Go long

Rack and pinion sets are thoroughly modern devices that deliver precise motion, even over unlimited lengths.

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Linear motion is indispensable to moving machines; it transports tools and products efficiently and controllably. The mechanisms that generate linear motion are generally ranked by their axial velocity and acceleration, axial forces versus structural volume, life, rigidity, and positioning accuracy.

Two common linear systems are linear motors and ballscrew drives. Rack-and-pinion drives are often overlooked as past-generation technology with limited positioning accuracy. However, this assumption is invalid.

Precision-ground mounting surfaces to tight tolerances, wear-resistant surface treatments, individually deburred gear teeth, and compact, low-mass designs are boosting performance. In fact, rack-and-pinion drives compare favorably to linear motors as well as roller or ground-thread ballscrews.

New-generation rack-and-pinion systems offer high dynamic performance and unlimited travel distance. Some include premium servogears and actuators with backlash less than 1 arc-min., efficiency to 98.5%, and far more compact sizes than standard servomotor-gear combinations. Some preassembled gear-pinion units can even run true to 10 µm, for safety and smooth motion.

Typical rack-and-pinion applications include gantry, transport, and packaging machines that carry from a few pounds up to several tons. Next-generation rack-and-pinion sets are also used in woodworking, high-speed metal cutting, and assembly machines.

Geometry and surface details

Rack-and-pinion performance has improved with general technological advances. For example, state-of-the-art **machining** and **grinding** have greatly advanced rack-and-pinion precision.

More specifically, some premium rack pieces are laser etched for cumulative pitch error ±12 µm over a 500 mm length, which allows for hand selection of target accuracy. This is useful for matching rack pieces in parallel, for dual-drive gantry applications. In fact, that level of precision allows several kinds of machines to run without external feedback devices; in contrast, other linear systems require expensive external feedback devices for commutation and positioning.

A **helical** rack with an optimized helix angle is preferred for quieter running at higher speeds and a higher load carrying capacity due to the higher tooth contact ratio. Single-pitch error between helical teeth can reach 3 µm. A pinion profile shift or *addendum* modification prevents undercut; it also balances bending stresses, for higher load capacity. Helical gearing engages smoothly and quietly — which helps improve surface finish, for example, when machining tight-tolerance parts.

Lubrication is key

Rack-and-pinion sets last longest when properly lubricated. Appropriately greased sets are also most capable of reaching highest rated speed. For many rack and pinion systems, the most common method is an automatic lubrication kit or greasing device. These devices come in various sizes or volumes, and are controlled electronically.

Different settings can be selected to control the amount of grease that flows over time — dependent on the motion cycle of the rack and pinion. A charged canister maintains pressure when not in use; closing a two-wire switch activates flow.

The grease travels through a hose into a hollow *greasing pinion,* a felt gear with radial holes where the grease is applied to either the rack or the pinion through the holes. Here, the design determines which half of the set is actively greased: For example, lubricating the rack for a high-speed application can prevent grease from being flung away.

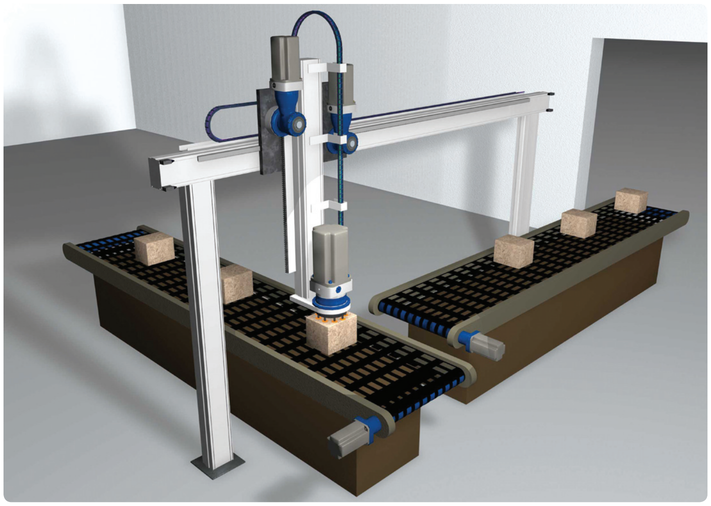
In any case, the correct amount of grease required for the application can be applied automatically and accurately, for little maintenance.

Rack-and-pinion integration

Mounting options abound for rack-and-pinion sets. Some racks use special mounting surfaces to ensure accuracy, while others deliver suitable performance even with basic installation. The design's inherent flexibility can be leveraged for better control: Unlike direct-driving linear motors, rack-and-pinion sets allow adjustments in pinion size, gear ratios, and damping — to stabilize closed-loop control.

There are pitfalls: Putting the pinion and rack teeth too far apart causes backlash, which degrades precision. Compromised or misaligned mounting can also damage gearbox bearings — causing higher motor current draws, noise, and even failure. For best performance, a pinion should be properly distanced from the rack, mounted on a flat surface and perpendicular to the gearbox to within about 25 µm for many applications.

Advances in rack-and-pinion gearing and the decrease in ser-



Rack-and-pinion sets can be used in vertical applications. Two things limit practical speed are the pinion-driving device (for example, the servomotor) and the process of keeping the rack and pinion lubricated.

votechnology prices mean that usually, servomotors are paired with rack and pinion systems. Stepper motors are a viable option, but servomotors are preferred for their precision.

Preloading

Sometimes, rack-and-pinion sets are preloaded to eliminate backlash and increase stiffness. Here, two pinions run on the same rack. A master pinion drives the mechanism as in a usual setup; meanwhile, a slave pinion can generate torque to apply an opposing force to the teeth that it engages. In this way, inertia and resistance prevent backlash, even during load changes; system rigidity also increases, and boosts control dynamics.

If the components are selected correctly, there are no significant drawbacks to preloading a rack-and-pinion system. On the other hand, mechanical preloading can actually decrease the overall machine stiffness. For example, a spring-loaded split pinion would lower the system stiffness:

$$\frac{1}{C_{sys_{NEW}}} = \frac{1}{C_{sys}} + \frac{1}{C_{spring}}$$

Note that unlike more sophisticated electronic preloading, these traditional preloading pinions cannot work together; one always opposes the other, which slightly reduces efficiency.

In more sophisticated rack-and-pinion sets, *electronic* preload is held to its maximum while the system is still. The master and slave pinions — both actively powered — push on rack teeth facing in opposite directions. Then when the machine accelerates, the master pinion drives the machine forward, while the slave pinion eases off opposing force preload. When the system slows to a steady speed, the slave pinion comes to contact the tooth flank equivalent to the one engaged by the master pinion; then the two pinions drive in the same direction, while still preventing backlash.

Finally, when the system decelerates, the slave pinion returns to applying force on the opposing tooth flank, to help slow the load.

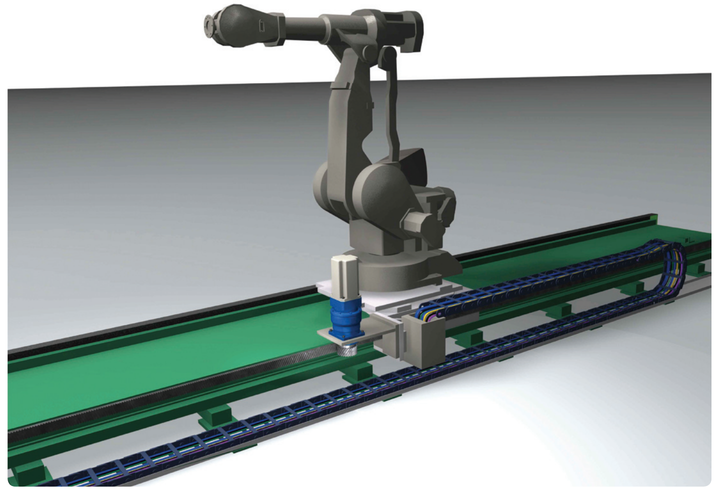
Stepper motors are a viable driving option for rack-and-pinion sets, but servomotors are more commonly paired with the mechanisms.

Rack-and-pinion versus ballscrews

Ballscrews cannot accelerate like rack-and-pinion sets; nor can they maintain the same speeds. Their stiffness is lower and less constant.

Rack-and-pinion sets have lower mass moment of inertia and higher natural frequency and efficiency over ballscrews. There are fewer components [read: more reliability] to save time during installation. Also, length is unlimited: An engineer can run these as far as factory space will allow, and the only additional cost is just that of adding additional pieces of rack.

Ballscrews can run up significant cumulative errors over total travel length. For example, deviation over four meters of travel for a rolled screw drive may vary between 300 and 1,700 µm. Even ground-thread ballscrew deviation over four meters ranges between 30 and 110 µm. With two paired rack-and-pinion systems, cumulative error for the same travel length is only 12 to 40 µm. This makes rack-and-pinion sets suitable for even gantry drives.



Rack-and-pinion actuators often have acceleration rates and peak speeds nearly as good as those of linear motors. In many cases, the machine frame and structure — not the actuator — limit peak speeds from rack-and-pinion and linear-motor systems.

For applications with long travel lengths, ballscrews have high mass moments of inertia that limit critical speed and axial load capacity; even preloaded ballscrew efficiency only reaches 90% or so. Such long-stroke applications benefit from a switch to rack-and-pinion sets — with efficiency to 97%.

Adjoining parts such as bearings influence ballscrew rigidity, housing bores, or nut housings, making it difficult to ensure stable system behavior under dynamics. Deviation of spindle stiffness depending on nut position over the spindle length compounds this problem.

In contrast, rack-and-pinion drives offer constant stiffness over the complete travel length plus good system behavior — for superior control system behavior. Finally, unlike rack-and-pinion systems, ballscrews only allow one carrier per linear axis and are not suitable for short-stroke applications. Why? Greasing demand dictates that only some balls circulate through the nut.

Rack-and-pinion versus linear motor

Compared to linear motors, rack and pinion systems can offer similar performance but at far less cost. They are smaller, allowing a more compact, less complex machine design. The absence of magnetic forces vastly decreases the need for support structures to absorb high normal forces, so standard guide rails can be used. Linear motors have overall efficiency to 90% — though sometimes it's considerably lower. Because of this inherent inefficiency, linear motors often require water cooling.

In comparison, rack and pinions need no cover; the guidance system can be exposed to metallic particles, and safety restrictions are minimal. Better rack-and-pinion sets do not require expensive linear scales and external brakes, either; standard motor feedback devices and brakes are enough.

In many cases, linear motors require complete machine redesign — partly because huge normal forces from the attraction between the primary and secondary have far-reaching consequences. An easier option, ready-to-mount rack-and-pinion systems facilitate blind assembly for additional cost savings — and cut assembly time to roughly 10 minutes per meter travel length.

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