

direction information in the feedback signal. The ability to detect direction is critical if encoder rotation stops on a pulse edge. Without the ability to decode direction, the counter may count each transition through the rising edge of the signal and lose position. Another benefit of the quadrature signal scheme is the ability to electronically multiply the counts during one encoder cycle. In the times-1 mode, all counts are generated on the rising edges of channel A. In the times-2 mode, both the rising and falling edges of channel A are used to generate counts. In the times-4 mode, the rising and falling edges of channel A and channel B are used to generate counts. This increases the resolution by a factor of four. For encoders with sine wave output, the channels may be interpolated for very high resolution.

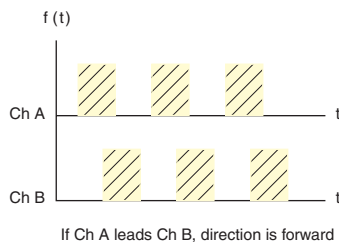


Figure 33—Quadrature encoder output provides direction as well as position feedback.

Tachometers

For applications requiring velocity regulation, speed can be either measured directly or derived from encoder-supplied position information. For higher quality speed control, a tachometer is used which produces a voltage or current level proportional to the speed of the motor. Tachometer feedback can change instantaneously with speed change, allowing faster correction and tighter regulation from a controller.

Origin and Limit Switches

An origin switch is a device that defines a repeatable reference point. The switch may be mechanical, such as an on/off switch or hall effect sensor, or it may be an optical device, such as the index pulse (top zero) of optical encoders (Figure 32). Limit switches are used to prevent motion from proceeding beyond a defined point. They are usually located at the ends of stage travel immediately before the stage's hard travel stops. They can be mechanical or optical and are designed to cut motor power when a limit is encountered. Limit switches are most often associated with linear stages, but rotary stages can also make use of them to avoid problems like cable wind-up. Mechanically actuated micro-switches are often used to cut motor power and prevent over-travel. The repeatability of mechanical switches is limited by their hysteresis and susceptibility to wear.

Control Theory Terminology

Common motion systems use three types of control methods. They are *position* control, *velocity* control and *torque* control.

The majority of Newport's motion systems use position control. This type of control moves the load from one known fixed position to another known fixed position. Feedback, or closed-loop positioning, is important for precise positioning.

Velocity control moves the load continuously for a certain time interval or moves the load from one place to another at a prescribed velocity. Newport's systems use both encoder and tachometer feedback to regulate velocity.

Torque control measures the current applied to a motor with a known torque coefficient in order to develop a known constant torque. Newport's motion systems do not employ this method of control.

Following Error

Following Error is the instantaneous difference between actual position as

reported by the position feedback device and the ideal position, as commanded by the controller.

Settling Time

Settling Time is the amount of time elapsed between when a stage first reaches a commanded position and when it maintains the commanded position to within an acceptable pre-defined error value (see Figure 34).

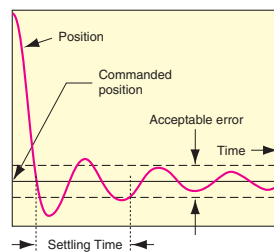


Figure 34—How settling time is defined.

Overshoot

Overshoot is the amount of over-correction in an under-damped control system (see Figure 35).

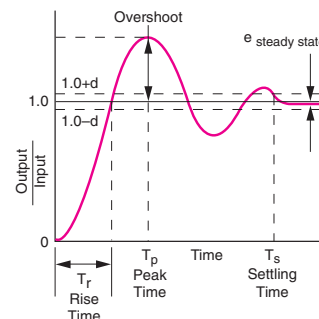


Figure 35—Response for a system using only proportional controls leads to overshoot and non-zero steady-state errors.

Steady-State Error

Steady-State Error is the difference between actual and commanded position after the controller has finished applying corrections (see Figure 35).

Vibration

When the operating speed approaches a natural frequency of the mechanical system, structural vibrations, or *ringing*, can be induced. Ringing can also occur in a system following a sudden change in velocity or position. This oscillation will

lessen the effective torque and may result in loss of synchronization between the motor and controller.

Settling times and vibrations can best be dealt with by damping motor oscillations through mechanical means such as friction or a viscous damper. When operating a stepper system, some additional methods that can change resonance vibration frequencies are:

- Half stepping or microstepping the motor
- Changing the system inertia
- Accelerating through the resonance speed ranges
- Modifying drivetrain torsional stiffness

Velocity Profiles

In order to achieve smooth high-speed motion without over-taxing the motor, the controller must direct the motor driver to change velocity judiciously to achieve optimum results. This is accomplished using shaped velocity profiles to limit the accelerations and decelerations required.

Trapezoidal Profile

The trapezoidal profile changes velocity in a linear fashion until the target velocity is reached. When decelerating, the velocity again changes in a linear manner until it reaches zero velocity. Graphing velocity versus time results in a trapezoidal plot (see Figure 36). Advanced controllers allow user modification of the acceleration/deceleration with more advanced controllers allowing individual settings for acceleration and deceleration.

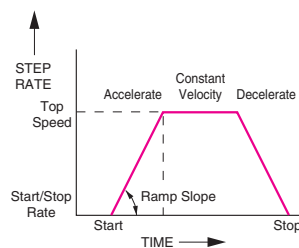


Figure 36—Trapezoidal motion profiles are required to obtain higher speeds without skipping steps or stalling.

S Curve Profile

A trapezoidal velocity profile is adequate for most applications. Its only disadvantage is that it may cause some system disturbances at the “corners” that translate in small vibrations, which extend the settling time. For demanding applications sensitive to this phenomenon, the velocity profile can be modified to have an S shape during the acceleration and deceleration periods. This minimizes the vibrations caused in a mechanical system by a moving mass.

Control Loops

Open-Loop Control

Open-loop refers to a control technique that does not measure and act upon the output of the system. Most piezoelectric systems and inexpensive micrometer-replacement actuators are open-loop devices.

Open-loop positioners are useful when remote control is desired for improved accessibility or to avoid disturbing critical components by touching them.

Stepper and ministepper motors often use open-loop as well. The count of pulses is a good indicator of position but can be unpredictable unless loads, accelerations, and velocities are well known. Skipped or extra steps are frequent problems if the system is not properly designed.

Open-loop motion control has become very popular. Advances in ministepping technology and incorporation of viscous motor-damping mechanisms have greatly improved the positioning dependability and reduced vibration levels of today’s highest quality stepper devices.

Open-loop is by no means a synonym for crude. Even inexpensive open-loop devices can achieve very fine incremental motions. Nanometer-scale incremental motions are achievable by open-loop piezo-type devices.

Open-loop systems infer the approximate position of a motion device without using an encoder. In the case of a piezo device, the applied voltage is an indicator of position. However, the relationship is

imprecise due to hysteresis and nonlinearities inherent in commonplace piezo materials.

Closed-Loop Control

Closed-loop refers to a control technique that measures the output of the system compared to the desired input and takes corrective action to achieve the desired result. Electronic feedback mechanisms in closed-loop systems enhance the ability to correctly place and move loads.

Closed-Loop Control Techniques

Depending upon how the feedback signals are processed by the controller, different levels of performance can be achieved. The simplest type of feedback is called *proportional* control.

Other types are called *derivative* and *integral* control. Combining all three techniques into what is called PID control provides the best results.

Proportional Control

A control technique that multiplies the error signal (the difference between actual and desired position) by a user-specified gain factor K_p and uses it as a corrective signal to the motion system. The effective result is to exaggerate the error and react immediately to correct it.

Changes in position generally occur during commanded acceleration, deceleration, and in moves where velocity changes occur in the system dynamics during motion. As K_p is increased, the error is more quickly corrected. However, if K_p becomes too large, the mechanical system will begin to overshoot, and at some point, it may begin to oscillate, becoming unstable if it has insufficient damping.

K_p cannot completely eliminate errors; however, as the following error, e , approaches zero, the proportional correction element, $K_p e$, disappears. This results in some amount of steady-state error.

Integral Control

A control technique that accumulates the error signal over time, multiplies the sum by a user-specified gain factor K_i and uses the result as a corrective signal to the motion system. Since this technique also acts upon past errors, the correction factor does not go to zero as the following error, e , approaches zero allowing steady-state errors to be eliminated.

But the integral gain has an important negative side effect. It can be a destabilizing factor for the control loop. Large integral gains or integral gains used without proper damping could cause severe system oscillations. The contribution of integral gain to the control loop is limited by the integral saturation limit, K_s .

Derivative Control

A control technique that multiplies the rate of change of the following error signal by a user-specified gain K_d and uses the result as a corrective signal to the motion system. Since this type of control acts to stabilize the transient response of a system, it may be thought of as electronic damping.

Increasing the value of K_d increases the stability of the system. The steady-state error, however, is unaffected since the derivative of the steady-state error is zero.

PID Control

The combination of *proportional* plus *integral* plus *derivative* control. For motion systems, the PID loop has become a very popular control algorithm (see Figure 37). The feedback elements are interactive, and knowing how they interact is essential for tuning a motion system. Optimum system performance requires that the coefficients, K_p , K_i , and K_d be tuned for a given combination of motion mechanics and payload inertias.

Feed Forward Loops

When using a PID control algorithm, an error between the desired and actual positions must exist in order to generate a corrective input. The implication of this

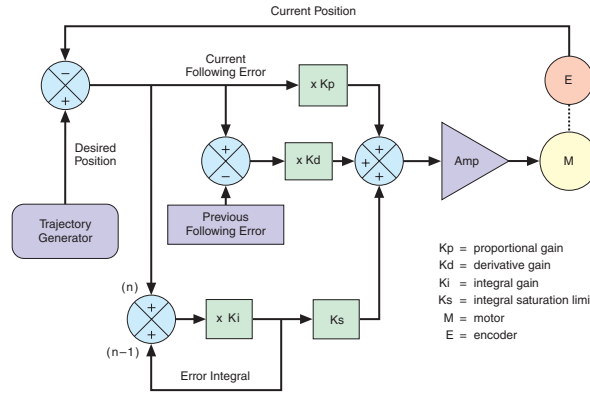


Figure 37—PID control implemented using position feedback.

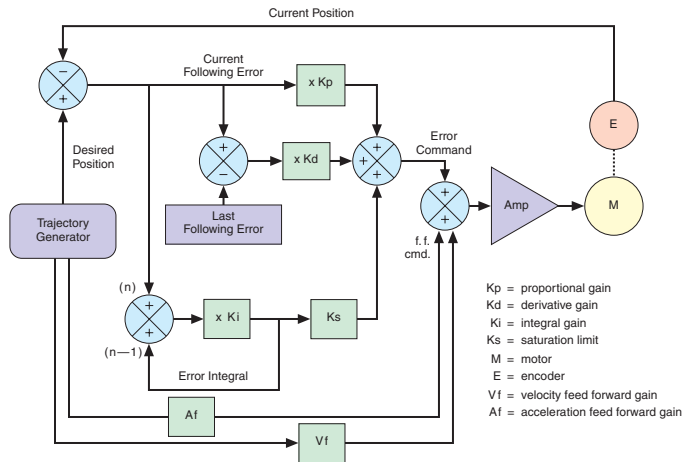


Figure 38—Adding a feed forward loop to the PID controller reduces following error and improves overall system performance.

is that there will always be some non-zero *following error*. The goal when using a feed forward loop is to minimize following error. The concept in using a feed forward loop is to predict how the system will function in future updates and to make corrections now based on those estimates (see Figure 38).

The corrections are generally implemented by multiplying the desired velocity with the velocity feed-forward gain factor V_f . The same technique can be used to apply an acceleration feed-forward correction signal. This correction is being used to reduce the average following error during the acceleration and deceleration periods.

Combining feed forward techniques with PID allows the PID loop to correct only for the residual error left by the feed forward loop, thereby improving overall system response.

Positioning Trajectory Options

Motion without Interpolation

There are three types of non-interpolated motion: *single-axis*, *simultaneous*, and *synchronized* motion.

Simultaneous and synchronized motion are both multi-axis (see Figure 39). The difference between them is that simultaneous motion is unsynchronized (see Figure 40).

Motion with Interpolation

When the controlled load must follow a particular path to get from its starting point to its stopping point, the coordination of axis movements is said to be interpolated. There are two types of interpolation: *linear* and *circular*.

Linear Interpolation

Linear interpolation is required for multi-axis motion from one point to another in a straight line. The controller determines the speeds on each axis so that the movements are coordinated. True linear interpolation requires the ability to modify acceleration. Some controllers approximate linear interpolation using pre-calculated acceleration profiles (see Figure 41).

Circular Interpolation

Circular interpolation is the ability to move the payload around a circular trajectory. It requires the controller to modify acceleration on the fly (see Figures 42 and 43).

Contouring

With contouring, the controller changes the speeds on the different axes so that the trajectories pass smoothly through a set of predefined points. The speed is defined along the trajectory and can be constant, except during starting and stopping (see Figure 44).

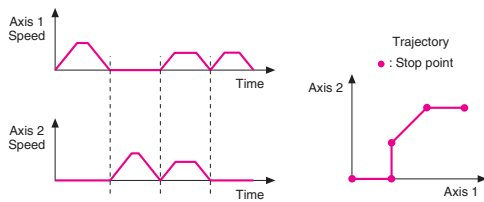


Figure 39—With synchronized motion, multiple axes may or may not move together.

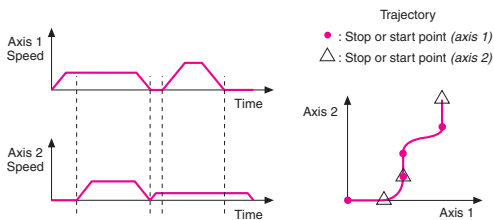


Figure 40—With non-interpolated motion several axes can move simultaneously, but are not coordinated.

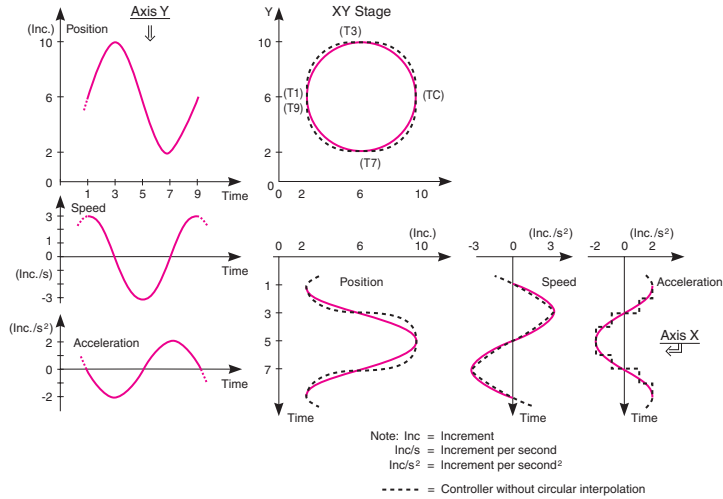


Figure 43—To be able to control stages in “real” circular interpolation, a controller must be able to modify the acceleration on the fly.

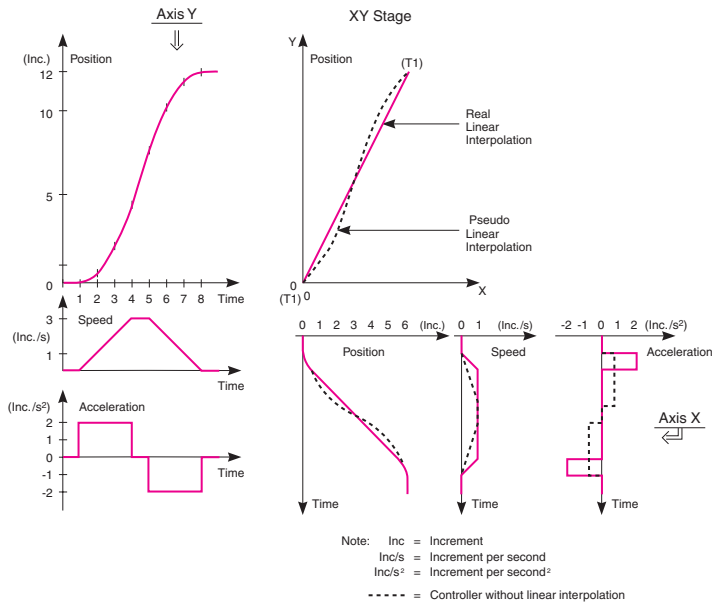


Figure 41—“Pseudo” linear interpolation is obtained with controllers using precalculated acceleration ramps.

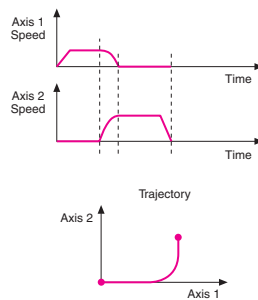


Figure 42—Simple circular interpolation.

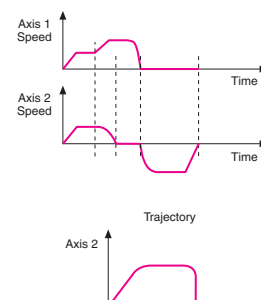


Figure 44—Applications such as laser writing require unusual trajectories executed at constant speed.