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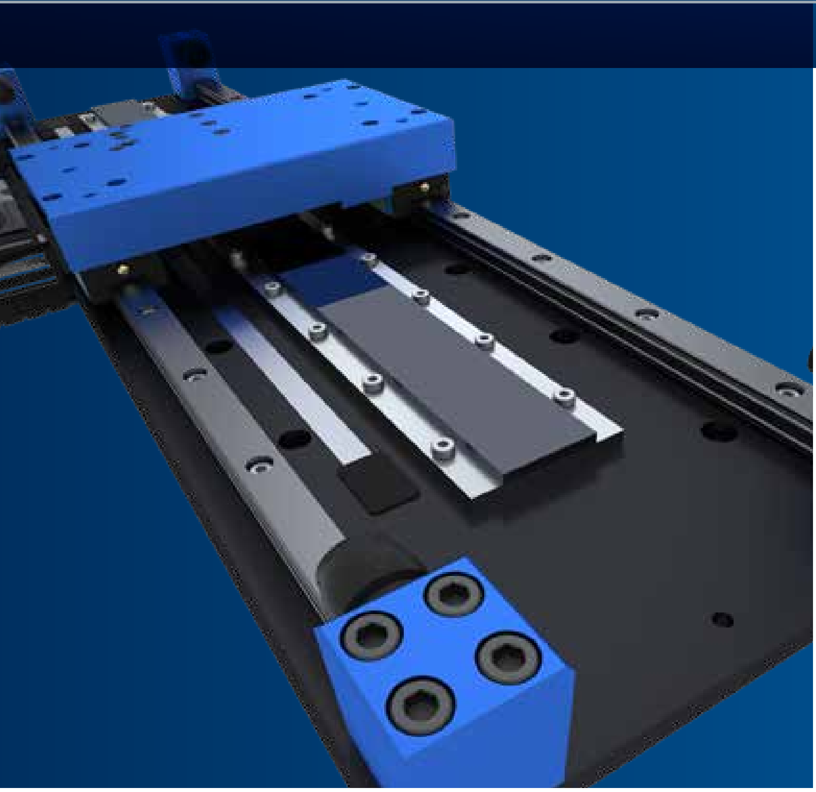
WHEN ARE LINEAR MOTORS THE RIGHT CHOICE?

HOW DO THEY MEASURE UP WITH BALLSCREW, BELT, AND RACK & PINION ACTUATORS?



This document examines the characteristics of linear motor stages and compares them with those of other linear actuators to determine what types of applications are best-suited for them.

4 most common linear actuators:

- Linear motor stages
- Ballscrew actuators
- Belt actuators
- Rack & pinion actuators

For a linear motor stage, linear bearings are essentially the only point of mechanical contact and frictional wear.

INTRODUCTION

Knowing when and how to apply linear servo motor technology requires that you understand the components that comprise a linear motor stage, as well as the components that are used to make other linear actuators that rely on rotary servo motors. These include ball screw, belt, and rack & pinion actuators.

This article compares each technology using a few key metrics. The advantages and limitations of each mechanism are crucial when deciding how to apply the technology. As a result, the reader should be able to more readily identify the most effective mechanism for a given application.

TYPES OF LINEAR ACTUATORS

A wide array of linear actuators exists in the motion control industry. However, the four most common of these are linear motor stages, ballscrews, belts, and rack & pinion.

1. Linear Motor Stages

Let's begin with a definition of a linear motor stage. The distinguishing feature of a linear motor is that the load moves without any mechanical power conversion.

The linear force generated by the motor coil is directly connected to the load. In a linear motor, the motor coil propels itself along the magnet track. The motor coil is attached to the carriage, sometimes called a "slide".

The load is bolted directly to the carriage. The carriage is held in place by linear bearings with rails secured to the base. The linear bearings are the only point of mechanical contact and frictional wear, apart from the bending of cables.

This simple fact results in huge performance benefits for a linear motor stage. The position of the carriage is reported to the control system through a linear encoder.

The encoder has two parts, the scale mounted to the base, and the moving read head.

Other parts of a typical linear motor stage are the cable management system and end stops.

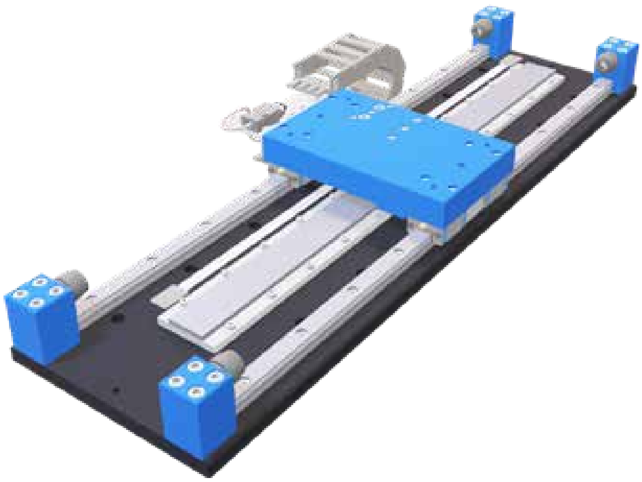


Figure 1: A typical linear motor stage

2. Ballscrew Actuators

The ballscrew is the standard go-to actuator for a wide variety of applications.

These also have a carriage that moves on linear bearings and rails. But the force to move it is transmitted through a nut from a rotating screw. This nut is typically comprised of a system of enclosed recirculating ball bearings which minimize friction.

The screw is driven by a rotary motor. The encoder in the motor provides position feedback to the control system. The screw is held in place with bearings at each end and connects to the motor through a flexible coupling.

3. Belt Actuators

Similarly, a belt actuator also has a carriage which moves on rails with linear bearings. This carriage is driven by direct connection to a timing belt riding on two pulleys. The pulleys are held in place with bearings and connect to the motor with a flexible coupling. The encoder on the motor provides position feedback to the control system.

4. Rack & Pinion Actuators

A rack and pinion system is typically comprised of a motor that drives a pinion, moving itself along a fixed rack, like a train on a track. The motor is mounted to the carriage, driving the pinion through a gear reduction to move the entire assembly.

Ballscrew, belt, and rack & pinion actuators all utilize rotary motor technology

Figure 2: Ballscrew actuator

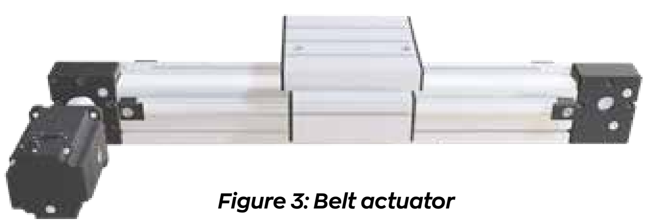


Figure 3: Belt actuator

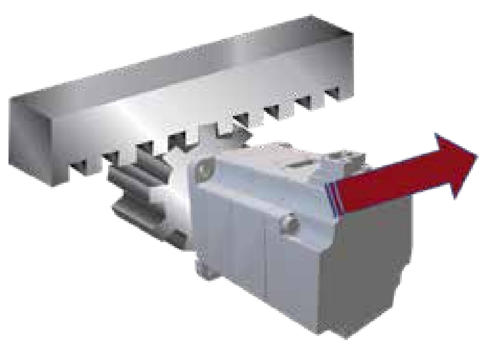


Figure 4: Rack & Pinion Actuator

The initial cost of linear motor stages is significantly higher than that of ballscrew, belt, or rack and pinion actuators.

METRICS

Now let's look at how each of these technologies compare in terms of the metrics listed in Table 1.

It is important to first define each of these metrics, before discussing the strengths and weaknesses of each technology. Please bear in mind that this is not a strict and absolute evaluation, but represents general industry trends.

INITIAL COST

Let's start with the bottom line, initial cost. As we'll see, the linear motor generally has the highest overall performance. It goes to reason, therefore, that the initial cost is also generally higher than other technologies.

Ballscrews are significantly less expensive than linear motors. But they are more expensive than belt actuators, which tend toward the low end of the cost spectrum.

Rack & Pinion is tough to compare. These tend to be used in physically large systems with much larger and heavier payloads. The cost of rack and pinion is far lower at that scale than linear motors, ballscrews, and belts, but at a smaller scale that advantage is often less distinguishable.

SPEED AND ACCELERATION

Motion control systems have the need for speed. Faster, better, and more means a quick return on your investment. This translates to not just high top speed, but fast acceleration.

The linear motor can accelerate quickly to reach high speeds, typically around 5 m/s. It is the performance champion for the mechanism with both high speed and acceleration.

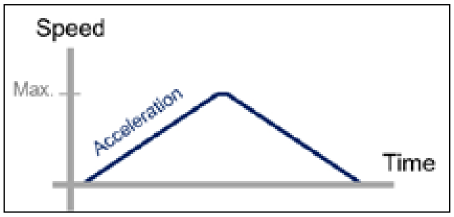


Figure 5: Speed and acceleration vs. time

Screw driven actuators can have strong acceleration, but above the critical speed a screw will oscillate.

But the linear motor stage is the performance champion for mechanisms with both high speed and acceleration.

Metric	Standard				With Full Closed Loop		
	Linear Motor	Ballscrew	Belt	Rack & Pinion	Ballscrew	Belt	Rack & Pinion
Initial Cost	High	Med.	Med.	Low	High	Med.	Med.
Speed and Acceleration	Best	Good	Best	Better	-	-	-
Length	Better	Good	Best	Best	-	-	-
Vertical Load	Good	Best	Better	Good	-	-	-
Rigidity	Best	Better	Good	Better	-	-	-
Load Mass	Good	Better	Good	Best	-	-	-
Backlash	Best	Better	Good	Better	-	-	-
Position Settling Time	Best	Better	Good	Better	-	-	-
Accuracy and Repeatability	Best	Better	Good	Better	Best	Better	Better
Wear and Maintenance	Best	Good	Good	Good	Best	Best	Best
Environment	Good	Good	Best	Good	-	-	-

Table 1: Comparison of performance of different mechanisms

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Ballscrew actuators can be limited at faster speeds and longer lengths due to screw oscillations.

This critical rpm design limitation is dependent on the diameter and length of the screw.

The screw lead can be designed to move further for every turn. This increases the linear speed for the same motor rpm. But it also means more motor torque is required to move the same load.

It also may negatively affect the repeatability and accuracy, which we'll discuss more later on.

With a faster screw the reflected inertia also increases dramatically, thereby reducing control loop stability, and increasing settling time. As a result, a larger, more expensive motor may be required. Occasionally these constraints have a snowball effect resulting in a very oversized or even impossible solution.

Belts can also be fast, about the same as linear motors. But as we'll see later, they have nowhere near the same precision.

Rack and Pinion systems can reach very high speeds, higher even than linear motors. But they typically don't accelerate quickly since they are designed to move large and heavy loads longer distances.

LENGTH

That brings us to length. The large systems driven by Rack and Pinion can also be quite long and it is cost effective to increase the length with additional rack segments with little impact on performance.

Linear motors can also be used in applications with long stroke, but the cost of magnet track and absolute encoder tape is significant. Performance, however, is unaffected by overall length.

Ballscrew length is limited once again by the critical speed of the screw. Longer screws begin to oscillate at a lower RPM, and negatively impact tuning by lowering resonant frequencies. We'll discuss this more later. A larger screw diameter helps to achieve useable speeds.

This means large motors are required to drive the longer screws, even with a small load, unless the speed is very slow.

Belt drive designs are easily lengthened with minimal increase in cost. However, the effect of belt stretch becomes proportionally worse, resulting in reduced accuracy and repeatability. And like the ballscrew, along with increased length comes decreased stiffness and lower resonant frequencies.

VERTICAL LOAD

Horizontally oriented motion is the most common, but vertical or inclined axes are required in many applications.

This means the force of gravity is constantly pushing the load down. This force must be overcome by the motor while the axis moves or holds position. When the machine powers off, a braking system can prevent the vertical axis from falling.

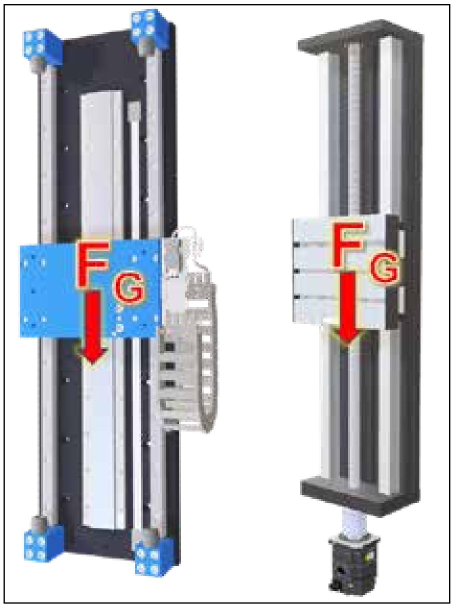


Figure 6: Force of gravity on vertically oriented linear motor stage and ballscrew

For vertical loads, linear motor stages should always be equipped with a counterbalance or linear holding brake.

The most rigid of all the actuator technologies is the linear motor stage, as there is no coupling or mechanical linkage.

The load is connected directly to the motor through the carriage.

Rotary holding brakes are commonly found in servo motor designs to lock the motor shaft when powered down. This makes the ballscrew or belt an excellent choice for vertical loads. A vertical rack and pinion also works well for the same reasons.

Linear motors are a bit more complex with vertical loads. A counterbalance or linear holding brake should always be used. A linear holding brake may be mounted externally or fit under the carriage to brake against the rail.

RIGIDITY

Machine Rigidity, or stiffness, and its inverse, compliance, are important to understand. Every mechanically connected element has a level of rigidity; a spring constant. This rigidity along with the mass of each element, defines the natural frequencies of oscillation for the system. If these frequencies are too low, the release of energy can cause a significant disturbance to the motor. This interferes with the control system algorithms that position the load.

Belt drive systems generally have the lowest rigidity and therefore the lowest natural frequencies. The belt is like a spring and there are natural frequencies between the carriage and the pulleys. Another loss of rigidity occurs between the drive pulley and the motor coupling. As the motor begins to turn, first the coupling deflects according its spring constant. Then the belt deflects, before the load finally moves. The rigidity is further complicated since it depends on the position of the carriage and resulting length of belt in the direction of the force exerted through the pulley.

Ballscrews have much higher rigidity, but the same principles apply. The motor turns the coupling, which deflects, which turns the screw which also deflects to some extent. Long, thin screws will have lower rigidity than short wide ones.

Rack and pinion is a little different. These maintain a constant and relatively high rigidity at the point of mechanical connection regardless of the load position. But oscillations are likely to originate within the load itself if it is large and complex.

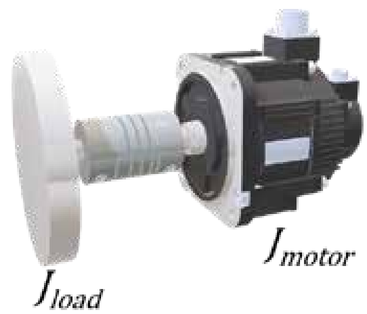
The most rigid of all these actuator technologies is the linear motor. There is no coupling or mechanical linkage to deflect. The load is connected directly to the motor through the carriage. If there are any frequencies of oscillation, they will come from the load itself and not from the mechanical system

LOAD MASS

Hopefully by now it is quite evident that rigidity and resonant frequency are related to load mass. This is summarized in a key performance metric called the load to motor inertia ratio.

Servo systems are commonly sized for a load to motor inertia ratio less than 10:1 for acceptable control of the load by the motor through the flexible coupling. Load mass is one of the most critical elements in mechanical system selection, so it is important to understand these well.

Load to motor inertia ratio is more accurately called mass ratio and is of less importance in a linear stage because the motor is directly coupled to the load.



$$Inertia\ Ratio = \frac{J_{load}}{J_{motor}}$$

Figure 7: Load mass results in Moment of Inertia Ratio

While it's not the fastest to accelerate, the clear winner on moving heavy loads is the rack and pinion actuator.

The load on a linear motor is more like an extension of the carriage itself. A linear motor has no coupling to reduce the rigidity of the system. Load mass is nevertheless important for linear motors, as it limits the acceleration and deceleration rate according to Newton's law.

It also affects linear bearing life. Low friction means that nearly all the power to stop a moving load must be supplied by the electronic drive system, which can also limit the maximum load.

While it's not the fastest to accelerate, the clear winner on moving heavy loads is the rack and pinion. These are often used on large gantry systems.

Ballscrews can also be sized to move very heavy loads, commonly applied in applications with moderate length and speed requirements. However, the inertia ratio and low resonant frequencies associated with heavy loads tend to limit the application.

Belt mechanisms tend to have lower practical weight limits, as do linear motors. Acceleration and therefore top speed can be limited with heavy loads.

BACKLASH

The performance of linear actuators can suffer from an effect called backlash. This is lost motion when the mechanism reverses.

The ballscrew has a level of backlash between the nut and the screw. This can be reduced with preload, which in turn causes the nut to wear out faster.

For the belt system, backlash occurs between the teeth of the belt and pulley. The same can occur between the teeth of the rack and pinion and within the teeth of any gearbox.

Manufacturers have developed ways to reduce the backlash in actuator technologies, and electronically compensate for it in the control system. But there is always some level of backlash and it tends to get worse as the mechanism wears.

It means that the position of the load cannot be exactly determined by the position of the motor encoder. And it can also lead to tuning instability and noisy operation as the load effectively disconnects from the motor for a short time upon reversal.

The linear motor is the only mechanism that can truly claim zero backlash.

Position feedback is measured with a linear scale, with the read head, carriage, and load bolted together as

Reducing position settling time is especially important for applications with many short moves.

The settling time in a linear motor can often be reduced to zero with good tuning

Accuracy is a measure of the deviation from the ideal, but what's more important is repeatability, also called precision.

SETTLING TIME

Rigidity, load mass, inertia ratio, and backlash are all interrelated factors that worsen the position settling time of a mechanism.

Position settling time is the time delay between the end of the commanded move and when the mechanism actually stops. Reducing this delay is especially important for applications with many short moves. Waiting for the machine to stop can represent a significant fraction of the cycle time.

The settling time in a linear motor can often be reduced to zero with good tuning, due to its high rigidity and zero backlash. It may be necessary to mitigate vibrations originating in the load itself.

Achievable settling times for the ballscrew and belt generally follow the level of mechanical rigidity and backlash, with screws generally outperforming belts.

The same goes for rack and pinion, although fast moves and low settling time are typically not the focus with these larger machines.

Remember that the position of these mechanisms is measured through the encoder of the rotary servomotor. The encoder may indicate that the load has settled with a low settling time. But what that really means is that the encoder has stopped moving. The load may still be in motion and not yet settled or experiencing vibration and oscillation. Rigidity and backlash interferes with the measurement of settling time through the encoder of a rotary servomotor. However, in the linear motor, the encoder is fixed to the load itself, reporting the true settling time of the load.

ACCURACY AND REPEATABILITY

Backlash and rigidity also contribute to a mechanism's positioning accuracy and repeatability. Accuracy is a measure of the deviation from the ideal; in this case, position.

If the machine is commanded to move 4 mm, does it move exactly 4.000 mm? Or if you were to measure it externally, did it only move 3.999?

What's often more important is repeatability, also called precision. Because if the machine can move 3.999 repeatedly when you command 4.0, then simply adjust the command until it does repeatably move to the required position.

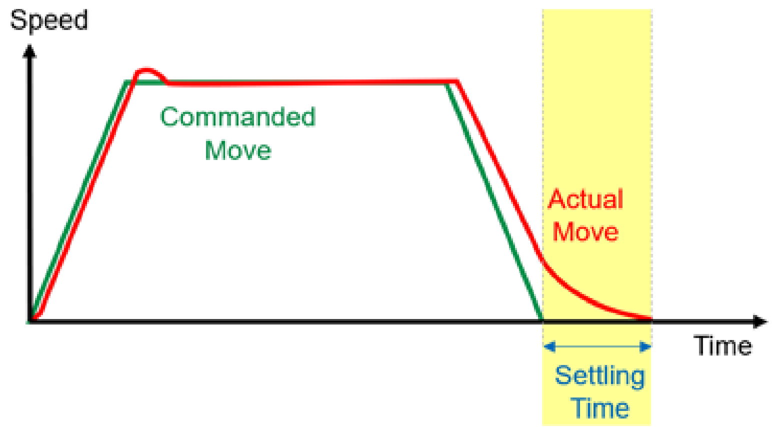


Figure 8: Settling Time of Actual Move

Full Closed Loop allows the position loop of the rotary motor to be closed by linear encoder feedback.

As with settling time, accuracy and repeatability are a function of machine rigidity and backlash. The control system measures position at the encoder. Rigidity and backlash add an element of uncertainty to those measurements. Additionally, the manufacturing process of a belt, ballscrew, or rack and pinion will affect the accuracy and repeatability. Only the linear motor by natural design measures the load directly and moves it without the backlash and compliance problems that can plague mechanical actuators.

FULL CLOSED LOOP

So why not compensate for the shortcomings of ballscrews, belts, and rack & pinion mechanisms by adding a linear encoder?

Yes, this is possible, and one term for this in the industry is “Full Closed Loop”. This allows the position loop of the rotary motor to be closed by linear encoder feedback.

However, adding a linear encoder adds significant cost and complexity. The linear scale must be accurately placed. The read head clearance to the linear scale must be accurately aligned. And now you’ll have a cable track for cable management on the carriage.

And most servo amplifiers don’t support a second encoder input without additional hardware cost. Servo tuning will also be affected and must be completed again.

In short, if the performance of an existing system must be improved, then full closed loop is a viable option. But it is generally not a significant cost savings compared to having used a linear motor in the first place. Adding full closed loop will improve repeatability and accuracy, but does not do much to improve rigidity, settling time and wear.

So for new applications it is important to consider whether or not a linear encoder on a belt, ballscrew, or rack & pinion will really save money in the long run.

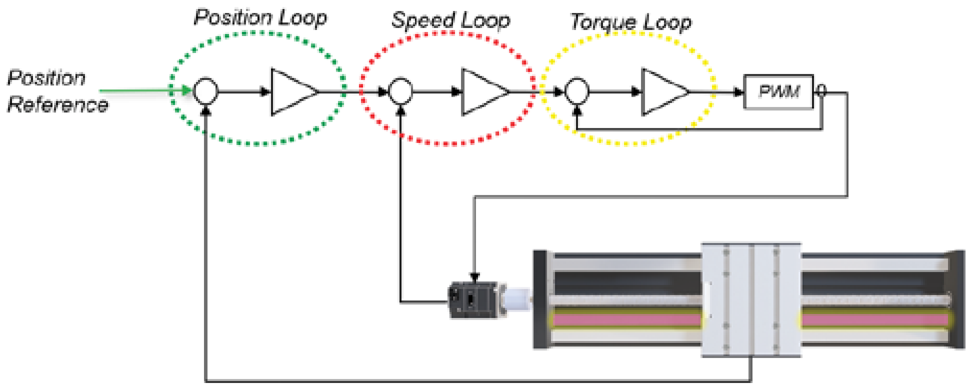


Figure 9: Full Closed Loop Linear Encoder on Ballscrew

In the linear servo, only the linear bearings wear out. But until they utterly fail, that stage will position accurately, at least in the linear direction.

Linear motors can be easier to make clean room compatible as the wear of linear bearings is the only source of contamination.

WEAR AND MAINTENANCE

There is no avoiding the fact that all mechanisms wear. Let's take some time to understand what part of the mechanism wears and what happens to the system performance as a result.

In the linear servo, only the linear bearings wear out. But until they utterly fail, that stage will position accurately, at least in the linear direction. Pitch, yaw, and roll of the carriage cannot be detected by the linear encoder and will deteriorate over time.

Some linear bearings require regular lubrication, but self-lubricating linear bearings are commonly available.

The same principle applies to linear bearings on a ballscrew, belt, or rack and pinion. But these mechanisms have other moving parts that wear out. The screw itself, the nut, the bearings on the screw, motor bearings, belts, rack, pinion, and gearboxes all wear out, even with regular lubrication.

From day 1, the performance of these mechanical systems begins to decline. The backlash and stiffness get a little worse every day.

Therefore expect position settling time, accuracy, and repeatability to continually degrade as time goes on. The linear motor bearings do eventually wear out, but quite gracefully by comparison.

ENVIRONMENT

Different mechanisms are best suited for different industrial environments. Consider the magnetic field of the magnet track of a linear motor which may attract magnetic particles.

A bellows protection system will help keep particles off the magnet track. While linear motors don't require a clean room, they do their best in reasonably clean environments free of excessive dust and oil. The linear scale can still work with some interference, but for very dirty environments consider a linear motor with an inductive or magnetic linear encoder.

The ballscrew is used commonly in machine tool and other dirty environments, although the screw also must be protected. Belts and rack & pinon also work well in many environments.

Clean rooms are on the other side of the spectrum, where it is critical to reduce the number of microscopic particles emitted by the actuator.

Linear motors can be easier to make clean room compatible as the wear of linear bearings is the only source of contamination. The wear points of ballscrews, belts, rack & pinion or other mechanisms with mechanical power transmission are generally less desirable for clean room operation due to the number of particles ejected during operation.

It is important to consider long term cost and performance in order to determine the right actuator, especially in the middle ground of applications where any of the four actuator types can be used.

SELECTION

When selecting the right actuator for an application it is important to consider long term cost and performance.

There are applications with specific constraints which logically eliminate a linear motor from consideration. Other applications have long been the strength of linear motors; long stroke or high speed, fast acceleration, precision and accuracy.

But there's a middle ground where linear motors are often overlooked in favor of the traditional solutions of ballscrews, belts, or rack & pinion.

Solving these applications with linear motors can save money in the long run while providing exceptional and stable performance over the life of the machine.

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