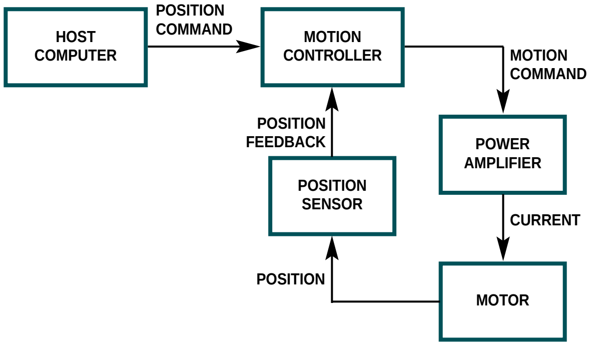
SYSTEM ELEMENTS

DC MOTORS

OVERVIEW

The motion controller is part of a complete closed-loop system which also includes the power amplifier, motor, and an encoder. Such systems, also known as servo systems, sense the motor position and feed the position signal back to the controller. A typical servo system is shown in the figure below.

Elements of a Servo System



The operation of the various system elements may be described by comparing the servo system with the human body. The combination of the motor and power amplifier is analogous to the muscle that moves the human arm. The motor is the device that generates the motion; the power amplifier generates the current required to drive the motor. For example, the amplifier takes a low-current signal and amplifies it to a higher level of current of 10 A.

The controller is the intelligent element that commands the motion. As such, it operates as the brain of the system. It generates a signal, referred to as the motion command, which is applied to the power amplifier. The function of the position sensor is analogous to human eyes. It senses the position of the motor and reports the result to the controller, i.e. closes the loop.

A closed-loop system receives its command from an outside source, often a host computer. Continuing our human society analogy, the command source may be seen as the Boss, generating commands and often requesting status reports. The commands can also be generated by other sources such as a programmable controller, terminal, or set of switches.

The following discussion briefly describes system elements. The focus is on the most common type of control system, digital position systems controlling DC motors and utilizing incremental encoders. However, most of the discussion applies to systems utilizing AC or hydraulic motors with resolvers or absolute encoders, etc.

DC MOTORS

DC motors convert electrical energy to mechanical energy, or more specifically, convert current into rotational torque. The key parameters of a DC motor are the torque constant K_t, the armature resistance r, the moment of inertia J_m, and the maximum torque level. The torque constant is expressed in units of Nm/A or oz-in/A and indicates the amount of torque that the motor generates for a unit of current. For example, a DC motor with a torque constant of 0.1 Nm/A converts a current of 2 A to a torque of 0.2 Nm. The armature resistance is the total resistance of the armature winding and the brushes; it is expressed in ohms. The moment of inertia J_m is the sum of the moments of inertia of the rotating parts of the motor; it is expressed in units of kg-m^2 or oz-in-s^2.

A motor is also characterized by the level of torque it can produce. The motor torque capability is expressed by two parameters: the continuous value and the peak value. The continuous torque is what the motor can produce continuously, often at any speed, without overheating. The peak torque is the maximum that can be generated for short periods of time without causing mechanical damage or demagnetization. The peak torque is several times the continuous torque. The motor can generate any level of torque below the peak torque so long as the root-mean-square (RMS) value of the torque is within the continuous torque level.

The current that drives the motor is generated by a power amplifier. The operation of such amplifiers is described in the next section.

SYSTEM ELEMENTS

POWER AMPLIFIERS, INCREMENTAL ENCODERS

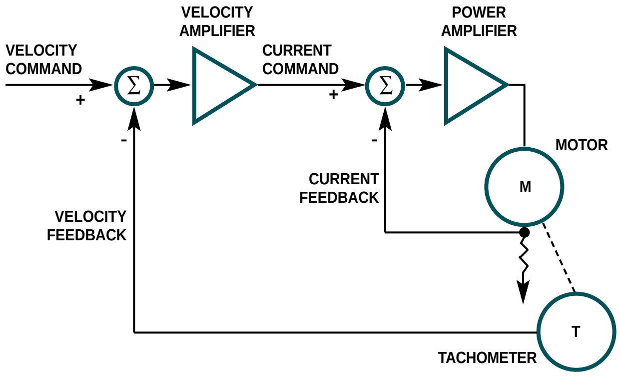
POWER AMPLIFIERS

Power amplifiers receive a command signal, typically an analog signal within the range of ±10 V, and amplify it to the required level of current. Such amplifiers can be configured in the current or velocity mode. The velocity mode is preferred when velocity feedback is utilized; otherwise, a power amplifier typically is configured in the current mode.

In the current mode, the amplifier produces a current that is directly proportional to the input voltage. This is achieved by a current feedback loop which monitors the current and assures that it is proportional to the command signal. Current amplifiers are characterized by the current gain K_a which indicates the amplification per 1 V of command signal.

Amplifiers can also be configured in the velocity mode. Here the amplifier includes a voltage amplification stage which compares the applied voltage with the motor velocity and amplifies the difference before it is applied to the current loop. Such an amplifier is shown in the accompanying figure.

Elements of an Amplifier in Velocity Mode



Amplifiers use one of two methods to generate the required voltage or current: linear amplifiers that produce constant output voltage or pulse-width-modulated (PWM) amplifiers that generate a voltage switching between the high and low levels. Most amplifiers today, especially those with power ratings above 100 watts, are switching amplifiers using the PWM method to minimize power losses. Linear amplifiers are more common when low power is required.

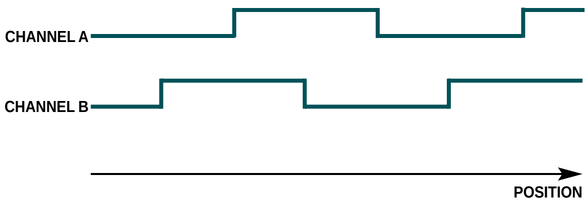
Now that we have discussed the operation of motors and amplifiers, we will proceed to describe the operation of the position sensors. The most common sensor is the incremental encoder.

INCREMENTAL ENCODERS

Incremental encoders generate pulses that represent the shaft position. The encoder output includes two signals, commonly called Channel A and Channel B, which generate N pulses per revolution. The two signals are shifted by a quarter of a cycle, as shown in the accompanying figure. The shift between the two signals enables the controller to determine the direction of rotation, depending upon whether Channel A leads Channel B or vice-versa. The shift of the two signals also increases the sensor resolution by dividing each encoder cycle into four quarters, or quadrature counts. Thus, an encoder with N cycles per revolution produces 4N quadrature counts per revolution.

Most encoders produce square wave signals with TTL levels. Other forms include sinusoidal signals or square waves at higher voltages. Industrial systems often use encoders with differential signals, i.e. channels A and B with their complements. These devices reduce system sensitivity to noise. Incremental encoders may also produce a third signal known as the index or marker pulse. This signal appears once per revolution and can be used for initialization purposes.

Output Signals of an Incremental Encoder



SYSTEM ELEMENTS

MOTION CONTROLLERS

MOTION CONTROLLERS

The motion controller performs the intelligent tasks of the system as shown in the block diagram below. The basic tasks of the motion controller include:

- Decoding position feedback
- Generating the desired position (profiling)
- Closing the position loop
- Stability compensation

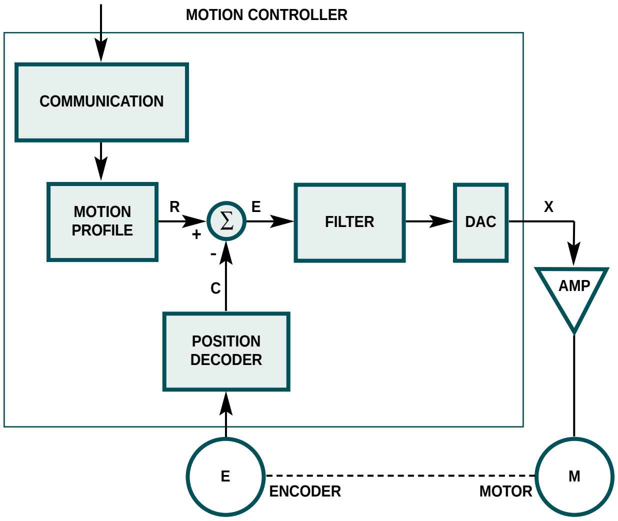
The most fundamental function of the controller is to decode the motor position and to close the loop. The motor position C is determined from the feedback signal (often an incremental encoder) and compared with the desired or reference position R. The difference of R-C is known as E, the position error.

The objective of the controller is to reduce the value of the position error E to a minimum without causing system oscillations. To achieve this, the controller often includes a stabilizing filter whose output is applied via the digital-to-analog converter (DAC) to the amplifier and the motor.

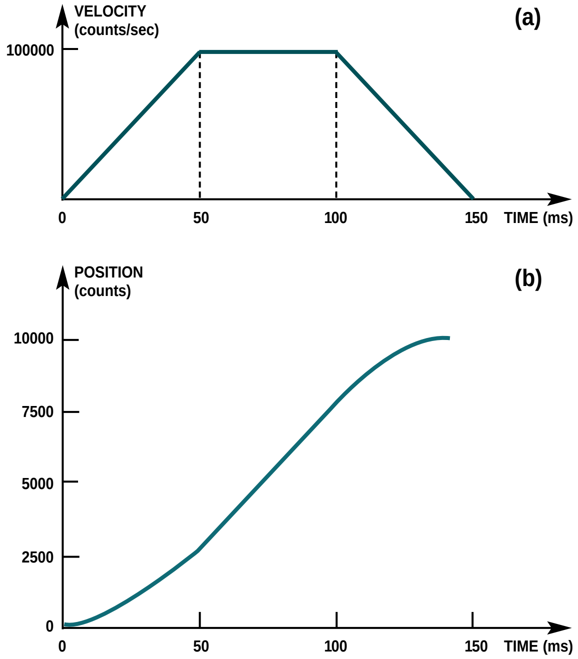
The most common type of stabilizing filter is proportional-integral-derivative or PID. The proportional term is for speed of response. The derivative term provides stability and damping. The integral term is for system accuracy. Properly tuning a servo system for optimum performance involves adjusting the proportional, integral, and derivative coefficients or KP, KI, and KD.

The motion controller also performs "profiling" functions, generating a time-dependent position function R(t), which corresponds to the required velocity profile. In the velocity profile shown below, the motion time of 150 msec is divided equally between the acceleration, slew, and deceleration. The slew velocity is 100,000 count/sec and the total displacement is 10,000 counts. Typically, the motion requirements are specified by the host in terms of the total distance, slew speed, and acceleration. It remains for the controller to generate the position profile R(t) shown as a time-dependent function. Since the motor position C follows R, the generation of the profile R controls the motion path and rate. In addition to the basic tasks described above, an advanced motion controller may per-

Elements of a Motion Controller



Desired Velocity Profile (a) and Corresponding Position (b)



form high-level functions such as processing commands from a host computer, program sequencing, I/O processing, and error handling. It is these high-level functions that allow the controller to operate as a complete stand-alone machine controller.

To describe the operation of the system, consider an example with the following parameters:

PARAMETERS	DEFINITION
$K_t = 0.1$ Nm/A	*Motor torque constant*
$J_m = 10^{-4}$ kg m^2	*Moment of inertia*
$r = 2\Omega$	*Motor resistance*
N = 500 lines/rev	*Encoder line density*
$K_a = 3$ amps/V	*Amplifier current gain*

Suppose the system is required to be at position zero (R=0) but the actual motor position is -20 (C = -20). The controller determines the position error according to the equation E = R - C, resulting in an error of 20 counts. The error signal E is then processed by the filter. Assume the combined gain of the filter and the DAC is 0.1 V per count: this implies that an error signal of 20 counts produces a motion command signal X of 2 V.

The signal X is applied to the amplifier with the given gain of 3 amps/V, resulting in a current of 6 amps. When the current is applied to the motor, it produces a torque T_g which equals the product of the current and the torque constant K_t. In this case, the positive torque of .6 Nm is generated which drives the motor forward, reducing the position error. The generated torque accelerates the motor at the rate a where:

$$a = T_g / J_m$$

for the given system parameters, a = 6000 rad/sec^2.

As the motor moves closer to the desired position, the error E decreases and, along with it, the drive signal to the motor. When the motor reaches the desired position exactly, the position error drops to zero, as does the motion command signal. No current is applied to the motor while it remains in the commanded position. However, whenever the motor moves away, a correction torque is applied to force it back to the required position.

The motor may approach the required position in several ways. If the motor approaches the required position from one direction and stops, we say that the system response is overdamped. If the motor position overshoots the target several times before settling, the response is underdamped. Under some conditions the motor response may oscillate and never stop; such a system is called unstable. The system response is a function of the system hardware and PID filter parameters. The ideal system response has minimum risetime, minimum overshoot, and quick settling to the commanded position. Many tools, such as Galil's WSDK servo design kit software, are available to tune the PID filter for the optimum response.