Motion Electronics Design

Introduction

Motion control systems consist of three main components: motion controller, motor driver or amplifier, and a motion device. The primary purpose of a motion controller is to control the dynamics of the motion device. The motor driver converts the command signals from the motion controller into power signals required to drive the motor. The motion device is any mechanical device that provides motion and is actuated by a motor. Such motion devices typically contain feedback devices to provide information such as position and velocity to the motion controller (see Figure 26). Each section is further explained below.

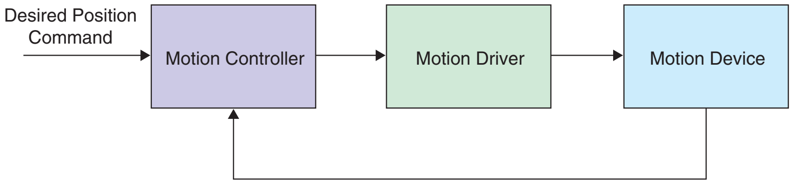

Figure 26—Basic motion control system.

Motion Controllers

In a motion system, the motion controller is used to control motion devices such as stages and actuators so that they move or stop in a desired manner. If the motion system is equipped with position, velocity, or torque sensors, the signals from these sensors are fed to the controller. In servo systems, the controller compares the actual signal to a desired value and takes corrective actions.

Common motion systems use three types of control methods: position control, velocity control, and torque control. Position control is used in applications where precise positioning and position tracking are of utmost importance. In these applications, the primary feedback device is an encoder. Velocity control is used in applications such as spindle, conveyor belts, and such where velocity regulation is of primary importance. In these applications, the primary feedback device is a tachometer. Torque control is used in applications such as robotics where the torque applied by end-effectors must be controlled accurately in order to grasp or release objects. In these applications, the primary feedback device is a torque/force sensor such as a strain gauge.

A majority of Newport's motion systems use the position control method. They use both encoder and tachometer feedback to attain high levels of positioning as well as velocity regulation. The purpose of the motion controller in these systems is to command a motor so that the actual position of the moving mechanism tracks the desired position specified by a preplanned trajectory.

While the main objective of a motion controller is to control a motion device, many advanced motion controllers provide various additional functions such as:

- Trajectory generation for moving devices from one point to another or for coordinating the motion of multiple devices
- Interface to let users configure and command the motion system to perform various tasks
- Monitoring end-of-travel limits, amplifier faults, feedback errors, etc. for safety of the system
- Digital input/output lines to synchronize external events to motion or vice versa
- Memory for storing and running on-board motion programs

Furthermore, the output of the motion controller can be configured depending upon the type of motor used to move a motion device.

To control stepping motors, most motion controllers send two digital signals to the motor driver (amplifier). The driver must interpret these signals and provide appropriate commutation to rotate the stepping motor. These signals can be used in one of two ways:

Step and Direction – one signal is pulsed to command the driver to step the motor and the other indicates the desired direction of motion.

Plus (CW) *and Minus Pulses* (CCW) – one signal is pulsed to command the driver to step the motor in the positive direction, and the opposite signal is pulsed to command the driver to step the motor in the negative direction.

A stepper motor control system does not require position feedback. The motion controller can simply provide the correct number of pulses to rotate the stepper motor the appropriate amount for a desired move. However, for improved positioning accuracy, a more sophisticated stepper motor system can also incorporate a feedback system (e.g., shaft-mounted rotary - or glass-scale linear -encoder) that can be used to directly monitor the position and provide the motion controller with actual displacement information. The motion controller can then provide a quasi-servo closed-loop positioning system that adds or subtracts output pulses to the driver to correct for positioning errors.

For DC Servo motors, conventional motion controllers feed an analog voltage to the motor driver that varies from –10Vdc to +10Vdc. This command signal is often referred to as the DAC control signal. The motion controller adjusts the DAC output in order to make the actual position of the motion device accurately follow a desired position. (See Closed-Loop Control section) To control servo motors in positioning applications, the motion device (i.e. stage) must provide some type of position feedback.

A third mode used for brushless DC servo motors requires the motion controller to send two DAC control signals. These two sinusoidal signals are shifted 90° (or 120°) out of phase and used to directly commutate the motor. This method can also be used to commutate stepper motors, eliminating the need for complicated driver electronics.

Motor Drivers

A motor driver receives input signals from a controller and converts them to power to drive a motor. A motor driver can be a simple amplifier or it can be an intelligent device that can be configured through software for varying operation parameters. There are three classes of motor drivers available to support the different types of motors used in motion control.

Stepper Motor Drives

The stepper motor drive receives input signals from the motion controller commanding it to step the motor to a commanded position. The stepper motor drive then applies current to the stepper motor windings in order to move the stepping motor to the next step (increment). This basic operation is known as the *Full Step* operation of a stepper motor. In this mode, if power is removed from the motor, the stepper motor will not move significantly from its current position due to its inherent holding or detent torque.

A more sophisticated stepper motor driver is capable of applying current to both windings of the stepper motor simultaneously. Proportioning the current of the two windings allows precise control of the position of the motor rotor between detent positions. Using this method known as *Microstepping*, the motor driver can divide the input step command by 1 to 1000 microsteps. This provides a much higher positioning resolution for stepping motors and minimizes resonance problems inherent to stepper motors over the speed range of the motion device. However, in this mode, if power is removed from the motor, the motor will move to its closest detent or full-step position.

High-Voltage Chopper Technology

A simple four-phase driver is suitable for basic, low performance applications. But, if high speeds are required, quickly switching the current with inductive loads becomes a problem. When voltage is applied to a winding, the current (and therefore, the torque) approaches its nominal value exponentially (Figure 27). When the pulse rate is fast, the current does not have time to reach the desired value before it is again turned off, so the total torque generated is only a fraction of nominal.

The time required for the current to reach its nominal value depends on three factors: the motor windings' inductance, its resistance, and the voltage applied.

The inductance cannot be reduced, but the voltage can be temporarily increased to bring the current to its desired level faster. The most widely used technique is a high voltage chopper.

If, for instance, a stepper motor requiring only 3 V to reach the nominal current is connected momentarily to 30 V, it will reach the same current in only 1/10 the time.

Once the desired current value is reached, a chopper circuit activates to keep the current close to the nominal value (Figure 28).

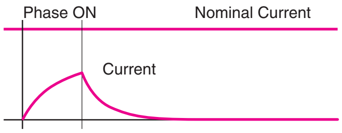

Figure 27—Exponential current build-up in the motor is too slow for high speed applications.

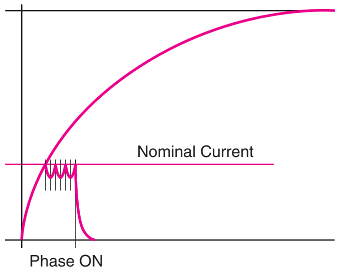

Figure 28—A high voltage chopper helps a stepper motor reach full current faster, enabling higher speeds.

DC Servo Motor Drives

Drivers for DC Servo motors simply convert a –10Vdc to +10Vdc analog control signal from the motion controller to a usable current to drive the motor.

DC Brushless Motor Drives

Most brushless DC Motor drives are simple amplifiers that convert control signals from the motion controller to a usable current to drive the motor, with the motion controller providing the motor commutation. In some applications, however, the motor drive is an intelligent device that receives an analog input similar to the DC servo motor drive. In this case, the driver must have some internal microprocessing capability and requires feedback from the motor in order to commutate it.

Brushless DC motor drives are available in three basic types. One type accepts a single analog ±10 Vdc control signal (which represents either velocity or torque) from the motion controller and Hall effect signals from the motor, which is needed for commutation reference. Another type accepts two analog ±10Vdc commutation signals from the controller and, therefore, does not require Hall signals from the motor.

Lastly, there are intelligent drives that can "self-commutate" (generate its own sine and cosine commutation signals). These drivers are very flexible and can use the stage's encoder feedback or Hall effect signals for motor commutation.

Feedback Devices

A feedback device's basic function is to transform a physical parameter into an electrical signal for use by a motion controller. Common feedback devices are encoders for position feedback, tachometers for velocity feedback, optical or mechanical switches for end-of-travel information, index signals for a fixed reference position, and hall effect sensors for brushless motor phase information.

Indirect Metrology vs. Direct Metrology

The location in the motion system from which the feedback device performs its measurements directly affects the quality of the data fed back to the controller. The closer the feedback device is to the subject being controlled, the more effective it will be in helping the controller achieve the desired result. When controlling position, for example, measuring the linear position of the stage carriage directly provides higher quality feedback than measuring the angular position of the lead screw and inferring carriage position through knowledge of the drive train architecture between the encoder and the carriage (see Figure 29). The former is known as direct output metrology and avoids the drive train induced errors like backlash, hysteresis, and windup that can affect the latter type, known as indirect measurement.

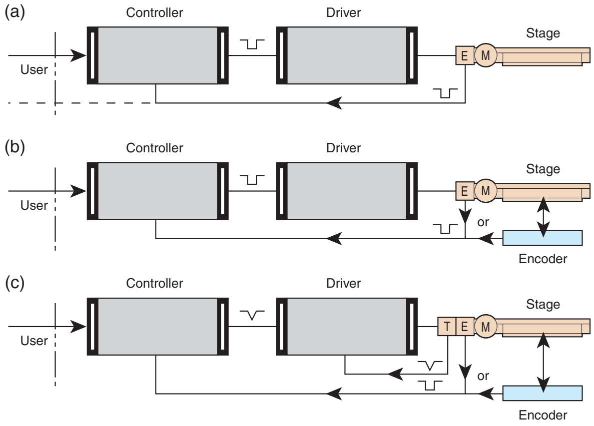

Figure 29—Closed-loop systems. a) Using indirect metrology rotary encoder b) Using direct metrology linear encoder c) Using encoder for position feedback and tachometer for velocity control

Rotary Encoder

A rotary encoder can differentiate a number of discrete positions per revolution. This number is called its points-per-revolution and is analogous to the steps-per-revolution of a stepper motor. A DC motor with a 2000 points (counts) per revolution encoder is like a stepping motor with 200 steps per revolution when driven by a 10x microstep driver. The speed of an encoder is in units of counts-per-second. Linear and rotary stages and actuators incorporating indirect metrology use rotary encoders measuring the motor shaft or lead screw angle to report position. Conversely, rotary encoders can also be used on rotation stages for direct output metrology.

Linear Encoder

A linear encoder is used when direct verification of the output accuracy, resolution, and repeatability of the positioning system is desired. These encoders can be used as direct output metrology devices to overcome many of the inaccuracies present in mechanical stages due to backlash, hysteresis and lead screw error.

Optical Encoders

Although there are various kinds of digital encoders, the most common is the optical encoder. Rotary and linear optical encoders are used frequently for motion and position sensing. A disc or a plate containing opaque and transparent segments passes between a light source (such as an LED) and detector to interrupt a light beam (Figures 30 and 31). The electronic signals generated are then fed into the controller where position and velocity information is calculated based upon the signals received. Optical encoders can be further subdivided into absolute and incremental encoders.

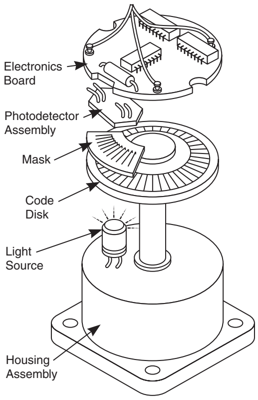

Figure 30—Optical rotary encoders commonly use a stationary mask between the code wheel and the detector.

Absolute Encoders

Absolute encoders contain multiple detectors and up to 20 tracks of segment patterns. For each encoder position, there is a different binary output so that shaft position is absolutely determined. With absolute encoders, the position information is available even if the encoder is turned off and on again.

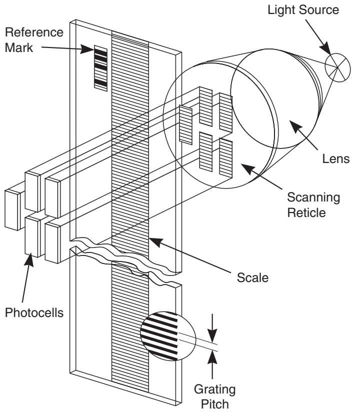

Figure 31—Optical linear encoders direct light through a glass scale with an accurately etched grating to photocells on the opposite side.

Incremental Encoders

When lower cost is important, or when only relative information is needed, incremental encoders are preferred. Their output consists of electronic signals corresponding to an increment of linear or rotational movement. Many incremental encoders also have a feature called the index pulse. An index pulse occurs once per encoder revolution in rotary encoders (Figure 32). It is used to establish an absolute mechanical reference position within one encoder count of the 360° encoder rotation. The index signal can be used to do several tasks in the system, such as resetting or presetting the position counter, or generating an interrupt signal to the system controller.

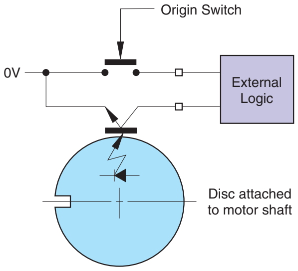

Figure 32—To get sub-micron repeatability using an index pulse from an encoder, homing should always be approached from the same direction.

Quadrature Encoders

A quadrature encoder is a particular kind of incremental encoder with at least two output signals, commonly called channel A and channel B (Figure 33). Channel B is offset 90 degrees from channel A. The addition of a second channel provides 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.

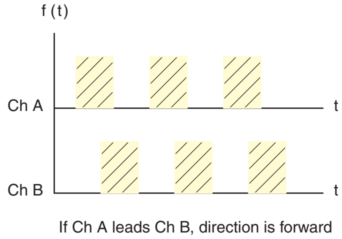

Figure 33—Quadrature encoder output provides direction as well as position feedback.

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).

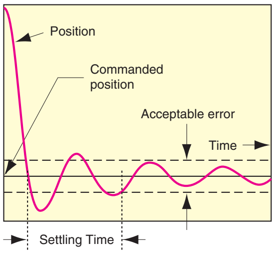

Figure 34—How settling time is defined.

Overshoot

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

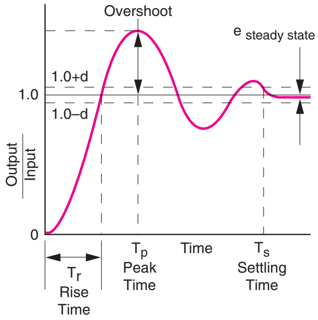

Figure 35—Response for a system using only proportional controls leads to overshoot and non-zero steady-state errors.

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