The right motor can position your application for success

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To design a product that uses motors for position control, you should understand the strengths and weaknesses of several motor types. Then, you can choose the best motor or motors and begin selecting or designing a suitable controller.

To most engineers, the thought of selecting a motor for a new design induces, at best, a heartfelt yawn. EEs just don't perceive motion control and the related discipline of manufacturing automation as fast-paced fields. The last several years, however, have seen a brewing battle for motor-selection supremacy. This battle has raised more than a few eyebrows and ruffled more than a few feathers. The hubbub over motor selection relates to dramatic changes that affect the entire motion-control industry. Branching away from their historically machine-tool-dominated past, motion-control vendors now use the latest electronic and software techniques to squeeze the maximum possible performance from each mechanical system.

Semiconductor wafer-fabrication equipment, medical-laboratory equipment, satellite-tracking systems, and packaging-automation systems are just a few of the product types that use modern motion-control techniques. There are several issues you should consider in selecting the right type of motor for position-control applications. To make an appropriate selection, you must understand how the motors work and the sorts of jobs for which each is best.

Motion control is the science of precisely controlling the position, velocity, and torque of a mechanical system. To accomplish this task, motion-control systems comprise a controller (nowadays, usually a numerical controller, often one based on a DSP IC), an amplifier, and a motor (**Figure 1**).

The high interest in choosing a motor relates as much to control-system architecture as it does to the performance of the motor as a separate component. This situation exists because different motors require different types of electronic controllers, which affect the cost and performance of the entire product.

All motors use electromagnetic fields to create torque or force. Most motors create torque along a rotating axis, but a motor designer can "stretch" the device along a plane to produce linear motion. Whether the motor is rotary or linear does not affect the basic method by which it creates torque or force.

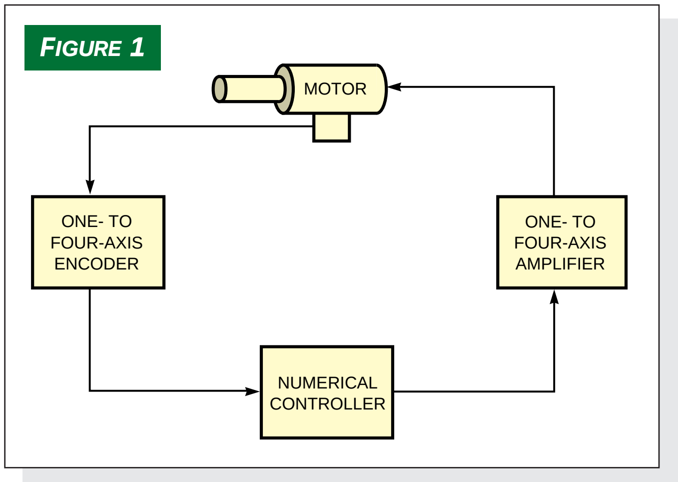
There are three major motor types common in position-control systems: step motors; dc-servo motors (dc motors with brushes), in which the current-carrying windings move and the second field is stationary and usually comes from a permanent magnet; and brushless-dc motors with a moving permanent magnet and stationary current-carrying windings.

Besides these forms of motors, many other motor types exist, including ac-induction, ac-synchronous, and variable-reluctance motors. These motors more typically control velocity or torque—not position, however.

Motors 101

Motor design is a complicated and specialized craft

FIGURE 1



A typical position-control system incorporates a numerical controller (often based on a DSP IC), an amplifier, and a motor.

involving the study of magnetics, materials, permeability properties, and other disciplines. Nevertheless, all of the motors used in position control have a few characteristics that system designers should understand.

These characteristics are important because they affect other parts of the control system and, therefore, the cost of the overall system. Many engineers are adept at reading motor specifications for total torque, size, and power. These engineers are less likely to appreciate other implications of how the motors create torque. The motor design profoundly affects characteristics such as smoothness, mean time between failures (MTBF), and controller cost.

Three concepts that you must understand are phasing, commutation, and position feedback. If you understand these characteristics, you can properly select a motor for almost any application.

"Motor phasing" refers to the number of phases that the control system supplies to the motor terminals. You can think of a motor phase as a complete electromagnetic circuit that the controller (amplifier) drives to create torque. Some motors, such as dc servos, have only one phase (at least externally), whereas other motors, such as steppers, have two, three, or five phases.

A motor that presents more than one phase to the outside world is a "multiphase" device. A controller for a multiphase motor sequentially excites the phases to maintain motor rotation. Controlling the phase-excitation sequence is called commutation.

Each phase of a multiphase motor requires an amplification circuit. Therefore, the number of phases is a key contributor to the overall system cost. For example, a two-phase step motor, as the name implies, requires two separate amplification circuits. A three-phase brushless-dc motor requires three amplification circuits. If you purchase a motor amplifier as a complete unit, the amplifier contains all of this circuitry. The cost of items such as the case and connections tends to mitigate the cost difference between, say, a dc-servo-motor amplifier and a brushless-dc-motor amplifier. However, if you construct your own amplifier using devices such as MOSFETs and drivers, the choice of motor type directly affects the number of components required and therefore the board space and board cost. **Table 1** summarizes the most common configurations of motor types, the number of phases, and the number of motor lead wires.

TABLE 1—MOTOR CONFIGURATIONS

Motor type	Step motor	DC servo	Brushless dc
No. of phases	Two, three, or five (two is most common)	Two	Two or three (three is most common)
No. of motor leads	Two to eight	Two	Three for three-phase, four for two-phase

"Motor commutation" refers to the technique for properly sequencing the motor phases. By definition, a single-phase device, such as a dc-brush motor, requires no external commutation. The motor is still commutated, but commutation takes place entirely within the motor. In a dc-brush motor, for example, brushes or contacts inside the motor continuously sequence the phases to keep the motor rotating.

For multiphase devices, such as step or brushless-dc motors, the external control electronics perform the commutation. In brushless-dc motors, Hall sensors typically control the commutation. The signals from these sensors allow the controller to excite each of the three motor-phase coils at the right time based on the shaft angle of the motor. The controller uses the Hall sensors to create three motor-coil currents 120 electrical degrees apart.

Another popular brushless-dc-motor commutation scheme is sinusoidal commutation, which typically uses the motor's position encoder to generate continuously varying sinusoidal signals. Using this scheme, these signals are also phased 120 electrical degrees apart (**Figure 2**). This technique results in smoother motion with no discontinuities in the resultant motor torque output.

STEP MOTORS: ALIVE AND WELL

Of the three motor types used in position-control systems, step motors have perhaps gone through the most dramatic evolution. For years, popular opinion has held that step motors are inherently unsophisticated and would gradually disappear as higher performance servo motors (dc brush and brushless permanent magnet) become more affordable. However, something funny happened on the way to the future. Far from being relegated to low-end applications, step motors have found themselves competing head-on with other motors in sophisticated applications in which size, cost, and power are most important.

Leading the way are new types of step motors with novel configurations, such as three- and five-phase windings. Another important advance is the availability of skewed-rotor and flux-control motors, both of which can produce smoother, more powerful motion.

Perhaps the most dramatic improvements have been on the control side, however. Recent advances in amplifiers include high-efficiency, high-current, step-motor drivers that use special current-modulation techniques to control oscillations and reduce noise. Equally important is the development of a new generation of trajectory-control chips. By implementing features such as encoder feedback, programmable starting velocities, and S-curve profiling, these chips have significantly expanded the range of step-motor applications.

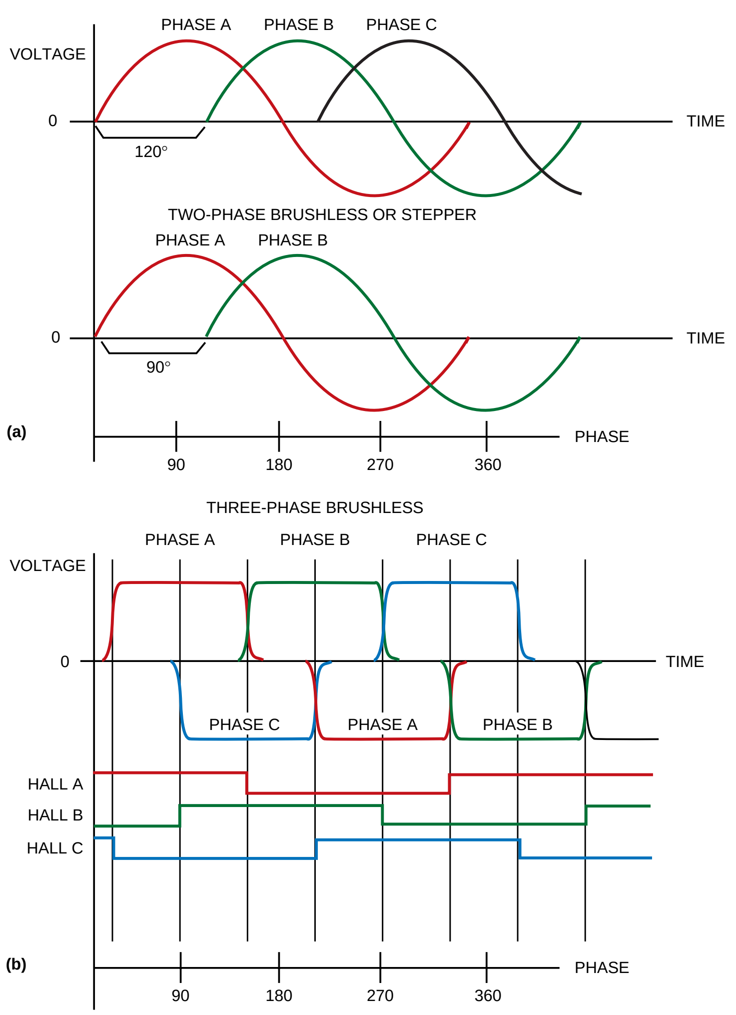
Most engineers do not think step motors require commutation, but commutation occurs in the circuits that drive these motors. The commutation techniques that the amplifiers employ have special names, such as "full-step," "half-step," or "microstep drive." These names refer to the number of power levels the amplifier applies to each motor coil during an electrical cycle (see **box** "Step motors: alive and well).

A full-step drive applies a full-positive or full-negative signal. A half-step drive separates the applied signal into three levels (full positive, zero, and full negative). A microstep drive generates a more-or-less sinusoidal signal that provides the maximum smoothness and highest degree of control. Whatever the drive method, typical step motors have two phases and require that the signal phases be 90 electrical degrees apart (**Figure 3**).

Table 2 summarizes the most common commutation techniques for each motor type, along with the relative advantages and disadvantages of each method.

When used in positioning applications, position feedback controls a servo motor's position or confirms that a step motor has arrived at the desired position. To maintain their position, servo motors, such as dc-brush or brushless-dc devices, require position feedback at all times. By continuously comparing the desired position with the instantaneous rotor position (actual position), the control system directs these motors to a certain location (target position) or commands them to move through a certain path. A position-feedback device generates a signal proportional to the actual position. The difference between the target and actual positions produces a motor command, which the motor-drive circuit amplifies. The use of feedback to achieve the desired position is called "servo control" and typically uses a stabilization element, such as a PID (proportional, integral, derivative) filter, to generate

FIGURE 2



Some drive systems provide near sinusoidal excitation, as you can see from the waveforms for a three-phase brushless motor (a, top) and a two-phase motor, which can be either brushless or step (a, bottom). Using Hall sensors to generate position-feedback signals that drive a half-step controller produces the waveforms of (b).

TABLE 2—COMMUTATION TECHNIQUES

Motor type	Commutation/drive method	Advantages and disadvantages
Step motor	Full step	Simple to build but noisier and subject to instability at low speed
	Half step	Smoother and somewhat more stable at low speed
	Microstep	Smoothest motion but somewhat more complex to implement; this technique is gaining popularity as the cost of electronics decreases
DC servo	None required	
Brushless dc	Hall based	Simple and inexpensive but may have greater torque ripple
	Sinusoidal	Smoother with less torque ripple but more complex to implement

the motor-command value.

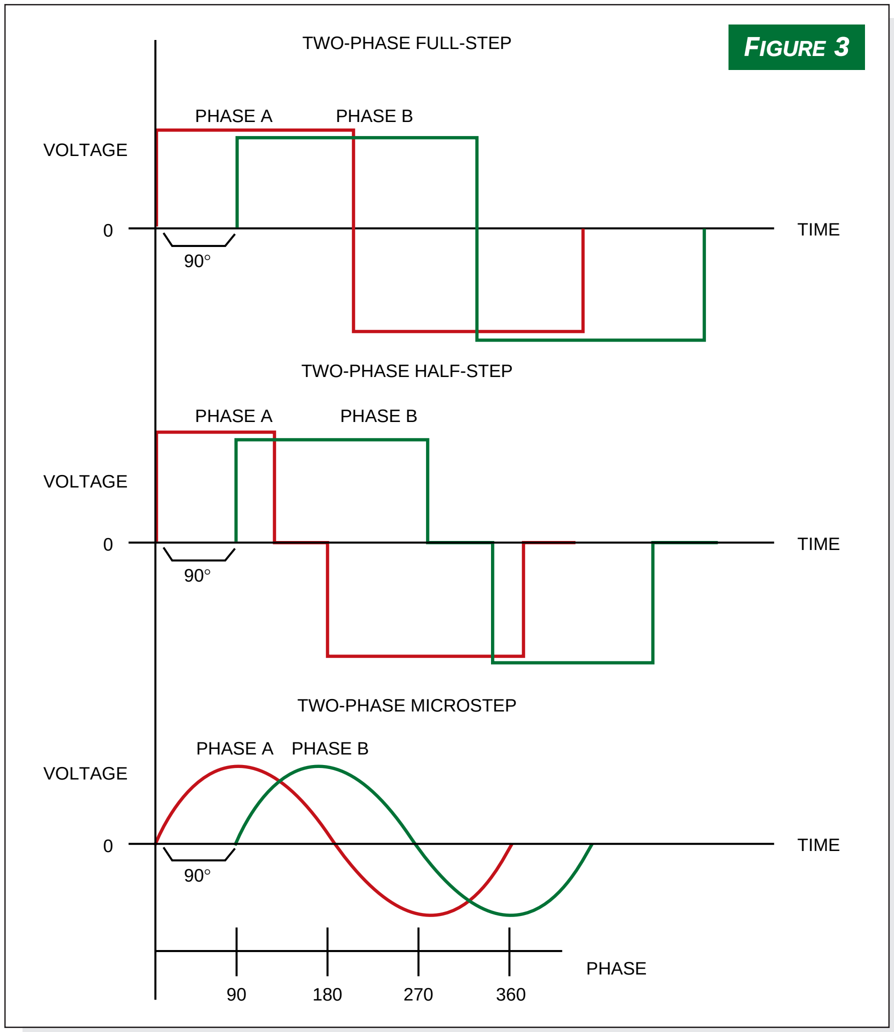
Step motors operate on a different principle. If the coils receive constant dc excitation, the position remains the same. Continuously rotating the phases through one electrical cycle after another causes the motor to move a precise number of steps or microsteps. Each quarter electrical cycle is a “step.” Step-motor controllers generate high-speed step and direction signals to create continuous motion at a constant or accelerating velocity. The amplifier uses the direction signal to determine the phase sequence. Changing the direction signal reverses the motor direction.

A step motor positions itself without using feedback. Nevertheless, step-motor applications increasingly use position feedback for extra safety. Many types of encoders exist (**Table 3**).

Now you can determine which motor type to use in a particular application. The various motor types have different attributes that you should weigh against your application requirements (see **Table 4** and **box** “Taking advantage of motor variety”).

As indicated above, step motors are self-positioning and therefore require no external device, such as an encoder, to report their position. This feature immediately gives step motors a cost advantage over servo motors, which require an encoder to operate in a position mode. Furthermore, a step motor does not usually require a permanent magnet in its rotor or stator. Instead, step motors can consist mainly of copper wire, which carries the current that creates electromagnetic force, and iron or other “soft” ferromagnetic materials, which focus the magnetic flux.

FIGURE 3



Full-step (top), half-step (center), and microstep (bottom) controllers produce excitation waveforms that replicate sine waves with varying degrees of accuracy.

In addition to being relatively inexpensive, step motors are also brushless: The external circuits make no electrical contact with the rotor. Because of this construction, step motors are free of such mechanical-commutator problems as

TABLE 3—COMMON ENCODERS

Encoder type	Advantages and disadvantages
Incremental quadrature	Low cost, common, and accurate but not absolute; requires initialization to establish the "home" position
Absolute optical	Provides absolute position to 16-bit or greater resolution; expensive
Resolver	Provides absolute position and is rugged but requires R/D (resolver-to-digital) converter circuit, which can be expensive
Precision potentiometer	Relatively inexpensive and absolute but use with digital controller requires A/D converter; also may drift over time; wears out eventually
Laser interferometer	Very accurate but expensive; generally provides relative position information, but some versions provide absolute information

TABLE 4—MOTOR-CHOICE PARAMETERS

Desired characteristic	Favors use of	Comments
Low cost	Step or dc brush	Brushless-dc motor costs are coming down but are still well above step-motor or dc-brush-motor costs
Smooth operation (minimal noise or vibration)	DC brush or brushless dc	Brushless-dc motors can be made smoother using high-performance commutation techniques, such as sinusoidal commutation
High-speed operation	Brushless dc or dc servo	Step motors are generally unsuitable for applications beyond 5000 rpm
High torque-to-size ratio	Brushless dc or step	Step motors provide high torque only at relatively low speed
Ease of use	Step	No feedback required and no servo tuning
Single-phase operation (lower amplifier cost)	DC servo	Both step and brushless-dc motors are multiphase devices, which require more than one amplifier circuit per motor

degradation because of wear or arcing. Finally, step motors produce a relatively high torque for a given package size and also have a high holding (resting) torque.

Despite these advantages, step motors have a few drawbacks. The most significant are that step motors create noise, which is often audible, and induce vibrations that can disturb the load or affect parts of the system that are sensitive to vibration. Microstepping techniques and even mechanical dampers can reduce vibration, but these approaches seldom eliminate the problem.

Another significant limitation of step motors is their relatively low top speed. Although step motors have occasionally been driven to 10,000 rpm and beyond, for most systems, 5000 rpm or less is the most you can expect. In addition to a low top speed, step motors deliver torque that drops significantly at higher velocities.

Because of these limitations, step motors are generally unavailable in power ranges above several hundred watts. The most common National Electrical Manufacturers' Association (NEMA) motor sizes for step motors are 17, 23, and 34. Larger sizes are sometimes available but are less common.

You can find dc-brush motors in a variety of applications, including positioning and speed or torque control. By itself, a dc-brush motor has no sense of position. To use it in a positioning application, you must connect it to a position-feedback device (usually an encoder). The encoder provides the position information, and the controller drives the motor using a PID algorithm or similar scheme.

DC-brush motors are available in many sizes as high as or even higher than 1 kW. The motors can operate at speeds exceeding 10,000 rpm. Finally, dc-servo motors are smooth and relatively quiet.

DC-brush motors have two primary disadvantages. The first is that they require a mechanical device for commutation. The brushes of this type of motor can wear out or cause electrical arcing, which generates electromagnetic interference (EMI).

Another disadvantage is that a dc-servo motor produces a relatively low output torque for a given size. This characteristic stems from the current-carrying coils in the motor's rotor. These coils dissipate substantial power. The rotor has a high thermal resistance to the motor frame. The thermal resistance limits the energy that you can extract from the coils and, in turn, limits the motor's output.

In the last several years, brushless-dc motors have been gaining popularity because they meet the requirements of many applications with few compromises. Brushless-dc motors are relatively smooth and quiet and require no mechanical brushes for commutation. In addition, the rotors of brushless-dc motors carry no current. Instead, the current flows through stator coils, which are solidly connected to the motor case, allowing heat to efficiently dissi-

TAKING ADVANTAGE OF MOTOR VARIETY

Three motor types dominate the modern world of automation: step, dc-brush, and brushless-dc motors. At first glance, these motors seem to present drastically different control requirements. Some motors require encoders; others require external commutation. Some motors are multiphase; others are single-phase. Because of the challenges of dealing with this diversity, many designers build entire applications with just one type of motor, thereby simplifying the controls. Unfortunately, different sections of a machine may benefit from different motor types. Using just one type inevitably leads to compromises in system performance.

New motor-control products may change this situation. IC-based motion controllers from several vendors perform universal motion-control operations, including generating motion profiles, encoder inputs, and motor-command signals. At the same time, these ICs automatically manage the complex motor-specific portions of the control problem. These portions include commutation and deriving feedback signals from encoder outputs.

To provide a unified interface to the user, these chip sets provide a command language that is independent of the motor type. As the price of electronic controllers decreases, these new chip sets should address the growing interest in mixing and matching motor types within a machine to optimize the performance and cost of the overall system.

pate. This construction allows brushless-dc motors to generate high torque for a given package size.

Finally, brushless-dc motors are available in a variety of power ranges as high as or higher than 1 kW. The motors can also operate at high speeds. Some motors can rotate at 30,000 rpm and more.

Despite these important advantages, brushless motors have two main disadvantages. The first is that they are more expensive than dc-servo or step motors. The cost results in part from brushless motors' relatively low manufacturing volumes. In addition, brushless motors' geometry creates a magnetic circuit that includes large low-permeability gaps. With normal permanent magnets, these gaps would produce unacceptably low flux density. The solution is to use rotors made from rather expensive, high-coercivity, rare-earth, permanent-magnet materials. The second disadvantage of brushless-dc motors is that they require external commutation, which increases the complexity of the controls and requires the use of Hall sensors or equivalent phasing tracks in an optical-encoder disk.

The truth about motor selection is that there isn't—at least not yet—a perfect motor for all applications. Motor choice depends on a number of parameters, including the mechanical characteristics of the application, tolerance for noise, desired speed range, and cost.

Before starting a motion-control project, try to determine your system's requirements as a whole. Factor in the cost of both the motor and the control system. Also, consider your own comfort level with more complex technologies, such as PID/servo control and external commutation.

Whatever motor type you choose, there are many reputable companies that provide components, modules, or complete control systems to help you achieve success. For more information, try a few motion-related Web sites, including the Association of Industrial Motion Engineers (www.wmich.edu/engineers/AIME) and the Motion Control Home Page (www.motioncontrol.com). EDN

Author's biography

Chuck Lewin is president of Performance Motion Devices Inc and a member of the Association of Industrial Motion Engineers. He has been working in motion control for eight years, has been designing DSP-based motion systems for five years, and has written several articles on the practical aspects of motion control.

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