Achieving Positioning Accuracy Goals

A motion control system is only as accurate and repeatable as each component that it comprises. Definitions of these qualities and how to test for them are available in international standards.

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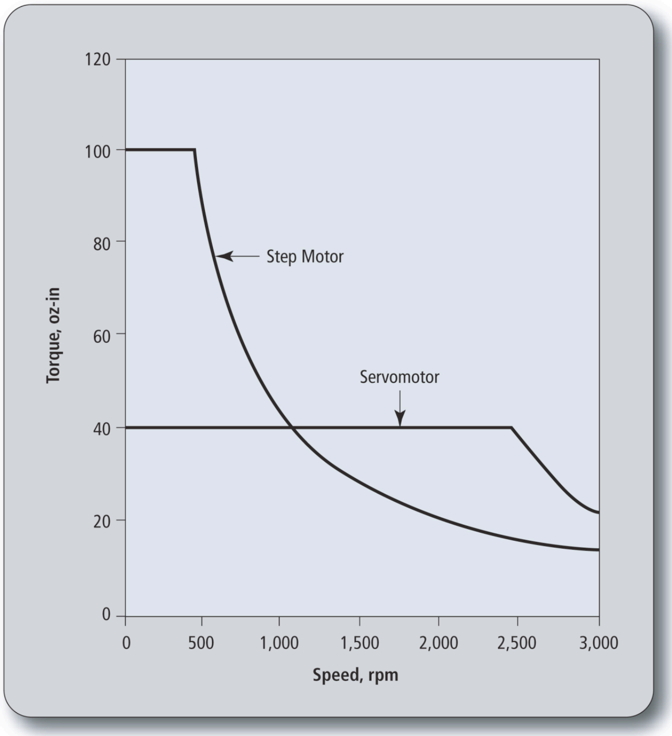
The task of choosing the correct mix of motion control components for a successful servo positioning system involves a combination of art, science, and experience. Some say it also includes a little luck, but luck is not needed when you fully comprehend the principle of operation, accuracy, resolution, and repeatability of each component in the system. Unfortunately, some of the errors that contribute to system inaccuracy are not easily observable; they are measured empirically. However, that too, should not be a major concern. For example, ISO 230-2:1997(E) and ASME B5.54-1992 standards are available to help quantify these parameters.

Component Selection

As in any motion system, the first factors to consider are speed and torque. They usually determine whether the system should host a stepper motor or a servomotor. Steppers usually are superior for systems that operate at speeds lower than 1000 rpm and less than 200 Watts. In addition, they may have higher torque than a servomotor for the same size package at a specific RPM range. By comparison, servomotors are preferred for speeds above 1000 rpm and power levels above 200 watts. They possess a reasonably high and predictable torque over the entire speed range. If a closed loop is desired, then the advantages of the stepper are quickly lost and the servomotor would be the logical choice. Each has a unique set of parameters that contribute to its accuracy, resolution, and repeatability.



The next issue concerns feedback devices. Steppers do not require feedback but may use them as a secondary feedback source. They are typically operated in an open loop method because their controllers deliver a directional signal to the motor as well as one or more pulses per step, with a predetermined step size (such as 1.8 degrees) referred to as the cardinal step. Servomotors, on the other hand, use feedback devices by definition. The feedback is used for the position, velocity, and commutation information in the case of brushless motors. Servo systems require one or more feedback signals in simple or complex configurations, depending on the specific needs of the motion system. Feedback loops include position, velocity or speed, acceleration/deceleration, and sometimes "jerk," which is the first derivative of acceleration.

Not to be overlooked are the drives and controllers. Some combine the two functions while others are contained in separate packages. A trend toward combining these two functions within the motor housing as well is being seen. The drives comprise the power needed to operate the motor with the phase-current switching devices that advance the rotors. The intelligence for determining the speed, torque, and direction is contained in the controller. Both steppers and servomotors need these elements, but the circuits are unique to each motor type. Some servo systems now include stepper like control functions (step/direction) to facilitate those familiar with only steppers. Some servo-like positioning is being seen with stepper-like motors creating Switched Reluctance or Variable Reluctance motor system. These are not common nor are they used in low cost systems.

To aid in the selection process, different vendors usually have component selection software as well as modeling tools. Model-Q is one such vendor-supplied tool from

Danaher. It can simply aid in the correct selection of the motor and predict thermal performance within limits of the selection. Usually there is a tradeoff of simplicity and accuracy. There are also off-the-shelf solutions from Visual Solutions (VisSim®), MathCad®, or Matlab®. More performance related than the vendor supplied software, these tools supply an accurate expectation of power, thermal, resonant characteristics, as well as aiding in the selection of mechanics. Modeling can aid in understanding the system long before metal is cut and the design is cast in concrete. There is a range in modeling techniques from simple size selection to finely detailed performance and physical constraint models indicative of high performance requirements. An analogy is like comparing an automobile rental agency map with a satellite enhanced topographical map. The rental map may allow you to chart your direction, but the with the topographical map, you would be able to extrapolate your likely fuel consumption, time in route, and basic loading for information if you were towing a load.

Error Budgeting - Resolution

Resolution must be viewed from two sources, electrical and physical. The electrical resolution for steppers relates to the step size, while the resolution for servomotors relies more on the encoders resolution. The physical limitations may be due to the transfer mechanisms such as couplings, belts or lead screws and their associated windup, backlash, dead-band or hysteresis.

The step size is predetermined for stepping motors, but the actual displacement depends on the capability of the drive (Micro-stepping or half-stepping) and the motor itself. The synchronization of the system can come into question as well. A stepper may become desynchronized based on load, inertia, step rate and the characteristic resonance of the load to motor ratio. Once in motion, it can lead or lag several steps from that which was commanded and remain there. Thus, the electrical resolution is better than the actual resolution that the physical system can achieve. The manufacture of the stepper comes into play with the accuracy of the rotor to armature without a feedback device to confirm the load's position. The best way to decide the resolution errors in this system is to actually measure its response over the expected operating temperature range, expected loads, and the frequency range.

Some stepper motor control systems do employ feedback devices. If a stepper with feedback is employed, it merely allows for additional steps after detection of synchronization loss. It is not a dynamically adjustable variable like a servo loop. When a feedback device needs to be on board, it's a wiser choice to use a servomotor as the added cost for the stepper system will now approach most servomotor designs. Most servomotors now come with built-in feedback encoders or a mounting surface to conveniently attach one. The position errors associated with servomotors basically stem from the resolution of the feedback device when the servomotor is properly sized to handle the load and frictional forces.

The physics constraints of a stepper must be realized as well. In the cardinal step (Usually 200 steps/revolution) the motors individual commutations create harmonic disturbances with a high frequency content. These have been known to excite and even destroy things like couplings or in some cases, excite other harmonics. They are quite noisy in this state as well. Micro-stepping either binary or decimal may cure the noise, but if your intention is to accelerate at 1000 rad/sec^2 and achieve a final velocity of 6300 rad/sec (approximately 1000 RPM), then a frequency of 3.2 Mhz would be required with a setting at 1/16th steps. Although this is a common step size, this would not be a commonly available step rate, or an easy one to control relative to grounding and shielding. This application would favor a servomotor.

Inertial loading of the system is an important evaluation point. The performance of a stepper can quickly be compromised if the inertial load changes during the move. Articulated axes have reflected inertia changes based on the position. Servo systems react quickly enough to inertial load changes and are a superior choice for these.

Many vertical applications can benefit from the stepper holding torque. A stepper, when holding positions, can hold at full or any portion of the systems current within the thermal limitations of the motor. Since it does not servo when in position, it is truly completely still and only the load disturbances are evident. Servo systems on the other hand, are never actually still without a dead band. These disturbances are of course at the minimum resolution of the system, but are there. In the case of requiring a load to be completely still, the application favors a stepper.

More often than not, stepper motors or servomotors drive an intermediate component, such as a lead screw or a ball screw, located between the motor's output shaft and a load. The screw has its own set of errors with respect to accuracy, repeatability, and resolution that must be figured into the system's error budget. The screw thread size, backlash, play, and hysteresis, are just a few factors that are part of the equation.

Another factor to consider is the effect of one axis on another in a multiple-axes system. For example, in a three-axis system with the X-axis components riding on the Y-axis and Z-axis and so on, numerous displacements between them arise from torque, skew, and lead screw errors. Sometimes referred to as crosstalk, the errors in each axis may be as little as five or six microns, but they can add up by the time they reposition the load. As a result, the mechanical structure of the system supporting all the components must be rigid enough to prevent excessive distortion and consequential inaccuracies.

Another form of stress in the system is caused by Coriolis accelerations. Most of us have felt this effect on a carnival ride called the Scrambler©. This is an application where one rotating load is being carried by another rotating load. As each is being rotated, the forces and accelerations can accumulate on the system in unintended ways based on the cross product of the individual rotary velocities. Bearings, supports and motors must be designed to handle these loads without distortion, resonance or failure.

For systems that require extremely high accuracy and resolution, the actual lead screw errors should be mapped and used with a controller that can use the error mapping information to compensate for lead errors. The same positioning system should also be checked for periodic errors. This helps determine the errors that come from ball screws, lead screws, and interpolation errors from encoders and controllers.

Repeatability and accuracy

Motion systems are usually specified to perform any one or a combination of three different types of moves with consequential backlash and hysteresis. These include unidirectional, point-to-point bi-directional, and contouring modes. Unidirectional moves require point-to-point repeatable moves with the destination point being approached from only one direction. These applications include high-quality lead screws and ball screws without encoders, which are repeatable to within three or four microns. But, compared to repeatability, accuracy for these same systems is more difficult to achieve, because it must also serve as a measurement system. However, highly repeatable, unidirectional systems usually are also highly accurate, because the target positions can be offset to compensate the inaccuracy.

Bi-directional repeatability is typically more difficult to achieve than unidirectional because mechanical systems have to deal with backlash and hysteresis. Backlash appears when the commanded load direction is reversed but the load does not respond immediately. Here, a rotary encoder mounted to the motor would indicate reverse motion, but the actual motion follows after several encoder counts. Many motion controllers can compensate for highly repeatable gear backlash, but fail to handle other components such as ball screws and lead screws that have less predictable backlash. Supplying a secondary encoder for the position information can compensate for backlash. High accuracy/repeatability systems often use a position sensor outside of the motor. Care must be taken with these systems since the hysteresis or dead-band would now be enclosed within the position loop. Sometimes this can lead to the undesirable effect of oscillations based on the control lagging the velocity information.

Hysteresis is evident when the system is commanded to reach the same destination from opposite directions. A rotary encoder coupled to the motor would indicate that the load reached the same destination, but in fact, the actual position difference is larger than the backlash alone. This hysteresis is caused by unseen clearances and elastic deformations. A linear encoder can compensate for backlash and hysteresis in a screw driven positioning system. The hysteresis must still be minimized to avoid the aforementioned control problems with oscillation. Systems with hysteresis potentials must have the friction minimized. Friction will exasperate bi-directional repeatability and accuracy.

Bi-directional accuracy relates to repeatability in much the same way as in unidirectional motion. Bi-directional systems also use their accuracy requirements for measuring devices, and they can have their inherent positional inaccuracies compensated by offsetting the target positions.

Contouring applications are the most difficult to handle. These are dynamic systems that require high accuracy while in motion. High-quality screw systems suffer accuracy errors that are two or three times larger than when used in point-to-point applications. High-quality encoders should be selected and the systems should contain motors and drives that can be finely tuned. Usually the high performance control systems will also need to contain some sort of resonance controlling feature sometimes not necessary in a point-to-point move. The cutting machines of course must reject the resonant disturbances to avoid the distorted path and thus distorted cuts.

Linear encoders and controllers used for contouring systems may have limited bandwidths that prevent them from fully correcting positional errors while in motion. Secondly, linear encoders measure position errors at the encoder read head, not at the carriage surface. Radial tolerances produce what's called abbe errors. Depending on the moment arm, a few arc-seconds may contribute to an accuracy error in excess of the intended tolerance. Using the trigonometric formula "Y" = r tan (θ), the approximate contribution of error is calculated.

Since a contouring operation involves removing metal or some other material, and an error signal, however small, is necessary to exist before it can be corrected, some metal may be removed from the work piece before the system responds. Unfortunately, the metal removed cannot be replaced. Special tooling paths are calculated during entry to the contour prior to cutting is sometimes required. In a typical routing type application, the Z-axis controls the cutting and is not engaged until the system X and Y-axes are stabilized. Like differential equations, your data is not valid until the required time for stabilization has occurred.

Drives

Motion control systems typically employ one or a combination of four basic components: belts, ball screws, lead screws, and linear motors. Belt-drive systems are the least expensive and are often used for high speed, relatively light-load applications. They tend not to be very accurate or repeatable and run at about 60% duty cycles.

Ball screws and lead screws are the next most often used components. Lead screws typically cost less than ball screws but also are less accurate for the same speed and load capacity. However, a few leads screws are available for high-precision applications, but also are extremely expensive.

Ball screws offer more load and speed range choices for high accuracy and high efficiency systems. Unlike lead screws, ball screws have rolling surfaces that wear less than sliding interfaces and are preloaded to eliminate backlash at the cost of friction. Ball screws come in three grades: commercial, ground, and rolled. Commercial ball screws are primarily used for actuators, and not suitable for most positioning applications.

Ground ball screws are more expensive than the commercial grade, but they have much higher accuracy and operate extremely smoothly over the entire displacement. They are often specified for the highest resolution systems such as contouring. By comparison, rolled ball screws are more accurate than commercial ball screws but less than ground ball screws. The ground ballscrews can typically be ordered as single or double nut style. The double nut applications have two Ball-nuts on the same screw that are preloaded against one another. This reduces the backlash to minimum but changes the frictional and critical speed characteristics.

Lead screws and ball screws are somewhat speed-limited since they tend to resonate at their first natural resonant frequency. The critical speed depends on the diameter of the screw, the distance between screw supports, and the rigidity of the supports. Critical screw speeds are usually above 2500 rpm, except for unusually long screws. Oil and mercury filled dampers are available to help here, but they have a significant inertial load that precludes their use in high acceleration environments.

Lastly, linear motors deliver higher speed and higher accuracy. They are directly driven, intrinsically eliminate backlash, contain minimal wear surfaces, and are used for high throughput systems. They are commonly more expensive than the other systems, although the costs continue to drop. There are iron-core permanent magnet linear motors can easily produce peak forces in excess of 1500 lbs continuous with over 3500 lbs peak (Danaher Motion IC55-250). They can operate at speeds and accelerations not possible with any other method. Their frameless nature allows these motors to be integral into a machine thereby reducing resonant characteristics of couplings. In the case of high speed and accelerations, there are iron-less linear motors capable of high accelerations (12g or greater) and speeds approaching 20 m/s (787 in/s). No alternate technology exists for these applications.

Structures

Some of the less obvious but critical errors come from the support structure (machine base), certain types of bearings, and couplings. The errors are specified as roll, pitch, yaw, straightness and flatness, straight-line accuracy, and resolution. For example, the machine base must be machined to critical straightness and flatness specifications and ground to eliminate angular errors and ensure the best drive and encoder accuracy possible. Material selection can range from casual to requiring a physicist.

Aluminum, steel, stainless steel, and cast iron are typical materials used for machine structures and positioning systems. Aluminum’s advantages include lightweight, easy fabrication, and relatively low cost. When aluminum is not stiff enough, steel is selected; but it is not as corrosion resistant, more difficult to work with, and more expensive. Stainless steel is used for applications needing high corrosion resistance, but it is most expensive and most difficult to fabricate. Finally, cast iron is best for damping vibration in machine tool applications.

Typical bearings include dovetail slides, which are stiff and can handle high loads. On the other hand, mechanical bearings -- both recirculating and non-recirculating types have lower friction and hence longer life. The former type handles higher loads and longer travel, while the latter type is better suited for lighter loads and smoother operation.

Both types of bearings come in either ball bearings or cross roller bearings and can be used in applications requiring a straight-line accuracy of up to one micron per 25 mm. Precision grade bearings can achieve a cumulative running parallelism error of 10 microns over 1 m.

Couplings are as critical as all the other components in the system to ensure high resolution while minimizing overshoot and settling times. Aluminum beam couplings, for example, should be judiciously selected and used. They are torsionally compliant which produces windup, loses resolution, and generates high overshoot and long settling time. Oldham and bellows couplings should be considered first to minimize these problems.

Moreover, Oldham and bellows couplings are two to three times stiffer than beam couplings and reduce the resonance problems characteristic of beam couplings.

Multi-axes Considerations

Two major types of errors must be considered in multiple axes systems: orthogonal and stack-up errors. Orthogonal errors come from axes that are not truly perpendicular. Stack-up errors occur when one motion axis supports another, such as the X-axis riding on the Y-axis. Although the angular errors of one axis affect the other axis, they can be compensated because they are highly repeatable. The critical thing to know is that they are present.

When specifying multiple axes, collision avoidance must also be dealt with. Many times, interacting multiple axis systems can have an overlooked error that the path to two specific “safe” positions can create a collision as well as the standard collision avoidance of ensuring that two axes cannot simultaneously occupy the same space. It may require an undertaking of the machine software or the motion controller software or both.

Another error arises from coordinated motion between axes. That is, the linear errors of each axis in a two-axis system will combine after linear interpolation on each axis, as well as the orthogonal and stack-up errors. What are the consequences of this?

Proceed with this example. If two 90-degree axes have a simultaneous coordinated move of the same velocity, the result must be a straight line at 45 between the two axes in a properly coordinated system. Coordination errors may result in lines that are curved, jagged, or distorted. Circles become ovals and diamonds may have a rhombus resultant.

Environmental Considerations

When choosing a motor, the physical environment needs consideration. Facilities with high heat and vibration would not be served well by using a system not suited for this. An encoder may function fine for the common motion control needs, but an axis situated above a molten metal stamping operation had better have a resolver or the likelihood of premature failure will result in some all expenses paid trips around the world. Other environmental situations concern noise. In a large open loud manufacturing environment, a stepper motor may operate fine for the application load and be a good choice. If this same axis is in a laboratory where noise is an issue, the commutation noise from this style motor would be obtrusive. A sinusoidal commutated brushless motor would certainly be the preferred choice.

Table 1
Drive System Components

Component	Repeatability	Accuracy	Resolution	Speed	Notes
Belt	Low	Low	Low	High	Light loads, Low cost
Linear Motor	High	High	High; 0.25 microns or less possible	High	No backlash, Low wear, High throughput
Lead Screw, commercial grade	Good	Good to low	Good	Moderate, above 2500 rpm	Low cost, smooth motion, low noise, Low duty cycles (60%)
Ball Screw, Commercial Rolled	Good	Less than 200 microns/300 mm,	Good	Moderate, above 2500 rpm	Moderate load, Low cost, For actuator use
Ball Screw, Ground	High	50 microns/300 mm, to 3.5 microns/300 mm	High	Moderate, above 2500 rpm	Most expensive, Smooth motion, Best choice. (See standards JIS 1192 & DIN 69051)
Ball Screw, Precision Rolled	Good	200 microns/300 mm to 25 microns/300 mm	Good	Moderate, above 2500 rpm	Performance between ground and commercial grades.
Lead Screw, High Precision	High	High; 0.25 microns/rev and 2.5 microns/300 mm possible	High	Moderate, above 2500 rpm	High cost, Low duty cycles (60%)