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Choosing the Right Linear Drive Train

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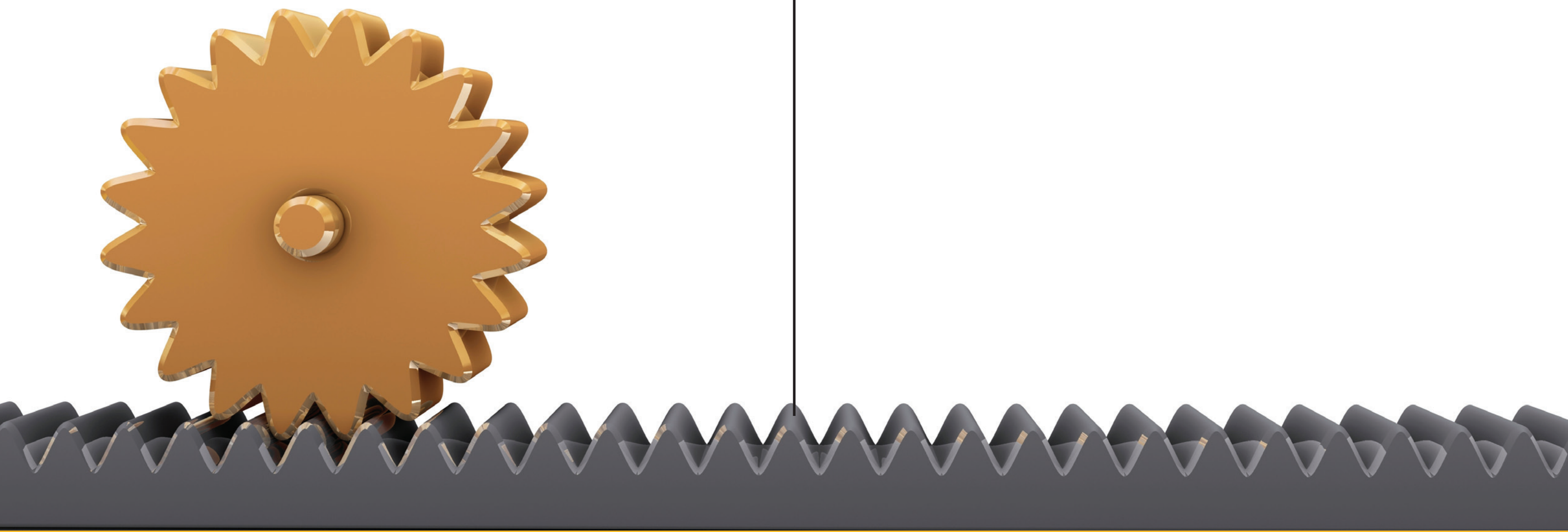
Take the Guesswork Out of Choosing the Right Linear Drive Train for Your Next Positioning Application

Introduction
Whether you are designing your own motion solution, selecting components from a supplier, or working with a system solutions provider, understanding drive train selection is a key to a successful and reliable machine. This paper will outline the key performance characteristics to take into account for your next motion application. The goal of the paper is to provide you with guidelines to make your decision easier, faster, and more accurate.

Overview
Selecting the right drive train for motion in your machine is like balancing an elephant on a beach ball. There are multitudes of key operating characteristics that are both required and desired from the machine design. Each of the different potential drive trains that can be applied to solve your motion problem has a unique performance in each of the characteristics relative to the other technologies. Therefore, making the right selection is not always about maximizing a singular characteristic, but defining a good level on a number of different fronts. Like our elephant example, it is about reaching a point of equilibrium by balancing the most important of the key performance characteristics. We will provide you with an overview of the key characteristics, categorized into logical groups, and then provide insight into how to focus on the vital few for the application. Finally, we will provide an overview of the 5 most common drive train technologies and highlight the strengths and weaknesses of each. Again, in the end, we want to save you time and pain by making your decision easier, faster, and more accurate.

When evaluting the different drive train technologies, there is always a give and take that has to be weighed out, to arrive at the most appropriate technology.



The Key Performance Characteristics – The PETS Principle

The list of potential performance characteristics that you might be interested in is significant. To focus the selection process we start by classifying all of the options in the following 4 major categories:

- Precision
- Expected Life
- Throughput
- Special Considerations

Within each of these categories there are a number of potentially important performance characteristics.

Precision:
1. Resolution – smallest incremental step that can be made.
2. Repeatability – ability to go back to the same commanded position repeatedly. This can be a taught point.
3. Accuracy – ability to go exactly a specified distance from a known origin. This allows for teaching of only one point to provide the ability to position to all other points within travel inside of the accuracy specification.
4. Velocity Control – ability to maintain a constant velocity over a move. Key for scanning and other "on the fly" type applications.

Expected Life:
1. Mechanical Efficiency – high efficiency results in longer life and lower energy consumption.
2. Mechanical Wear Resistance – wear is a function of the type of friction in the drive train. Lower friction results in reduced mechanical wear.
3. Contamination Resistance – depending on the cleanliness of the environment, this can be a non issue. This is a function of the type of friction in the device and the sealing that can be employed to protect the drive elements.
4. Maintenance – how often and to what degree to you need to perform preventative maintenance on the device, like applying lubrication or making adjustments.

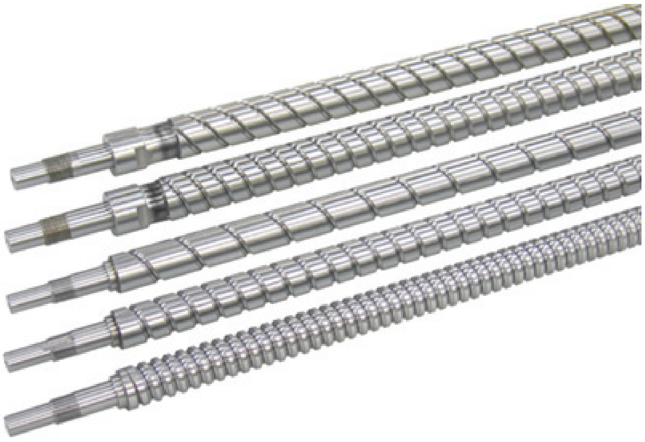
Throughput:
1. Speed Capacity – the actual linear speed that can be generated. More critical in applications with longer relative travel (more of the move time is spent at the top speed).
2. Maximum Acceleration – the rate at which velocity can be increased to reach top speed. More critical in applications with shorter relative travel (more of the move time is spent in acceleration and deceleration).
3. Frequency Response – the spring rate or stiffness of the drive train, which determines how quickly it can respond to change requests (how long it takes to settle or stop ringing after you tell it to stop).
4. Duty Cycle – how long can the drive train run without a rest.

Special Considerations:
1. Force Density – mechanical advantage is a key element of force density.
2. Material Cost – cost tends to go up as you optimize a performance.
3. Implementation Cost – costs that are over the material cost, typically integration or maintenance costs.
4. Travel Length – some drive trains have physical limitations on how far they can effectively provide linear translation.

This white paper will focus on the 5 most commonly used drive train technologies in linear motion today. If there are other technologies or form factors that are being considered for an application, the basic construct and prioritization should apply.

1. Ball Screw – Threaded rod and matched ball nut with recirculating ball bearings between nut and screw interface surfaces. The rolling ball bearings provide for high efficiency and duty cycle.

Ball screws are an ideal solution for application requiring high precision, repeatability, and force density. Ball screws can achieve moderate speed, but are limited based upon screw whip. It can be relatively difficult to properly align the screw to the line of travel to ensure maximum life and minimize the maintenance required. A ball screw can be quite noisy depending upon the grade of the screw.



Ball screw's offer high precision, effiiency, duty cycle, and force density. For these reasons ball screws have become a staple to the world of linear positioning.

2. Lead Screw – Threaded rod and matching threaded nut sliding interface surfaces. In some cases the nut is preloaded against the screw to reduce backlash.

Lead screws are an ideal device for low duty cycle applications, or applications requiring small adjustments. Lead screws are typically about half as efficient as a ball screw, so they will require about twice the torque to achieve the same thrust output of the screw. One positive of the low efficiency is its inherent resistance to back driving; this may be ideal for vertical applications, which would otherwise require a brake to hold the payload under loss of power. Given that lead screws are a friction device, they can exhibit resonance.

Lead screws offer about half the efficiency of ball screws, and have duty cycle limitations, but can be an ideal drive train for vertical applications that might otherwise require a brake.

3. Timing Belt – Two cogged pulleys, typically one driven and one idler, tied together with a timing belt that has a carriage attached. The most simple and common drive train in linear motion.

Timing belts are a robust mechanism for high-speed applications requiring long life and maintenance-free operation where precision greater than 100 microns is required. Design hurdles associated with belt drives typically are reliable belt tensioning system, and rugged pulley bearings to handle thrust loads.

Timing belts are an exetremely robust drive train mechanism, and are ideal for applications that don't require high precision, but do require high speed.

4. Rack & Pinion – Machined linear gear (rack) and round mating toothed gear.

Typically the round gear is mobile and the rack is stationary. This drive train is ideal for very long travels requiring high speed, but this is not a precision technology. There are limited ways of removing system backlash from this drive train, and rack and pinion drives are often quite noisy.

Rack and pinion's drive trains can be ideal for extremely long travel lengths. Rack and pinions typically do not offer much in the way of precision.

5. Linear Motor – A row of magnets interfaces with an electromagnetic carriage to move a load in a linear direction. The only one of the technologies discussed that is direct drive (without the advantages and disadvantages of mechanical gearing).

Linear motors offer high speed, acceleration, and precision with minimal backlash, following error, and settling times. This is often one of the most costly technologies largely due to the cost of magnets and linear feedback devices needed. Force density can be difficult relative to the lack of a mechanical advantage, which also make using a linear motor in a vertical application difficult.

Linear motors are simply 'flattened' rotary servo motors, that are directly coupled to a payload. Linear motors offer high precision, speed, and acceleration. Linear motors are often quite costly to implement given the cost of linear feedback devices and magnets.

Focus on Precision:

Considerations:

- Always start with an understanding of your needs relative to Resolution. Starting with the proper minimum incremental step is the foundation for all other measurements regarding precision.
- The next most critical element of precision is repeatability.
- Higher levels of accuracy are a real system cost driver both from a material and implementation standpoint. First determine if you really need accuracy. Techniques to avoid requiring a system with true accuracy are either teaching or mapping system positions.
- Velocity control is typically only required for scanning applications with extremely high resolution or high-speed "on the fly" dispensing applications. This is another characteristic that will drive up the cost of the system when it is required.

Technology:

- Linear motors and precision ball screws are typically far superior for the precision characteristics. The majority of motion applications do not require these higher levels of precision, which is why the timing belt remains the commonly applied technology.

Technology	Resolution	Repeatability	Accuracy per 300 mm	Velocity Control
Ball Screw	Good (~5 micron)	Good (~5 micron)	Good (~15 micron)	Good (~1%)
Lead Screw	Good (~5 micron)	Moderate (~20 micron)	Moderate (~30 micron)	Moderate (~2%)
Timing Belt	Low (~50 micron)	Low (~50 micron)	Low (~250 micron)	Low (<5%)
Rack and Pinnion	Moderate (~20 micron)	Moderate (~50 micron)	Low (~150 micron)	Moderate (<3%)
Linear Motor	Excellent (<1micron)	Excellent (~1 micron)	Excellent (~5 micron)	Excellent (<1%)

Table 1: A relative comparison between technologies from the stand point of precision

Focus on Expected Life:

Considerations:

- Unless you have a situation where you have a dirty or otherwise harsh environment, mechanical efficiency is going to be the number-one characteristic to consider. High efficiency of your drive train device is going to equal long life and lower energy consumption, meaning that it will require less maintenance and will allow you to minimize the size of some of the upstream components like motors and/or drives.
- Wear resistance is typically a function of the type of friction involved in the mechanism. The lower the friction the device, the lower the wear. The one exception is for the linear motor. Although this drive train is “frictionless,” there are moving cables in many configurations that do create a wear point and may create a significant life limitation if not properly managed.
- In harsh environments, dirt resistance has to be a high priority.
- Maintenance is closely related to the efficiency and wear resistance. The ideal scenario is that no field maintenance is required for the intended life of the machine. Know that all mechanical devices have some life limitation. In design, it is critical to understand how wear or relaxation will impact the longer-term “precision” characteristics of the system.

Technology:

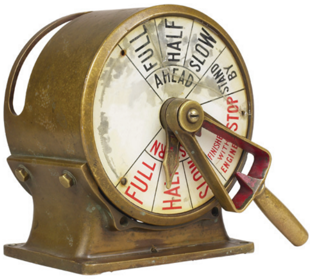
- Because of their high efficiency and limited maintenance requirements, timing belts are a go-to technology in this category.

Technology	Mechanical Efficiency	Wear Resistance	Dirt Resistance	Maintenance
Ball Screw	Excellent (80-95%)	Good (Rolling)	Moderate (Sealed)	Moderate (Lubrication)
Lead Screw	Low (10-50%)	High (Sliding)	Moderate (Sliding)	Moderate (Preload Adjustment)
Timing Belt	Excellent (80-90%)	Excellent (Tension)	Excellent (Harsh Environment)	Good (Belt Tension)
Rack and Pin-nion	Good (70-80%)	Moderate (Pinion)	Moderate (Jamming)	High (Lubrication)
Linear Motor	Excellent (Non-Contact)	Excellent (Cables)	Excellent (Needs to be covered)	Excellent (None)

Table 2: A relative comparison of expected life, one can ex-pect from the different drive train technologies.

Focus on Throughput:

Considerations:



- Depending on the length of travel required, either Speed or Accel/Decel will be the key criteria. If you have a longer travel where more of the cycle time is spent at the top velocity, Speed is most important. If you have shorter moves where more time is spent accelerating and decelerating, Accel/Decel is most important.
- If your application has very tight position requirements (high levels of precision) and is time sensitive, frequency response will be a key attribute. Most pick-and-place applications don’t require high levels of frequency response. This is an attribute that can be a cost driver when required.
- Duty cycle is typically a characteristic that should be checked and validated to ensure the selected design will work in the application.

Technology:

- Linear motors are unparalleled from a throughput perspective, due to the fact that they can achieve high speeds, high accelerations, and given that they have no mechanical compliance – a high-frequency response.

Technology	Speed	Acceleration	Frequency Response	Duty Cycle
Ball Screw	Moderate (<1.5 m/s)	Good (~3 G)	Good (30-50 Hz)	Excellent (100%)
Lead Screw	Low (<0.5 m/s)	Moderate (~2 G)	Low (0-30 Hz)	Low (50%)
Timing Belt	Excellent (>10 m/s)	Good (> 3 G)	Low (20-30 Hz)	Excellent (100%)
Rack and Pinnion	Excellent (>10 m/s)	Good (> 3 G)	Low (20-30 Hz)	Excellent (100%)
Linear Motor	Excellent (>10 m/s)	Excellent (> 5 G)	Excellent (50-80 Hz)	Excellent (100%)

Table 3: A relative comparison of throughput that each technology can attain

Focus on Special Considerations:

Considerations:

- Both material and implementation costs are key design considerations as we are always trying to get the right combination of either characteristics at the minimum cost.

- Force density is an issue of packaging. As machine designs continue to miniaturize, this becomes a more important characteristic to consider, especially when one takes this into consideration when specifying end effectors or tooling mounted to an axis.

Technology	Force Density	Material Costs	Needs to Implement	Travel Length
Ball Screw	Excellent	Moderate	Motor, Bearings (linear and rotary	Moderate (~5 feet)
Lead Screw	Excellent	Good	Motor, Bearings (linear and rotary	Low (~3 feet)
Timing Belt	Moderate	Excellent	Motor, Bearings (linear and rotary), Gearhead	Excellent (~30 feet)
Rack and Pinnion	Moderate	Moderate	Motor, Bearings (linear and rotary), Cables managment	Excellent (>40 feet)
Linear Motor	Low	High	Bearings (linear), Feed-back, Cable Management	Excellent (>40 feet)

Table 4: Some special considerations to take into account per each technology

Summary

As we stated at the outset, selecting the best drive train is a balancing act. If you optimize on one key performance characteristics, you are likely to give up something relative to another performance characteristic. It is important that you understand the performance requirements of your machine. Start at the beginning to understand your requirements relative to Precision, Expected Life, Throughput, and Special Considerations. Pick just a couple of attributes from each category and leverage the guidelines provided. If you are in need of a modular solution or a systems solution, contact Parker Hannifin and will we be more than happy to work through this process with you.

About the author:

Jim Monnich is the Engineering Manager in Parker's Life Science Automation group. Jim has over 30 years of experience in the electrical motion and control industry, specializing in mechanical and electrical design. His primary expertise is in servo and stepper systems, position feedback technologies, as well as design and development of motion mechanics - focussing in on the areas of sub-micron positioning, and ultra precision velocity control for scanning.

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