the runner block in relation to the guide rail (3). The stroke is limited only by the rail length.



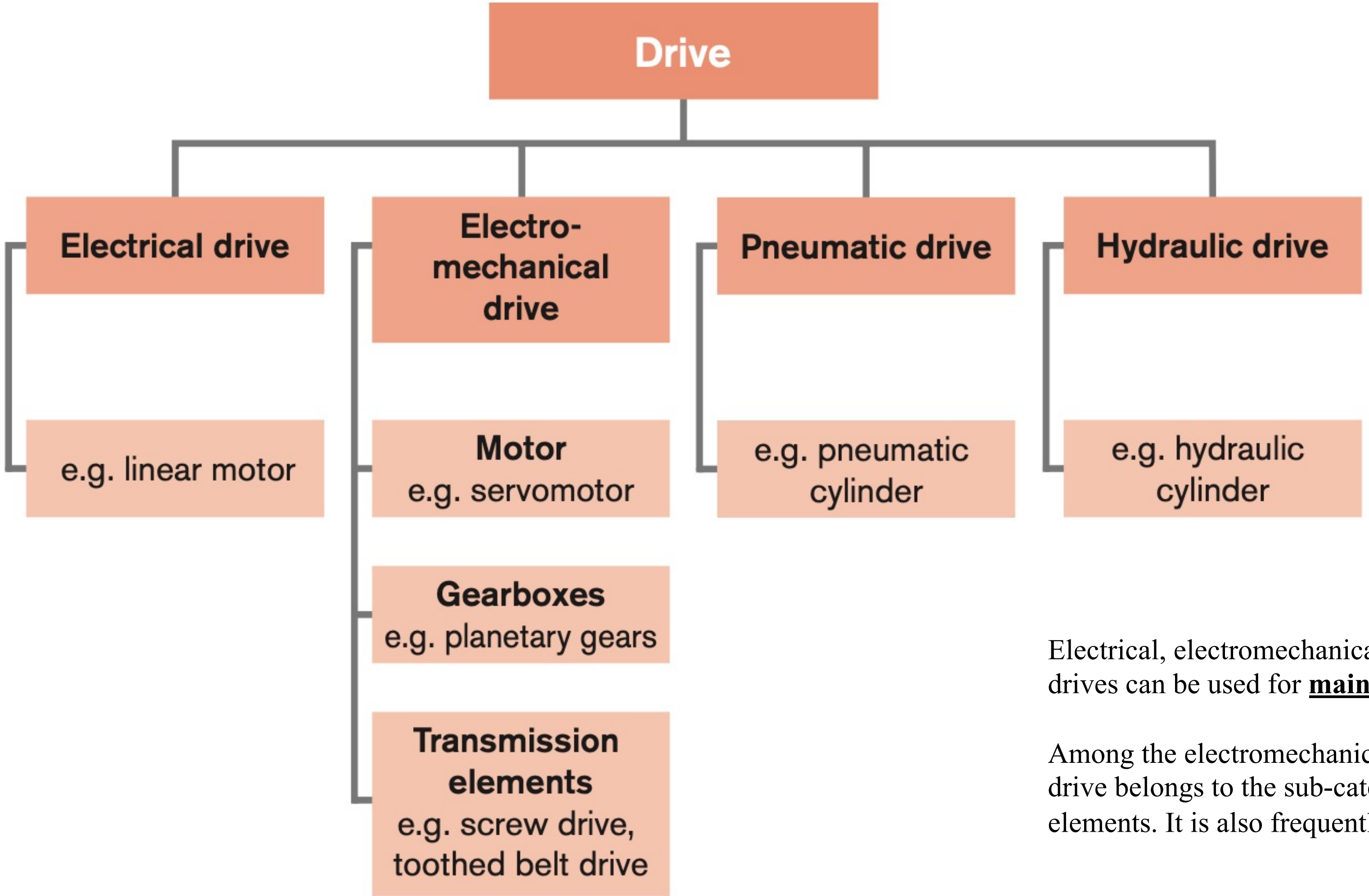
Rolling contact guide without rolling element recirculation



Rolling contact guide with rolling element recirculation

Drive

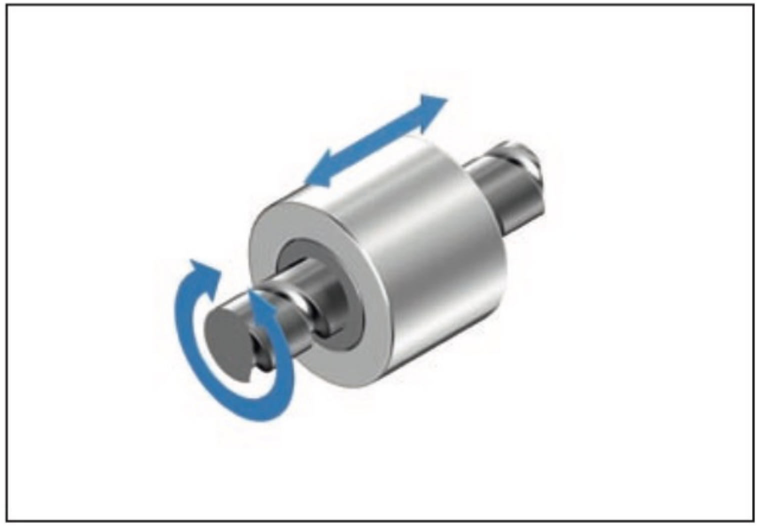
Drive Types



Electrical, electromechanical, pneumatic or hydraulic drives can be used for **main** and **auxiliary** drives.

Among the electromechanical drives, the ball screw drive belongs to the sub-category of transmission elements. It is also frequently called a feed component.

Screw Drive with Rolling Contacts

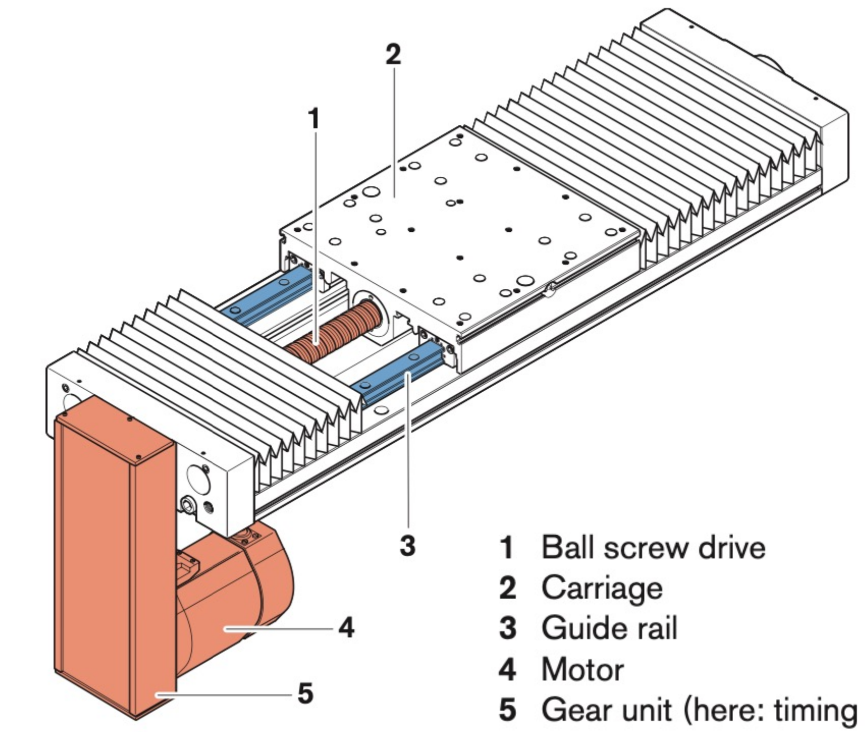


Screw drive

In a screw drive, a rotational movement takes place about an axis with a defined screw lead. Here rotary motion is converted into linear motion and vice versa.
In mechanical engineering, screw drives are classified as drive elements (transmission elements, feed elements).
Examples: ball screws (BS), acme screws

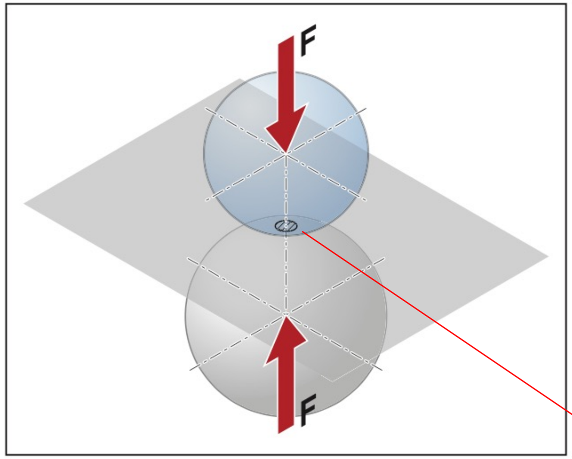
Structural design

The following illustration of a Ball Rail Table TKK shows the typical structural design of a drive unit with ball screw drive together with rail guides.

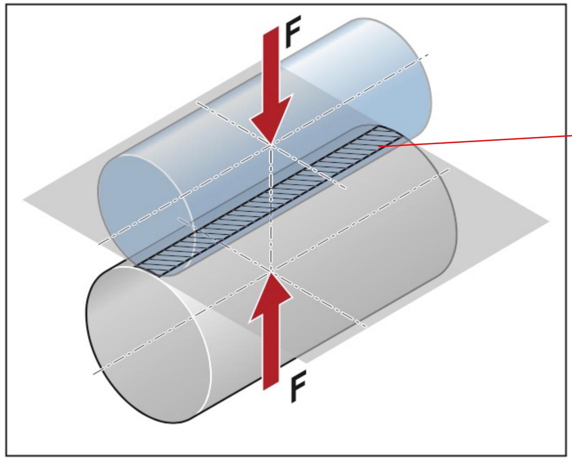


Ball Rail Table TKK with ball screw drive and ball rail system

Contact Areas in Balls and Rollers



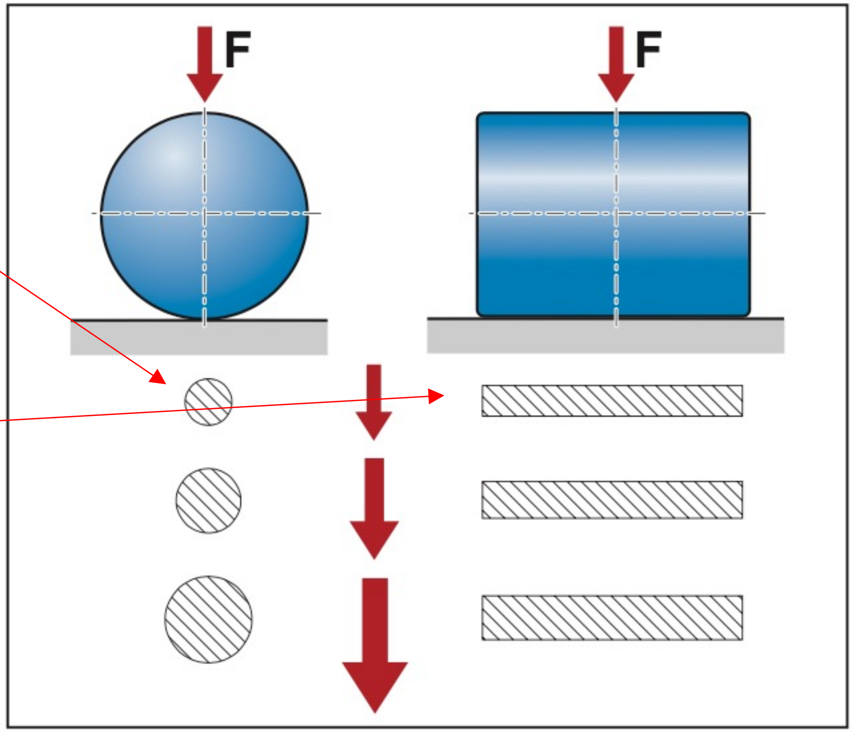
Point contact for ball rolling elements



Line contact for roller rolling elements

Contact area

Rollers have a larger contact area than balls. This larger contact area enables the rollers to transmit greater forces, leading to greater rigidity. Compared to balls, therefore, smaller sizes can be used to bear the same external load.



Contact area for balls and rollers under increasing load

Point contact in the case of balls

The rolling contact considerations for balls are based on the Hertz theory. This deals with the behavior of two curved bodies when they are pressed against each other by an external force.

The Hertz theory

The elastic deformation, the dimensions of the compression areas, the maximum surface pressure and the sub-surface stresses occurring during the rolling contact of balls can be calculated using the Hertz theory.

The simplest case is the contact of a sphere with a plane (idealized point contact). In this case, there is a relatively small circular contact area, leading to a very high surface pressure.

If balls with different diameters are compared, it becomes apparent that, in the case of larger balls, the deformation and the surface pressure are smaller under the same load. The load-bearing capacity therefore rises as the ball diameter increases.

Line contact in the case of rollers

The Hertz theory does not apply to deformation in the case of line contact. If two cylindrical rollers are pressed together with their axes parallel, a line-shaped contact is produced. The resulting contact area is elongated, with the shape and size of the contact area dependent only on the load and the length of the contact line. Elastic deformation during line contact is independent of the roller diameter. At a constant roller diameter, the load-bearing capacity rises with increasing roller length.

Ball Contact Conformity

Running tracks with contact conformity

In the case of rolling ball contact with planar running tracks, the high surface pressure and the absence of guided movement have an unfavorable effect. For these reasons, profiled running tracks offering contact conformity are used. This increases the contact area and reduces the surface pressure accordingly. Higher load-bearing capabilities can therefore be achieved. This also serves to guide the movement of the rolling element.

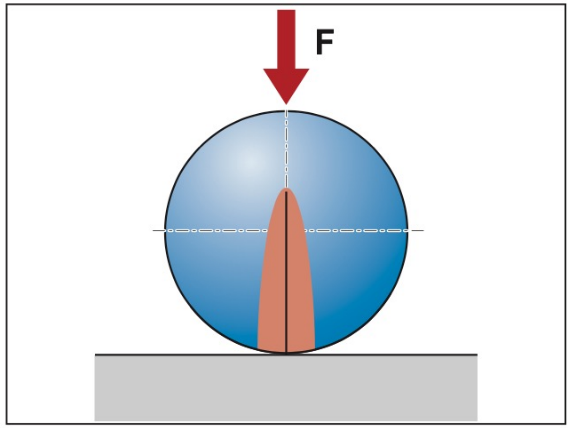
Definition of conformity

Conformity is the ratio of the running track radius to the ball diameter, expressed as a percentage:

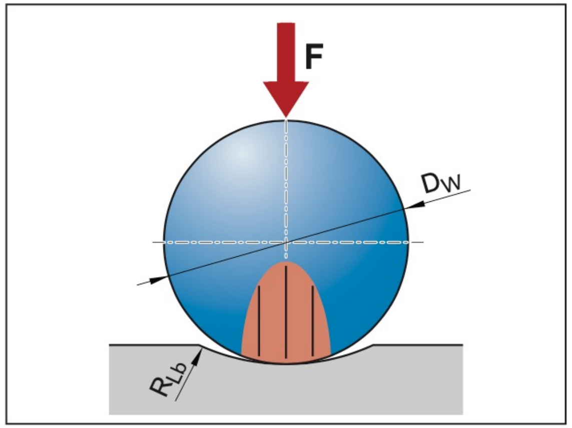
$$(2\text{-}1) \qquad \kappa = \frac{R_{Lb}}{D_W} \cdot 100\%$$

κ = conformity (%)
R_{Lb} = running track radius (mm)
D_W = ball diameter (mm)

A ball on a running track designed for contact conformity will deflect significantly less than a comparable ball on a planar running track. Also, where there is conformity between the ball and the track, the ball will have a longer life than a ball with point contact because of the larger contact area and the resulting distribution of the forces acting on it.



Stress distribution for a contact area without conformity



Stress distribution for a contact area with conformity

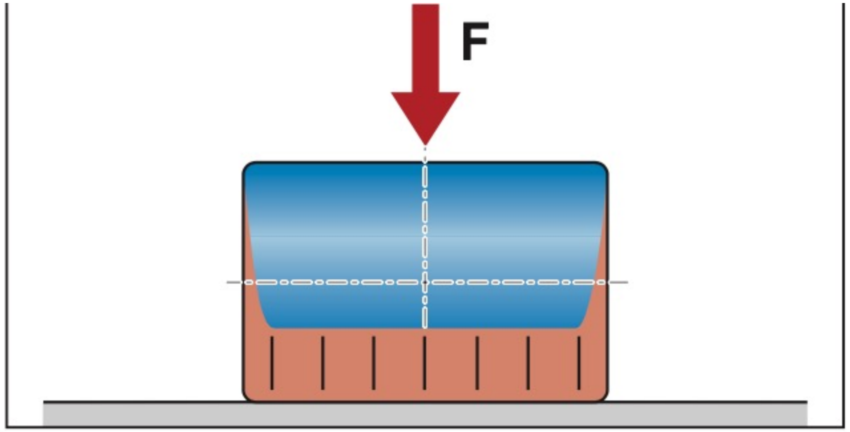
Logarithmic and Cylindrical Roller Profiles

Logarithmic profile

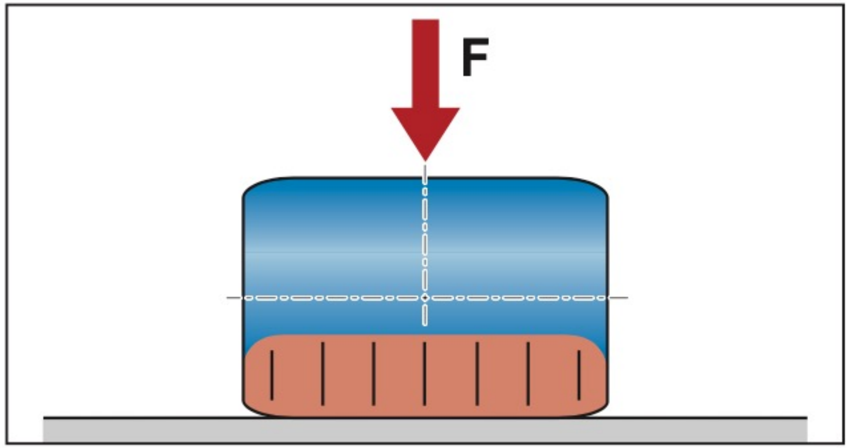
Rolling contact with rollers differs from that with balls. A distinction is made between rollers with cylindrical and logarithmic profiles. Both forms are approximately comparable in terms of their elastic deflection behavior.
Rollers with logarithmic profiles, however, offer further advantages:

- More even distribution of forces
- Lower peak stresses at the edges
- Correspondingly less edge contact

This results in longer life than with cylindrical rollers.



Stress distribution for cylindrical roller profiles



Stress distribution for logarithmic roller profiles

Elastic Deflection of Balls and Rollers

Elastic deflection

Elastic deflection means that no permanent deformation of the parts in contact occurs. Depending on the type of rolling element and the shape and area of the contacting surfaces, a force acting on the rolling element will lead to different degrees of elastic deflection:

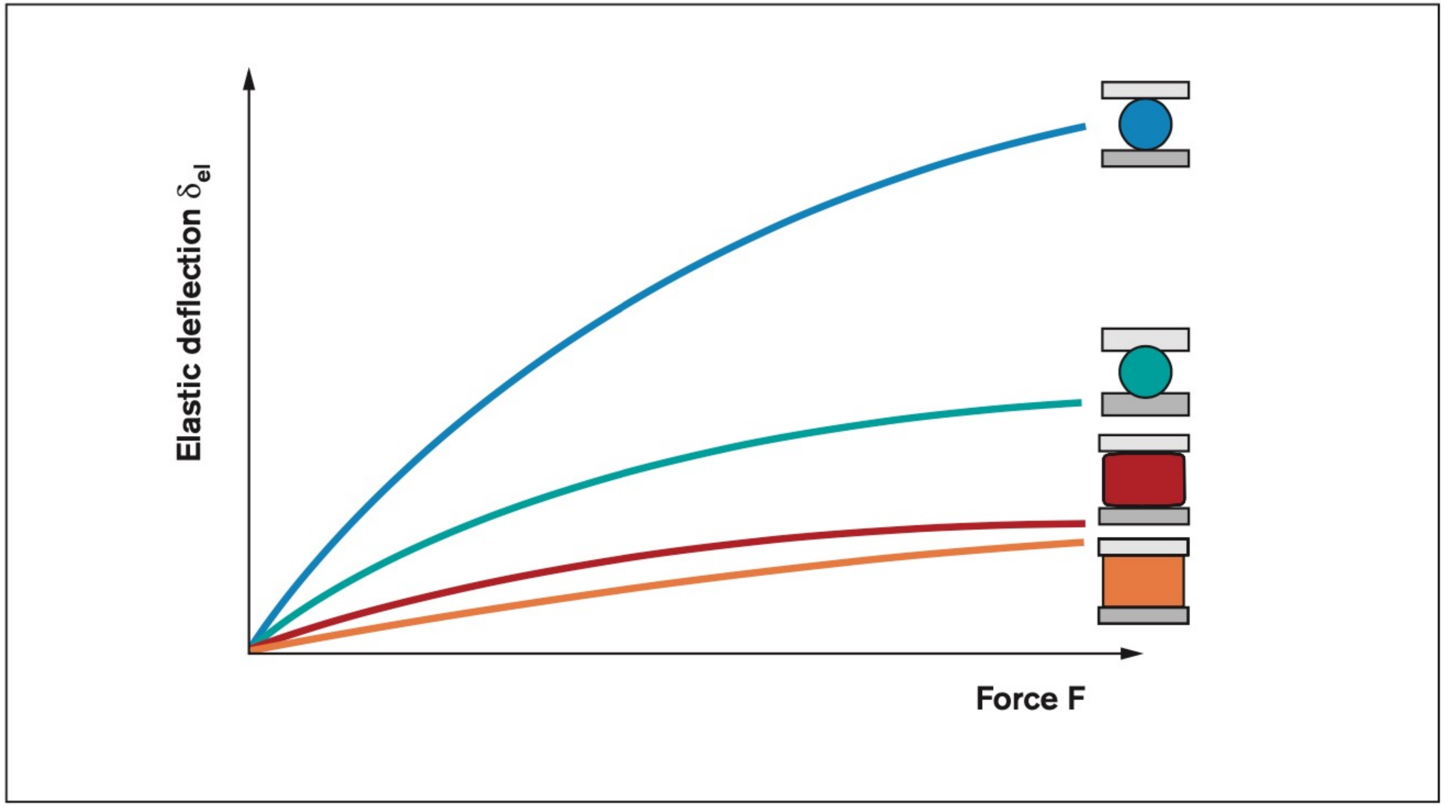
- Rollers deflect less than balls. Rollers have a significantly higher rigidity and a higher load-bearing capacity because of the larger contact area.
- The deflection behavior of rollers with logarithmic profiles and rollers with cylindrical profiles are approximately comparable.
- A ball on a running track with conformity will deflect significantly less than a comparable ball on a track with no conformity.

The graph shows the elastic deflection for the rolling contact conditions described.

- Ball and running track with no conformity
- Ball and running track with conformity
- Roller with logarithmic profile
- Roller with cylindrical profile

Assumptions:

- Balls and rollers with the same diameter
- Rollers in standard lengths

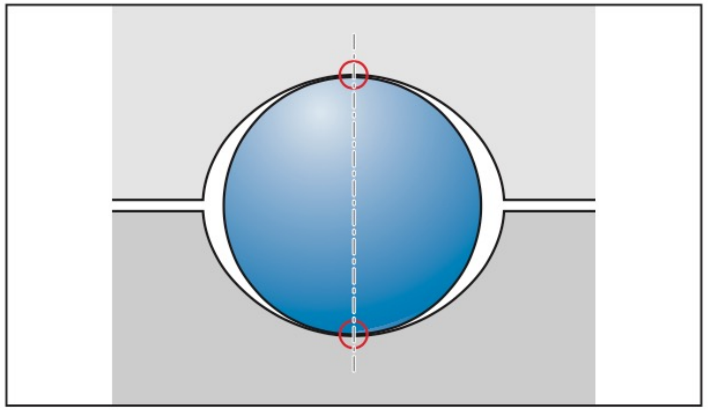


Exemplary comparison of elastic deflection in balls and rollers

Running Track Geometry for Ball Rolling Elements

The circular-arc raceway has two running tracks with conformity. This produces a 2-point contact between the running tracks and the rolling element.

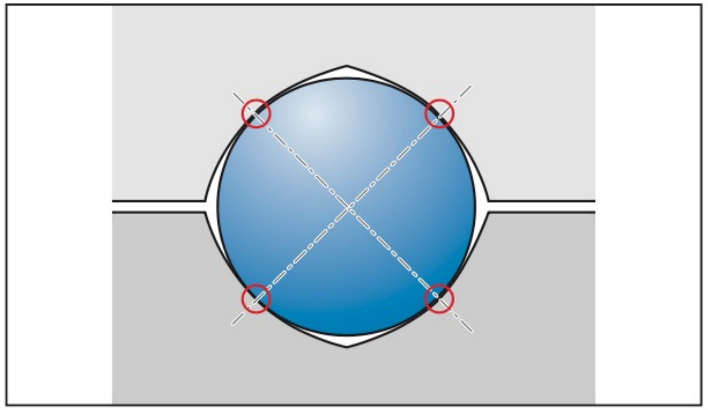
Circular-arc raceway
2-point contact



Circular-arc raceway with 2-point contact

In Gothic-arch raceways, the Gothic profile (derived from the pointed arch, a stylistic element in Gothic architecture) produces two running tracks with conformity per side. This results in 4-point contact with the rolling element.

Gothic-arch raceway
4-point contact



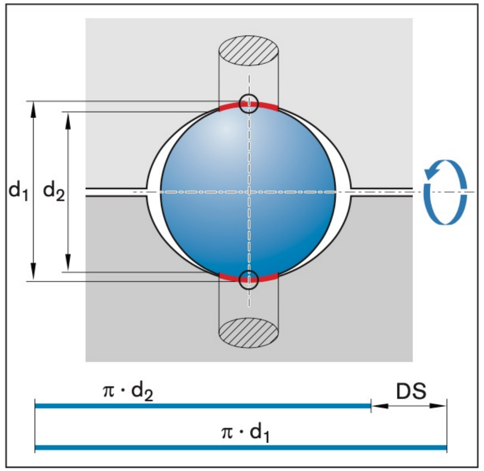
Gothic-arch raceway with 4-point contact

Differential slip

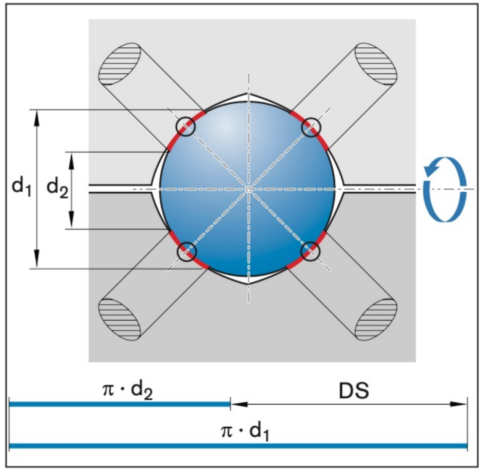
Unlike point contact, because of the curved running tracks with conformity, the ball has a larger, elliptical and similarly curved contact area. The ball therefore rolls in a diameter range of d_1 to d_2.

The different effective rolling diameters d_1 and d_2 in the contact area result in different rolling speeds, which leads to partial sliding friction. This effect is termed differential slip. The consequences of differential slip are a higher friction coefficient and hence a higher resistance to movement.

The differential slip is substantially greater in the 4-point contact Gothic-arch raceway than it is in the 2-point contact circular-arc raceway. The friction coefficient is therefore lower with 2-point contact than with 4-point contact.



Differential slip (DS) in circular-arc raceways



Differential slip (DS) in Gothic-arch raceways

Life Expentancy

$$L = \left(\frac{C}{F}\right)^p \quad (2\text{-}2)$$

L = nominal life
(100 km for linear guides or 1 million revolutions for ball screw assemblies)
C = dynamic load capacity (N)
F = bearing loading and/or sum of external force components acting on the bearing (N)
p = exponent of the nominal life equation, depending on the type of rolling element (–)

$p = 3$
for linear ball bearings and ball screw assemblies
$p = 10/3$
for linear roller bearings

- The **<u>nominal life</u>** *L* is the distance that a component can cover before the first signs of fatigue appear on the running tracks or rolling elements.
  - Lundberg and Palmgren have developed a calculation method for predicting the life expectancy of an anti-friction bearing as a function of the loading.

- **<u>Probability of survival</u>**
  - An individual bearing's probability of survival is the probability that the bearing will achieve or exceed a certain service life.
  - The probability of survival is therefore a percentage of a group of identical bearings that have the same calculated life expectancy when operating under identical conditions.

Nominal life L_{10}

The nominal life L_{10} is understood as being the achievable calculated life expectancy with a probability of survival of 90%. This means that 90% of a sufficiently large quantity of identical bearings achieve or exceed the theoretical life expectancy before material fatigue occurs.

Modified life expectancy L_{na}

If this probability is too low, the calculated life expectancy must be reduced by a certain factor, this being the life expectancy coefficient a_1 for the probability of survival. This results in the modified life expectancy L_{na}.

(2-3) $$L_{na} = a_1 \cdot \left(\frac{C}{F}\right)^p$$

$p = 3$
for linear ball bearings and ball screw assemblies
$p = 10/3$
for linear roller bearings

L_{na} = modified life expectancy (100 km for linear guides or 1 million revolutions for ball screw assemblies)
a_1 = life expectancy coefficient
C = dynamic load capacity (N)
F = bearing loading and/or sum of external force components acting on the bearing (N)
p = exponent of the nominal life equation, depending on the type of rolling element (–)

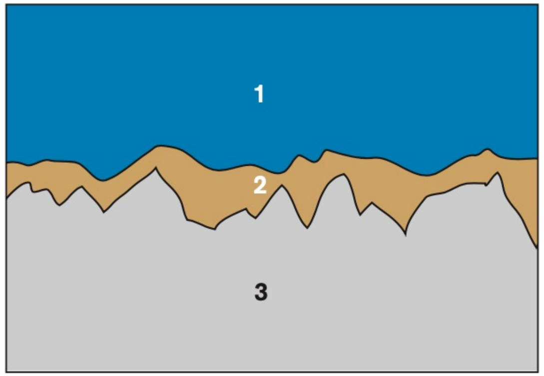
Probability of survival	(%)	90	95	96	97	98	99
a_1	(–)	1.00	0.62	0.53	0.44	0.33	0.21

Life Expentancy

Static or Dynamic Loading?

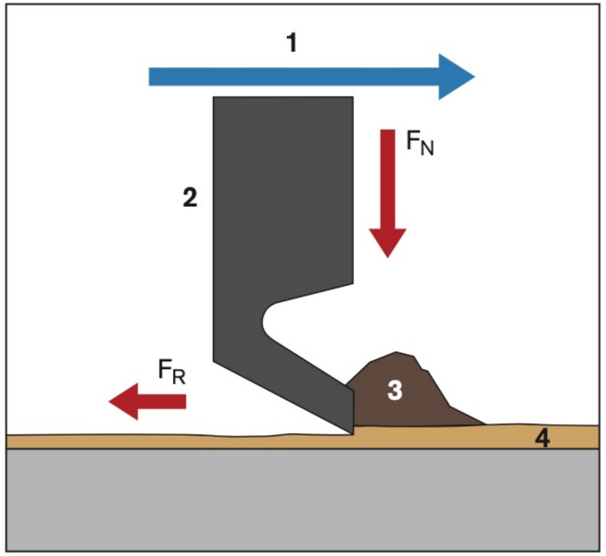
Lubrication conditions?

Sealing conditions?



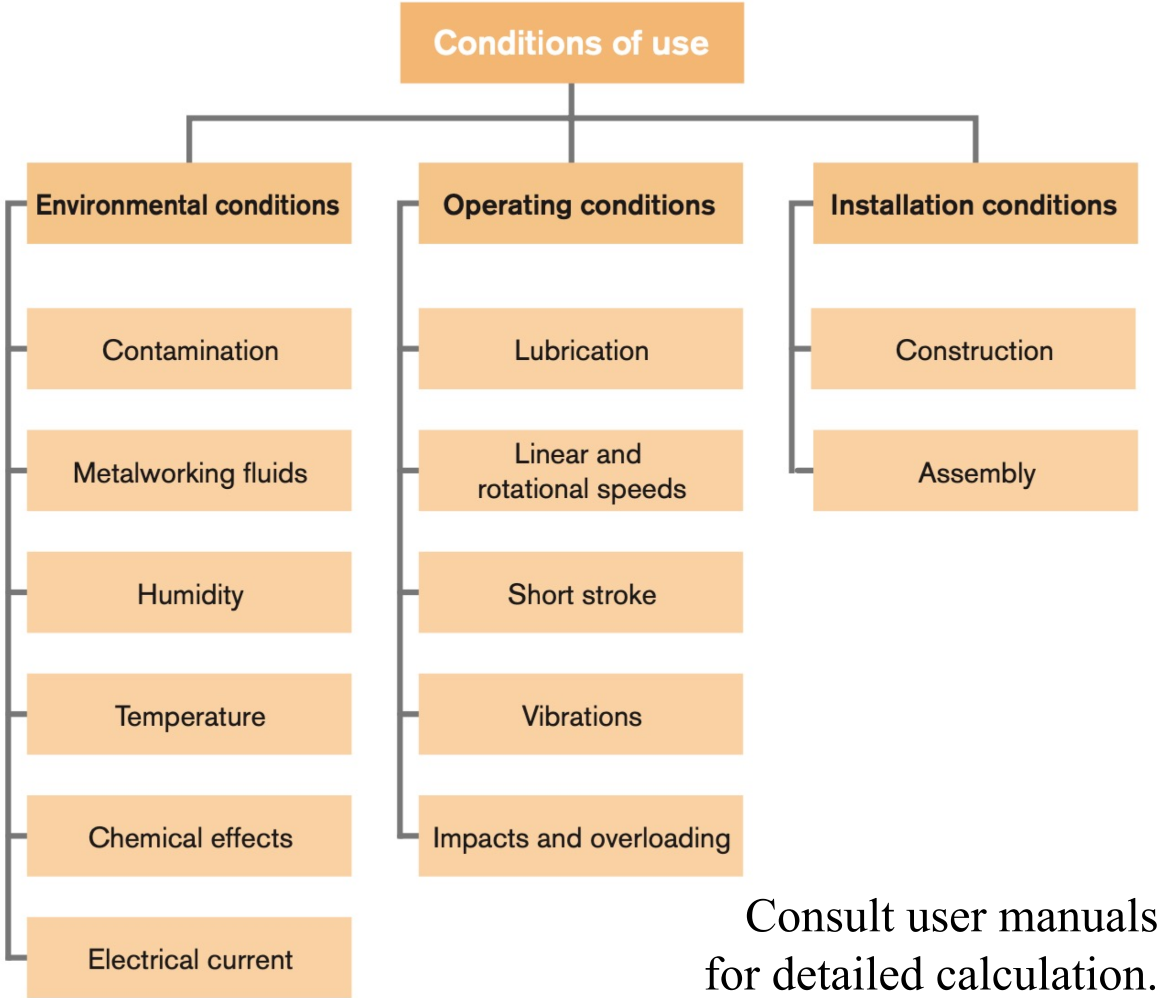
Greatly enlarged representation of the contact area

1 Rolling element
2 Lubricant
3 Running track

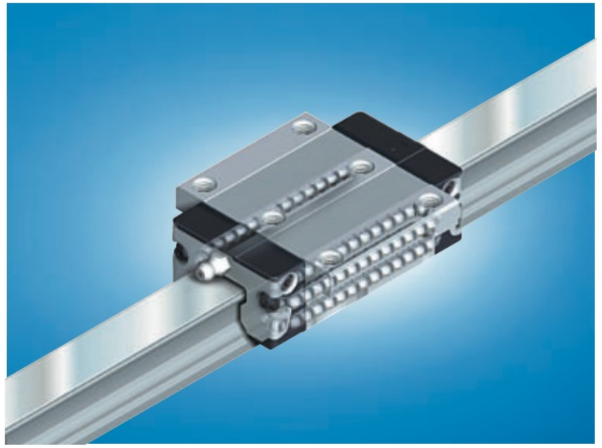


Wiper end seal of a linear motion guide

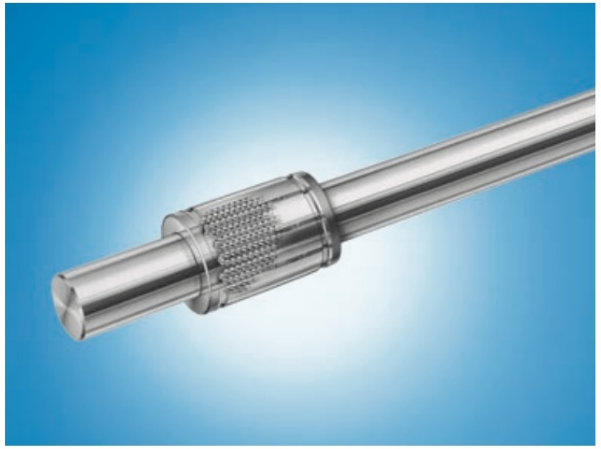
1 Direction of motion
2 Inner side of seal
3 Contamination
4 Lubricant
F_R Friction force
F_N Preload force



Consult user manuals for detailed calculation.

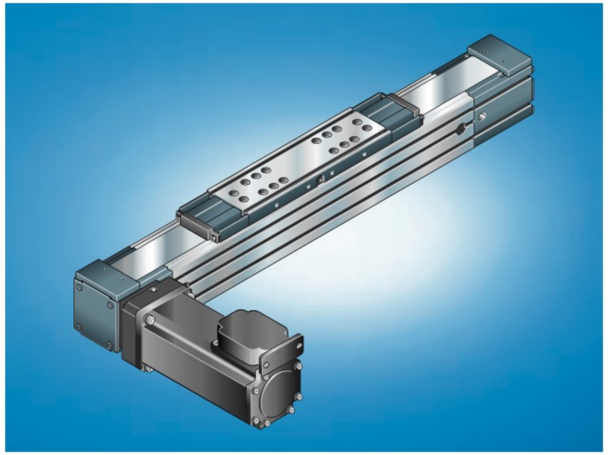


Ball rail system



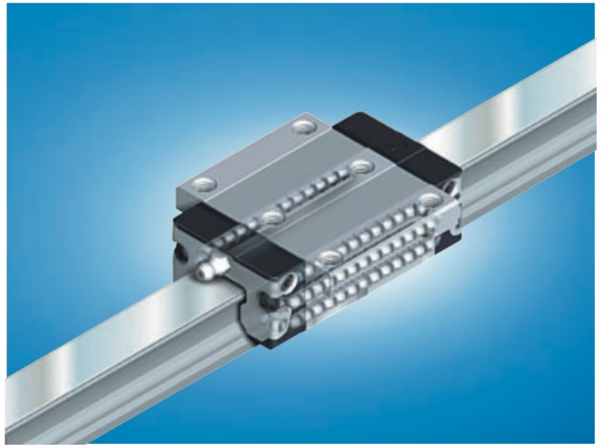
Linear bushing and shaft

Precision ball screw assembly



Linear module

Linear Motion Components

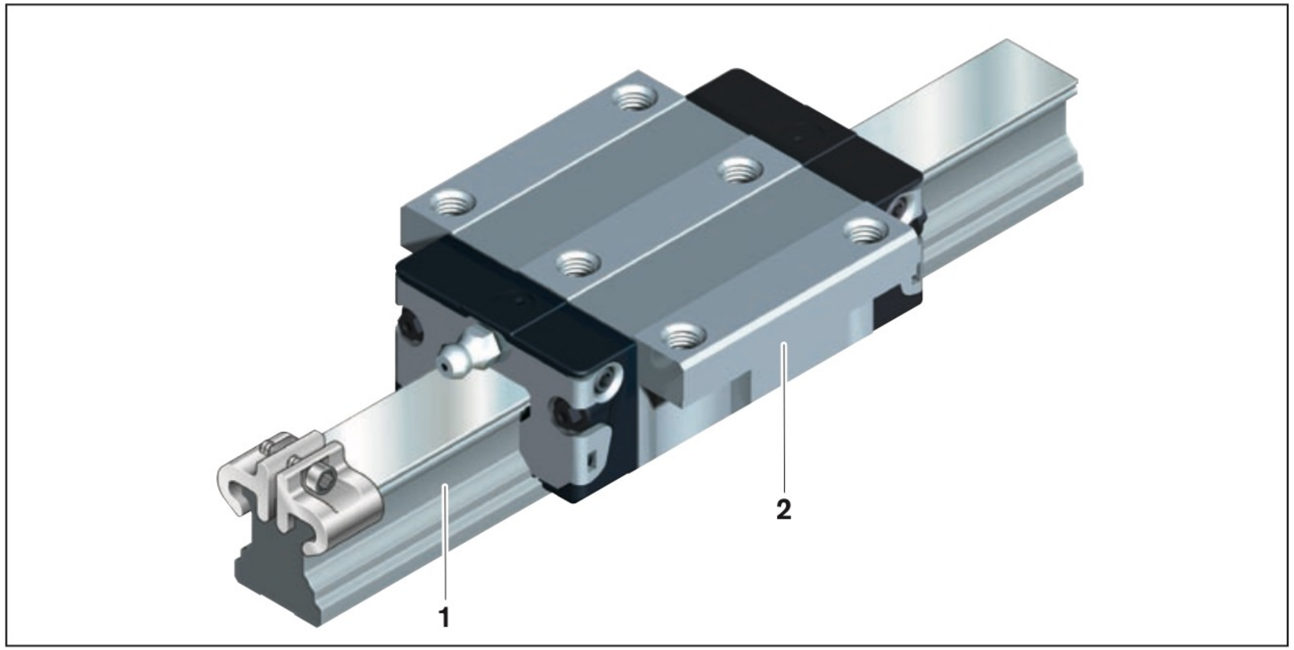

Ball rail system

high precision
low maintenance
low wear
low friction
highly accurate positioning

Profiled Rail Systems

Structural Design of a Profiled Rail System

Profiled rail systems consist of a **runner block** and a **guide rail**.

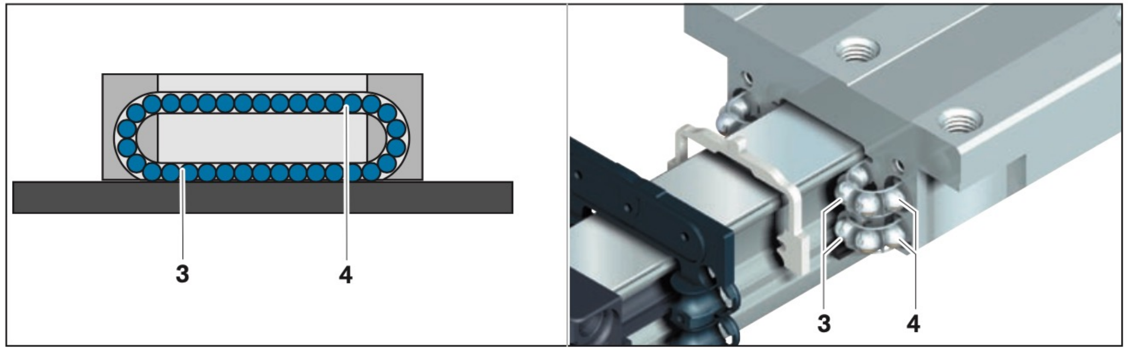


Profiled rail system (example: ball rail system)

1 Guide rail
2 Runner block

The runner block comprises several parts. It has one or more rolling element circuits with a load bearing zone and a return zone. In the load-bearing zone the rolling elements transmit the load from the runner block to the rail, and vice versa.

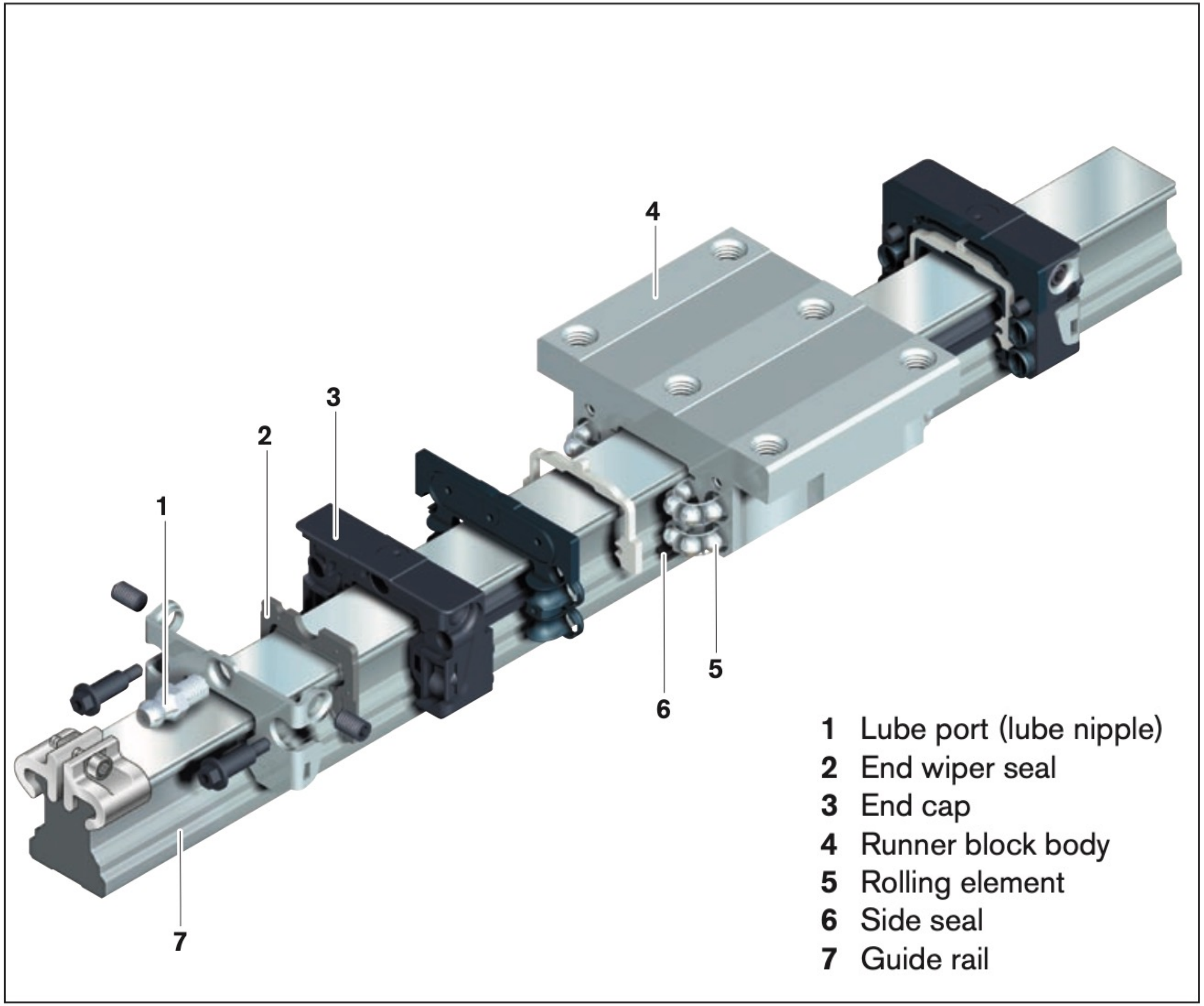
In the return zone the rolling elements are not subjected to loading and are guided around the circuit and back into the load-bearing zone. This recirculation of the rolling elements allows unlimited linear travel.



Rolling element load-bearing zone and return zone in a schematic representation (left) and as implemented in a ball rail system

3 Rolling element load-bearing zone
4 Rolling element return zone

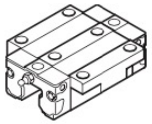
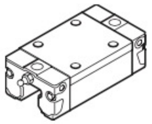
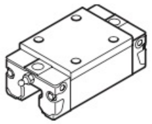
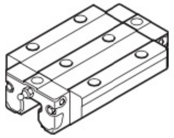
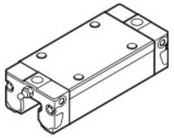
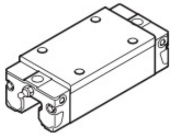
- A key component of the runner block is the body with its hardened raceways.
- The rolling elements are normally made from anti-friction bearing steel and are in rolling contact with the runner block and with the rail.
- The end caps contain recirculation pieces which guide the rolling elements from the load-bearing zone to the return zone, and vice versa.
- The end caps are also designed to accommodate sealing elements.
- A complete seal kit consists of the end wiper seals and the side seals, providing all-around sealing to prevent dirt or dust from working its way into the runner block.
- Runner blocks are lubricated via lube ports in the end caps to ensure full functionality of the guide.
- The guide rail has hardened running tracks to match the hardened raceways in the runner block.



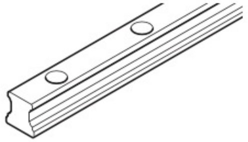
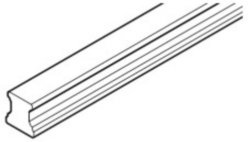
Structural design, as illustrated by a latest-generation ball rail system

Design Styles

Runner block design styles

	Series 1	Series 2	Series 3
Design style	Normal 	Slimline 	Slimline High 
	Normal Long 	Slimline Long 	Slimline High Long 

Guide rail design styles

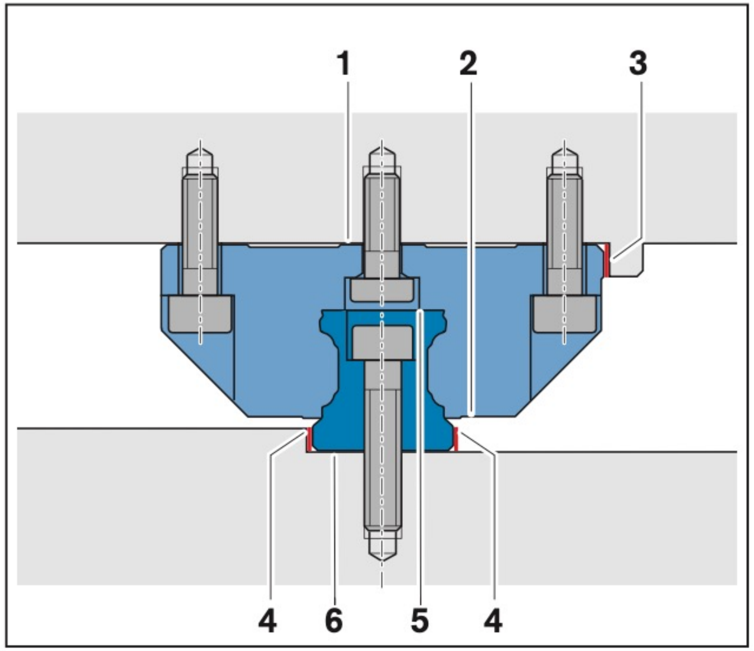
	Series 1	Series 2
Design style	For mounting from above 	For mounting from below 

There are, however, many more design styles available than those specified in the standard. Special applications and new machine concepts require specially engineered guides to achieve maximum performance. Runner block designs today include wide, short and low-profile versions. Guide rails are also available as V-guide rails with a dovetail fit.

Reference Surfaces and Edges

Because of their structural design, linear guides have various reference surfaces and edges for alignment with and mounting to adjoining structures. The bases of the runner blocks and guide rails serve as mating surfaces for mounting to the surrounding structure. They have threaded or countersunk holes to receive fixing screws.

The side surfaces serve to transmit forces laterally and to align the components during installation. They are called reference edges. The guide rail has two reference edges that can be used independently of each other. Runner blocks generally have one reference edge which must be taken into consideration during mounting. However, some runner block types can have two or more reference edges.



Reference surfaces and edges

1 Base of the runner block
2 Head of runner block
3 Reference edge on the runner block
4 Two reference edges on the rail
5 Head of the guide rail
6 Base of the guide rail

Coordinate System

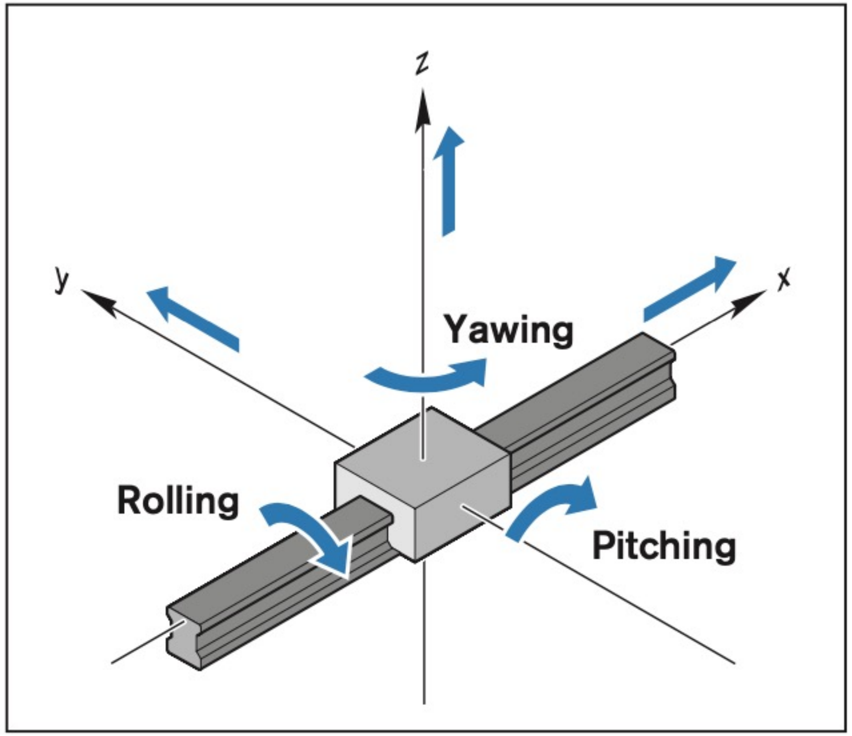
In profiled rail guides, movement or displacement of the runner block is governed by the coordinate system shown in the illustration. This coordinate system has 6 degrees of freedom. The X-axis is the direction of travel. In all other directions, movement is only possible as elastic deflection of the guide unit under load.

Linear degrees of freedom (along the axes):

- Direction of travel (X-axis)
- Lateral movement (Y-axis)
- Lift-off movement (Z-axis)
  Downward movement (Z-axis, negative direction)

Rotational degrees of freedom:

- Rolling (rotation about the X-axis)
- Pitching (rotation about the Y-axis)
- Yawing (rotation about the Z-axis)



Axial and rotational directions of movement

Internal Structure of Profiled Rail Guides

Manufacturers are free to design the internal structure of profiled rail guides as they wish. The guides produced by the various manufacturers differ in the way rolling contact is achieved. Specifically, these differences relate to:

- Rolling element shape (ball/roller)
- Rolling element size
- Rolling contact type (2-point/4-point)
- Conformity of ball contact
- Number of rolling element rows (2/4/6)
- Arrangement of rolling element rows (X/O)
- Contact angle

These differences result in different system characteristics in terms of the load capacity, rigidity and friction.

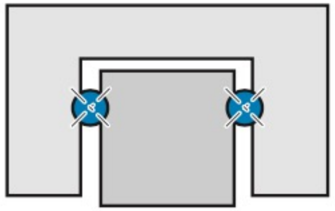
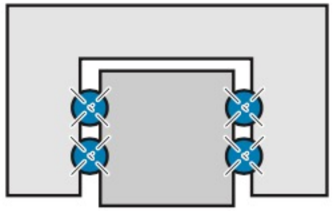
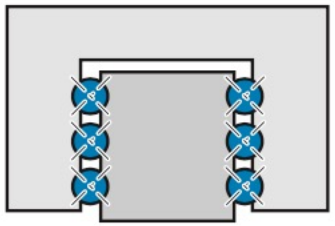
The influences of the rolling element shape and size, rolling contact and conformity were discussed earlier in Chapter 2, section 2.3. This section therefore deals only with the specific characteristics of profiled rail guides.

Number of Rolling Element Rows

The number of load-bearing rolling element rows is a basic distinguishing feature in profiled rail guides. It influences the load capacity, the rigidity behavior and the friction behavior of the profiled rail guide. The more rows a rail guide has, the greater the load capacity and the rigidity will be. However, this statement applies only when all other parameters remain constant, i.e. same rolling element shape and size, same type of rolling contact (2-point or 4-point), same conformity, same arrangement, and same contact angle.

It should also be noted that increasing numbers of rows result in increasingly complex and costly designs.

Rexroth uses only 2-row and 4-row designs in its ball rail systems. The roller rail systems have 4 rows. These designs allow a much more even distribution of the load across the rolling element rows than is possible with 6-row profiled rail guides.

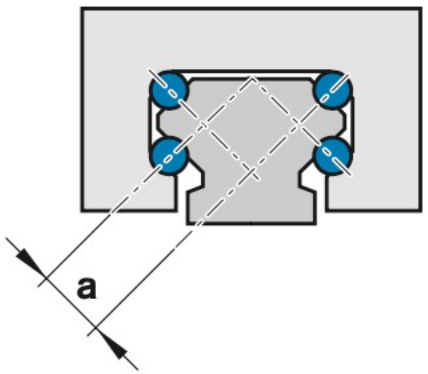
2 rolling element rows	4 rolling element rows	6 rolling element rows
		

Comparison of X- and O-Arrangements

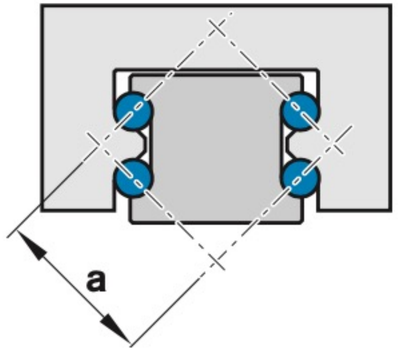
Just as in rotary rolling contact bearings, the raceways in profiled rail guides can be arranged in an X- or an O-configuration. The system characteristics of these two arrangements are identical except for their behavior when subjected to a torsional moment. They show no differences in behavior under down loads, lift-off loads and side loads or under longitudinal moments.

Because of its greater leverage (a), the O-arrangement can withstand higher torque forces than the X-arrangement. In same-size systems, the O-arrangement therefore offers higher torsional stiffness. Rexroth's 4-row ball and roller rail systems have an O-arrangement.

X-arrangement



O-arrangement



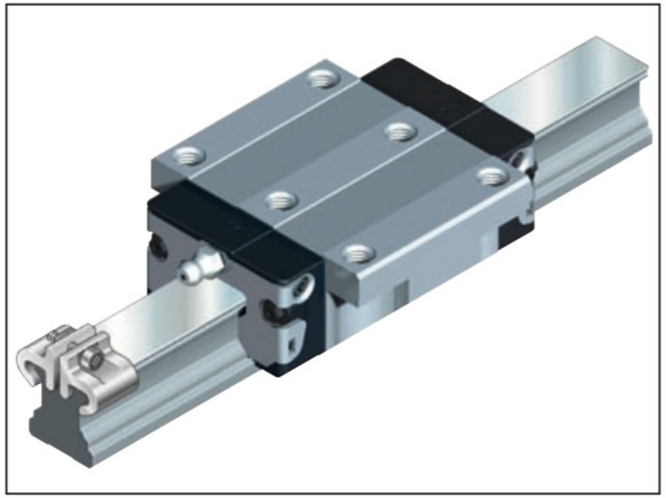
Product Selection Procedure

Many different parameters must be considered to arrive at the optimal choice of profiled rail guide. Though the selection procedure described below is a typical one, it may not apply to all applications. For some applications it may be useful to switch the order of the steps involved. Often, the starting situations will be different. While new-build projects generally give designers full freedom of choice, the range of available options will be restricted at the outset when modifying existing designs. Also, some types of guide are more commonly used in certain sectors and applications than in others. Another point to be considered at an early stage is the level of accuracy required, as this may eliminate some versions in the first place. It is therefore advisable to run through all the steps once to gain a better idea of the possible options before proceeding to select the product and perform the nominal life calculations.

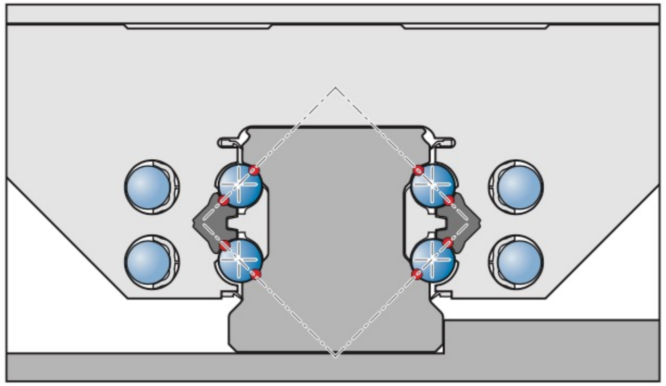
Procedure	
Step 1	Define the requirements
Step 2	Select an appropriate profiled rail guide
Step 3	Define the layout for the profiled rail guide
Step 4	Define the preload class
Step 5	Perform the calculations
Step 6	Define the accuracy class
Step 7	Define the peripherals
Result	Ordering details with part numbers

Ball Rail Systems

System Characteristics



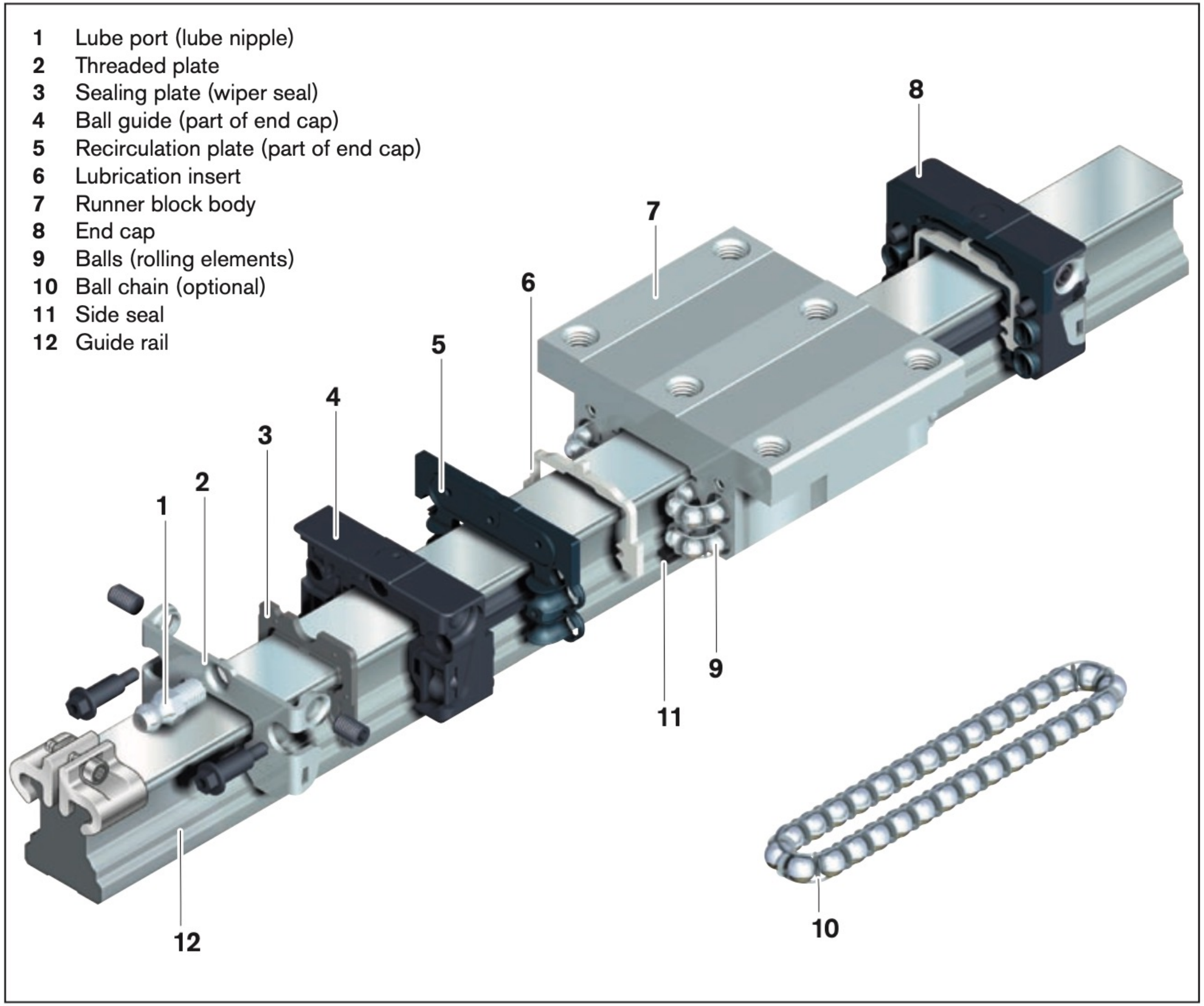
Ball rail system BRS



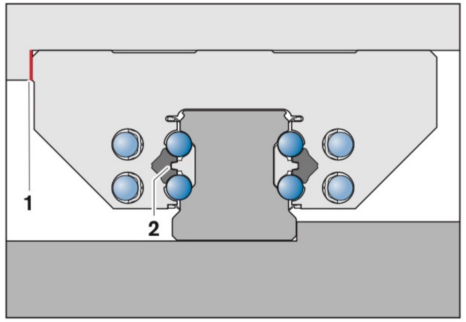
Four rows of balls in an O-arrangement

Features

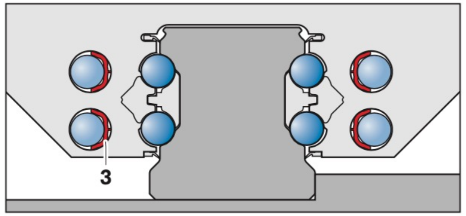
- High load capacities in all four major planes of load application
- High system rigidity
- Limitless interchangeability due to precision manufacturing
- Smooth running performance
- Zero-clearance movement
- Excellent high-speed characteristics
- Easy-to-achieve precision
- Very good travel accuracy with HP series runner bocks
- Long-term zero maintenance
- Minimum quantity lubrication system with integrated reservoir for oil lubrication (depending on version)
- Lube ports on all sides
- Optional ball chain
- Broad range of accessories for industry-specific solutions (seals, wipers/scrapers)
- High dynamic characteristics with high-speed runner blocks
- Optimum installation error compensation with super runner block
- Integrated, inductive and wear-free measuring system as an option
- Runner blocks in rust- and acid-resistant steel to EN 10088 available
- Up to 60% weight saving with aluminum runner block



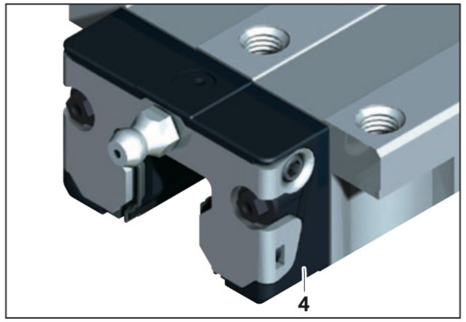
Structural design as implemented in a latest-generation ball rail system



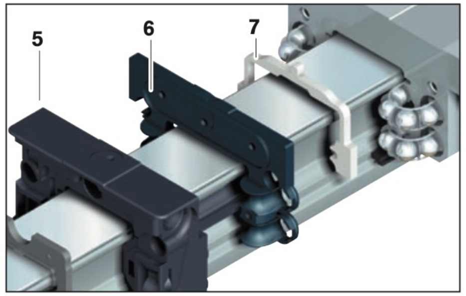
Steel inserts and reference edge in a runner block



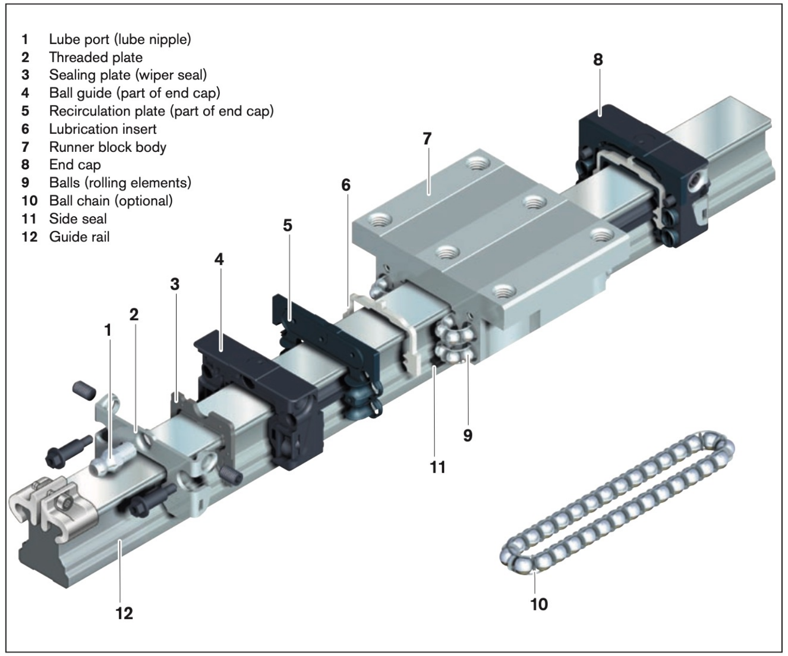
Recirculation sleeves



Complete end cap



Recirculation plate with lubrication insert



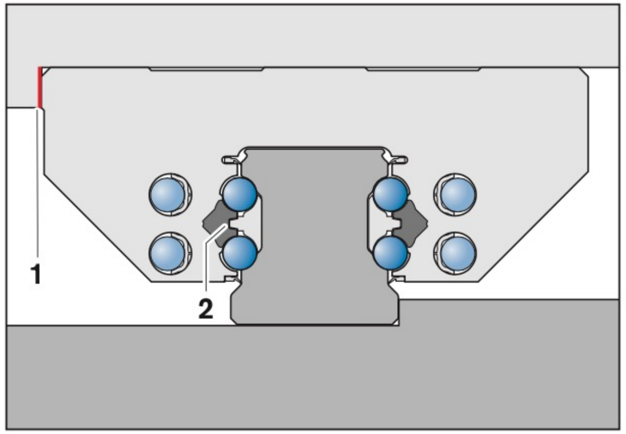
Structural design as implemented in a latest-generation ball rail system

Runner block body

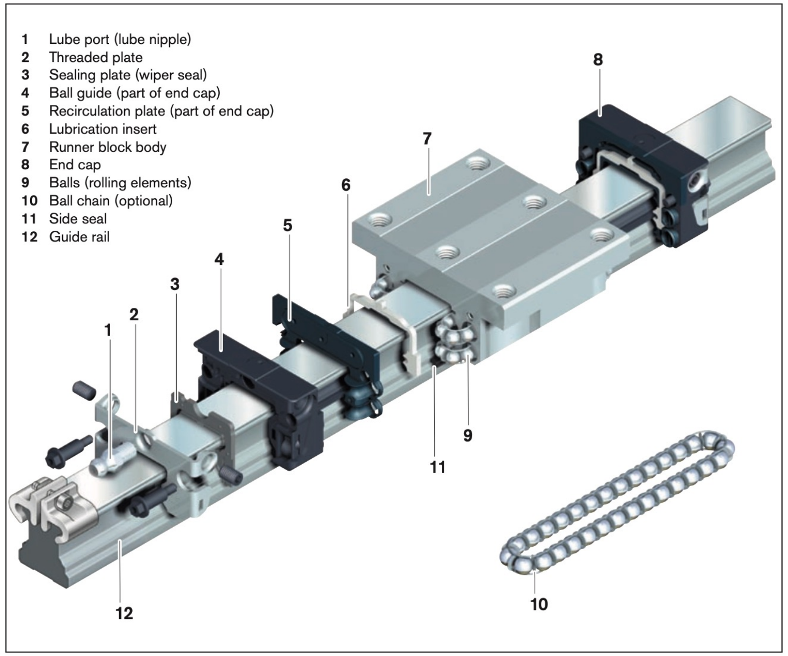
Depending on the version, the runner block body can be made from heat-treated steel or anti-friction bearing steel. For special applications, especially for use in industrial robots, the body is made from aluminum. The aluminum version offers weight savings up to 60% compared to the steel version. Each runner block has a lateral reference edge (1). This edge mates with the adjoining structure. It permits precise alignment during installation and serves to transmit side loads.

Steel inserts

The runner blocks have two hardened steel inserts (2) made from anti-friction bearing steel. These inserts transmit the load from the runner block body to the balls.



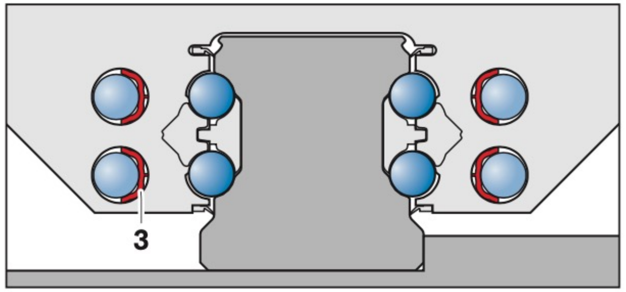
Steel inserts and reference edge in a runner block



Structural design as implemented in a latest-generation ball rail system

Recirculation sleeves

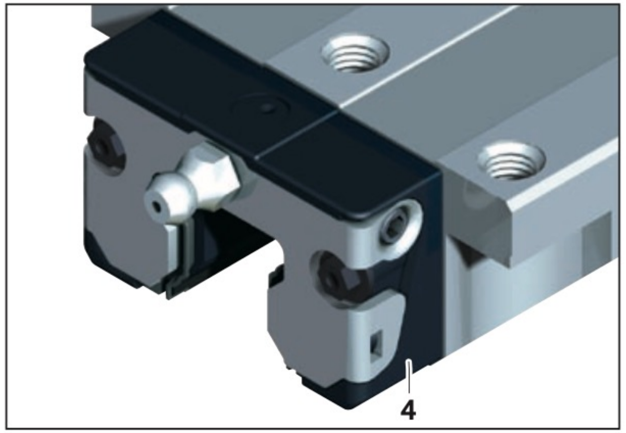
Each of the four ball return bores in the runner block body is lined with a sleeve (3). This sleeve ensures good, low-friction recirculation of the balls inside the runner block. It also acts as a guide for the optional ball chain.



Recirculation sleeves

End cap

The end cap (4) consists of the recirculation plate (6), the lubrication insert (7), the ball guide (5), the sealing plate, and the threaded plate.



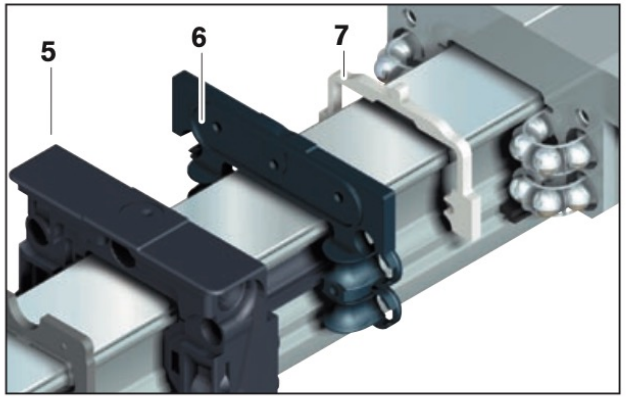
Complete end cap

Recirculation plate

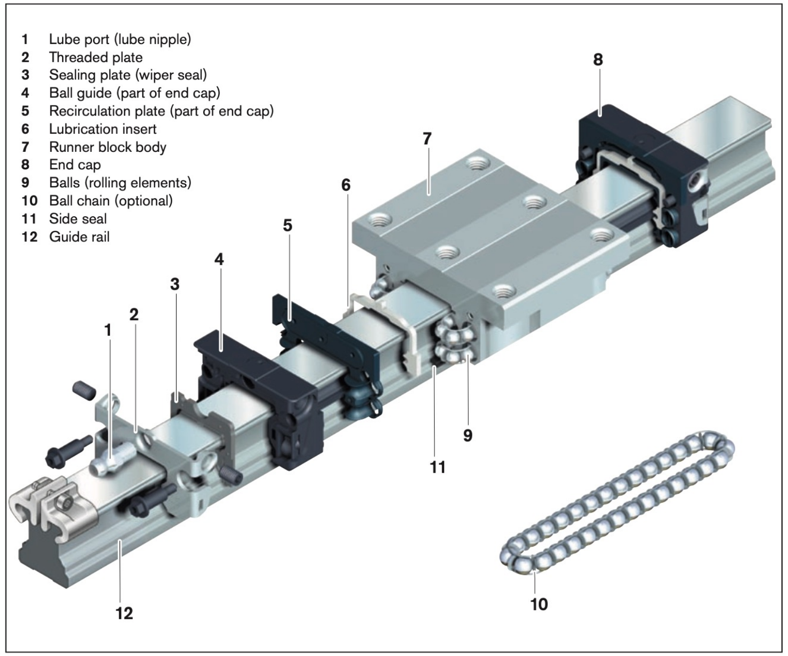
The recirculation plate (6) has specially designed lube ducts which conduct the lubricant directly to the lubrication insert, thus ensuring optimal lubrication results. It is thanks to this particular feature that long maintenance intervals or even lubrication for life can be achieved. The recirculation plate also picks up and redirects the balls inside the runner blocks.

Lubrication insert

The lubrication insert (7) is made from open-pored polyurethane foam. This foam soaks up the lubricant and releases it to the passing balls. The lubrication insert has been designed to allow lubrication with either oil or grease.



Recirculation plate with lubrication insert



Structural design as implemented in a latest-generation ball rail system

Ball guide

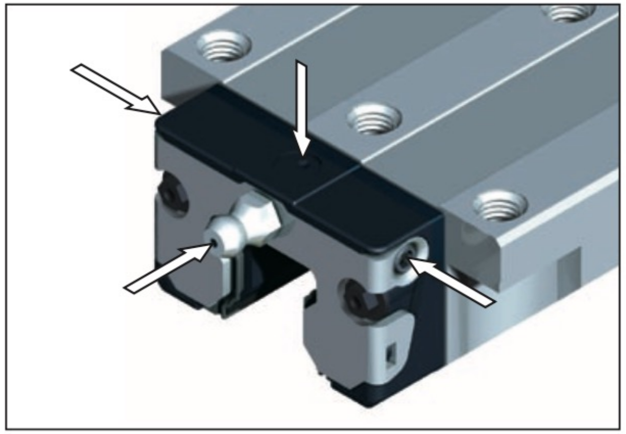
The ball guide is fixed in place by the recirculation plate. The balls are redirected in the space between these two parts. The ball guide also serves to retain the balls in the load-bearing raceway of the runner block when it is not mounted on the rail.

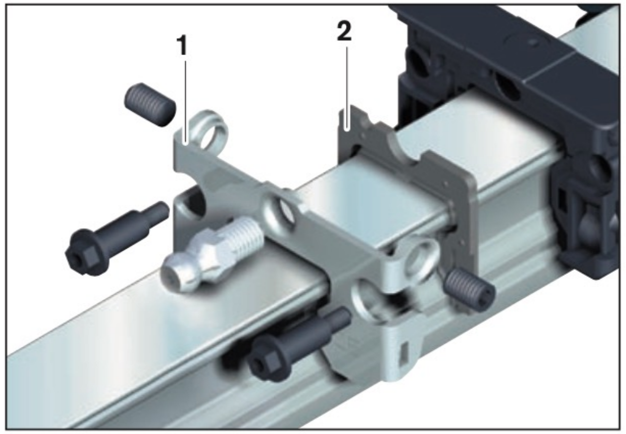
Lube ports

The ball guide also contains lube ports. The lube nipples or fittings of a central lubrication system can be inserted into these lube ports. The ports are located on the end face and at both sides. This allows lubrication from any of three directions without the need for an adapter. Lubrication from the top is also possible, by opening a pre-drilled hole. The hole can be punched open using a heated, pointed metal tool to allow lubrication through the machine table. An O-ring seals the interface to the machine table. High-profile runner blocks require an adapter to compensate for the height difference between the end cap and the runner block body.

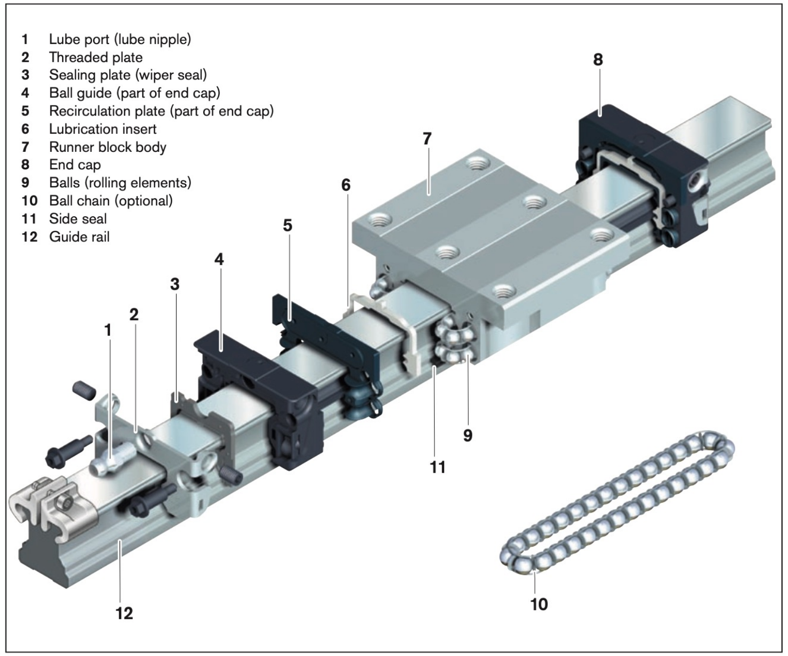
Threaded plate

The threaded plate (1) has two functions: it accommodates lube nipples and protects the end cap assembly. It is made from stainless steel.


Lube ports in the end cap



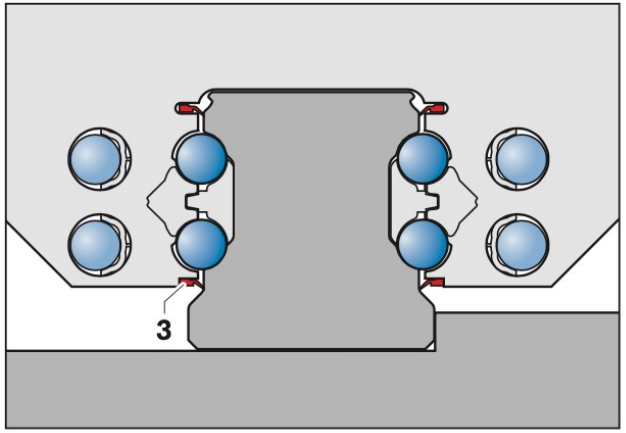
Sealing plate and threaded plate



Structural design as implemented in a latest-generation ball rail system

Sealing plate

The sealing plate (2) on the end face protects internal runner block components from dirt particles, shavings and liquids. It also prevents the lubricant from being dragged out. Optimized sealing lip geometry results in minimal friction. Sealing plates are available with a standard seal, low-friction seal, or a reinforced seal.



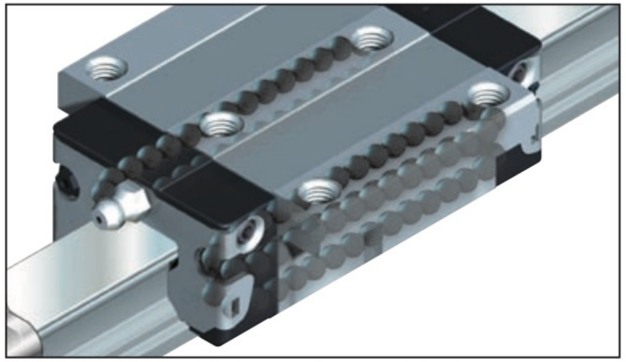
Integrated side seals in a ball runner block

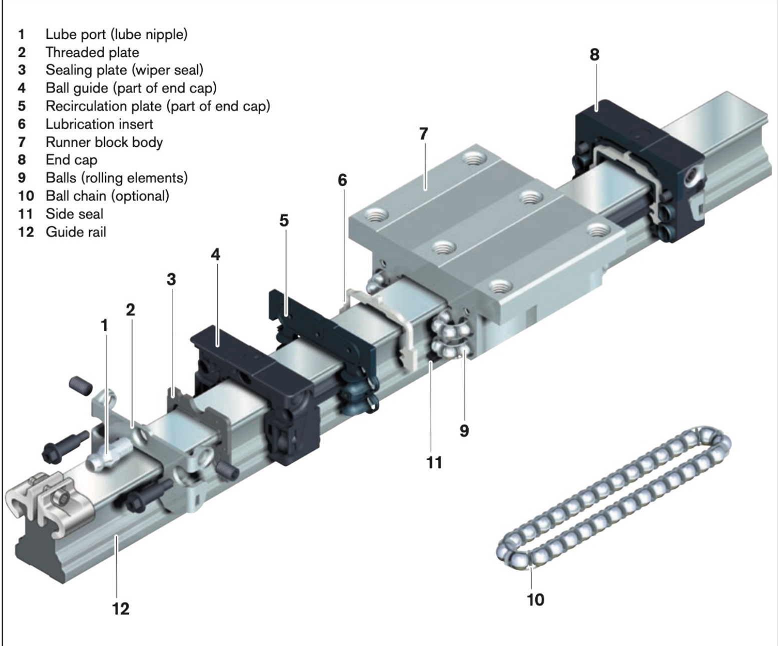
Side seals

Lateral sealing strips provide additional protection, keeping dirt and shavings out of the load-bearing zones. Each runner block has four of these side seals (3).

Balls

The rolling elements are balls. Normally, these are made from anti-friction bearing steel, grade 100Cr6. Stainless steel balls are used for runner blocks that will be operating in extremely hostile environments requiring corrosion-resistant elements. High-speed runner blocks have special ceramic balls. Because of their lightweight design, these balls deliver excellent dynamic performance. Ceramic balls are also good electrical insulators.

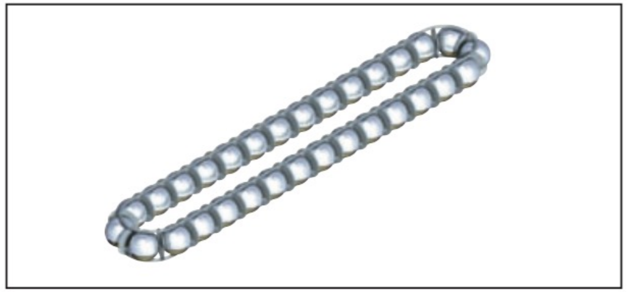

Ceramic balls for high-speed runner blocks



Structural design as implemented in a latest-generation ball rail system

Ball chain

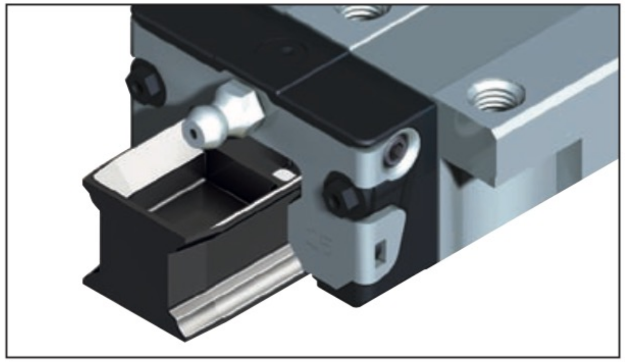
Runner blocks can also be equipped with a ball chain. The ball chain prevents the balls from bumping into each other and ensures smoother travel. This reduces the noise level. Runner blocks with ball chains have fewer load-bearing balls, which may result in lower load capacities.



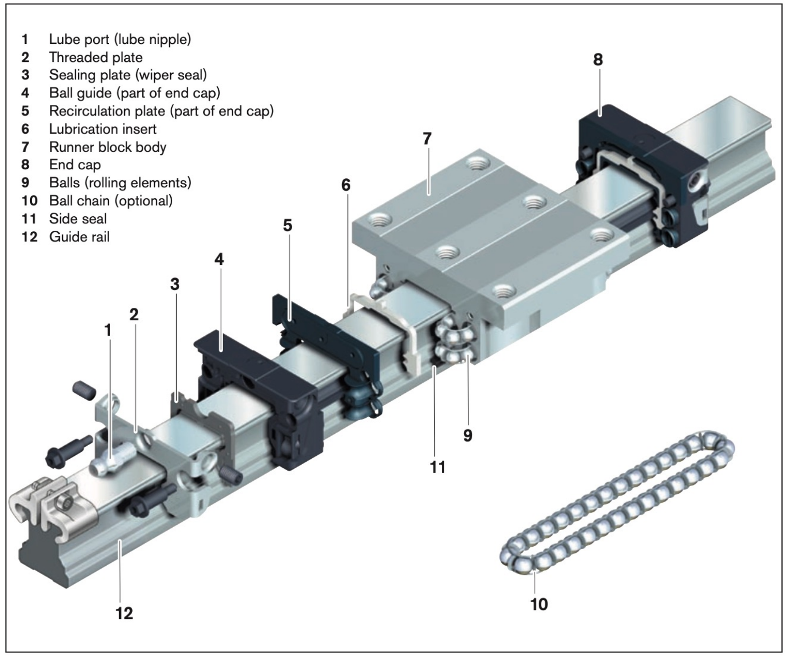
Ball chain

Transport and mounting arbor

Ball runner blocks are mounted on an arbor for shipment. This arbor protects the balls from damage during transport and makes it easier to mount the runner block to and remove it from the guide rail.



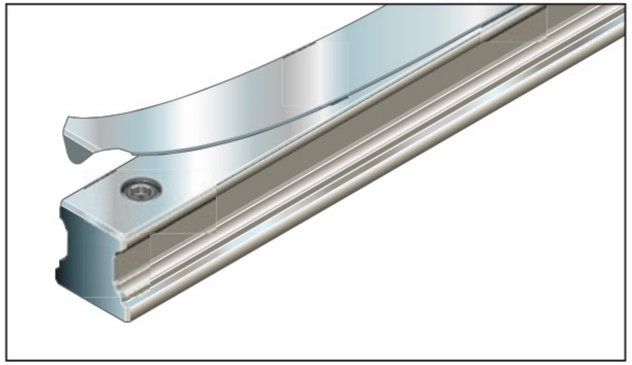
Transport and mounting arbor



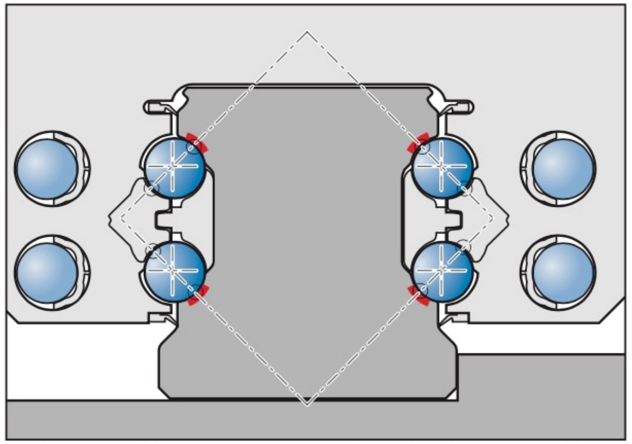
Structural design as implemented in a latest-generation ball rail system

Guide rail

The guide rail is made from heat-treated steel. This steel was specially designed to meet linear motion requirements and therefore offers optimal system characteristics. The four ground running tracks have a circular-arc profile with conformity. This geometry ensures ideal running performance and can also compensate to a certain extent for misalignments. The running tracks are inductively hardened and precision-ground. Rexroth guide rails are also available in hard chrome plated (Resist CR) or in corrosion-resistant steel (Resist NR II) versions. These rails can be used in environments with aggressive media, such as dilute acids, alkalis or salt solutions. Depending on the size, one-piece rails can be delivered in lengths up to 6 m. If longer lengths are required, several rails can be fitted end to end to produce a composite rail. Guide rails can be bolted into place from above or below. V-guide rails are installed by pressing them into the mounting base.



Guide rail for mounting from above (with cover strip to seal off the mounting holes)



Guide rail with four running tracks (circular-arc profile with conformity)

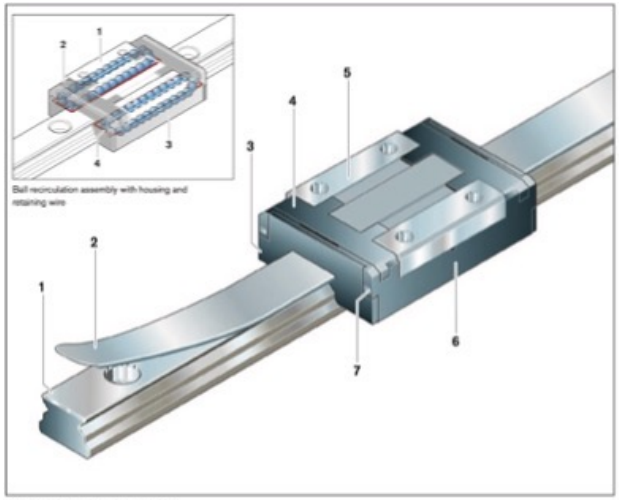
Application Areas

Ball rail systems are used in a wide variety of industries and applications.

Industry sector	Applications	
Metal-cutting machine tools	▮ Machining centers ▮ Lathes and turning machines ▮ Drilling machines ▮ Milling machines ▮ Grinding machines	▮ Nibbling machines ▮ Planing machines ▮ Electrical discharge machines ▮ Laser/light/photo beam machine tools
Assembly/handling technology and industrial robots	▮ Assembly equipment ▮ Assembly robots	▮ Multi-purpose industrial robots ▮ Gripping and clamping equipment
Woodworking and wood processing machines	▮ Belt saws ▮ Circular saws ▮ Planing machines ▮ Drilling machines	▮ Mortising machines ▮ Sanding machines ▮ Slitters
Rubber and plastics processing machinery	▮ Calendering machines ▮ Rolling mills ▮ Extruders	▮ Blow molding machines ▮ Injection molding machines
Food industry	▮ Filling machines ▮ Molding machines	▮ Confectionary technology
Printing and paper industry	▮ Paper and pulp machines ▮ Cutters for paper and cellulose	▮ Packaging machines ▮ Winders/rewinders ▮ Printing machines ▮ Paper converting machines
Automotive industry	▮ Car production lines	▮ Welding systems
Forming and stamping machine tools	▮ Bending machines ▮ Straightening/leveling machines	▮ Presses ▮ Wire bending machines

Other Types of Profiled Rail System

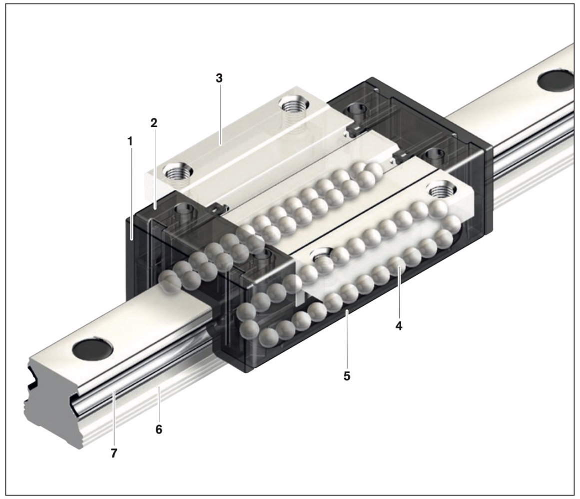
Miniature



Miniature ball rail system, size 12

1 Guide rail
2 Cover strip (rail seal)
3 Wiper seal
4 Ball recirculation
5 Runner block body
6 Housing
7 Lube holes
8 Funnel-type lube nipple

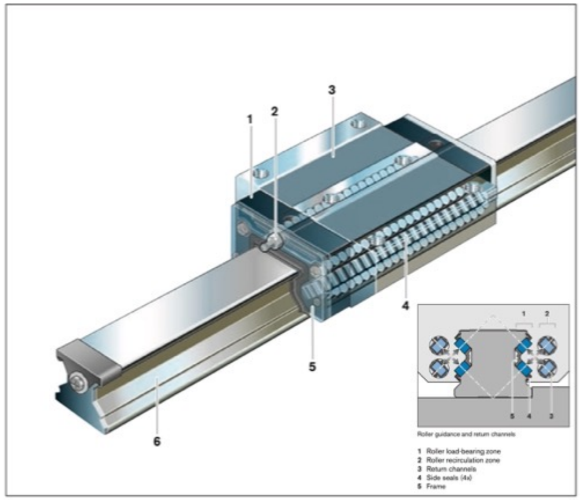
eLINE



Components of the eLINE ball rail system

1 Seal unit (wiper seal)
2 End cap
3 Runner block body with integrated steel insert
4 Row of balls
5 Housing
6 Guide rail body
7 Steel insert in guide rail

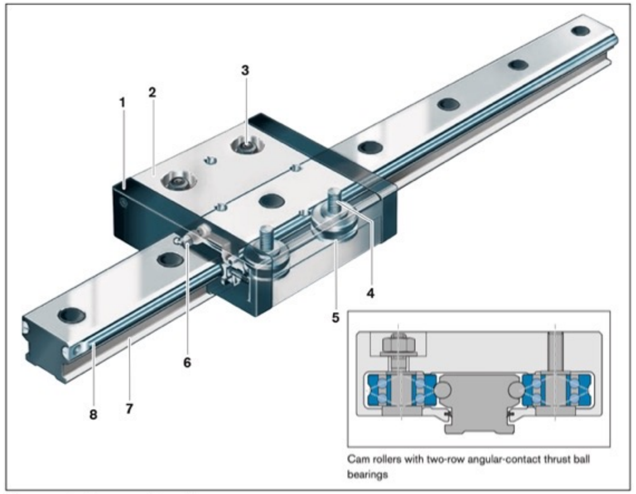
Roller



Roller rail system

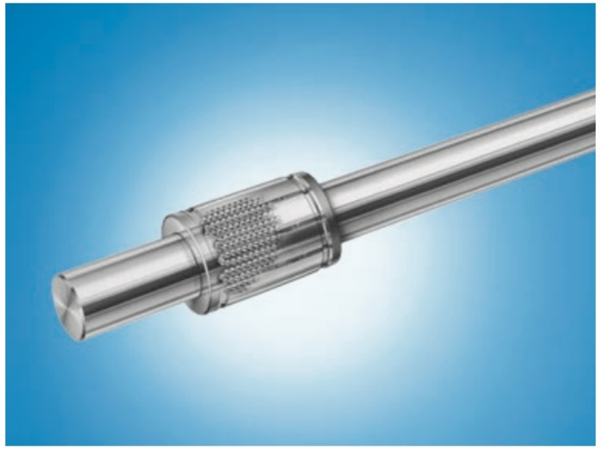
1 End cap
2 Lube port (lube nipple)
3 Runner block body
4 Cylindrical rollers (rolling elements)
5 End seal
6 Guide rail

Cam Roller



Components of the cam roller guide

1 Oil applicator/wiper unit
2 Runner block body
3 Eccentric cam roller spigot
4 Central cam roller spigot
5 Cam roller
6 Lube port (lube nipple)
7 Guide rail body
8 Precision steel shaft

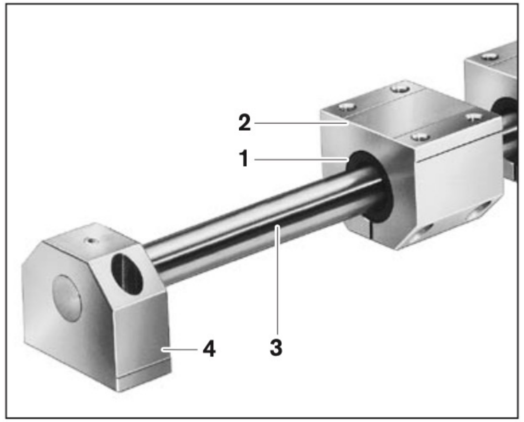

Linear bushing and shaft

Linear Bushings and Shafts

Structural Design of a Linear Bushing

Linear bushing guideways offer economical solutions for executing linear movements. Available in a great variety of designs, they can be used in many different industrial applications.

A linear bushing guideway consists of:
- One or more linear bushings (1, 5)
- One or more precision steel shafts (3) for guiding the bushings
- A housing (2) for connecting the bushings to the adjacent structure
- Shaft support blocks (4) or shaft support rails for holding the precision steel shafts



Main elements of a linear bushing guideway

1 Linear bushing
2 Housing
3 Steel shaft
4 Shaft support block

Linear bushings comprise:
- A steel sleeve or several segmental steel load-bearing plates
- A steel or plastic ball retainer
- Balls made from anti-friction bearing steel
- Possibly, steel holding rings and seals, depending on the design

5 Complete linear bushing
6 Holding ring
7 Seal
8 Segmental steel load-bearing plates
9 Balls
10 Ball retainer

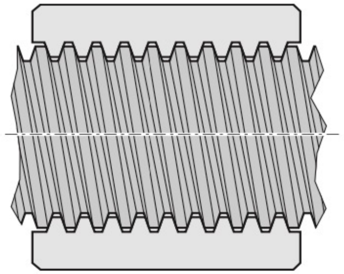
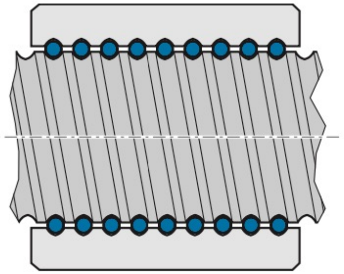
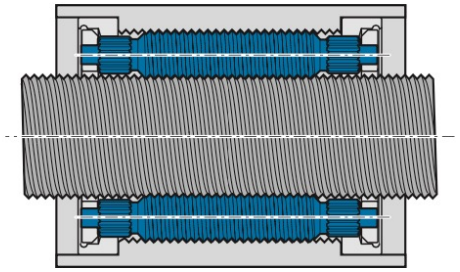
Example: Compact linear bushing

Precision ball screw assembly

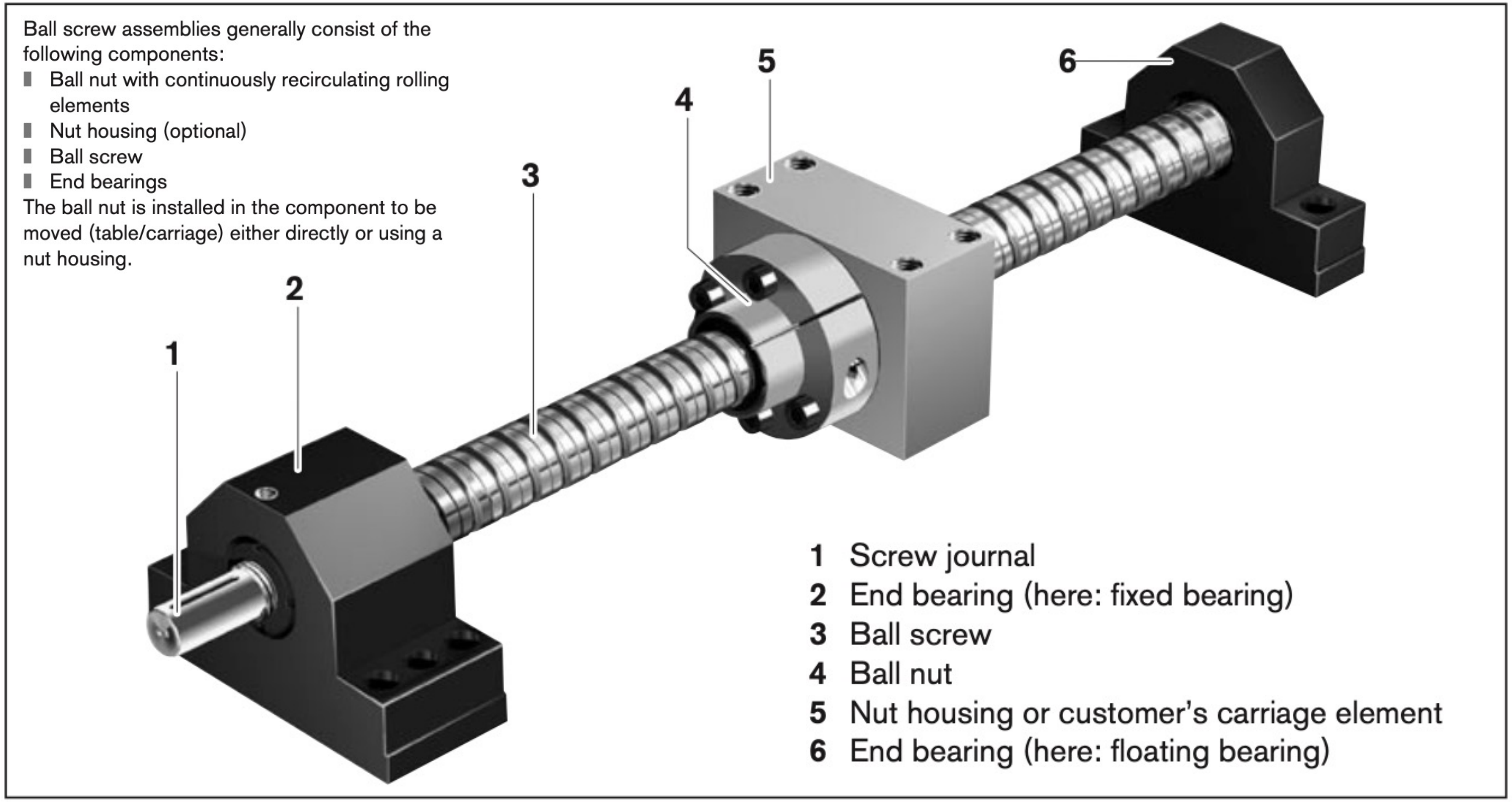
Ball Screw Drives

Screw Drive Overview

- In linear motion technology, the generation of “push-pull” or drive motion is just **as important as** precise guidance of the machine parts.
  - Alongside rack and pinion drives and linear motors, screw drives (screw-and-nut systems) play an important role as feed mechanisms.
  - These units convert rotary motion into linear motion.
- The most important representatives in this group of systems are
  - acme screw drives,
  - ball screw drives and
  - planetary roller screw drives.

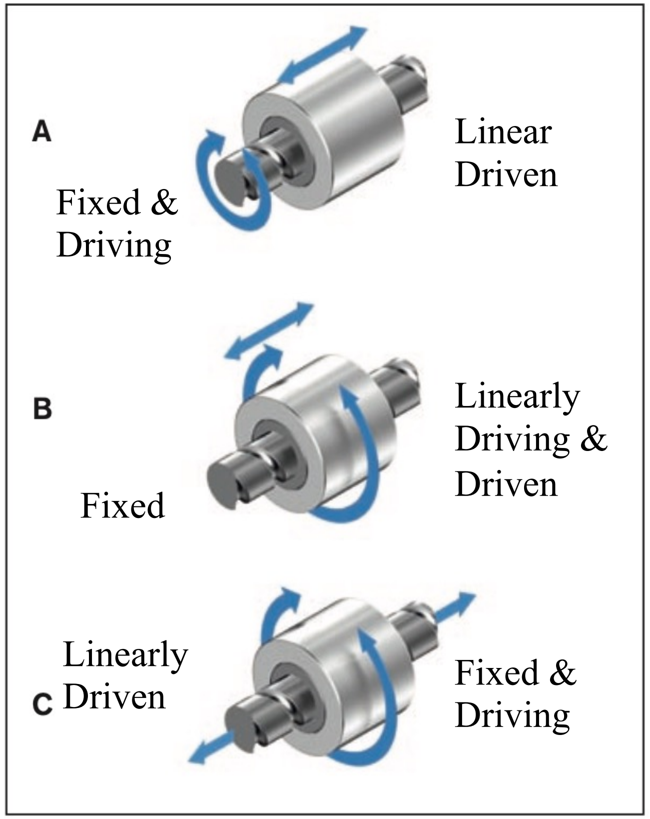
Screw drive type		Description
Acme screw drive		▮ Screw drive with sliding contact between the screw and the nut
Ball screw drive		▮ Screw drive with rolling contact between the screw, rolling elements and nut ▮ Rolling elements: balls
Planetary roller screw drive		▮ Screw drive with integral planetary gear ▮ Screw drive with rolling contact between the screw and the rolling elements and between the rolling elements and the nut ▮ Rolling elements: planetary rollers

Structural Design of a Ball Screw Assembly



Structural design of a ball screw assembly

Most ball screw assemblies are driven by a motor attached to the screw journal (1)

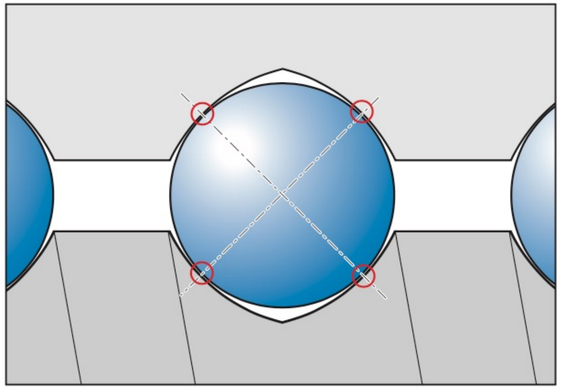


Operating principles of ball screw assemblies

Design Details

Ball Track and Point Contact

The balls run along a helical ball track (the thread, generally with a gothic profile) formed in a shaft. The ball nuts, too, are threaded, and it is the interaction of the ball movement along the screw ball track and along the ball nut raceways which converts rotary motion into linear motion.

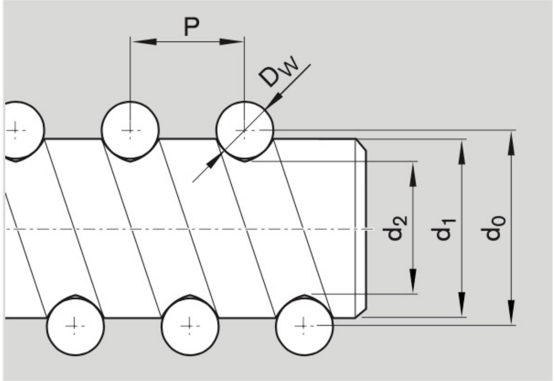


Gothic profile of the ball tracks in the screw and nut and contact points on the rolling elements

Screw Dimensions

Screws are specified by means of defined geometric parameters. These parameters are also generally used to specify the complete ball screw assembly.

P	=	lead (linear travel/revolution)	(mm)
d_0	=	nominal screw diameter (ball center-to-center diameter)	(mm)
d_1	=	screw outside diameter	(mm)
d_2	=	screw core diameter	(mm)
D_W	=	ball diameter	(mm)



Screw geometry

Screw Sizes

Screw sizes are specified according to the nominal screw diameter d_0, the lead P and the ball diameter D_W: d_0 x P x D_W
The specification for the lead P also includes the direction of rotation of the screw thread (R for right-hand or L for left-hand).

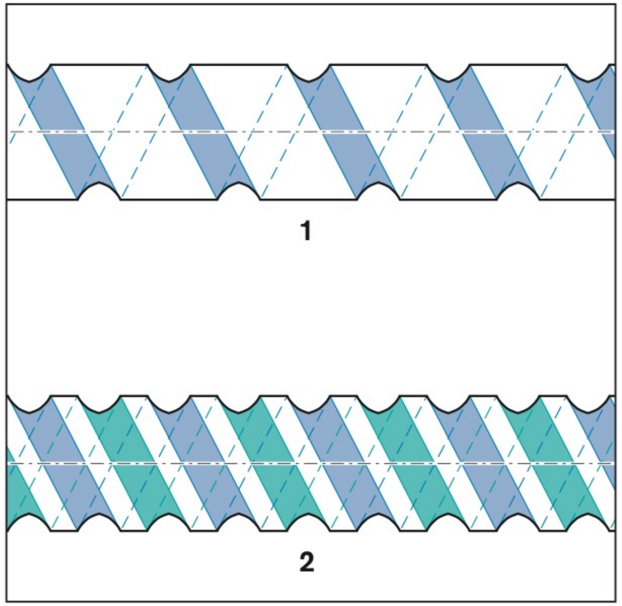
Example: 32 x 5R x 3.5 for a screw with a nominal diameter of 32 mm, lead of 5 mm, right-hand thread, and a ball diameter of 3.5 mm.

Multi-start Screws

Depending on the screw diameter, lead and ball diameter, screws can also be produced with more than one ball track. These screws are commonly called multi-start screws.

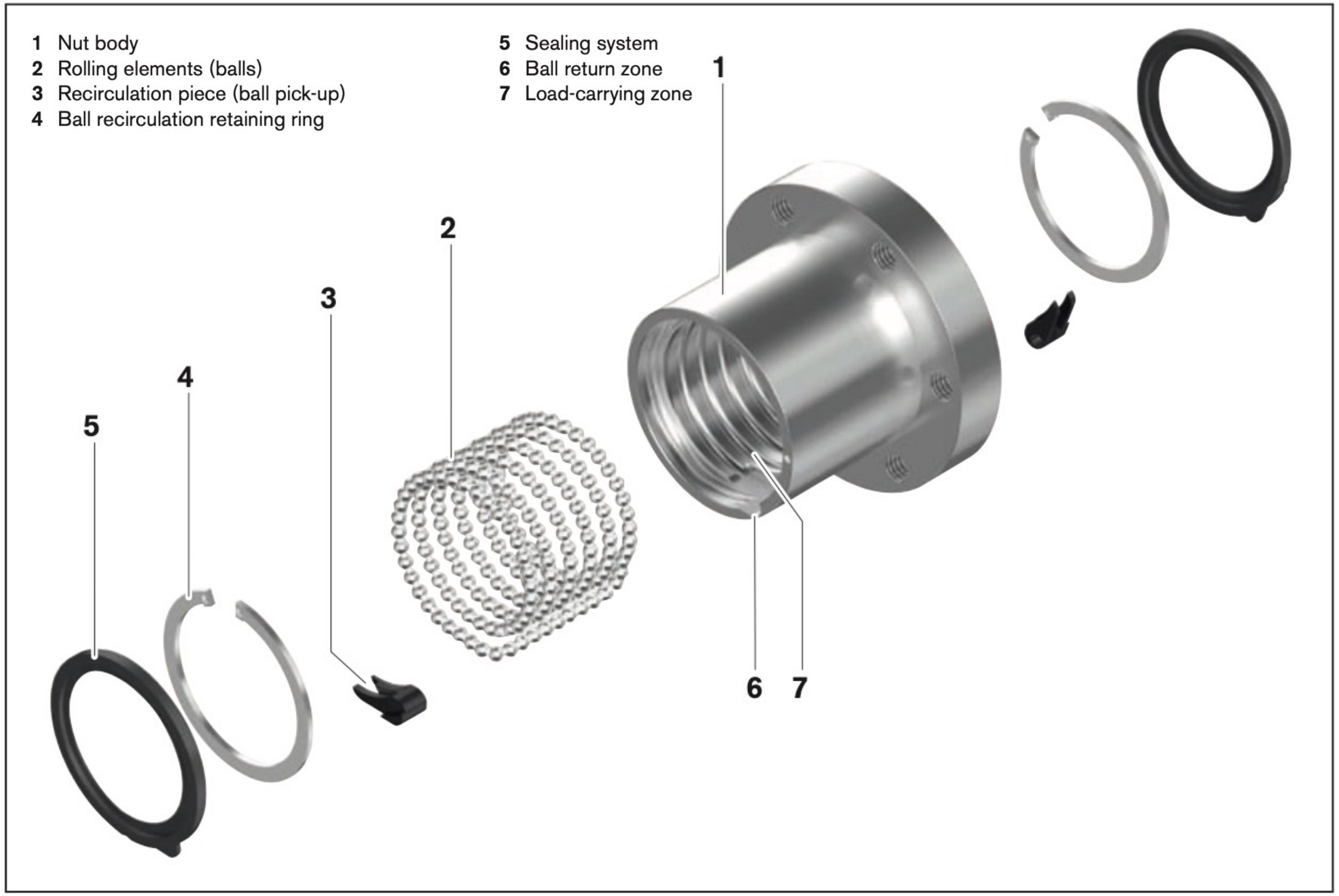
Screws with up to four starts are technically feasible today and have also been produced where appropriate. When used in combination with multi-start nuts, the resulting assemblies can achieve higher load ratings and therefore also have a longer life expectancy.

In general, ball screws are produced with a right-hand thread. For special applications (e.g. closing or clamping movements) screws with a left-hand thread or with right and left-hand thread can be used.



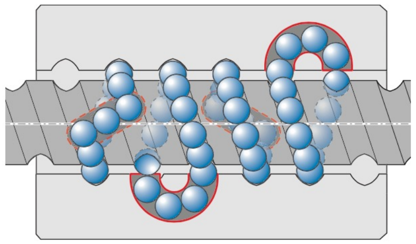
Single-start (1) and two-start (2) screw

Ball Nut & Recirculation Systems



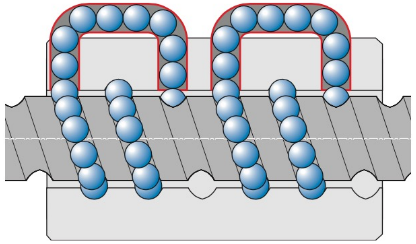
Structural design of a ball nut

Single-turn recirculation



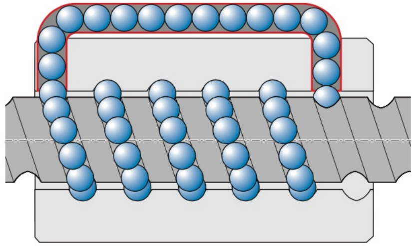
The single-turn recirculation system recirculates the balls from just one ball track turn. A recirculating piece inserted into the nut body guides the balls over the screw shoulder and into the neighboring thread turn.

Multiple-tube recirculation



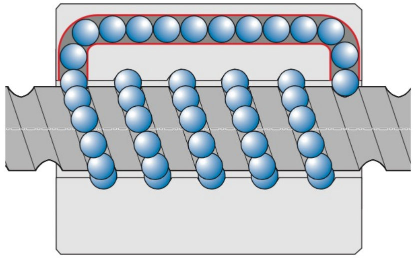
In this particular recirculation system, the balls are brought back to the threading by tubes spanning two or three ball track turns. A nut with several ball circuits will have several recirculation tubes.

Single-tube full recirculation



In this tube-type recirculation system, the balls in a circuit are returned via a single tube that spans the entire nut length and all the ball track turns.

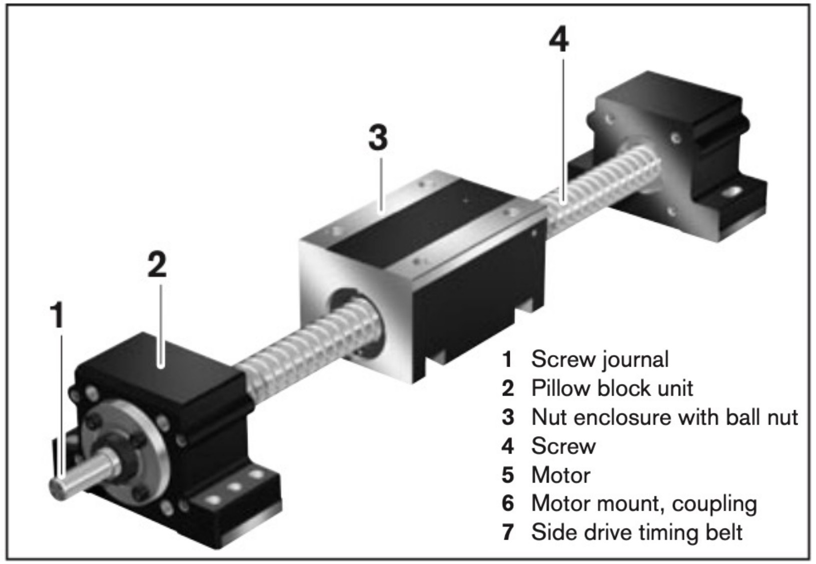
Integrated single-bore full recirculation



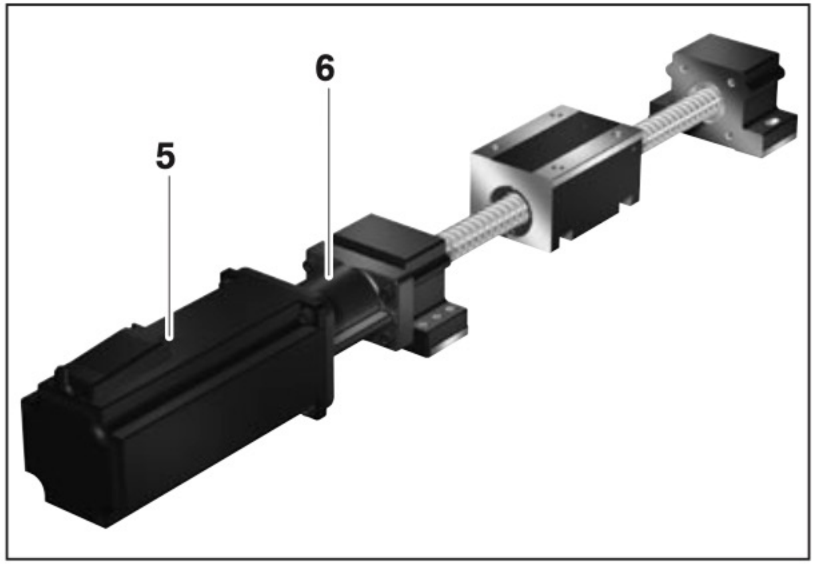
In this recirculation system, there is again only one recirculation duct spanning all the ball track turns. The balls are returned through a recirculation bore inside the nut. A nut designed for use with multi-start screws can comprise several ball circuits and will therefore have several recirculation bores.

Open Drive Units

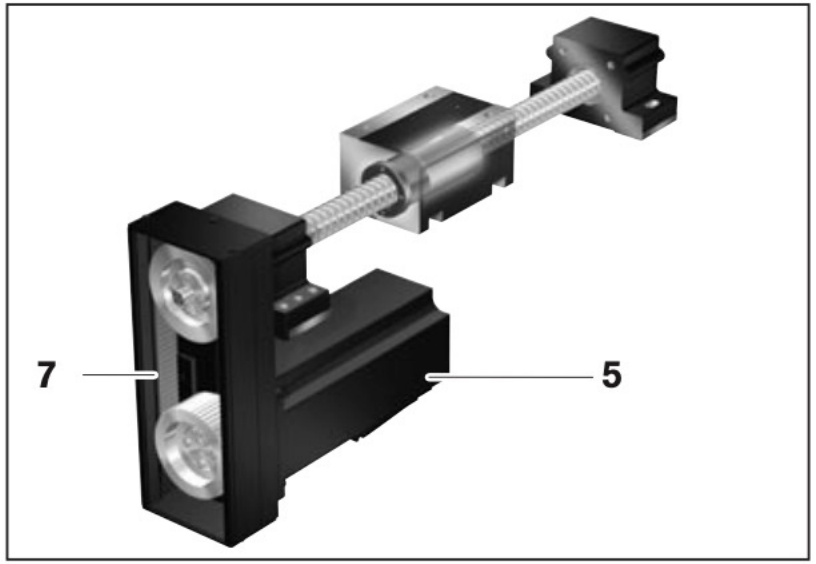
- The drive units comprise a precision screw and a cylindrical single nut (with zero backlash or preloaded).
  - The aluminum ball nut enclosure is finished on all sides and has reference edges on both sides.
  - The pillow block units are made of robust extruded aluminum profile with reference edges on both sides and mounting holes as well as a locating feature for motor mounting.



AOK drive unit



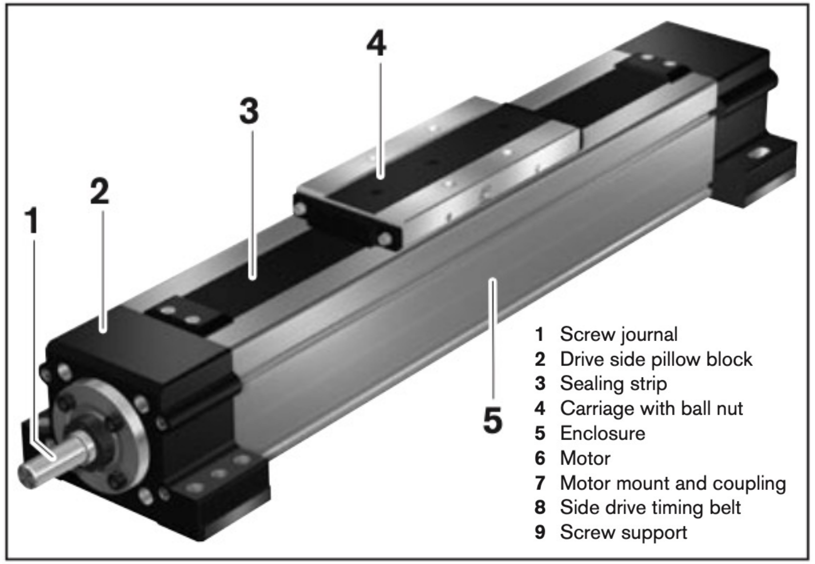
AOK drive unit with motor mount, coupling and motor



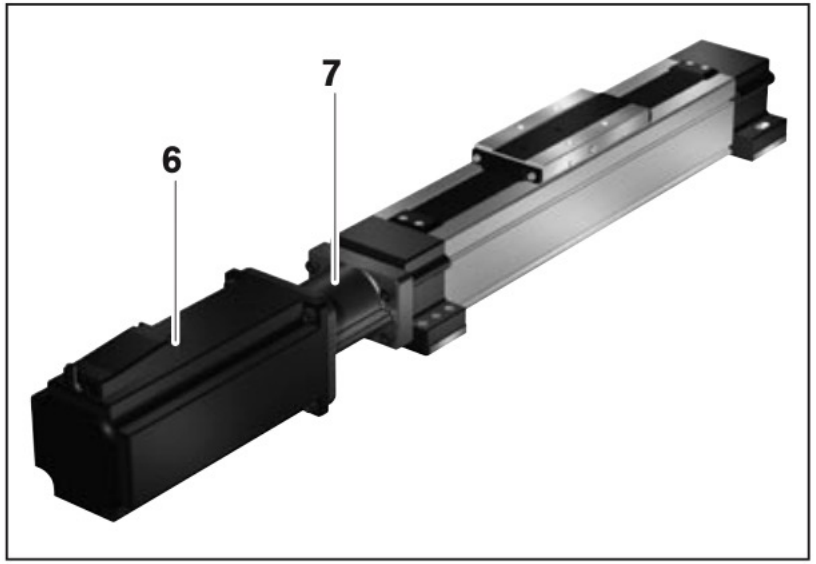
AOK drive unit with side drive timing belt and motor

Closed Drive Units

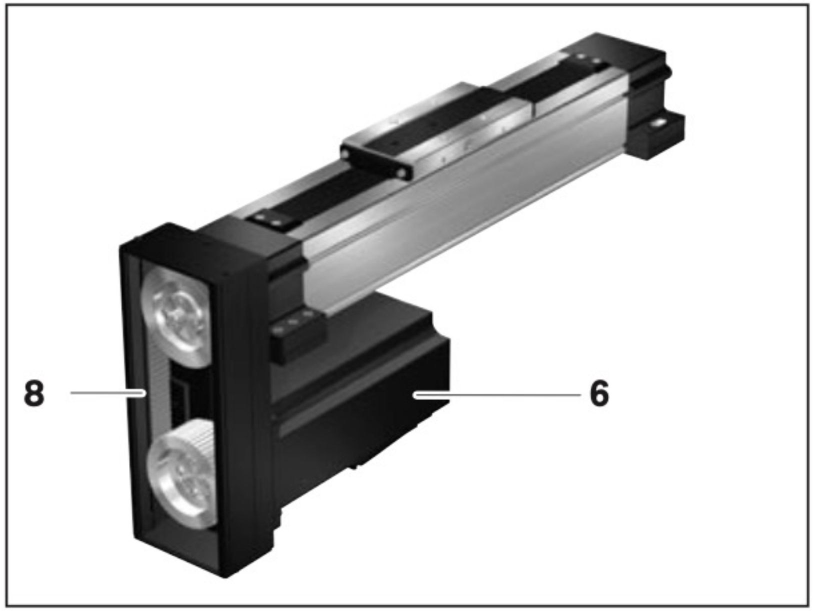
- The closed drive unit with ball screw assembly has the same basic structure as the open drive unit, but is additionally provided with an enclosure and sealing strip.
  - This eliminates the need to design and install protective structures.
  - The unit comes complete with aluminum extrusion profile encapsulation and a steel or polyurethane sealing strip.



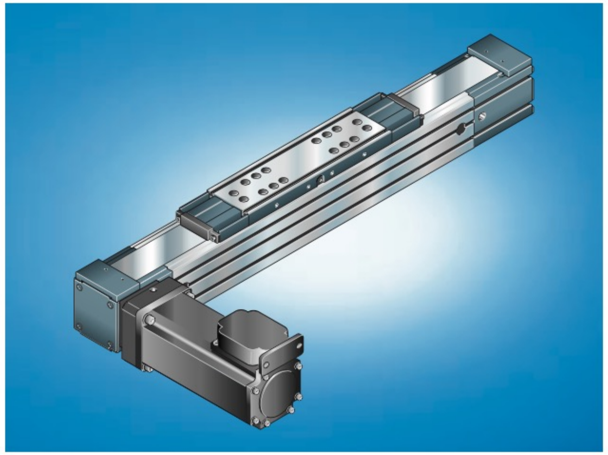
AGK drive unit



AGK drive unit with motor mount, coupling and motor



AGK drive unit with side drive timing belt and motor

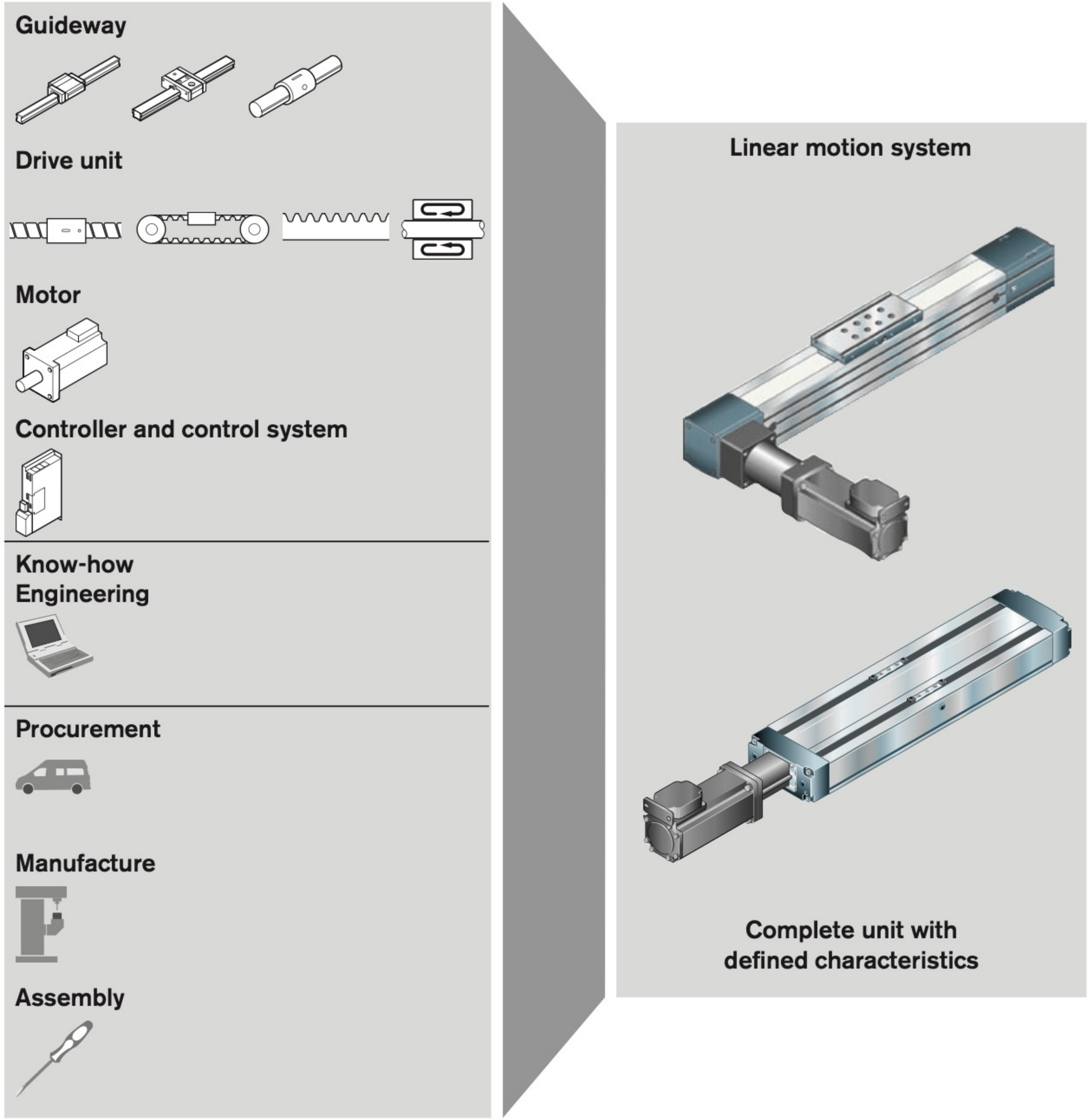

Linear module

Linear Motion Systems

Innovative Complete Solutions

- Linear motion systems are precise, ready-to-install guidance and drive systems that combine high performance with compact dimensions.
  - Available in a wide variety of configurations, they can be used in many different industrial sectors.

- Machinery and equipment can often be built more rapidly, more easily, and more cost-efficiently using standardized linear motion systems.
  - Design, project engineering, manufacturing and logistics are all significantly simplified.

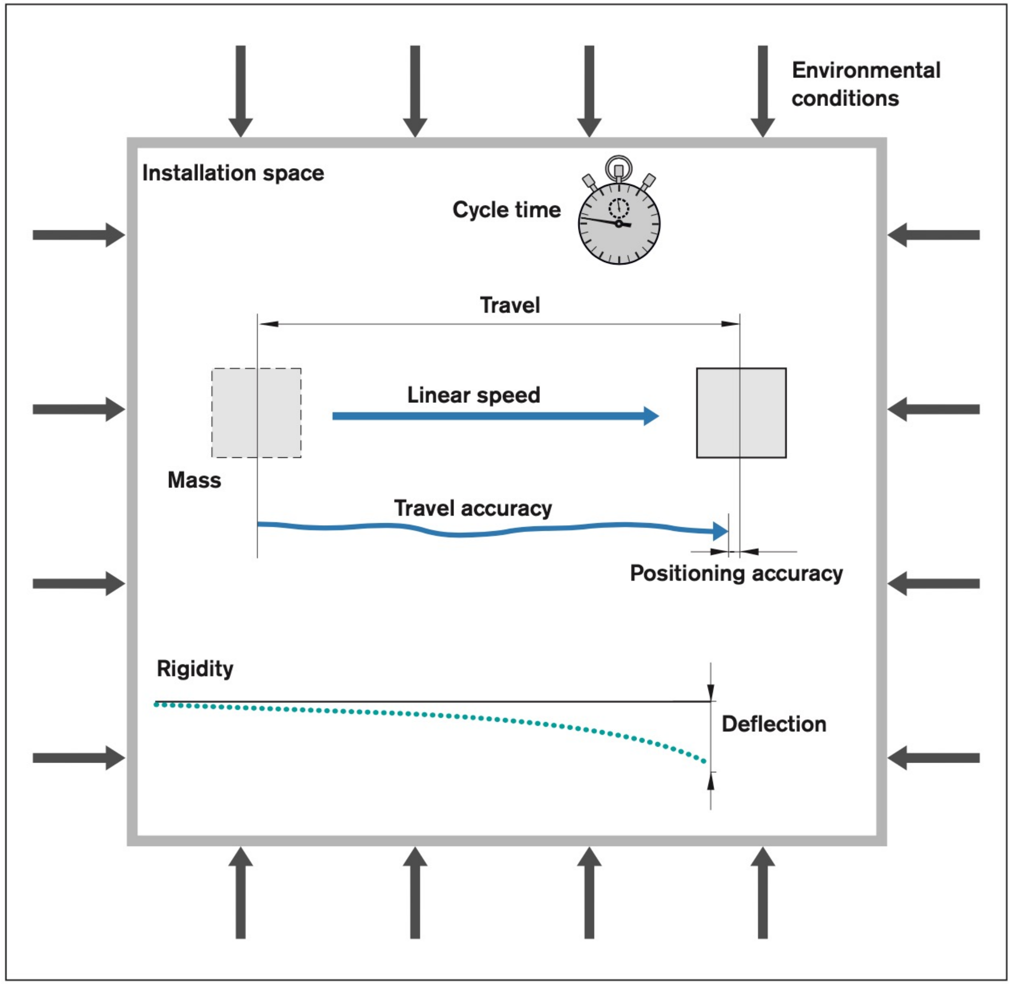


Customer Applications for Linear Motion Systems

- Essentially, a linear motion system can always be used whenever a linear movement is to be automated.
  - A mass is to be moved over a certain distance within a defined time.

- Typical tasks for linear motion systems are:
  - Handling (pick and place)
  - Assembly
  - Measurement tasks
  - Processing/machining

- Linear motion systems can be used in every sector:
  - Electronics and semi-conductor manufacturing Medical technology and pharmaceuticals industry
  - General factory automation
  - Woodworking
  - Food and packaging industries

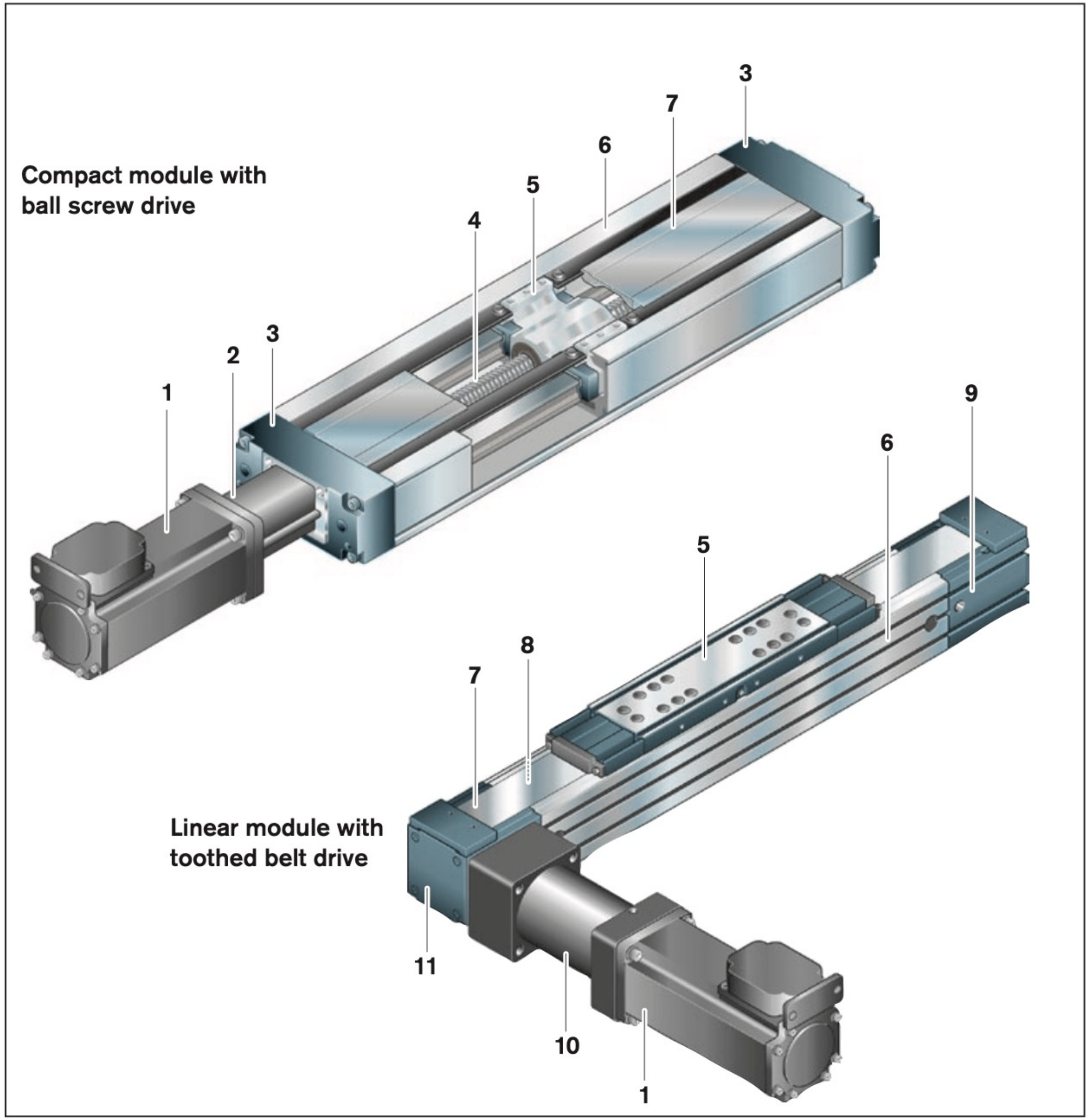


Parameters for using a linear motion system

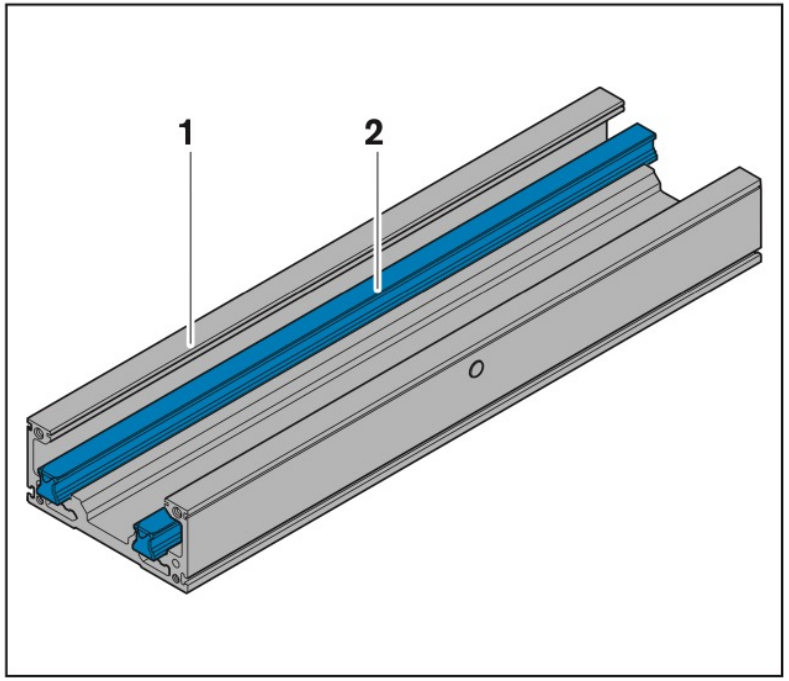
Basic Structural Design of Linear Motion Systems

Linear motion systems always have the same basic structure. They consist of the following components:

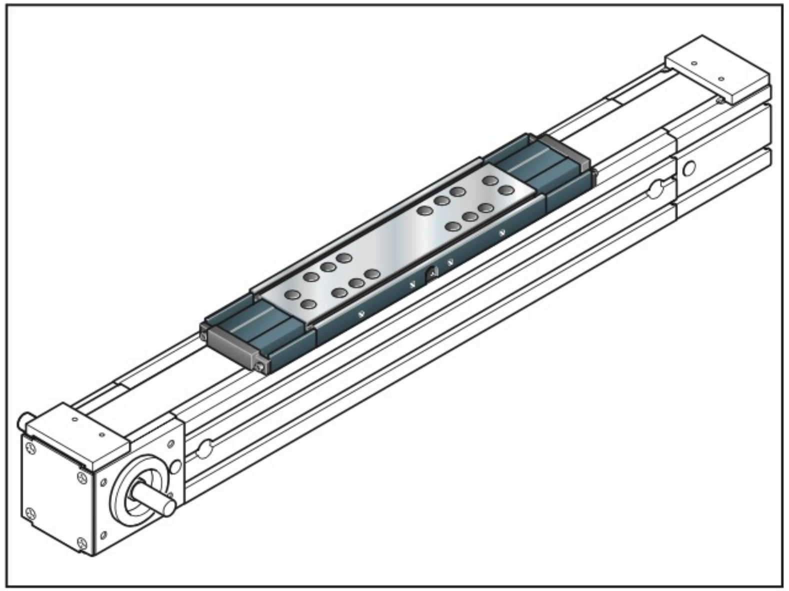
- Load-bearing profile (frame) with guideway (6)
- Carriage with runner blocks (5)
- End blocks with bearings (3) or drive end enclosure (11) and tension end enclosure (9)
- Drive unit, i.e. ball screw drive (4), toothed belt drive (8), linear motor, etc.
- Cover (7), e.g. cover plate, sealing strip
- AC servo motor, three-phase motor or stepping motor (1) attached either directly via a motor mount with coupling (2) or via a gear unit (10), with a controller and control unit
- Switches, socket and plug, cable duct
- Optional components such as screw supports, connection plates, clamping fixtures, position measuring systems, etc.



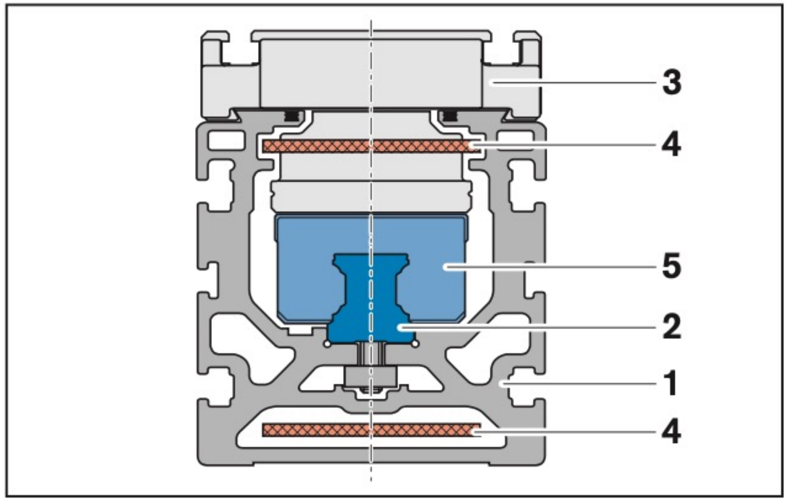
Structural design of linear motion systems



Frame with guide rails

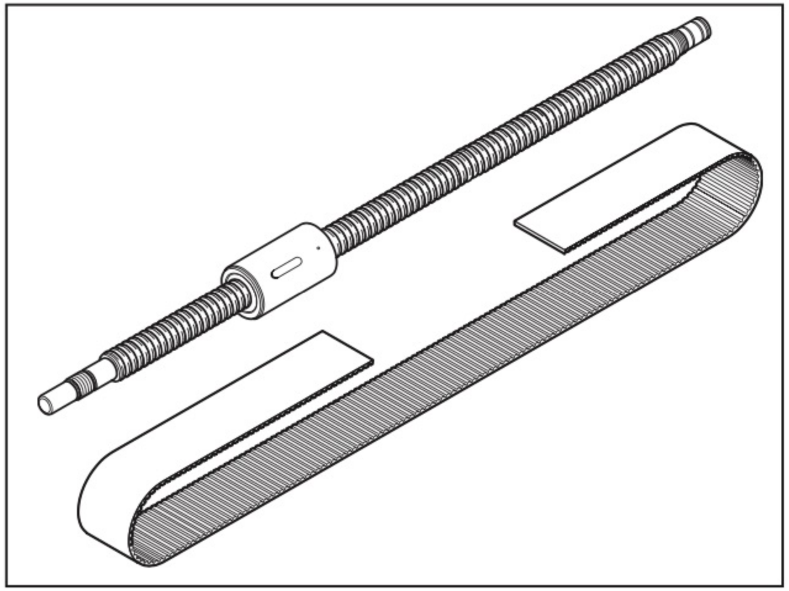


Carriage assembly

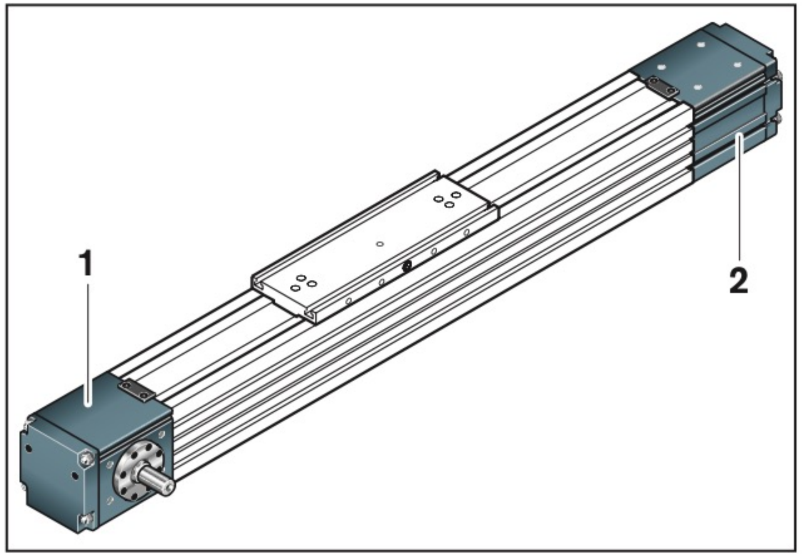


Cross-section of a linear module with toothed belt drive

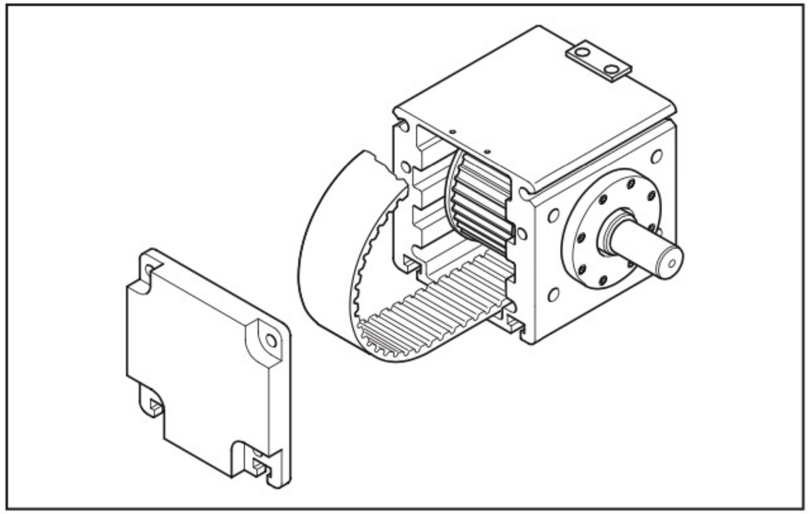
1 Frame
2 Guide rail
3 Carriage
4 Toothed belt
5 Runner block



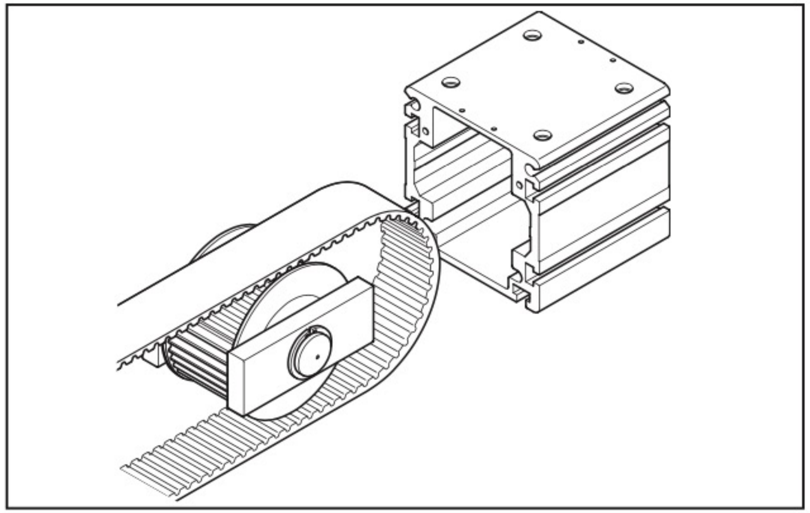
Ball screw drive and toothed belt drive versions



End enclosures



Drive end enclosure (1)

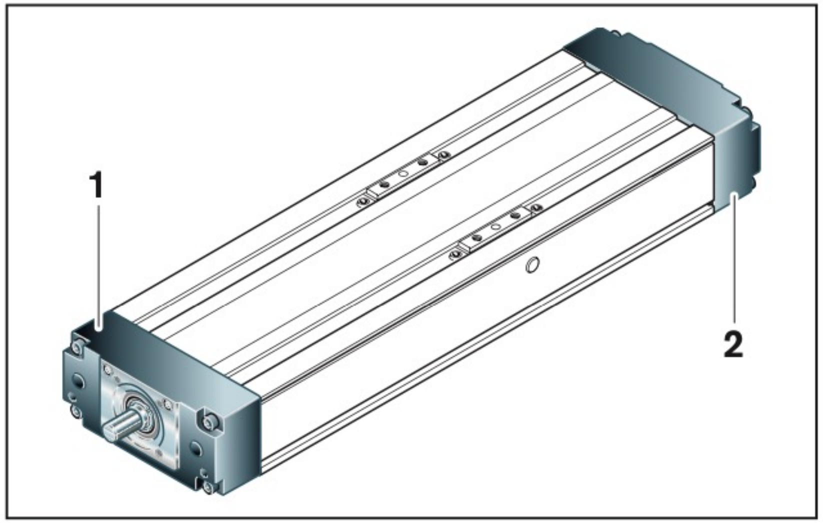


Tension end enclosure (2)

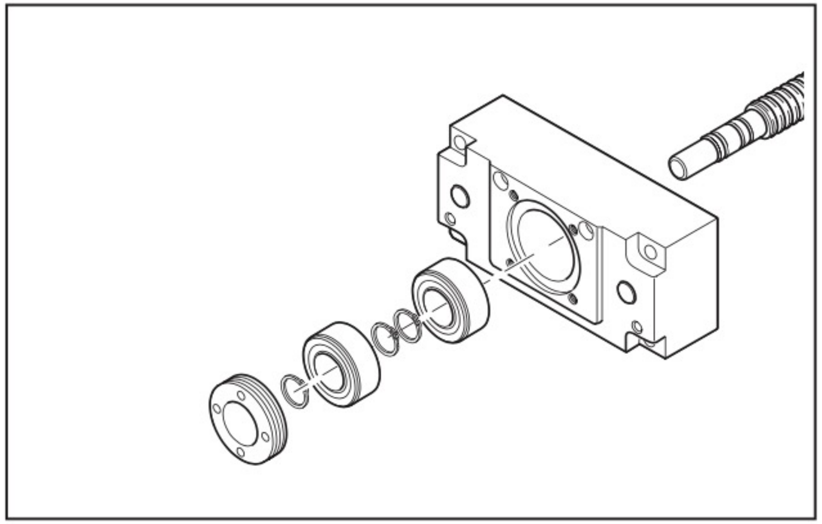
Ball screw drive

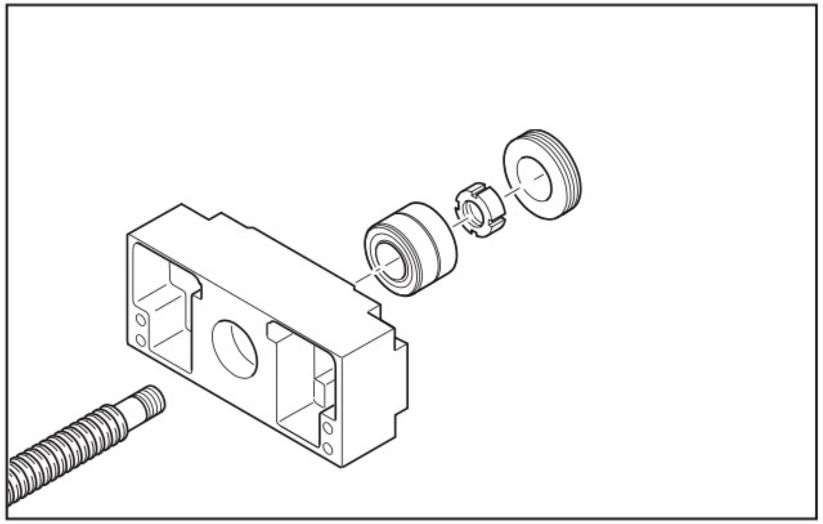
In linear motion systems with ball screw drive, the end enclosures are called end blocks. They accommodate the ball screw drive's end bearings. The screw shaft journal protrudes from one of the two end blocks to allow connection of the screw to the motor.

1 Drive end block
2 Idler end block



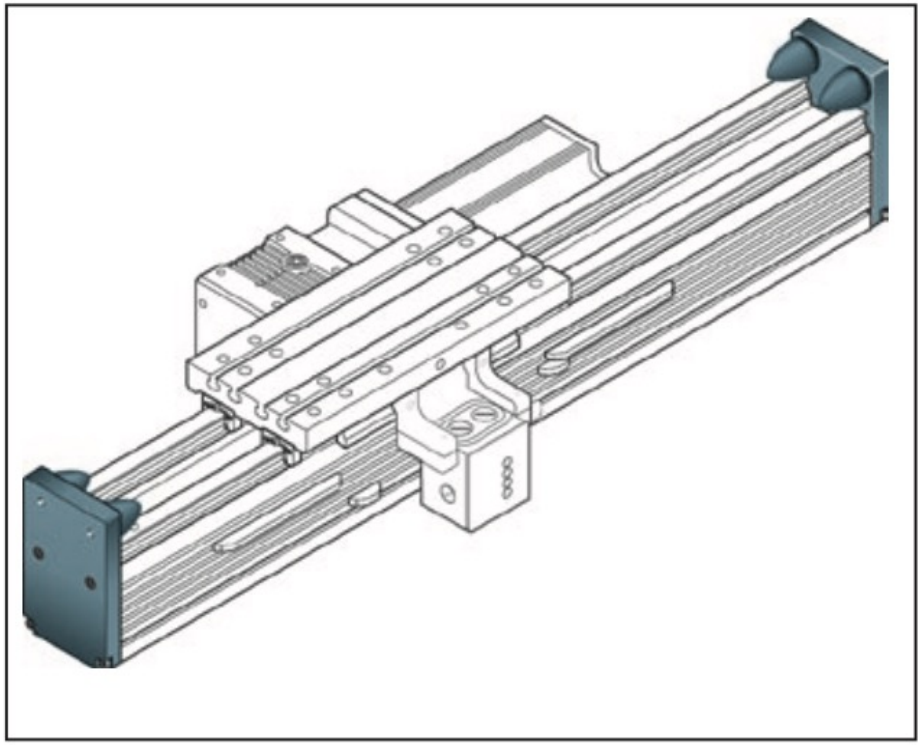
End blocks


End block assembly with fixed bearing (1)

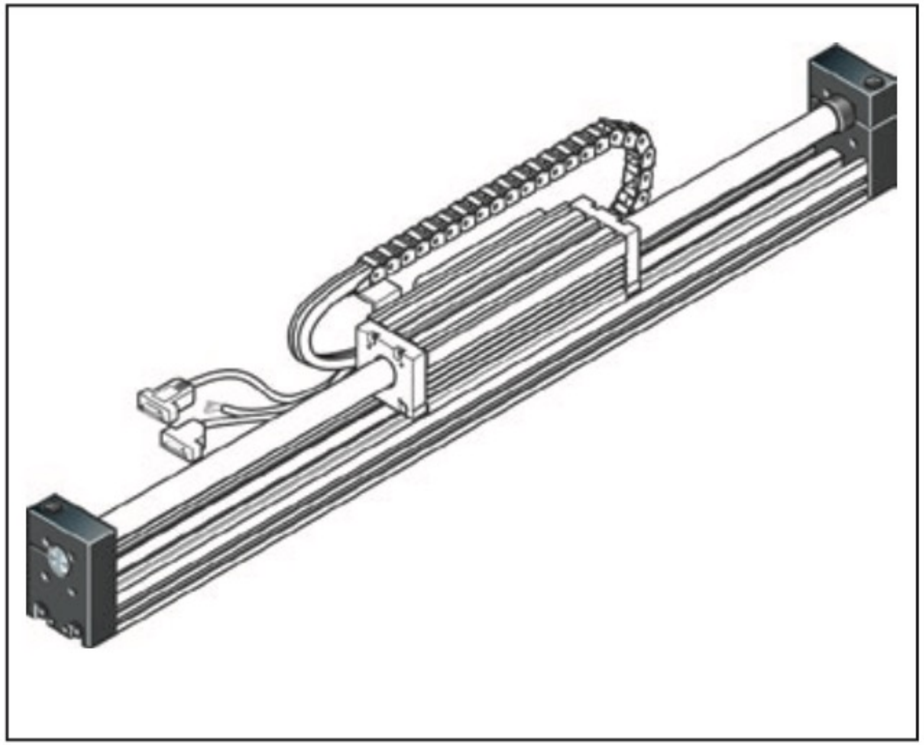

End block assembly with floating bearing (2)

Linear motor
Rack and pinion drive

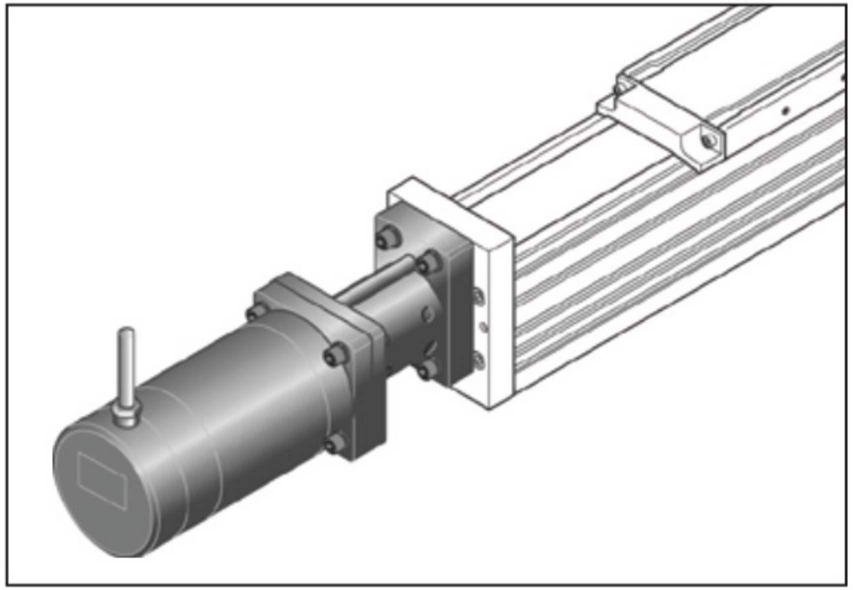
In linear motion systems with a linear motor or rack and pinion drive, the end blocks serve both as end covers for the frame and as stops to prevent the carriage from overshooting the end of the frame.



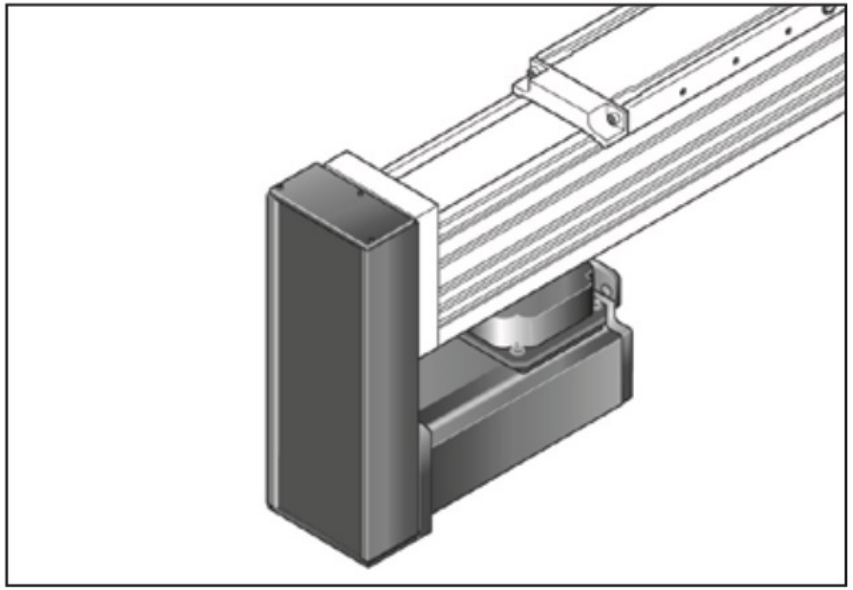
End blocks with buffers on a linear module with rack and pinion drive



End blocks with buffers on a linear module with linear motor



Motor mount with coupling and stepping motor



Gear unit as a timing belt side drive with servo motor

Motors

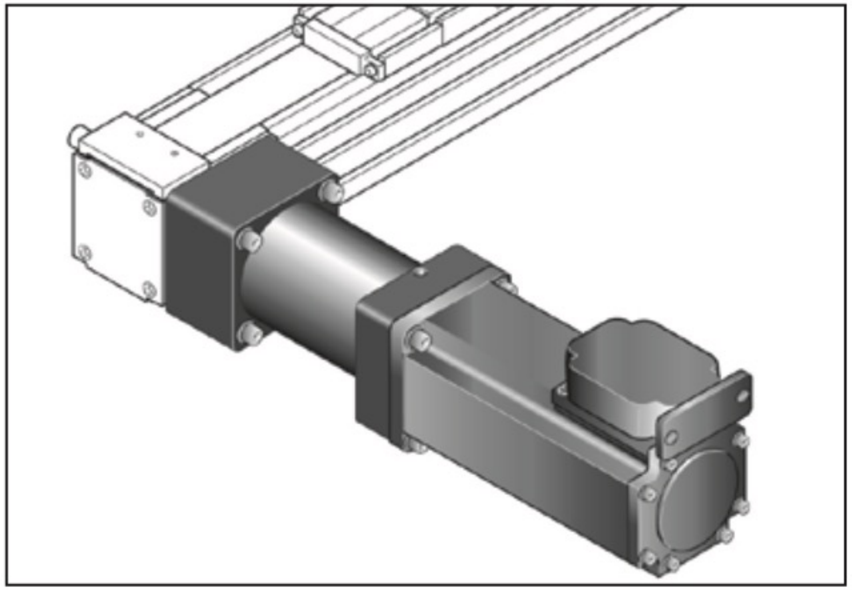
Linear motion systems with ball screw drive, toothed belt drive or rack and pinion drive are driven by motors. Rexroth offers a broad range of AC servo motors, three-phase motors and stepping motors. Depending on the application and the chosen combination of linear motion system and motor, the systems are driven either directly via a motor mount and coupling or indirectly via a gear unit. Timing belt side drives or planetary gears are used as gear units. A special form is a planetary gear unit that is integrated into the pulley in the drive end enclosure.

Gear Units

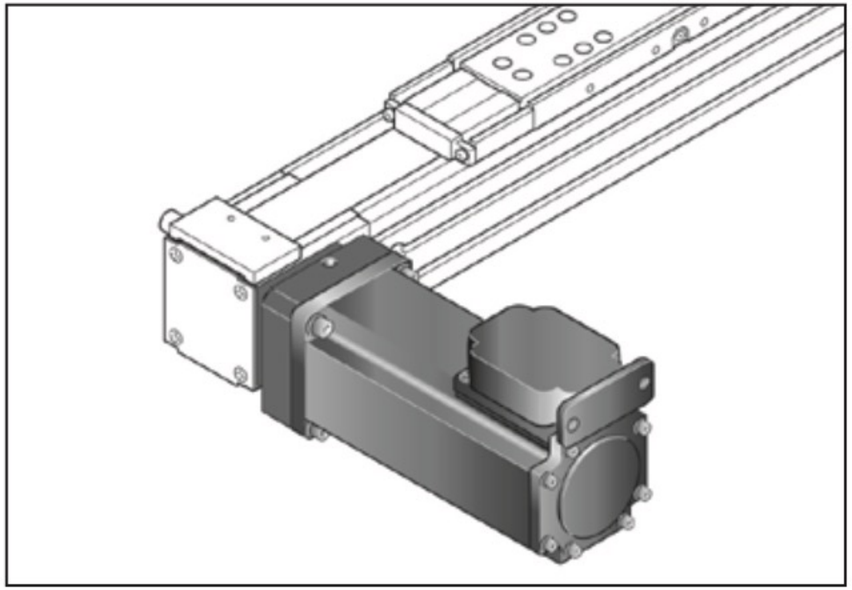
A locating feature and fastening thread are provided to facilitate the attachment of the motor or gear unit. A coupling transfers the drive torque stress-free to the linear motion system's drive shaft. Linear modules with rack and pinion drive are connected to the motor via a worm gear.

By using selectable gear ratios, the customer can adjust the drive torque to the specific application requirements and achieve the best match between the external load and the motor's moment of inertia. This is particularly important for optimizing the drive control loop and for obtaining highly dynamic drives.

If a timing belt side drive is used, the overall length of the linear motion system can also be reduced compared to a configuration with direct motor attachment.



Gear unit as a planetary gear with servo motor

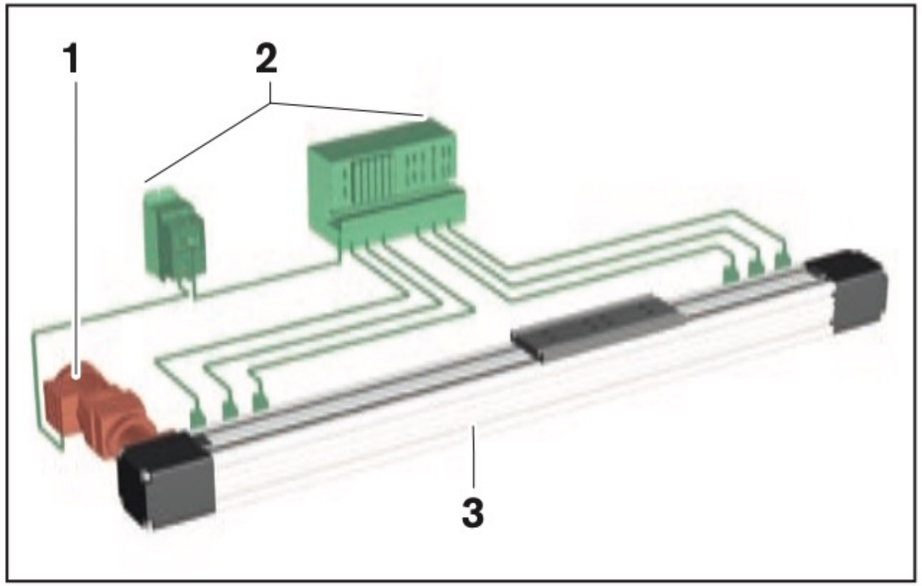


Integrated planetary gear and servo motor

Controllers and control units

Controllers and control units are available for all motor options. The complete unit, i.e. the linear motion system, motor, controller and control unit, can therefore be sourced directly from Rexroth.

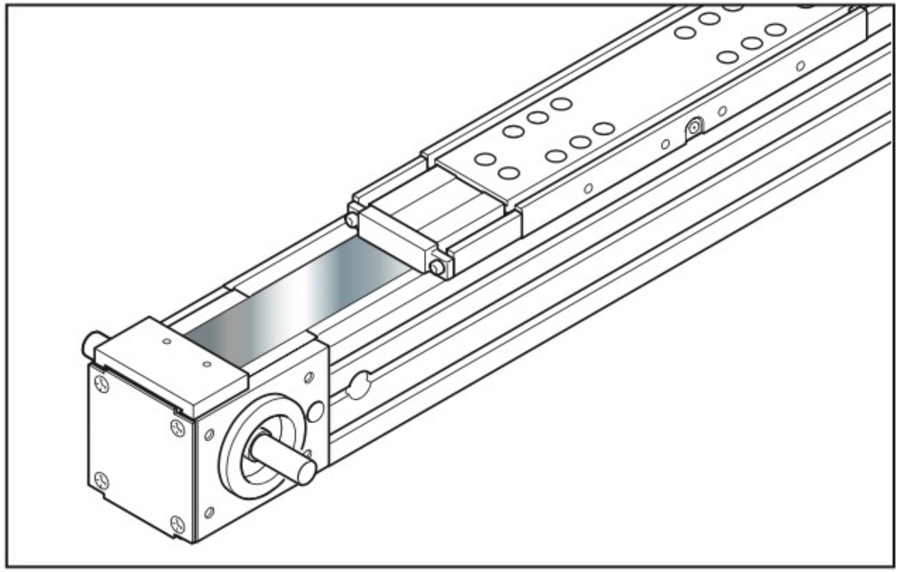
1 Motor
2 Controller and control unit
3 Linear motion system



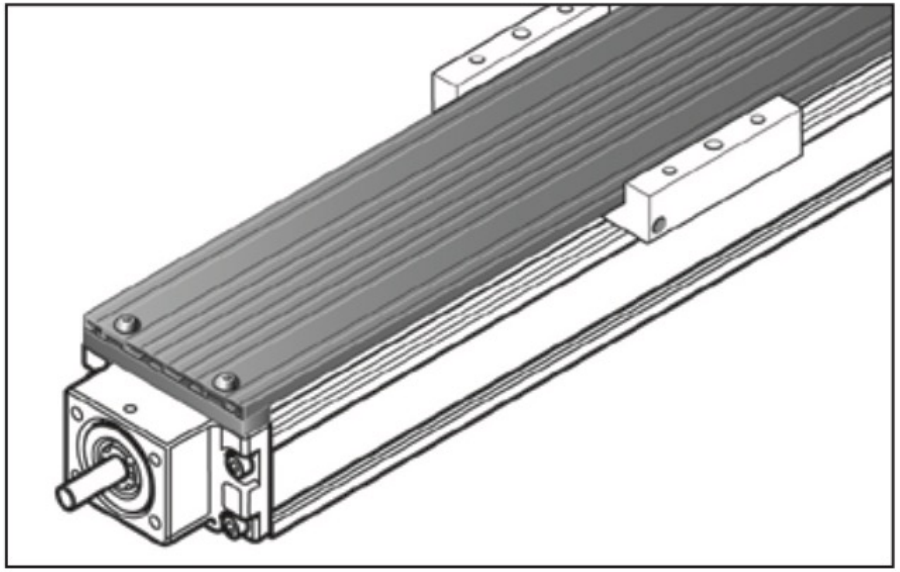
Linear motion system complete with control unit, controller and motor

Cover

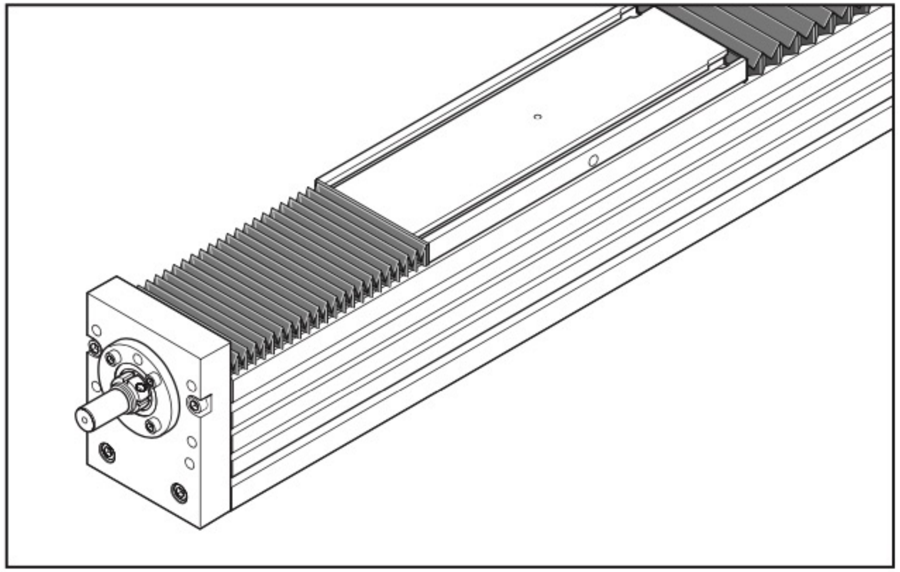
Some linear motion systems come standard with a cover to protect them from contamination. A cover can also be installed as an option in other linear motion systems. The cover may be designed as a sealing strip, cover plate or bellows, as appropriate for the type of system.



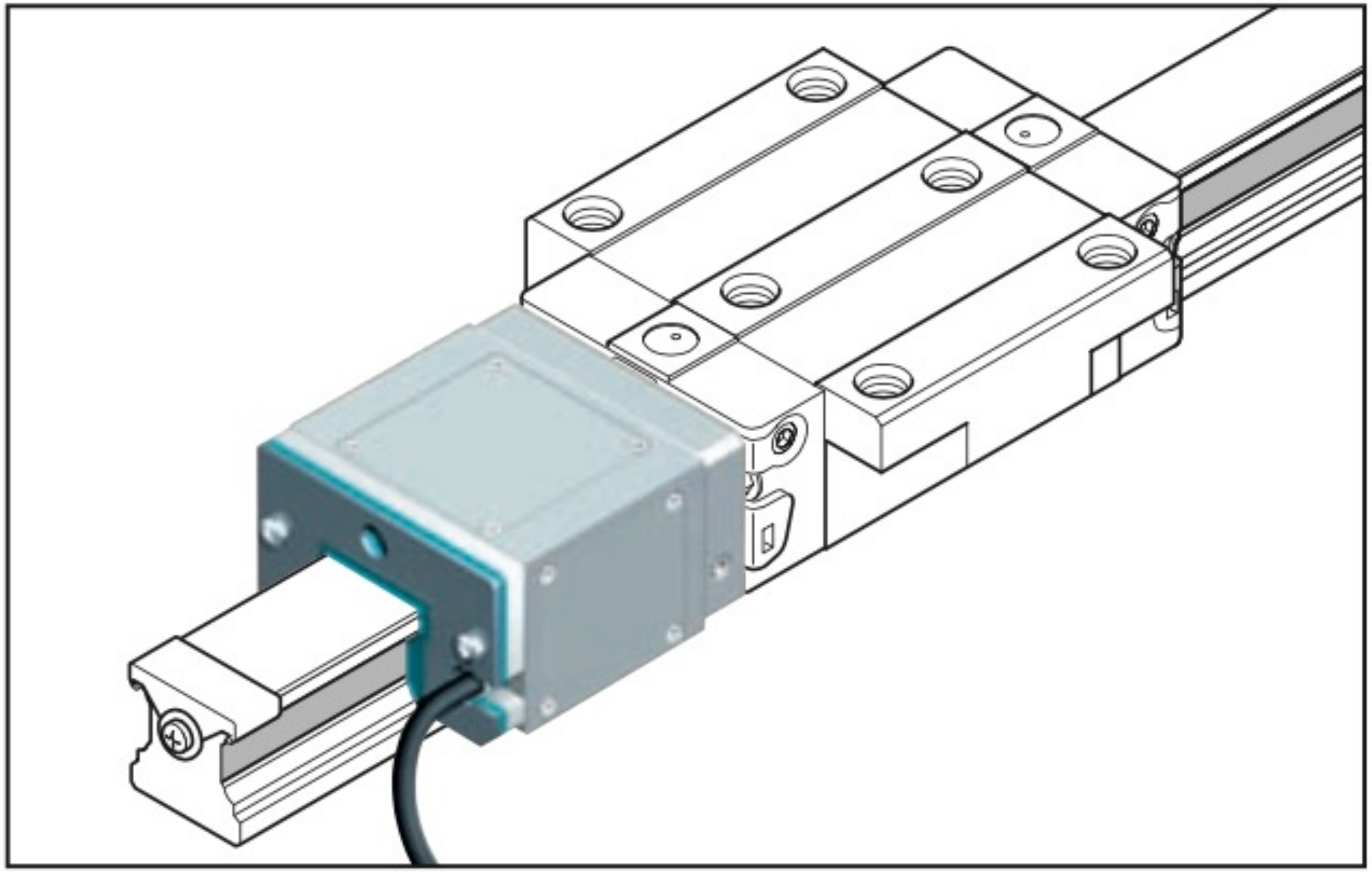
Sealing strip



Sheet metal cover plate



Bellows



Integrated inductive measuring system on the ball rail system

Linear motion systems can be fitted with position measuring systems. The choice of measurement principle will depend on the type of linear motion system used. Available options are:

- Optical systems
- Magnetic systems
- Inductive systems

Measuring systems can also be supplied as:

- Rotary systems (rotary encoders)
- Linear systems (e.g. integrated measuring system from Rexroth, glass scale)

All measuring systems can either be integrated or mounted externally, depending on the system design.

Switching systems

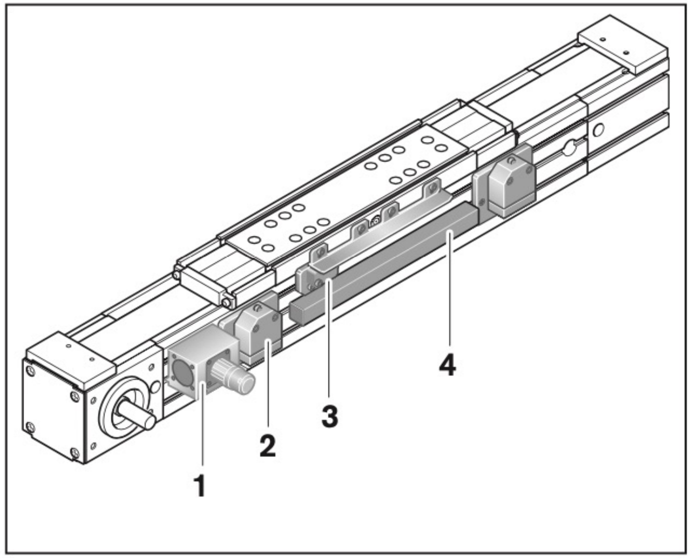
There are various switching systems available for linear motion systems. These can be used as limit switches or reference switches. Normally, the switches used on linear modules are either mechanical (2) or inductive (3). Compact modules are equipped with magnetic field sensors (Hall or Reed sensors).

Socket and plug

The switch wiring can be grouped and routed through a socket and plug. As a result, only one cable is needed for connection to the controller.

Cable duct

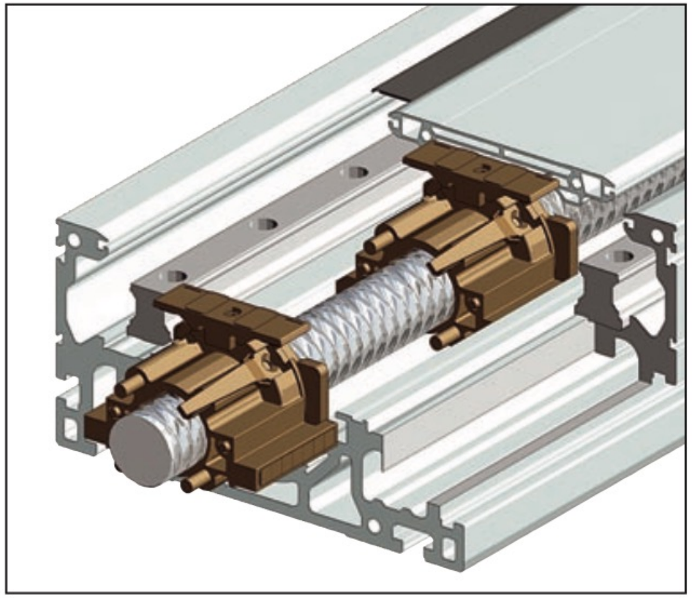
A side-mounted cable duct (4) serves to protect the switch cables (see section 6.8.4).



Switching system

Screw support

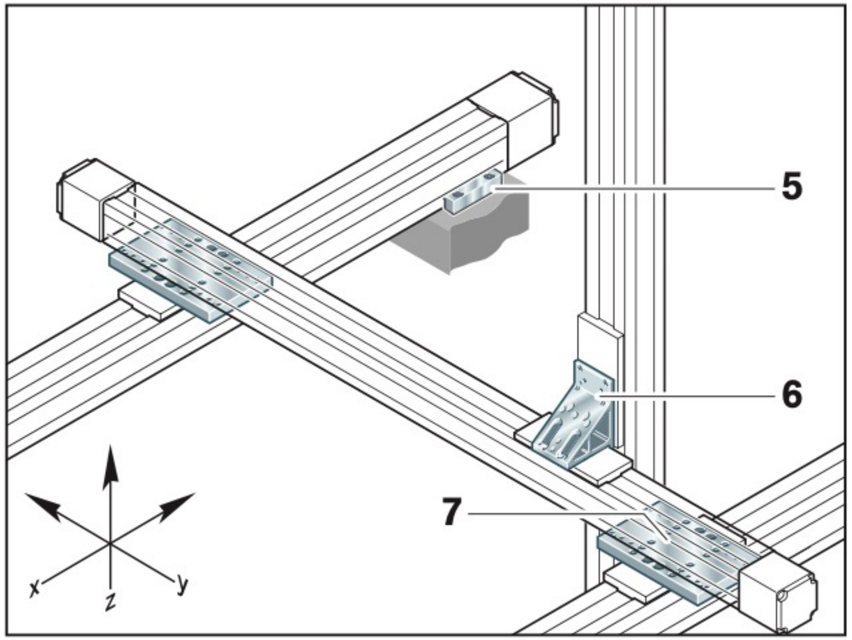
Linear motion systems with ball screw drive can be equipped with screw supports as an option. Screw supports make it possible to increase the stroke length or to achieve a significant increase in the maximum permissible speed while maintaining the same stroke length. The maximum permissible rotary speed is determined by the screw's critical speed.



Compact module with screw supports

Connection elements

For compact modules, connection plates (7) with the same T-slot design as the Rexroth construction profiles are available for connecting additional modules or for mounting of customer-built attachments. This enables the attachment of components to be standardized. For linear and compact modules, there are also connection brackets (6) for building X-Y-Z combinations. Clamping fixtures (5) can be used to fasten the linear motion systems to the mounting base.



Connection elements

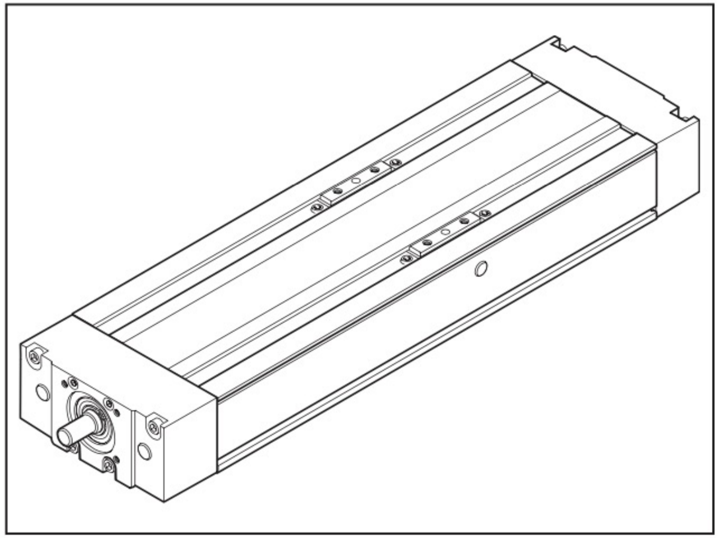
1 Plug
2 Mechanical switch
3 Proximity switch
4 Cable duct

5 Clamping fixture
6 Connection bracket
7 Connection plate

Type and Size Designations

For easy differentiation of the many versions of linear motion systems, Rexroth uses a simple identification system comprising a type and a size designation. The type designation consists of three letters, which define the type of system, guideway and drive unit used. This is followed by the size designation, which consists of the size of the linear guideway and the width of the frame.

The table below illustrates the coding system used for the type and size designations of Rexroth linear motion systems, using a compact module as an example. (The code letters are based on the German product names.)



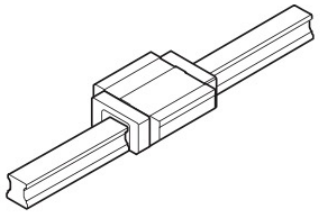
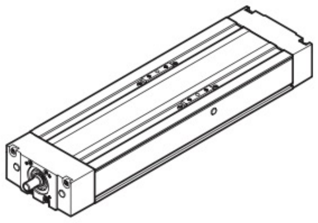
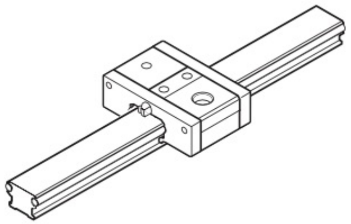
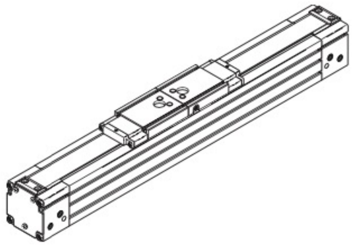
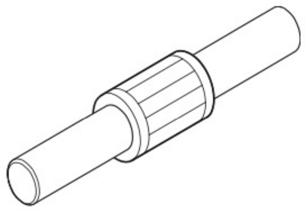
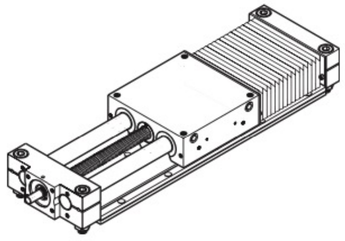
Example: Compact module CKK 20-145

Designation		Type			Size	
	Example: Compact Module	**C**	**K**	**K**	**20 -**	**145**
System						
	Linear Module, closed type (**M**)					
	Linear Module, open type (**L**)					
	Compact Module (**C**)	C				
	Precision Module (**P**)					
	Ball Rail Table (**T**)					
	Linear Motion Slide (**S**)					
Guideway						
	Ball rail system (**K**)		K			
	Integrated ball rail system (**S**)					
	Cam roller guide (**L**)					
	Linear bushing and shaft, closed type (**G**)					
	Linear bushing and shaft, open type (**O**)					
Drive unit						
	Ball screw drive (**K**)			K		
	Toothed belt drive (**R**)					
	Linear motor (**L**)					
	Pneumatic drive (**P**)					
	Rack and pinion drive (**Z**)					
	Without drive (**O**)					
Guideway dimension						
A	Rail width for ball rail systems (Example: A = 20 mm)				20 -	
d	Shaft diameter for cam roller guides Shaft diameter for linear bushings and shafts					
Frame dimension						
B	Width of the frame or the base plate (Example: B = 145 mm)					145

Identification system for Rexroth linear motion systems

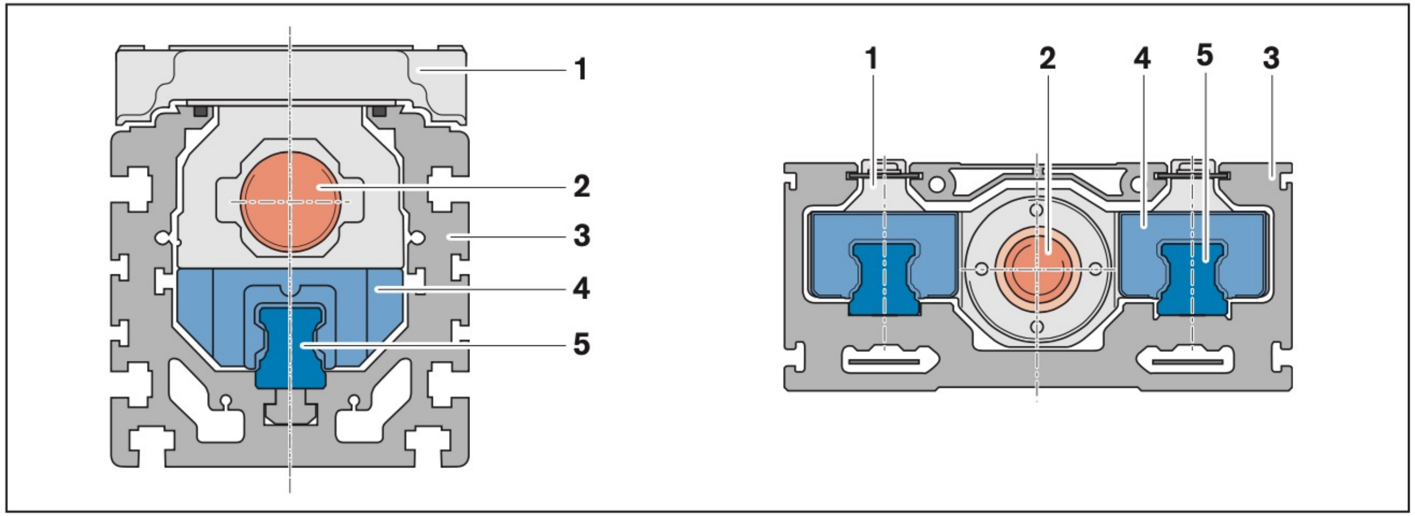
Guideway Types

- The guideways are always mounted to the frame.
- They are connected by screw fasteners and/or staking of the rail or shaft into the frame (ball rail system or cam roller guide).
- In the case of linear bushings and shafts, the shafts are fastened to shaft support rails or to shaft support blocks at the shaft ends.
- The application requirements for rigidity and precision are important criteria for selecting the correct linear guideway.
- The rigidity of the overall system depends on the type and number of guideways installed.

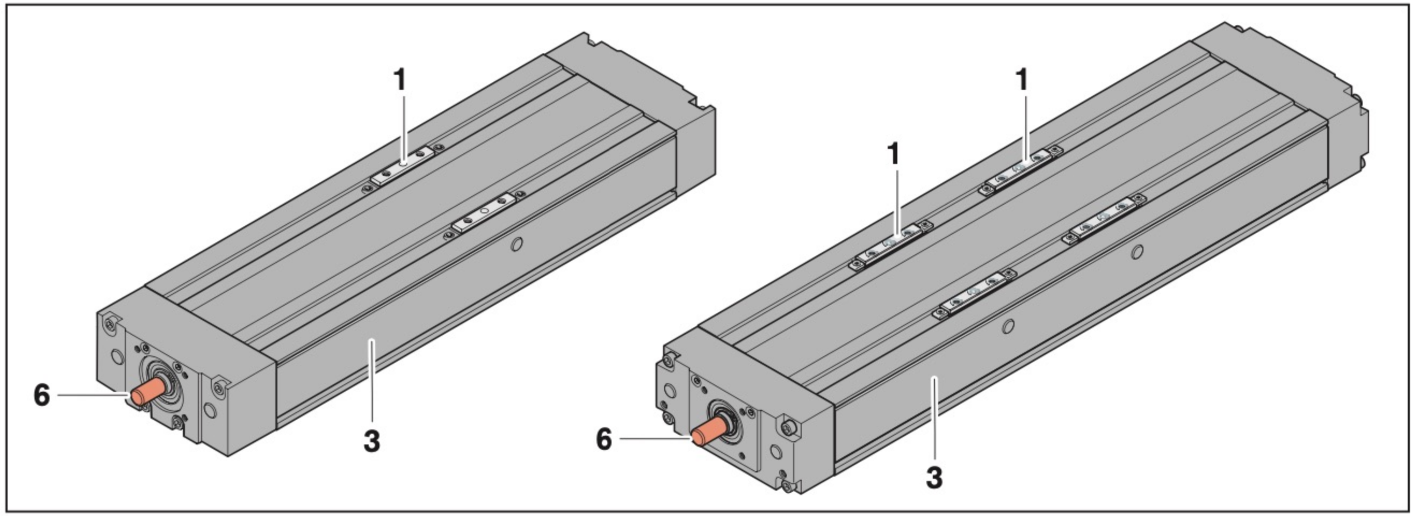
Guideway	Example	Characteristics
Ball rail system	**Compact module CKK**	
		▮ High rigidity ▮ High precision ▮ Comes standard with 2% C preload ▮ Travel speeds up to 5 m/s possible
Cam roller guide	**Linear module MLR**	
		▮ Low noise level ▮ High travel speeds up to 10 m/s possible
Linear bushing and shaft	**Linear motion slide SOK**	
		▮ Smooth running ▮ Insensitive to dirt ▮ Robust (particularly the closed type)

Number of guideways

In addition to the choice of guideway type, the number of guideways installed is also an important factor determining the linear motion system's overall rigidity. The number of guide rails or shafts as well as the number of carriages may vary.



Linear module MKK with one rail guide (left) and compact module CKK with two rail guides



Compact module CKK with one carriage per rail (left) and with two carriages per rail

1 Carriage
2 Ball screw drive
3 Frame
4 Runner block
5 Guide rail
6 Screw journal for ball screw drive

Load capacities and moments

In linear modules and compact modules with the same rail size the load capacities and moments will differ according to:

- Configuration with one or two rails
- One or more carriages

The table below gives a comparison of the load capacities and moments for two different linear motion systems:

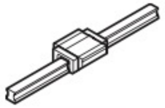
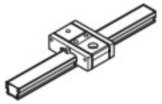
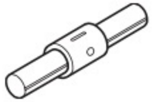
- Linear module MKK with one carriage running on a guide rail with two runner blocks
- Compact module CKK with two carriages running on two guide rails with four runner blocks

The rail width is the same in both cases.

Module	Number of guide rails	Number of runner blocks per rail	Dynamic load capacity C of the guideway	Dynamic moments	
				Torsional moment M_t	Longitudinal moment M_L
MKK 15-65	1	2	12 670 N	120 Nm	449 Nm
CKK 15-110	2	2	25 340 N	835 Nm	1 075 Nm

Overview

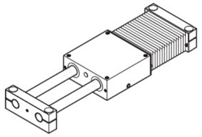
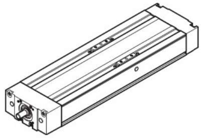
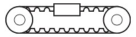
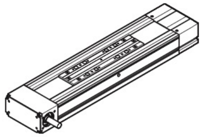
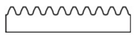
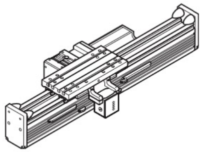
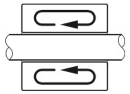
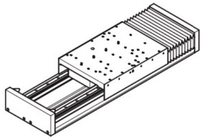
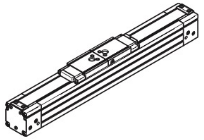
The following table shows the characteristics of the different guideway types:

Guideway	Load capacity	Preload possibilities	Rigidity	Linear speed	Travel accuracy	Noise characteristics
Ball rail system 	+++	+++	+++	++	+++	++
Cam roller guide 	+	++	+	+++	++	+++
Linear bushing and shaft 	++	++	++ 1) + 2)	++	++	++

1) Open type
2) Closed type

+++ Very good   ++ Good   + Satisfactory

Drive Unit Types

Drive unit	Example	Characteristics
Without drive 	Linear motion slide SGO 	▮ Manual movement ▮ Robust linear motion system
Ball screw 	Compact module CKK 	▮ High rigidity in the direction of travel ▮ High thrust force ▮ Repeatability ± 0.005 mm (zero backlash) ▮ Travel speeds up to 1.6 m/s
Toothed belt 	Compact module CKR 	▮ High travel speeds up to 5 m/s (MLR module: up to 10 m/s) ▮ Low rigidity in the direction of travel ▮ Repeatability ± 0.1 mm
Rack and pinion 	Linear module MKZ 	▮ Allows long guideways lengths ▮ Travel speeds up to 5 m/s ▮ Allows applications with multiple, independent carriages ▮ Low noise
Linear motor 	Ball rail table TKL 	▮ High travel speeds up to 8 m/s and high acceleration rates ▮ Short cycle times ▮ High positioning accuracy and repeatability ▮ Allows applications with multiple, independent carriages ▮ Virtually no down-time due to low number of wear parts ▮ Maintenance-free linear motor ▮ Low noise
Pneumatic 	Linear module MKP 	▮ No motor required ▮ Travel to fixed end positions (no intermediate positions) ▮ Travel speeds up to 2 m/s

Drive unit	Requirements				
	Thrust	Rigidity	Speed	Precision 1)	Noise characteristics
Ball screw 	+++	+++	+	+++	++
Toothed belt 	++	+	+++	+	++
Rack and pinion 	+++	+++	++	++	++
Linear motor 	++	+++	+++	+++	+++
Pneumatic 	+	0	+	0	++

1) Depending on the measuring system used, its accuracy, and the control system

+++ Very good
++ Good
+ Satisfactory
0 Adequate

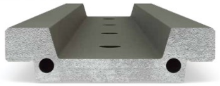
Selection Example

上海鸣志派博思自动化技术有限公司

SHANGHAI PBC&MOONS’ LINEAR TECHNOLOGY CO., LTD.

Step 1: Rail

Low Profile Rail



Tall Rail

Step 2: Bearing Type

Gliding Surface Technology
Plain Bearings

Cam Roller Technology
V-Guide Bearings

Profile Rail Technology
Profile Rail Guideways

Step 3: Drive

Lead Screw

Ball Screw

Belt

Step 4: Motor

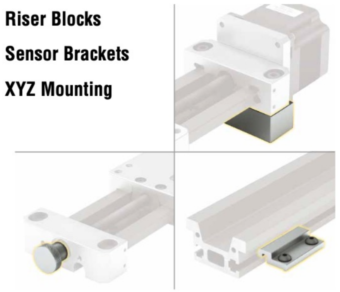
Stepper Motor

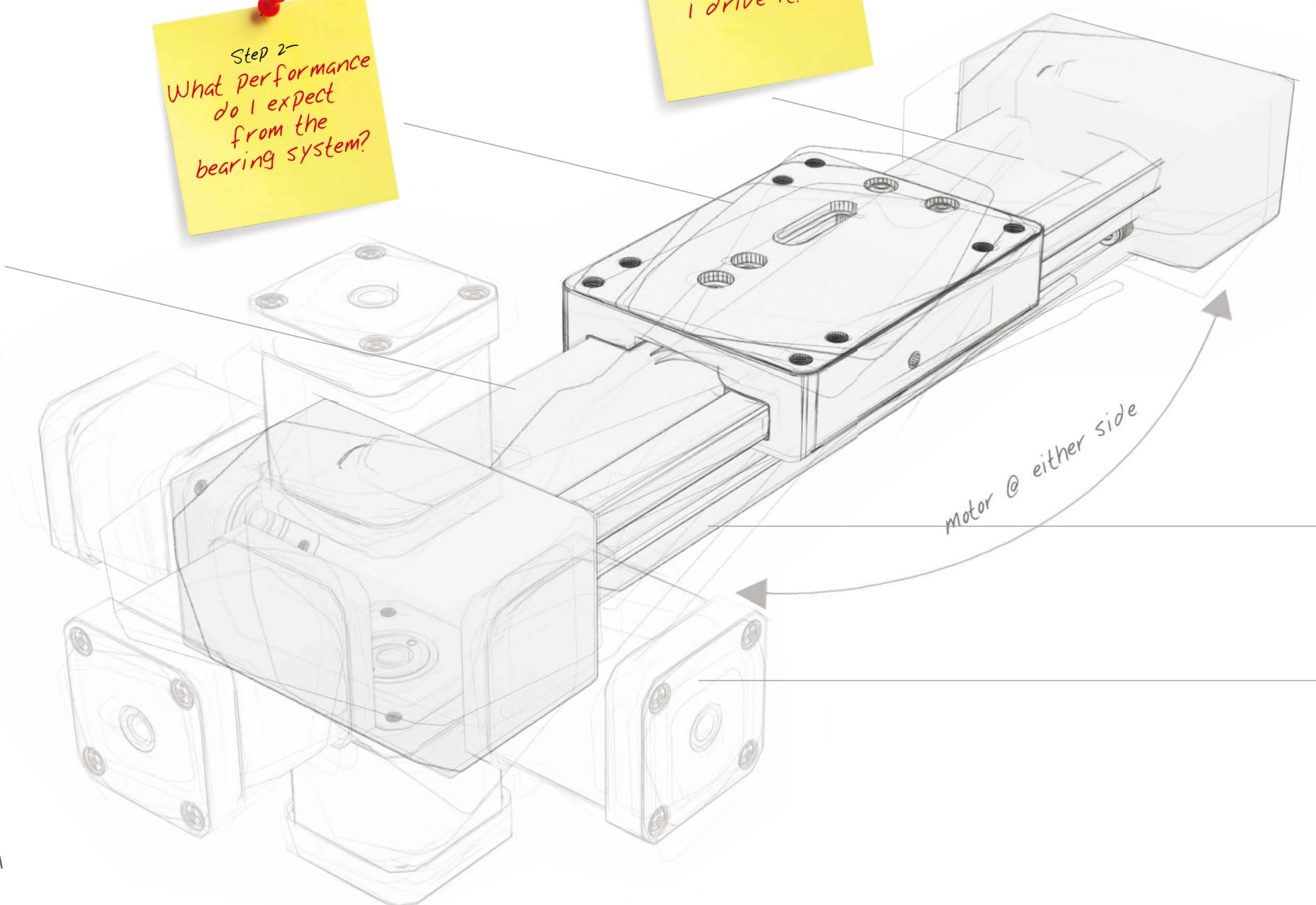
Integrated Stepper Motor

Servo Motor

Step 5: Accessories

Toe Clamps
Hand Knobs & Brakes
Riser Blocks
Sensor Brackets
XYZ Mounting

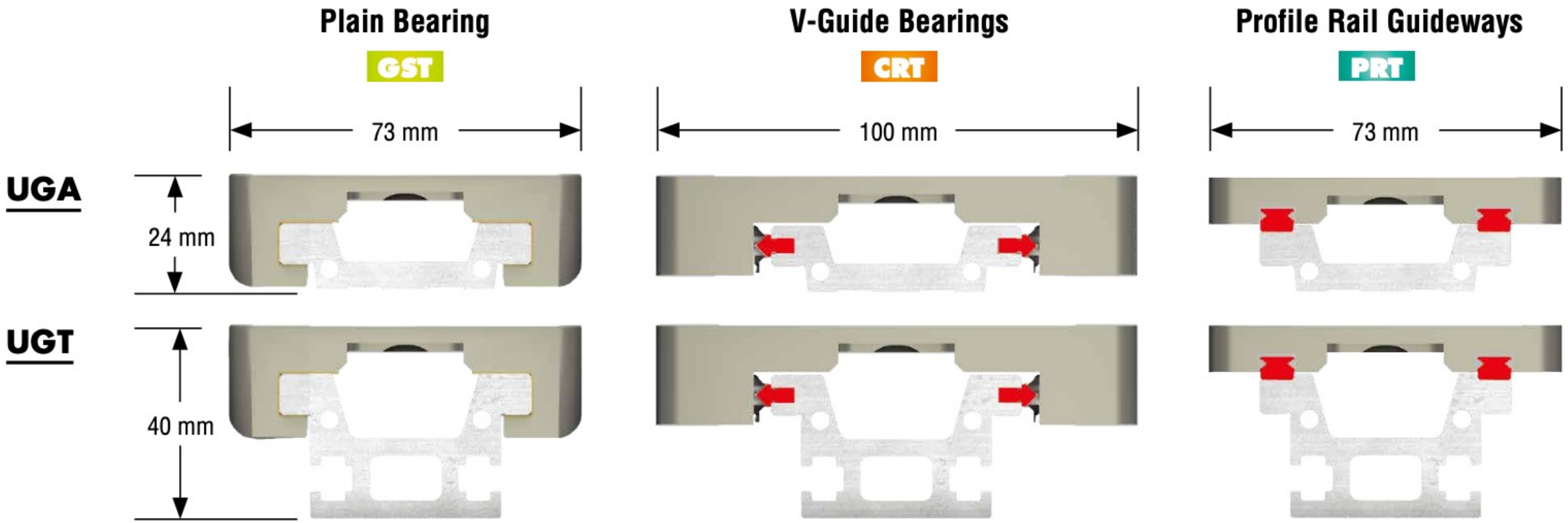




SIMO Series Bearing System

Three bearing system options are available with SIMO Series:
Plain Bearing, V-Guide Bearings and **Profile Rail Guideways**.

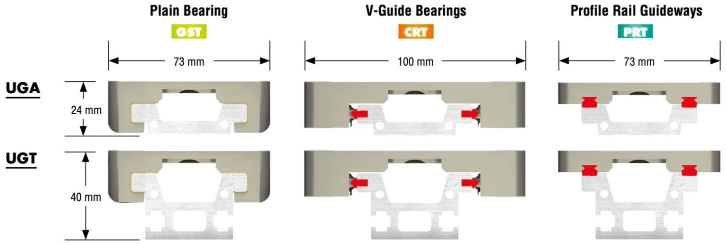
- Choose the bearing system that best supports the application requirements



SIMO Series Bearing System

Three bearing system options are available with SIMO Series: **Plain Bearing, V-Guide Bearings** and **Profile Rail Guideways**.

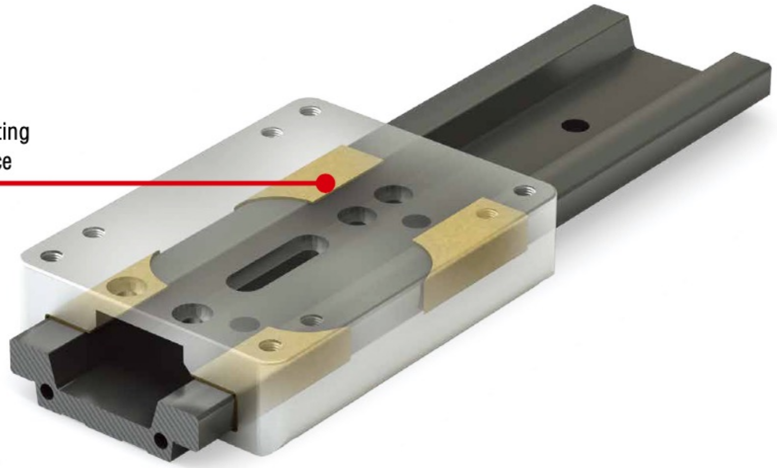
- Choose the bearing system that best supports the application requirements

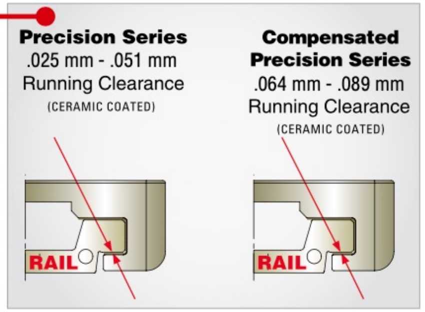


Gliding Surface Technology

PLAIN BEARING

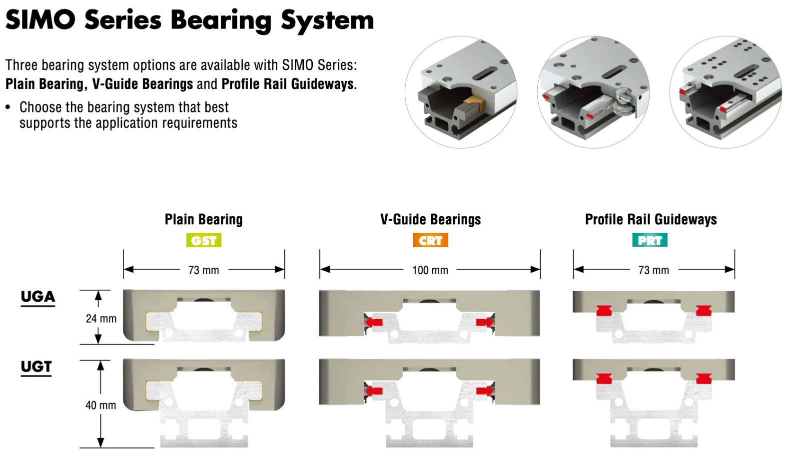
- Low cost
- Utilizes bonded **FrelonGOLD**® bearing surfaces
- Self-lubricating and maintenance free
- No catastrophic failure
- No metal-to-metal contact, vibration damping
- Max speed – 1.53 m/s (300 ft/min) (dry running)
- Wide temperature range
- Resists contamination
- Precision or compensated running clearance





Note: Plain bearings should comply with the 2:1 ratio rule.

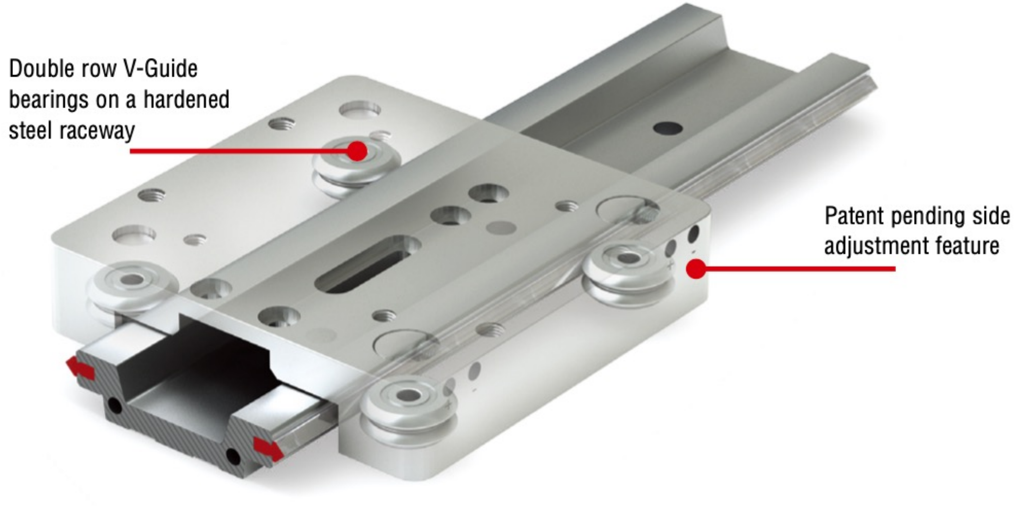
Bear Type Selection

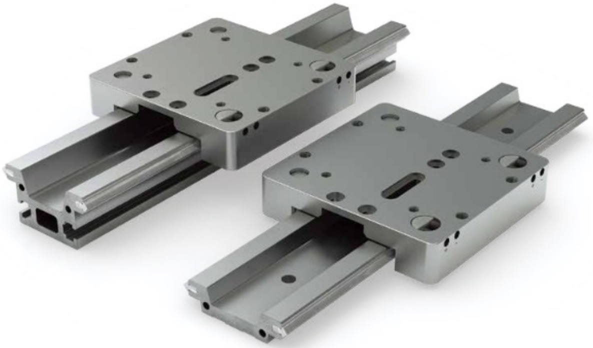


Cam Roller Technology

V-GUIDE BEARINGS

- High speeds – to 5 m/s (984 ft/min)
- Quick change of direction
- Good for cantilevered loads
- Handles contamination
- Built in lubricators standard
- Patented side-adjust preload feature
- 420 stainless steel race – hardened to RC60 – swaged in



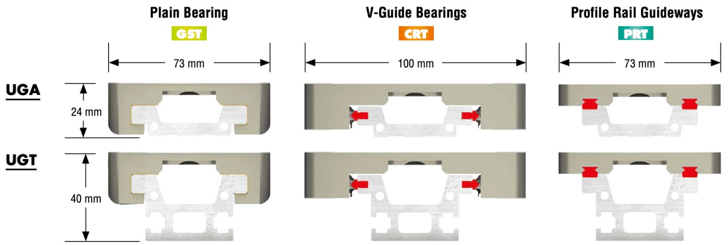


Bear Type Selection

SIMO Series Bearing System

Three bearing system options are available with SIMO Series: **Plain Bearing, V-Guide Bearings** and **Profile Rail Guideways**.

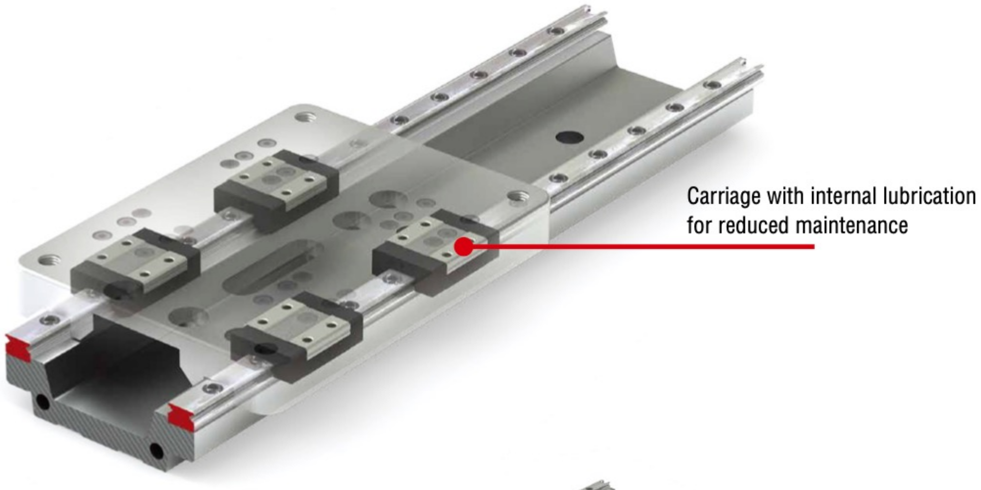
- Choose the bearing system that best supports the application requirements



Profile Rail Technology

PROFILE RAIL GUIDEWAYS

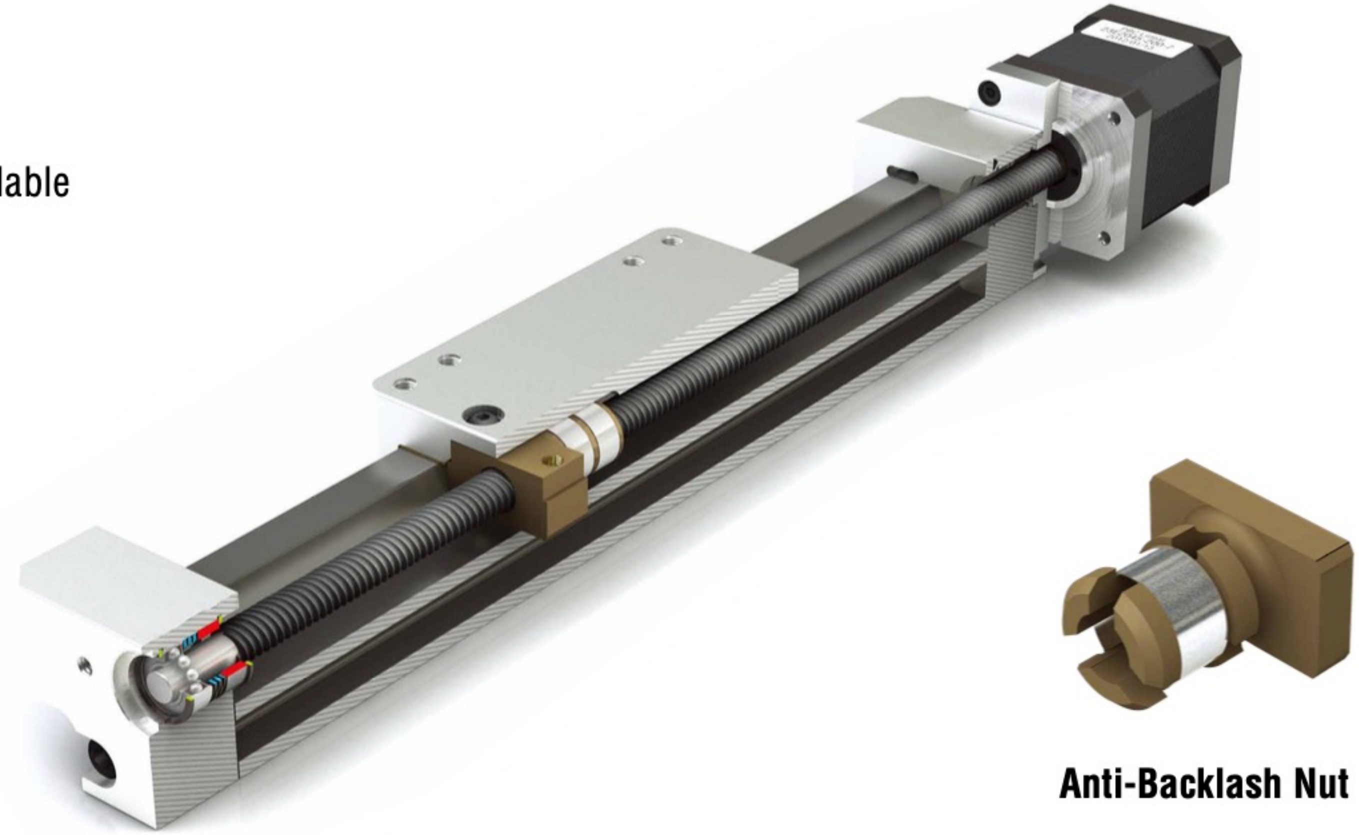
- High precision and high speeds – to 3 m/s (590 ft/min)
- Size: 7 mm recirculating ball bearing blocks
- Increased stiffness and preloaded bearing performance
- Supports cantilevered loads
- Extra long blocks for increased load capacity are available – consult factory



Bear Type Selection

LEAD SCREW

- Self-lubricating PTFE coated screw and polymer nut
- Fixed nut or Constant Force™ anti-backlash nut available
- 1, 2, 5, 10, 16 mm leads most common
- Other leads available – consult factory



Anti-Backlash Nut

Drive Type Selection

Standard Fixed Nut

NUT

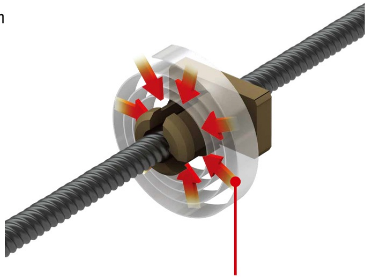
Constant Force™ Anti-Backlash Nut

An intuitive leap forward in nut design for lead screw applications, Constant Force Technology utilizes a constant force spring to apply a uniform pressure to the nut at all stages of the motion profile.

- Greater consistency and resistance to backlash
- Configurable for various torque requirements
- Patent pending self-adjusting anti-backlash feature
- Polymer nuts are self-lubricating and maintenance free

Standard Fixed Nut

- Good rigidity and vibration damping
- Polymer nuts are self-lubricating and maintenance free



Patent pending Constant Force Technology nut provides consistent anti-backlash operation

BALL SCREW

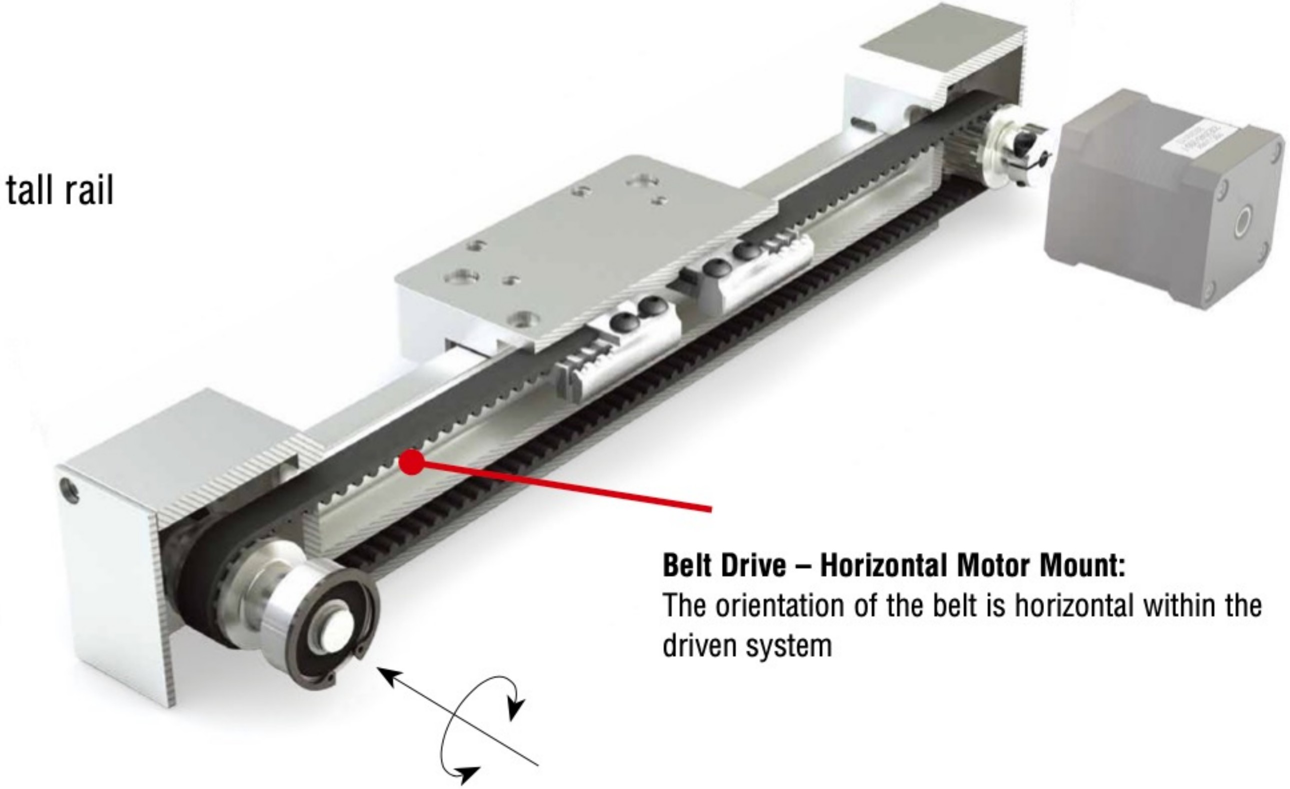
- For applications requiring precise positional accuracy
- Multiple leads available
- Selection of accuracy classes
- Consult factory for options

Drive Type Selection

BELT DRIVE

HORIZONTAL MOTOR MOUNT

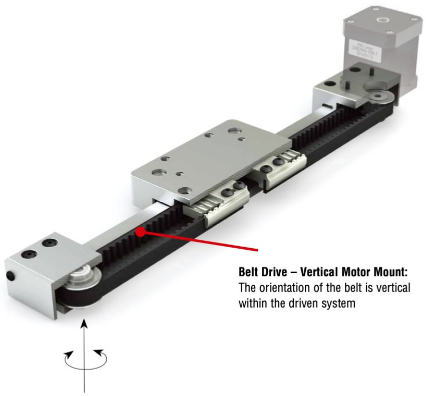
- Ideal for high speed applications
- Horizontal motor mount is available only with (UGT) tall rail



Drive Type Selection

VERTICAL MOTOR MOUNT

- Ideal for high speed applications
- Vertical motor mount is designed for (UGA) low profile rail
- Consult factory for use with (UGT) tall rail



SR4 STEPPER DRIVE

CE RoHS

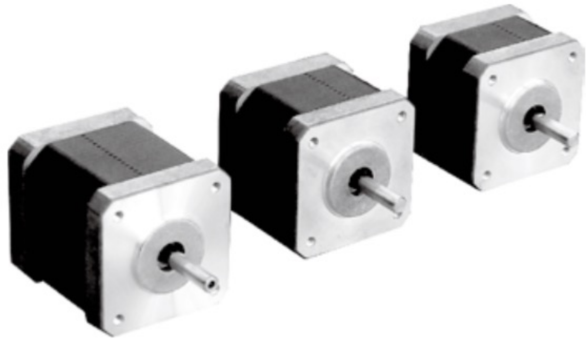
ELECTRICAL SPECIFICATIONS

Parameter	Min.	Type.	Max.	Unit
Power Supply	24	-	48	VDC
Output Current (Peak)	1	-	4.5	Amps
Cost current of digital input signal	6	10	15	mA
Step Frequency	2	-	2M	Hz
STEP minimum pulse width	250	-	-	ns
DIR minimum pulse width	80	-	-	us
Under Voltage Protection	-	20	-	VDC
Over Voltage Protection	-	60	-	VDC
Input Signal Voltage	4	-	28	VDC
Initialization time	-	-	2.5	S
Output current	-	-	100	mA
Output voltage	-	-	30	VDC

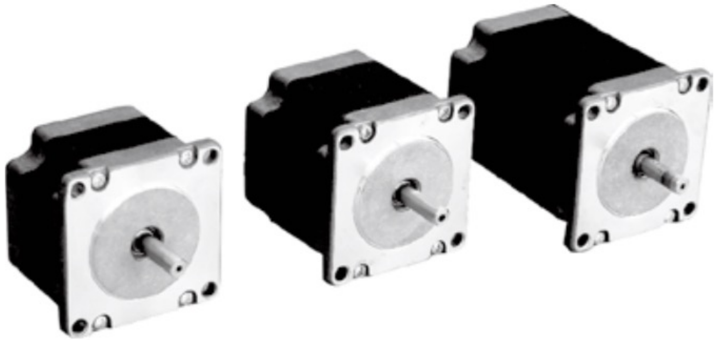
Motor Type Selection

Motor

STEPPER MOTOR



NEMA 17HD Series



NEMA 23HS Series

PARAMETERS

Model	Shaft	Wiring	Leads	Length"L"	Holding Torque	Current	Resistance	Rotor Inertia	Motor Mass	Dielectric Strength
				mm	N•m	A/Phase	Ω/Phase	g•cm2	Kg	
AM17HD2438-02N	Single Shaft			39.8	0.4	1.8	1.9	57.0	0.28	
AM17HD6426-06N	Single Shaft			48.3	0.5	1.8	2.3	82.0	0.36	
AM23HS3454-01	Single Shaft			62.8	0.85	1.6	3.2	123.0	0.6	
AM23HS3454-01	Single Shaft	A	4	76.0	1.8	2.2	2.9	460.0	1.0	500VAC 1 minute
AM23HS3455-01	Single Shaft			76.0	1.8	4.5	0.75	460.0	1.0	
AM23HS5412-01	Single Shaft			111.0	3.2	4.5	1.2	750.0	1.5	
AM24HS5401-10	Single Shaft			85	2.5	4.5	0.65	900.0	1.4	

- Matching SR4 stepper drive for above motor

Integrated Stepper Motor

CONTROLLER TYPE INTEGRATED STEPPER MOTOR-STM SERIES

DRIVE+MOTOR+CONTROLLER

The STM is an integrated Drive+Motor+Controller,fusing step motor and drive technologies into a single device,offering savings on space, wiring and cost over conventional motor and drive solutions.

- √ Dynamic Current Control
- √ Anti-Resonance
- √ Torque Ripple Smoothing
- √ Microsstep Emulation
- √ Stall Detection and Stall Prevention

PARAMETERS

Model	Amplifier Type	Current Control	Output Torque (N·m Max)	Power Supply (DC)
STM17□-1□□	Dual H-Bridge, 4 Quadrant	4 state PWM at 20 KHz	0.23	12-48
STM17□-2□□			0.38	12-48
STM17□-3□□			0.48	12-48
STM23□-2□□	Dual H-Bridge, 4 Quadrant	4 state PWM at 20 KHz	1.0	12-70
STM23□-3□□			1.5	12-70
STM24□-3□□			2.4	12-70

Motor Type Selection

SERVO MOTOR

FEATURES

- Power Range: 50 Watts to 500 Watts
- High torque in a small package
- Potted construction for maximum cooling and lowest temperatures
- Magnet structure designed for minimum cogging and minimum losses
- High Precision: Resolutions up to 17 bits (131072 PPR) absolute
- IP65 protection level

Motor Type Selection

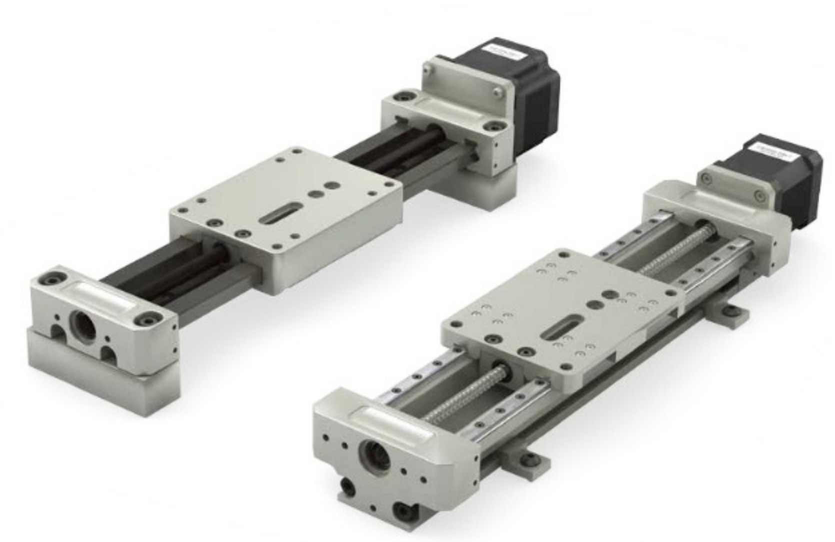
Accessories Selection

REPLACEMENT LUBRICATION KITS

Replacement lubrication kits are available for GST plain bearing systems and CRT v-wheel bearing systems.

T-NUTS

Roll in t-nut for 5 mm slot with M5 tap.

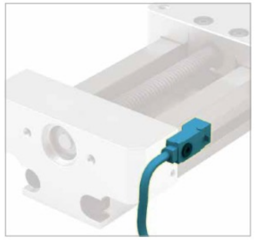


HAND KNOB

Hand adjustment knobs are used for manually adjusting screw driven systems

HAND BRAKE

Hand brakes are used to manually lock position in the GST screw driven systems

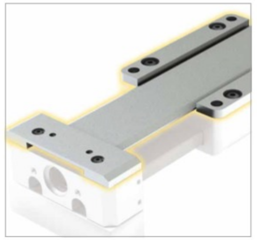


SENSOR BRACKETS

Sensor brackets accommodate a variety of sensor types

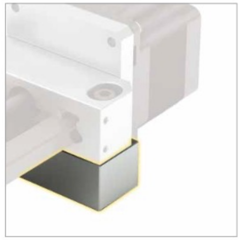
MOTOR MOUNT

Motor mount option for attaching a stepper, servo, or smart motor, etc.



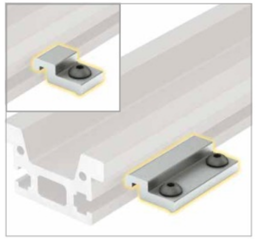
SYSTEM COVERS

Covers help keep raceways clear of debris and contamination



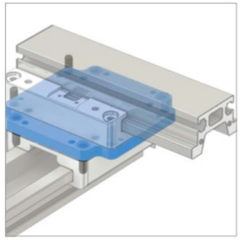
RISER BLOCK

Riser blocks provide clearance for the motor when using the (UGA) low profile rail



TOE CLAMPS

Large and small toe clamps are available to secure the (UGT) tall rail to the mounting surface



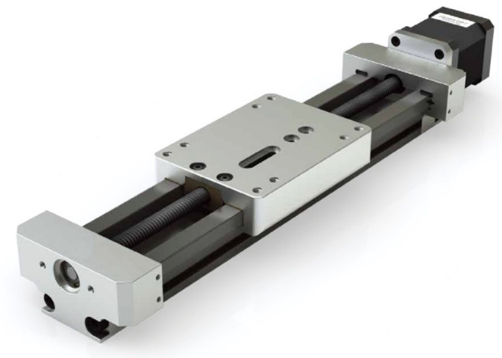
MULTI-AXIS MOUNTING PLATES

Mounting plates are available to easily configure multi-axis systems

Plain Bearings Module(GST)- Lead Screw Drive

OVERVIEW

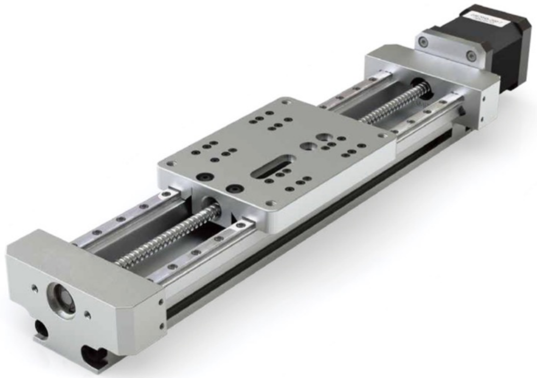
- Utilizes a self-lubricating and maintenance free nut
- Standard fixed nut or Constant Force anti-backlash nut available
- Lead screw material:
  - 10 mm diameter
  - 300 series stainless steel with PTFE coating
  - 1, 2, 5, 10, 16 mm leads most common
  - Other leads available – consult factory
- Ideal for a broad range of applications such as kiosks, assembly, automation, medical, and laboratory



Profile Rail Guideways(PRT) - Ball Screw Drive

OVERVIEW

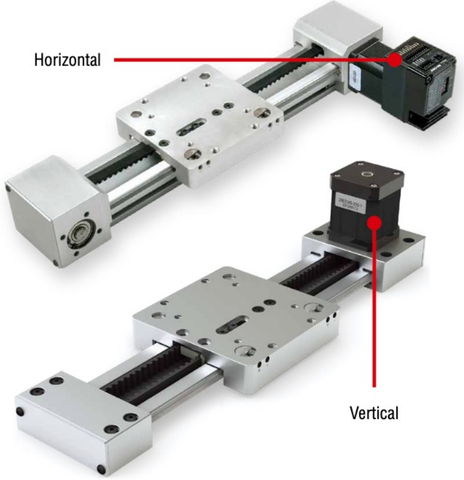
- Recirculating ball nut provides low friction drive
- Preloaded design for stiffness and rigidity
- Ideal for applications that require precise positional accuracy
- Consult factory with application requirements to optimize integrated screw and nut parameters
- Selection of leads
- Choice of screw accuracy class

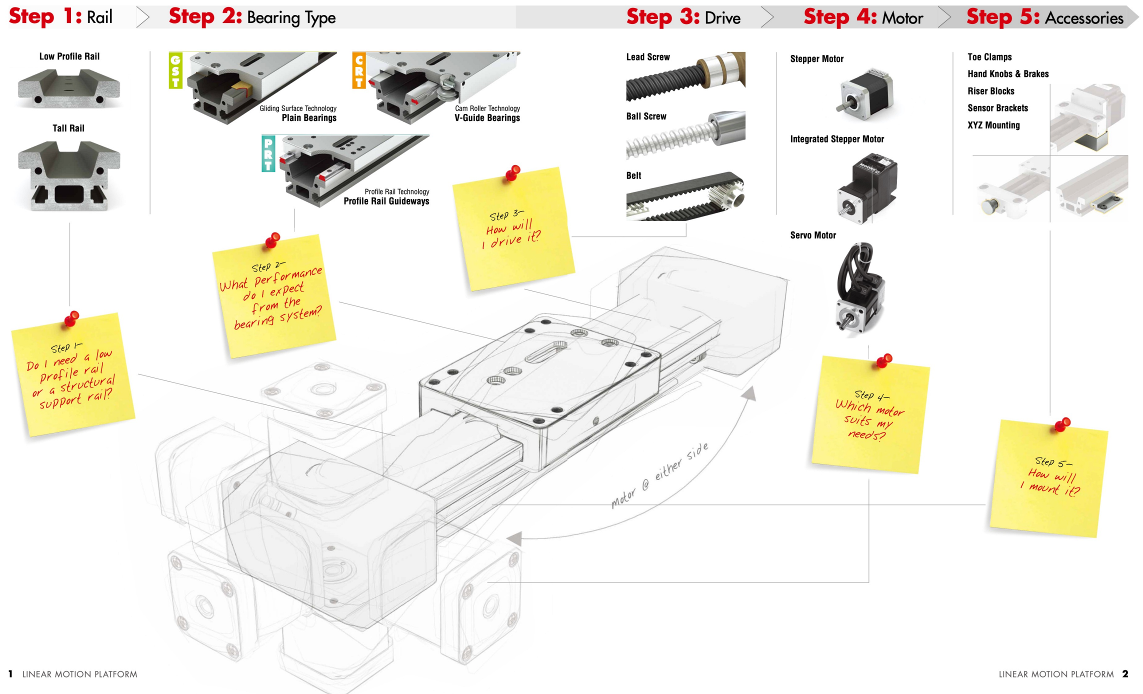


V-Guide Bearings Module(CRT) - Belt Drive

OVERVIEW

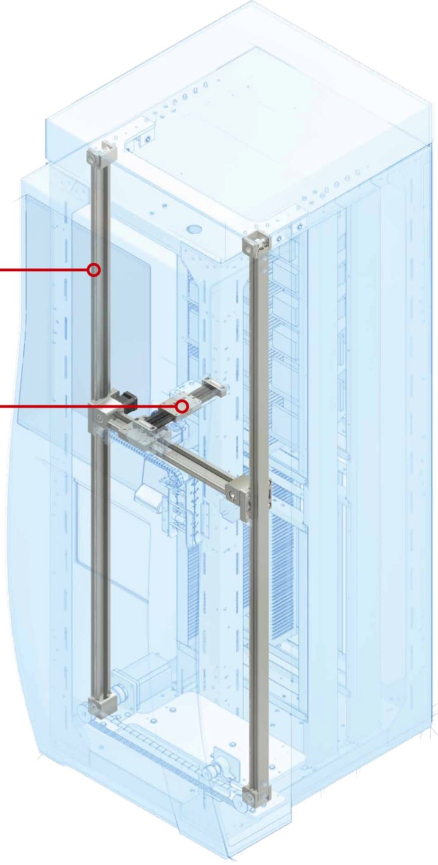
- Horizontal motor mount available in the tall profile (UGT) only
- Vertical motor mount allows for high speed performance in the (UGA) low profile rail
- Consult factory for (UGT) tall rail with vertical motor mount
- Ideal for higher speed, high duty cycle applications
- Belt material: nylon covered, fiberglass reinforced, neoprene
- Temperature range: 0° C to +80° C (32° F to 176° F)
- Rounded GT®2 tooth design creates better engagement with the pulley resulting in greater torque transfer, reduced vibration, and extended life



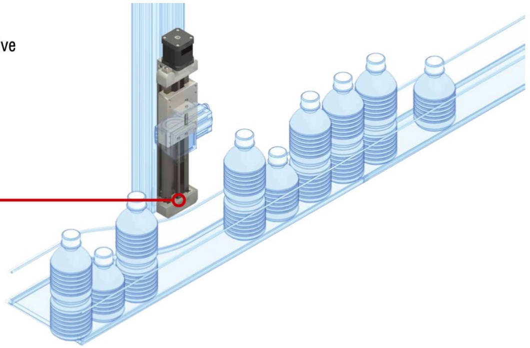


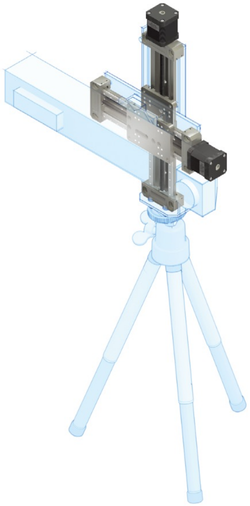
应用案例

KIOSK & AUTOMATED RETAIL: The SIMO Series tall rail (UGT) works well as a structural support – shown here in the X and Y axis in an automated dispensing application. The low profile (UGA) SIMO Series – shown in the Z axis – is ideal for fitting into tight spaces.

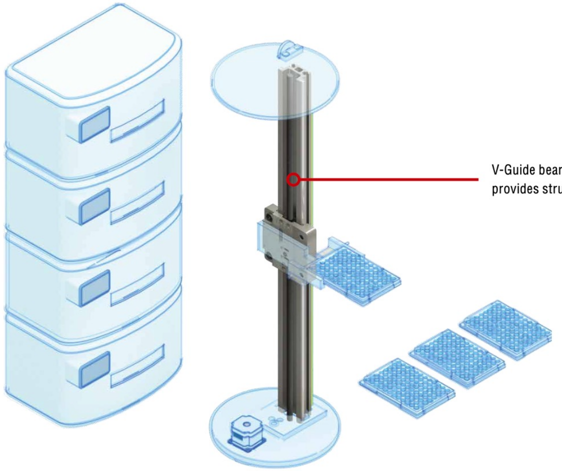


BOTTLING: The SIMO Series is ideal in bottling and food service applications that require repeatable motion and involve various load capacities.





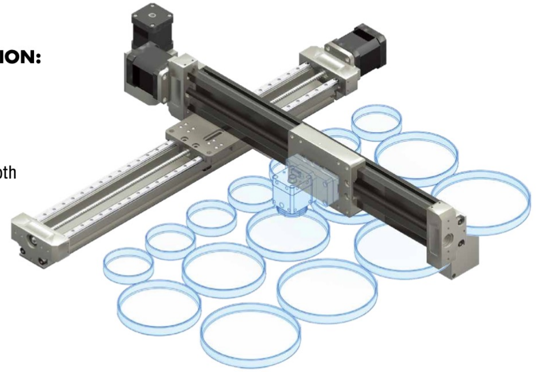
LASER CODING & BARCODE PRINTING: Inline barcode printers & scanners help industrial automation manufacturers reduce costs and improve quality. The SIMO Series' versatility provides dependable linear motion for even the most demanding coding applications.



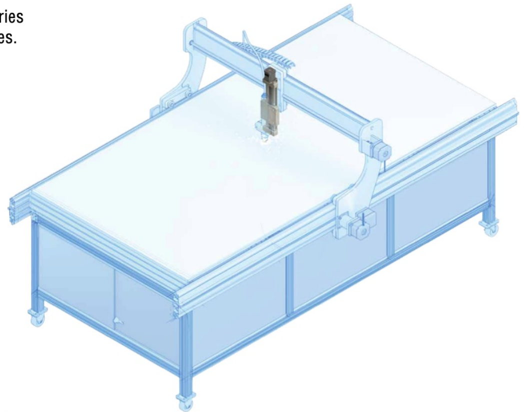
POLAR ROBOT: The SIMO Series can be used in vertically or horizontally oriented applications. The polar robot shown here provides repeatable motion and high accuracy.

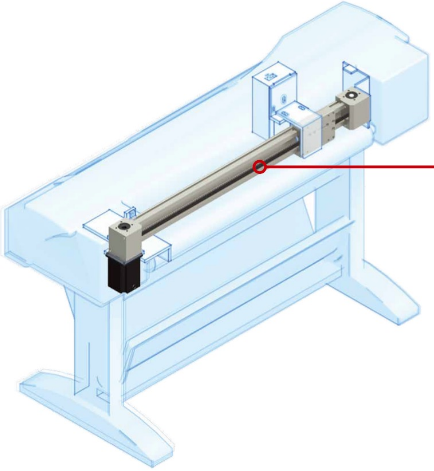
LAB AUTOMATION – PETRI CAMERA OPERATION: Combine the SIMO Series bearing options to create the ideal multi-axis solution – designed to fit the application. Shown here:

- X-axis – PRT with ball screw for precision, rigidity, and moment load capabilities;
- Y-axis – GST with lead screw for repeatability and smooth motion.



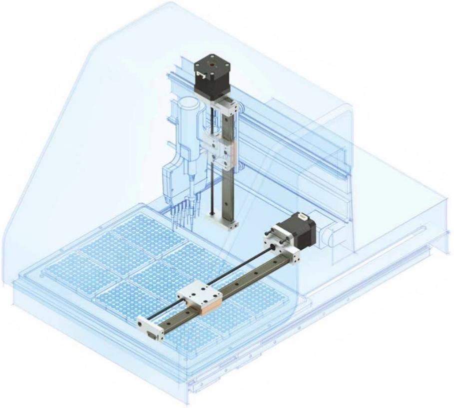
WATER JET & PLASMA CUTTER XYZ: The SIMO Series is easily integrated into water jet and plasma cutter assemblies. This type of machining requires rigid and precise linear motion and is often located in contaminated, wet, and dirty environments.



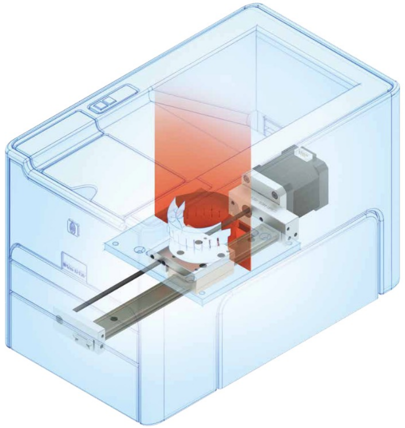


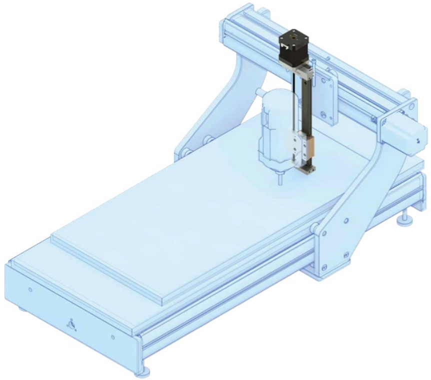
COMMERCIAL PRINTING: The SIMO Series is a cost effective solution for printers and scanners. The pre-assembled system reduces set-up time and requires little maintenance.

WELL PLATE HANDLING: Compact Series installed in an intricate well plate handler – providing accurate and reliable linear motion.



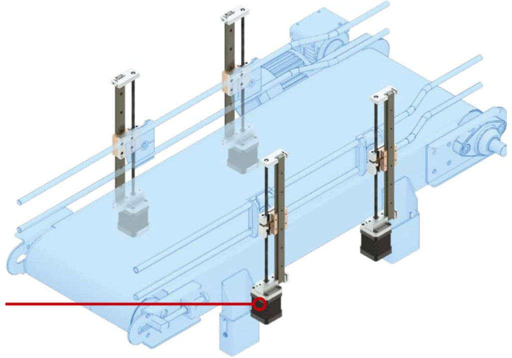
SCANNING EQUIPMENT: High precision and smooth operation are required when designing linear motion for laboratory scanning equipment. The plain bearing system utilizes FrelonGOLD® —a self-lubricating, maintenance free surface that does not require oil.





CNC ROUTER: The plain bearing version of the Compact Series is ideal for harsh, dirty environments such as a CNC router. The carriage acts as a wiper as it clears away contamination such as dust and debris from the rail.

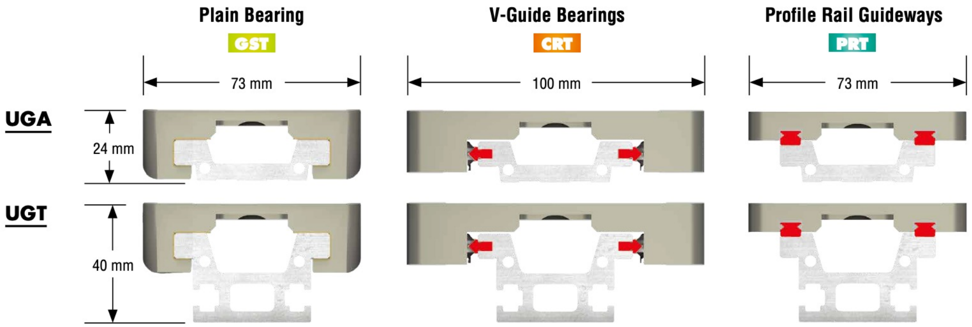
AUTOMATED CONVEYOR: Material handling conveyor systems utilize the Compact Series linear guide system for maintenance free, repeatable linear motion.



SIMO Series Bearing System

Three bearing system options are available with SIMO Series:
Plain Bearing, V-Guide Bearings and **Profile Rail Guideways**.

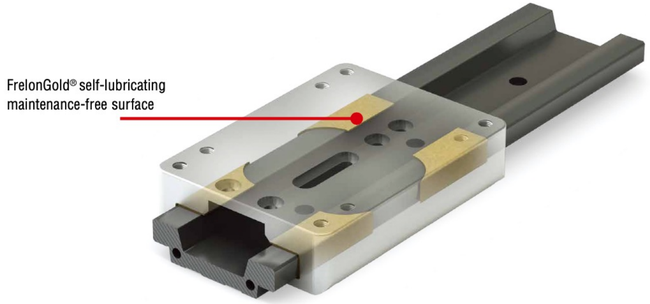
- Choose the bearing system that best supports the application requirements

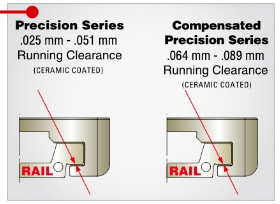


Gliding Surface Technology

PLAIN BEARING

- Low cost
- Utilizes bonded **FrelonGOLD**® bearing surfaces
- Self-lubricating and maintenance free
- No catastrophic failure
- No metal-to-metal contact, vibration damping
- Max speed – 1.53 m/s (300 ft/min) (dry running)
- Wide temperature range
- Resists contamination
- Precision or compensated running clearance



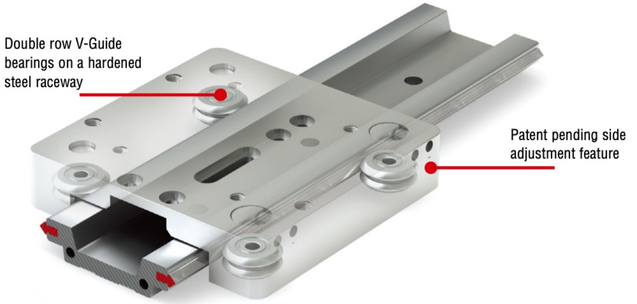


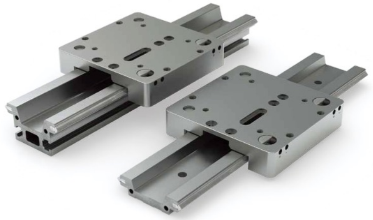
Note: Plain bearings should comply with the 2:1 ratio rule.

Cam Roller Technology

V-GUIDE BEARINGS

- High speeds – to 5 m/s (984 ft/min)
- Quick change of direction
- Good for cantilevered loads
- Handles contamination
- Built in lubricators standard
- Patented side-adjust preload feature
- 420 stainless steel race – hardened to RC60 – swaged in

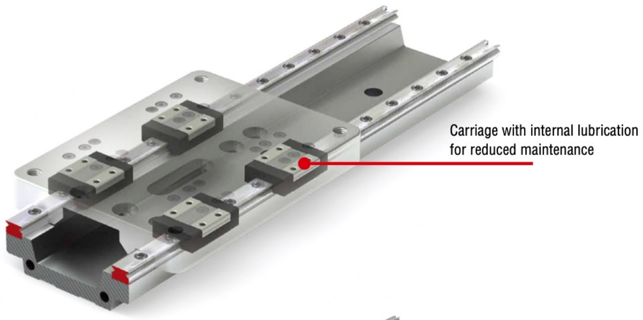




Profile Rail Technology

PROFILE RAIL GUIDEWAYS

- High precision and high speeds – to 3 m/s (590 ft/min)
- Size: 7 mm recirculating ball bearing blocks
- Increased stiffness and preloaded bearing performance
- Supports cantilevered loads
- Extra long blocks for increased load capacity are available – consult factory



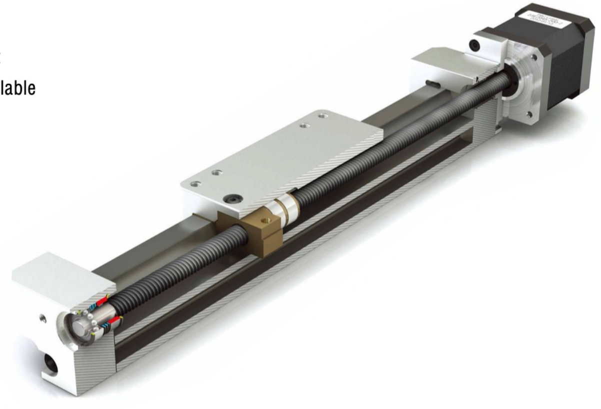
Drive Type Selection

Three drive types are available with SIMO Series:
Lead Screw, **Ball Screw**, **Belt Drive – Horizontal** and **Vertical Motor Mount**.

- Choose the drive type that best supports the application requirements

LEAD SCREW

- Self-lubricating PTFE coated screw and polymer nut
- Fixed nut or Constant Force™ anti-backlash nut available
- 1, 2, 5, 10, 16 mm leads most common
- Other leads available – consult factory

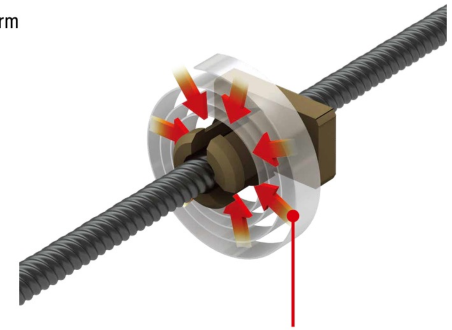


NUT

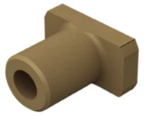
Constant Force™ Anti-Backlash Nut
An intuitive leap forward in nut design for lead screw applications,
Constant Force Technology utilizes a constant force spring to apply a uniform pressure to the nut at all stages of the motion profile.

- Greater consistency and resistance to backlash
- Configurable for various torque requirements
- Patent pending self-adjusting anti-backlash feature
- Polymer nuts are self-lubricating and maintenance free

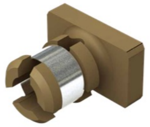
Standard Fixed Nut
- Good rigidity and vibration damping
- Polymer nuts are self-lubricating and maintenance free



Patent pending Constant Force Technology nut provides consistent anti-backlash operation



Standard Fixed Nut



Anti-Backlash Nut

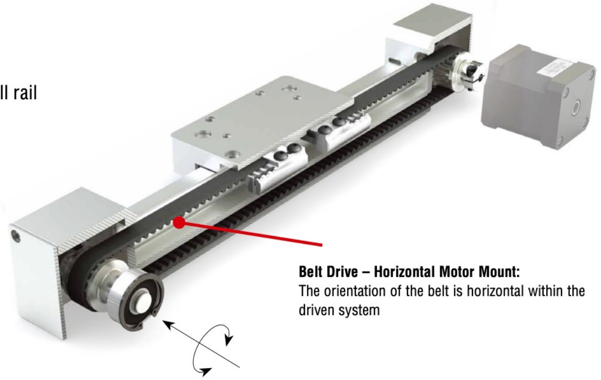
BALL SCREW

- For applications requiring precise positional accuracy
- Multiple leads available
- Selection of accuracy classes
- Consult factory for options

BELT DRIVE

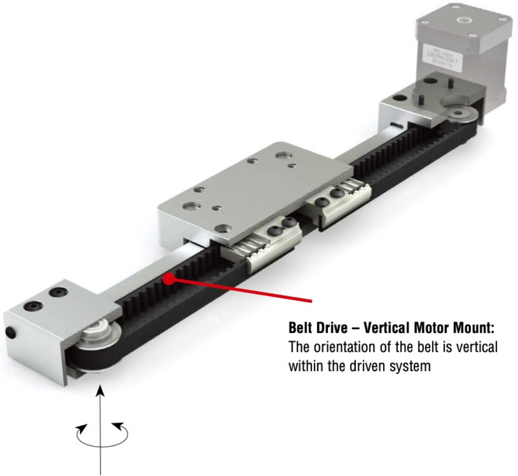
HORIZONTAL MOTOR MOUNT

- Ideal for high speed applications
- Horizontal motor mount is available only with (UGT) tall rail



VERTICAL MOTOR MOUNT

- Ideal for high speed applications
- Vertical motor mount is designed for (UGA) low profile rail
- Consult factory for use with (UGT) tall rail



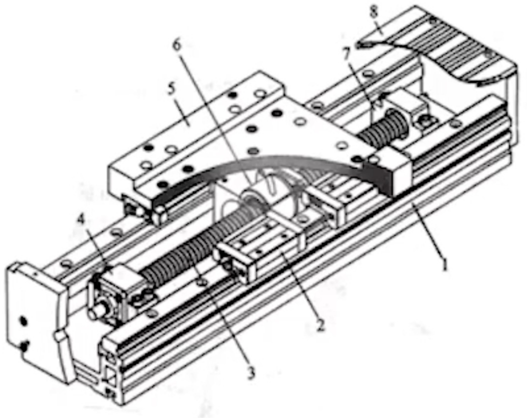
Working Principals of Linear Motion Platform

直线运动平台工作原理

丝杠传动的运动平台

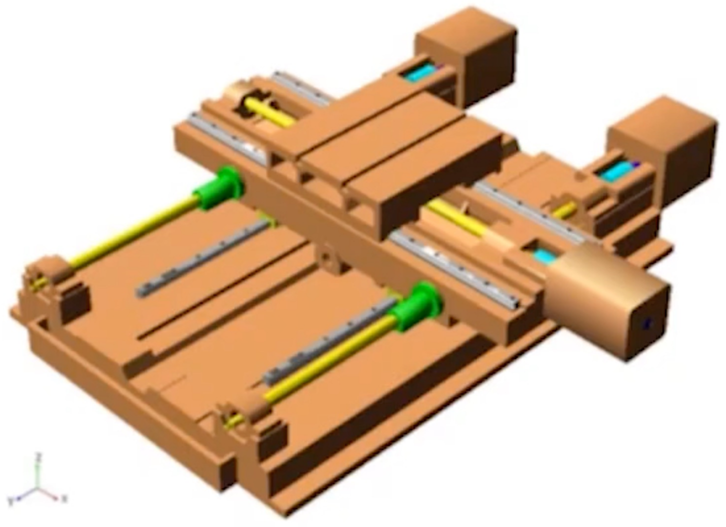
双导轨结构

单导轨结构



双导轨丝杠传动平台的结构

1-型材底座；2-滑块与导轨；3-滚珠丝杠；4-轴承座；5-平台；6-丝杠螺母；7-轴承座；8-防尘罩



Working Principals of Linear Motion Platform

直线运动平台工作原理

丝杠传动的运动平台

滚珠丝杠

- 丝杠强度的校核
- 验算极限转速和极限载荷
- 静态安全系数
- 丝杠寿命计算
- 平均轴向负荷与平均转速
- 支承轴承的寿命
- 丝杠进给系统刚度计算

滚动导轨

- 负荷计算
- 等效载荷计算
- 静态安全系数校核
- 平均负荷计算
- 寿命计算

支承滚动轴承

伺服电机

- 稳态扭矩计算
- 惯性扭矩计算
- 最大扭矩、功率计算
- 平均扭矩验算

联轴器

Design of Linear Motion Platform

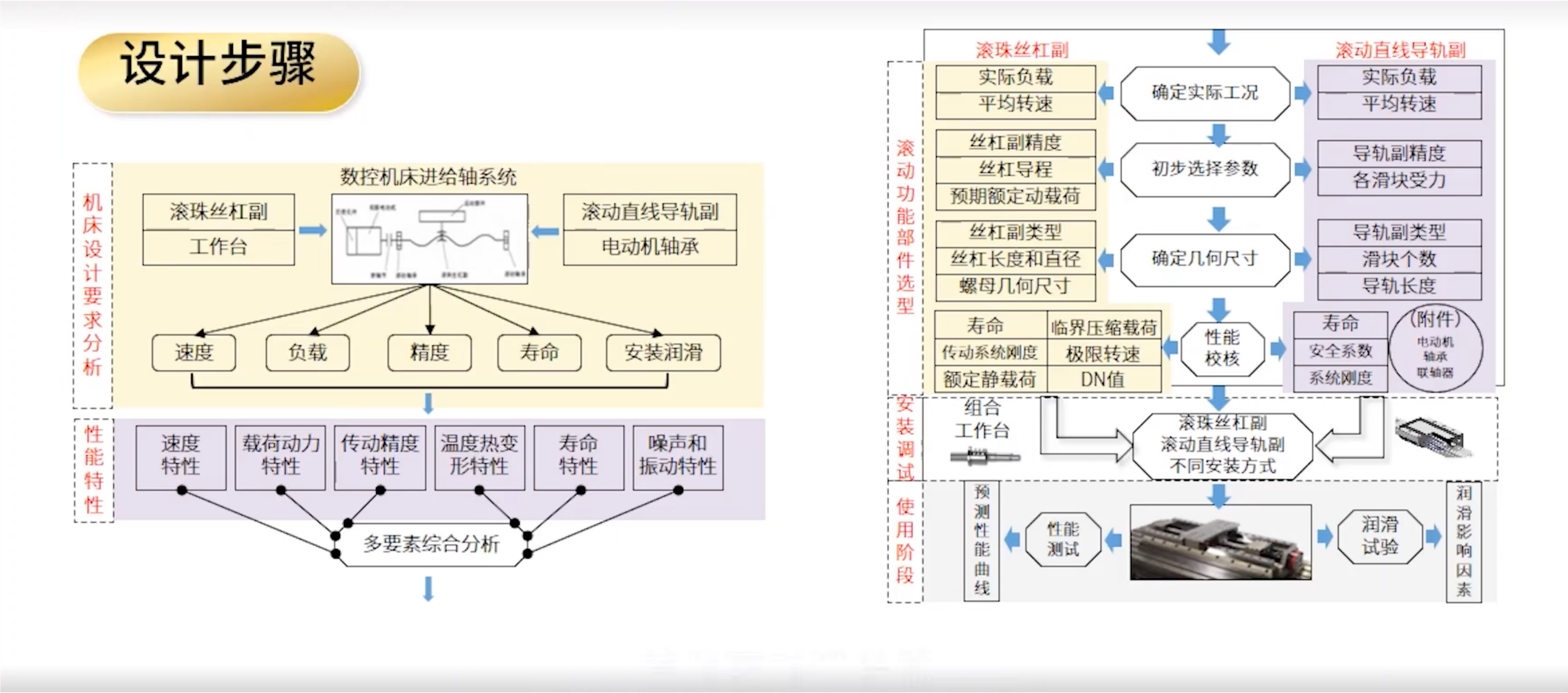
直线运动平台设计

功能部件选型原则

- 开则能动
- 动则精密
- 动则灵敏
- 动则高效
- 动则可靠

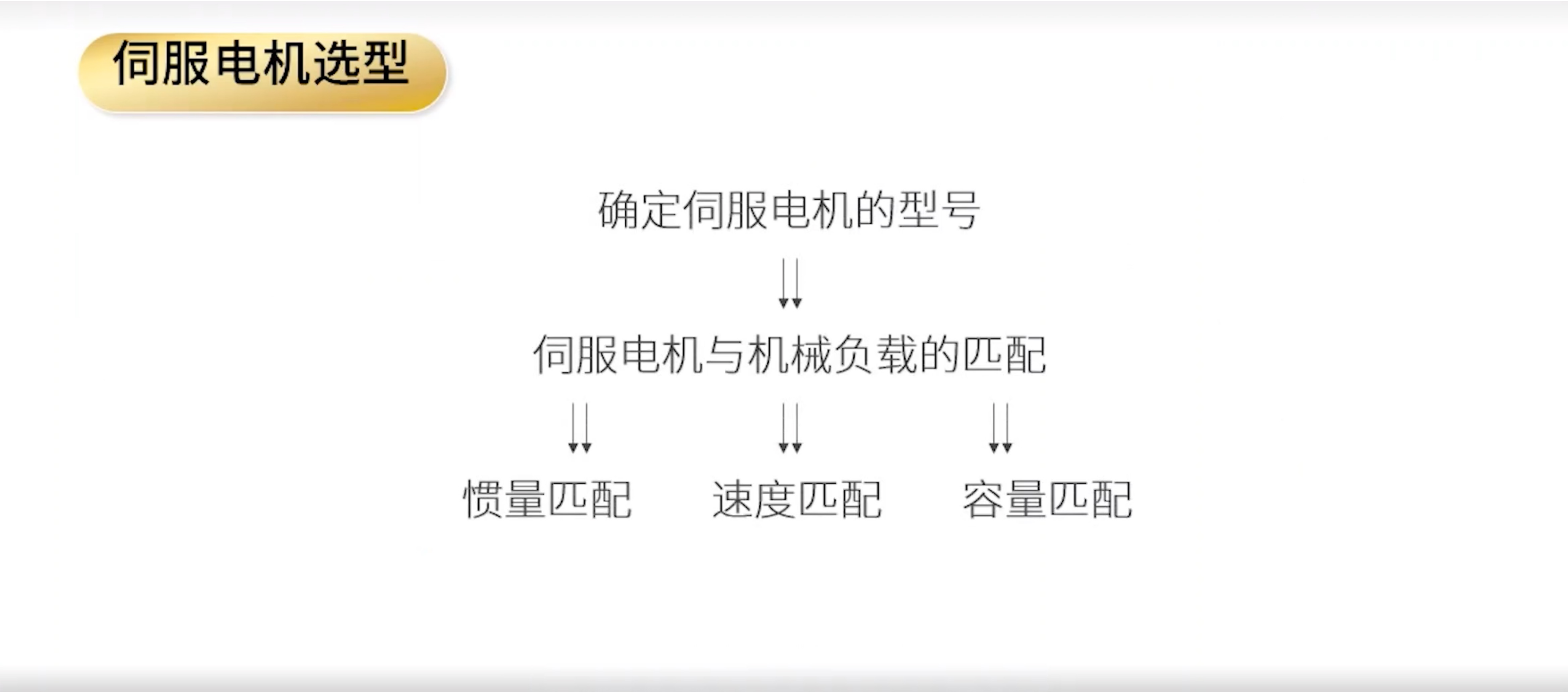
Design of Linear Motion Platform

直线运动平台设计



Motor Selection of Linear Motion Platform

直线运动平台伺服电机的选择



Motor Selection of Linear Motion Platform

直线运动平台伺服电机的选择

机械负载的类型

- 摩擦负载：$F_c = f \cdot N$
- 惯性负载：变速运动时产生惯性负载
  $F_L = -m\,(dv/dt)$ $M_L = -J_L[d\Omega/dt]$
- 工作阻力负载：切削力、上升重力等
- 其他：阻尼负载、弹性负载、流体动力等

} 机床

Motor Selection of Linear Motion Platform

直线运动平台伺服电机的选择

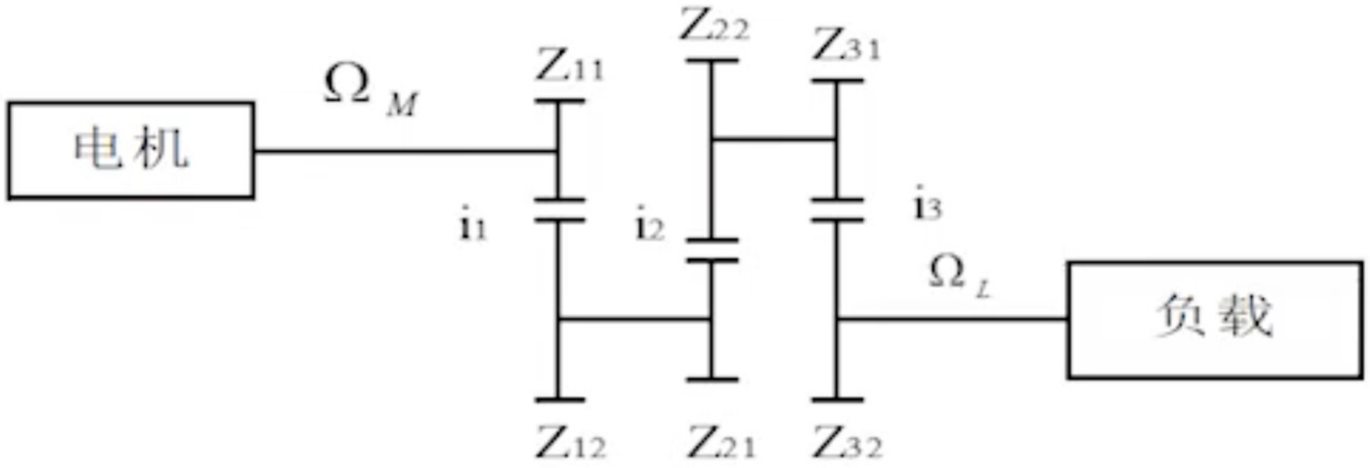
伺服电机与机械负载的惯量匹配

1）等效负载惯量的计算

旋转机械与直线运动的机械惯量，按照能量守恒定律，通过等效换算，均可用转动惯量来表示。

等效负载惯量

伺服系统中运动物体的惯量折算到驱动轴上的等效转动惯量



Motor Selection of Linear Motion Platform

直线运动平台伺服电机的选择

伺服电机与机械负载的惯量匹配

负载惯量J_L 和电机的惯量 J_m 必须合理匹配

2）步进电机的惯量匹配原则

检查起动能力:

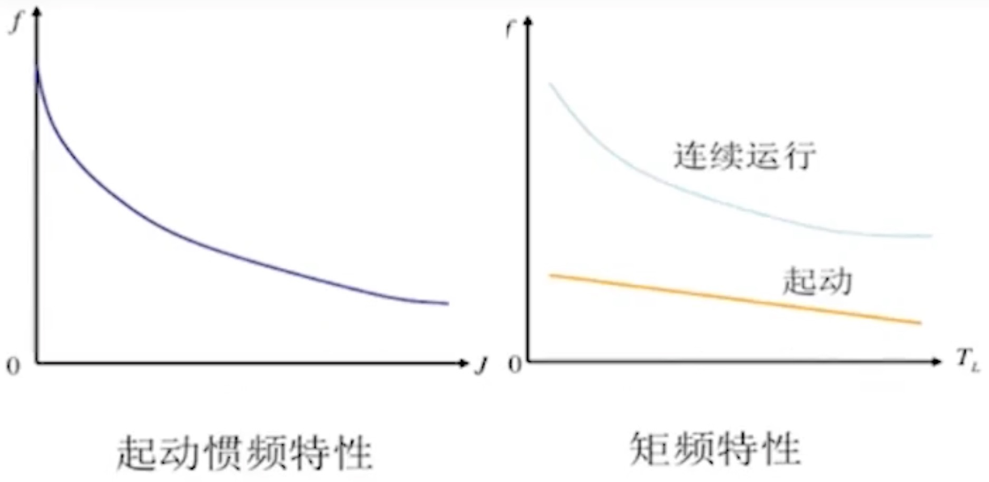
- 起动惯频特性曲线找出带惯性负载的起动频率
- 然后，再查其起动转矩和计算起动时间

查不到带惯性负载时的最大起动频率时近似计算:

$$f_L = \frac{f_m}{\sqrt{1 + J_L / J_m}}$$

使电机具有良好的起动能力及较快的响应速度，通常推荐:

$$J_L / J_m \le 4$$



f_L — 带惯性负载的最大自起动频率

f_m — 电机本身的最大空载起动频率

J_L— 折算到电机轴上的转动惯量

J_m—电机轴转子的转动惯量

Motor Selection of Linear Motion Platform

直线运动平台伺服电机的选择

伺服电机与机械负载的惯量匹配

负载惯量J_L 和电机的惯量 J_m 必须合理匹配

3）交、直流伺服电机的惯量匹配原则

小惯量伺服电机: $J_m \approx 5\times10^{-3} kg\cdot m^2$ $\quad J_L/J_m \le 4$

动态性能好，响应快;但容易发生对电源频率的响应共振，当存在间隙、死区时容易造成振荡和蠕动

大惯量伺服电机: $J_m \approx 0.1\sim0.6 kg\cdot m^2$ $\quad 0.25 \le J_L/J_m \le 4$

受惯性负载的影响小，常不需要传动装置而与滚珠丝杠等直联；调速范围大，低速范围速度刚度和动态性能优良，应用较广

Motor Selection of Linear Motion Platform

直线运动平台伺服电机的选择

伺服电机与机械负载的容量匹配

即：电机的额定转矩与被驱动的机械系统负载（转矩）相匹配

按转矩性质分为：驱动转矩 T_m、负载转矩 T_L、摩擦力矩 T_f和惯性转矩T_a（动态转矩）： $T_m = T_L + T_a + T_f$

- 转矩的匹配是对特定轴（一般为电机轴）
- 对特定轴的转矩称为等效转矩
- 如果力矩直接作用在特定轴上，则不需要换算，否则，必须换算成等效力矩

Motor Selection of Linear Motion Platform

直线运动平台伺服电机的选择

伺服电机速度匹配

依据式： $[J]_i = \sum_{j=1}^{k} J_j \left(\frac{n_j}{n_i}\right)^2 + \frac{900}{\pi^2} \sum_{j=1}^{k'} m_j \left(\frac{V_j}{n_i}\right)^2$ $[T_L]_i = T_{L1}\left(\frac{n_1}{n_i}\right) + T_{L2}\left(\frac{n_2}{n_i}\right) + \cdots + T_{LK}\left(\frac{n_k}{n_i}\right) = \sum_{j=1}^{k} T_{Lj}\left(\frac{n_j}{n_i}\right)$

- 同样功率的电机，额定转速高则电机尺寸小，重量轻
- 电机转速越高，传动比越大，等效转动惯量和等效负载越小

电机一般工作在高转速、低扭矩状态 ⟷ **减速器设计** ⟷ 机械装置工作在低转速、高扭矩状态

Assignment 05

To be submitted one week before the end of this semester.

- 参考台式铣钻床用户手册，自行撰写一个机械工具的用户手册（学期结束前一周提交）
- Based on the user manual of the milling machine provided by the class, please find a mechanical system, write a user manual for a mechanical tool or machine, and submit one week before the end of this semester.
- Link to submission to be provided later
- Make sure your machine of choice is with a reasonable level of complexity.
- Consult me or TA before making your final choice of the targeted mechanical system for analysis.

Thank you~

ME303 Introduction to Mechanical Design

Adapted from https://www.icourse163.org/course/HUST-1206698847