Choosing the Appropriate Drive Train Technology

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Today's electromechanical linear actuators are used in various industries and markets where linear motion is required. These applications include everything from simple household window actuation to high-duty cycle transfer robots in industrial environments, and even include precise micron positioning for the life science and laboratory automation industries. One thing all of these applications have in common is the linear motion drive train technologies they share. In this paper we cover the most popular drive train technologies, along with their major benefits and drawbacks. Determining the most suitable drive train technology for the application is the first step. It need not be difficult, but it is essential. Except for linear motor these drive trains utilize a rotary motor and convert rotary motion into a linear movement.

What is Dynamic?

We describe the dynamics of linear motion as the fundamental components that make up a move profile; speed, acceleration, move time, position and settling time. . Initially, the change in position and time must be known. Starting from a position $A = x_1$ at time $t_A = t_1$to reach a position $B = x_2$ at time $t_B = t_2$.

Speed of a non-uniform linear motion, or instantaneous speed, is a function of position change with respects to time as described by the equation below:

$$v = \lim_{\Delta t \to 0} \frac{\Delta x}{\Delta t} = \frac{dx}{dt}$$

And instantaneous acceleration is a function of speed change with respect to time as described by the equation below:

$$a = \lim_{\Delta t \to 0} \frac{\Delta v}{\Delta t} = \frac{dv}{dt} = \frac{d^2x}{dt^2}.$$

Typically, a motion profile is operated as an S-curve with smooth edges to lower shocks and vibrations to the machine and equipment, and to optimize the settling times. In this whitepaper we will not talk in detail about motion profiles, but use a simplified formula to calculate speed and acceleration for two common motion profiles; triangular and trapezoidal. In this example a 5kg load (m = 5kg) is moved a distance of .4 meter (d = 0.4 m) in a time of .5 seconds (t = 0.5 s).

Triangular Motion:
In a triangular motion profile the load is accelerated for half the move time (t=1/2) and decelerated for the remaining half of the move time. The peak speed will be reached right at the middle of the travel.

$$\mathrm{v} = 2 * \frac{\mathrm{x_2} - \mathrm{x_1}}{\mathrm{t_2} - \mathrm{t_1}} = 2 * \frac{0.4\ \mathrm{m}}{0.5\ \mathrm{s}} = 1.6 \frac{\mathrm{m}}{\mathrm{s}}$$

$$\mathrm{a} = 4 * \frac{\mathrm{v_2} - \mathrm{v_1}}{(\mathrm{t_2} - \mathrm{t_1})^2} = 4 * \frac{0.4\ \mathrm{m}}{0.25\ \mathrm{s^2}} = 6.4 \frac{\mathrm{m}}{\mathrm{s^2}}$$

Trapezoidal Motion:
In a trapezoidal motion profile the load is accelerated for 1/3 of the move time (t=1/3), moves at a constant velocity for the second 1/3 of the move time, and then decelerates for the remaining 1/3 of the move time.

$$v = 1.5 * \frac{x_2 - x_1}{t_2 - t_1} = 1.5 * \frac{0.4\ m}{0.5\ s} = 1.2 \frac{m}{s}$$

$$a = 4.5 * \frac{v_2 - v_1}{(t_2 - t_1)^2} = 4.5 * \frac{0.4m}{0.25\ s^2} = 7.2 \frac{m}{s^2}$$

These two examples illustrate the need to understand the total move profile. It also highlights a common mistake made in assuming that a 2 meter move in 1 second would need a 2 m/s speed.

What is thrust?

Thrust is explained using Newton's second law of motion:
"The acceleration **(a)** of a body is parallel and directly proportional to the net force **(F)** acting on the body, is in the direction of the net force, and is inversely proportional to the mass **(m)** of the body"

$$F = m * a$$

With the above acceleration we get thrust force required.

Thrust force required for triangular motion:

$$F = m * a = 5\ kg * 6.4\ \frac{m}{s^2} = 32\ N$$

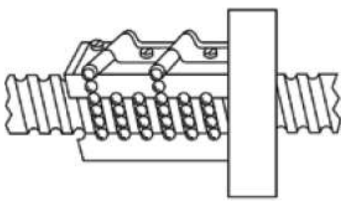
Thrust force required for trapezoidal motion:

$$F = m * a = 5\ kg * 7.2\ \frac{m}{s^2} = 36\ N$$

The difference in acceleration for the two moves results in higher thrust forces for the trapezoidal motion profile. This also illustrates how important it is to understand your motion needs.

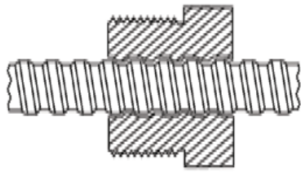
Dynamics, precision, thrust and stroke decide if a drive train can be used or not.

Screw actuators are the first drive train we will examine.



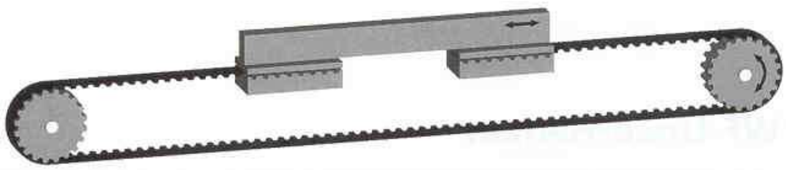
Ball screws provide a drive train that is used for higher precision and high duty cycle applications. The rotary motion of the screw is converted in a linear motion using balls that provide rolling element contact between screw and nut. The number of balls and circuits determine the thrust output capabilities. As the balls roll along the profile of the screw, there is nearly no energy lost. The efficiency of ball screws is high from $\eta > 90\%$ to $\eta > 96\%$ depending on the ball screw design and it can be operated at 100% duty cycle. The drawback is that these ball screws need to be greased and the rolling balls create noticeable noise. Also, to avoid whip and critical speed issues, speeds need to be reduced the longer a ball screw gets. Speed should also be limited to 80% of the critical speed to avoid exciting a screw with its natural frequency. Critical speed **(N)** is given knowing the root diameter of a screw **(d_r)** the bearing support **(C)** in correalation with the unsupported length **(L)** of the screw. C for rodless actuators is typically 1.47 using a design with a fixed bearing on the motor end and a floating bearing on the idler end, to compensate elongination thru temperature.

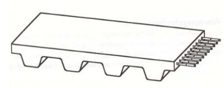
$$N = \frac{(4.76 * 10^6) d_r C}{L^2}$$



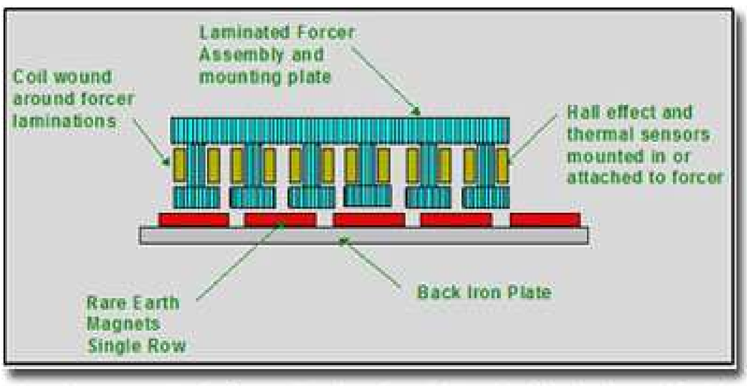
Lead screws provide a drive train that is used for high thrust force output with the ability to keep a stationary position without back drive even in vertical operations and avoid using a motor with brake. A lead screw will not back drive if the coefficient of friction is greater than the tangent of the lead angle. The rotary motion of the screw is converted into linear motion using a line contact between the screw and nut (unlike the ball screw which uses a point contact). The amount of surface pressure contact determines the thrust output that can be provided. As the nut slides along the screw, the operation is smooth, but friction consumes a lot of the energy given, making it less efficient versus ball screws. The efficiency of Lead screws can be as low as η < 40%. The lost energy due to friction creates heat and requires the screws to operate at duty cycle ranges from 10% to 60% depending on lead formation and nut material (e.g. plastic or bronze) in order to avoid premature wear. The drawback of Lead screws is the backlash due to the design that might be reduced with a higher preload, but backlash will increases with time as the nut wears out. Also, to avoid whip, speeds need to be reduced the longer a lead screw gets similar to a ball screw.

Belt actuators are used in medium to high dynamic applications with medium precision while they transmit medium thrust force over long strokes. The rotary motion given to a drive shaft pulley arrangement is converted into linear motion, with the teeth of the belt having line contact with the pulley. The width of the belt and amount of teeth in contact determine the thrust force output that can be achieved.





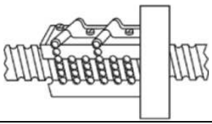
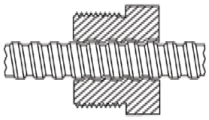
Using a belt with steel wires surrounded by polyurethane gives some elastic play and medium precision, but it can be very helpful for machines avoiding mechanical shocks to the whole system while increasing the overall performance. The efficiency of a belt actuator is high — η > 92% — and it can be operated at 100% duty cycle. Belts do not require lubrication and only little maintenance during their life time. The drawback is that belts need to be tensioned and that they are more sensitive to impact loads. Also, the available thrust force needs to be lowered adequately for higher speeds to avoid belt slippage and on very long strokes when the belt tension must be lowered. The life of a belt is impacted when the polyurethane decomposes over time.



In an iron-core motor, the forcer includes an iron plate made of laminations and "teeth" which have the motor coils wound around them. This design increases the force density significantly. (Courtesy of Parker Hannifin)

Linear motors, also widely known as direct drive motors, already incorporate the linear motor that creates the linear motion. Linear motors can be used in very slow to very high dynamic applications with high precision depending on the linear encoder system used and perform very smooth operation while they provide medium to low thrust force over seemingly endless strokes. A stationary magnet track and the forcer (package of windings in the carriage) interact to create linear motion, current is sent through the windings to create a magnetic field. The strength of field and interaction determines the thrust force capabilities. The efficiency of a linear motor actuator is high, typically on ironless motors with η > 98% and iron core motors η > 85% both while operating at 100% duty cycle. Linear motor drive trains do not require lubrication and are characterized with an almost endless life expectance. The weak point in the linear motor design is the continuously flexing cable that supplies the power to the forcer.

Compare the most popular drive trains we discussed above and select the most suitable for an application should now be easy and provide the most cost-effective solution and best availability. However, there are also other technologies that meet some specific requirements better than the ones above. Therefore, it is always good to have the right partner to discuss all other alternatives to find the most suitable solution. Parker can provide the competitive advantage and the most suitable, state-of-the-art technology for our customers.

	Ball screw 	Lead screw 	Belt 	Linear motor 
Dynamic	Better	Good	Best	Excellent
Thrust density	Best	Excellent	Better	Good
Stroke	Better	Good	Best	Excellent
Precision	Best	Good	Better	Excellent
Efficiency	Excellent	Good	Better	Best
Operation	Good	Excellent	Best	Better

For more information on Parker's complete line of linear technologies, please visit www.parkermotion.com.