Mechatronics Means Motors

Movement requires motors, and motors are now including smarter controllers to deliver better efficiency and performance.

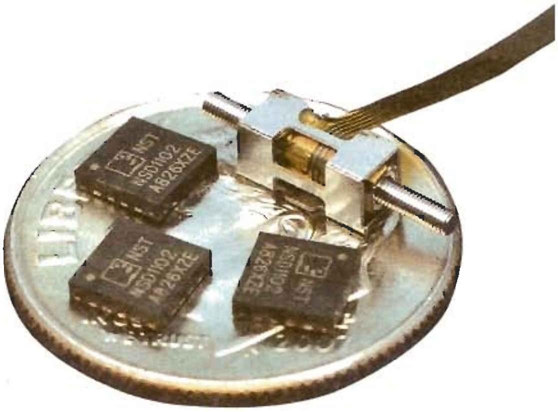
Simple electric motors turn when you apply power. They have been used this way since their inception. Yet today, a microcontroller may be sitting between the motor and the switch, and motors can be found everywhere from white goods to hybrid vehicles.

Electric motors are key to almost all robotic work as well, with a couple hydraulic motors included for good measure. Most electric motors utilize magnetics for motive power. But at the low end of the spectrum, it is possible to use piezoelectric crystals to construct tiny rotational and linear motors like Newscale Technologies' Squiggle Motor *(Fig. 1)*.

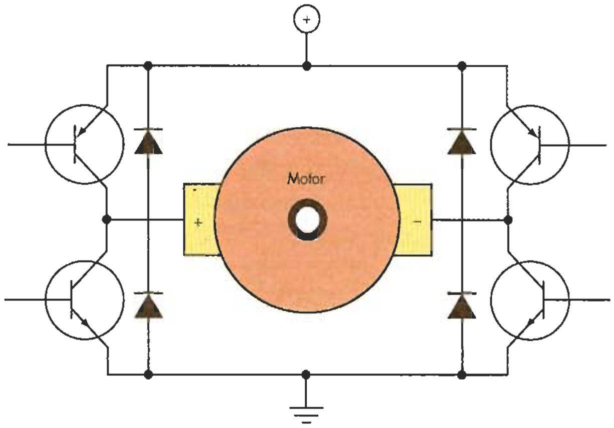
The plethora of options means that motors are more than just boxes with shafts sticking out. Issues such as power, torque, starting torque, efficiency, speed, speed control, and linearity come into play.

Coverage of this area can fill a library. Entire books have been written about single types of motors, and most EE curriculums have at least one motor course in the mix. Few computer science majors run into motors, and it is often rare for embedded developers to need a closer look at motors.

Still, motors are becoming closer cousins to embedded electronics because of the increase in motor control requirements in designs. That on/off switch is often replaced by a microcontroller pulling multiple duties as a capacitive touch input device, network node, and motor control. So for those developers, here's a whirlwind tour of motors and motor control.



1. Newscale Technologies' tiny Squiggle Motor is used in compact devices such as controlling the zoom lens of a digital camera.



2. The H-bridge is the most common method of controlling dc motors that need to operate in either direction. The diodes are critical to protecting circuits when switching because a dc motor is an induction load.

TYPES OF MOTORS

Electric motors are typically divided into three types: ac, dc, and piezoelectric. Universal motors can run on ac or dc current. Developers typically want to use a motor rather than design one. Before they can choose a motor for their application, though, they still need to understand the fundamentals *(see "Motor Terms," p. 36)*.

The most common motors are continuous rotational motors with a stator and rotor. The rotor contains an electromagnet or a permanent magnet. Electromagnets often require power that is usually provided through a commutator that is on the shaft of the rotor. Commutators are a source of wear, and the brushes employed in some motors, especially large motors, are often items that can be easily replaced.

Selecting a motor or motor technology can be a challenge. Requirements such as speed, torque, heat dissipation, power requirements, durability, precision, accuracy, and size need to be addressed. Motors often are chosen with high overcapacity because the characteristics of the operating environment are unknown or highly variable, or the developer doesn't know how to translate the system requirements into motor specifications. Sometimes limitations such as cost or the power supply are sufficiently high that more powerful motors can be chosen.

Yet these choices can lead to less efficient solutions. Likewise, some motors are chosen to match simple motor control requirements. A more complex motor control solution may be more efficient and less costly in the long run, so it pays to know the alternatives. This is especially true for small to midrange motors where non-dedicated microprocessor control is an option. In this case, the microprocessor in question may control the motor, but it has sufficient headroom to handle other aspects of a product such as the user interface plus system monitoring and control.

As the workhorses in the home and industry, ac motors revel in fixed locations accessible to the ac power distribution system that is readily available in most industrial countries. Heavy-duty ac motors aren't the only alternatives, though, with small and mobile solutions being used in a variety of applications.

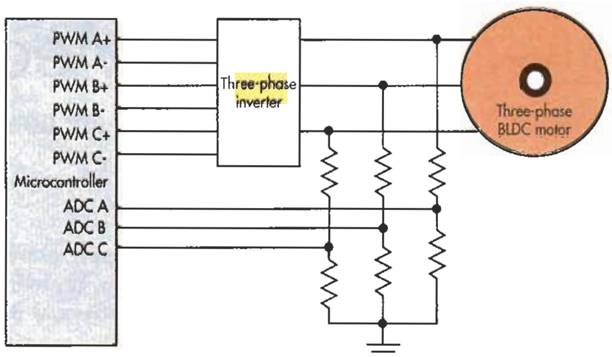
One of the most common ac motors, the induction motor, uses an electromagnet in the rotor but doesn't require a commutator because the stator induces the current in the rotor. Essentially, the motor is a transformer. The rotor has closed coils that typically have low resistance for handling large current.

Even though dc motors can address heavy-duty applications, they also are the motor of choice as size comes down. These types of motors fall into two categories: brushed and brushless. Brushless motors use permanent magnets in the rotor.

Brushed dc motors have an armature that must be powered. Separately excited or brushed dc motors have independently powered rotor and stator windings. A shunt configuration is simply a separately excited motor with the rotor and stator connected in parallel. A series configuration connects the rotor and stator windings in series. Some motors can switch between shunt and series configurations for more efficient startup.

The windings for a brushed dc motor can be wound around an iron core. Eliminating the core allows a lighter rotor that is desirable for rapid acceleration. These kinds of motors are often found in high-speed servos.

Much of the activity in the motor arena has focused on brushless dc (BLDC) motors because of the need for more active control for efficient operation. Low-cost microcontrollers make these motors very practical. Also, improvements in the computational power and performance of the processors enable developers to combine motor control functions with the rest of the application instead of having to dedicate a chip to a motor.



3. This typical circuit for a three-phase BLDC motor control uses "sensorless" EMF feedback.

Universal motors run off ac or dc current, though they are typically used with an ac source. Meanwhile, solenoids are common devices that are really linear motors. They can be found in automotive applications where an open/close operation is needed.

Linear motors have other applications as well. Some require precise movements, as in plotters. Magnetic levitation trains use linear motors for traction often combined with levitation support. In this instance, the stator is the track, but normally only a portion of the track will be active at one time.

Motor Terms

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Technically, the term **electric motor** includes all motors, but it's typically used to refer to rotational motors. In **linear electric motors**, movement is linear instead of rotational. The **stator** is the fixed part of the motor. The **rotor**, which is the part of the motor that moves, typically rotates. The **armature** is the rotor coil.

The **commutator** connects brushes on the stator to the coils on the rotor. It's used to reverse the current flow in the windings. It also includes a minimum of three segments to prevent dead spots. More segments can be used for better, more efficient operation. In **continuous motors**, the rotor moves continuously. In **stepper motors**, the rotor moves in increments. The **servo** provides positional feedback.

There are two types of **ac motors**: synchronous and induction/asynchronous. In synchronous motors, speed is independent of load. Synchronous motors also will hold position if the dc current is applied to the rotor and stator. They provide accurate speed and position controls using an open-loop system. And, they include active rotors or permanent magnet rotors. Induction/asynchronous motors include squirrel cage, slip ring, or solid-core rotors. They can include one, two, or three phases.

Brushed dc motors depend on how the coils are wound and connected. Windings can be separately excited, as each stator/rotor gets its own power source. With a shunt setup, the field and armature windings are connected in parallel, just like separately excited windings but with the same power source. Or, the field and armature windings can be connected in series for high current. Compound windings mix shunt and series arrangements. Meanwhile, **coreless dc motors** use a special case with only windings. Optimized for rapid acceleration, they're used in high-performance servos.

There are two types of **brushless dc (BLDC) motors**: servos and reluctance/continuous. The reluctance/continuous variety provides high power density and low cost. BLDC motors require a permanent magnet, usually in the rotor. They also offer low electromagnetic interference (EMI), and they don't need a commutator, brushes, or sparking. However, they require feedback motor control. Sensor feedback involves the Hall effect or rotary encoders, while sensorless feedback uses electrical feedback.

Universal motors can run on ac or dc, though they typically use ac. They're often used in locomotives that can use ac or third-rail dc. With their high-speed, high-torque, and compact design, they're typically used in blenders and drills. They also use a simple thyristor motor control.

Linear motors can be induction or stepper motors. There are ac and dc versions as well as brushed dc and BLDC versions. Finally, **piezoelectric motors** use crystals that change shape, making rotational and linear motors possible. They can range in size from small to extremely small.

Motor control with feedback makes the job of designing a system a little more complex, but there are benefits depending upon the kind of feedback provided. For example, quadrature encoders can provide position information in addition to velocity information. Hall effect and optical sensors are two common external feedback systems. Sensorless feedback refers to the use of a sensor that isn't an external device like Hall effect and optical sensors.

Piezoelectric motors are a special class of electric motors that do not use magnetic flux for movement. Instead, they use the deformation properties of some crystals when power is applied. They tend to be small and can be extremely small.

Piezoelectric motors are easier to construct than conventional electric motors of comparable size and performance. Their small size makes them a match for many portable applications, such as the lens zoom support in cell phone cameras.

MOTOR CONTROL

An on/off switch is often the only thing sitting between a motor and its power supply, but it provides limited control. It also can be inefficient. The lack of control takes this approach out of the realm of mechatronics, where computer control is key.

The next step up is electronically controlling the on/off switch. This is accomplished by using transistors for dc control and devices such as silicon controlled rectifiers, thyristors, and triacs for ac control. For ac control, variable power and speed can be attained by turning on power for a fraction of the power cycle because it is easy to set the threshold of these devices.

The H-bridge is normally used for handling dc motors, including BLDC motors, where rotation may be reversed as in drills or servos *(Fig. 2)*. Current flows through opposite pairs of transistors when they are turned on. Turning on all the transistors isn't a good idea. In this case, the motor doesn't turn and transistors get rather warm before acting like blown fuses.

Different power transistor technology, such as MOSFETs and bipolar, can be employed. The diodes are included in the circuit to protect the system during transition periods where back electromotive force (EMF) would cause undue stress.

Pulse-width modulation (PWM) signals from a microcontroller normally control the transistors. This provides the motor with speed control, and it works because motors are an inductive load. Another advantage of driving the transistors using a PWM signal is that the torque essentially remains constant. Changing speed by varying the voltage would also change the torque. This could be desirable in some instances, but an H-bridge generally will be driven via PWM signals.

4. Luminary Micro's RDK BDC BLDC reference kit is representative of motor control kits that come with a motor. The 32-bit Cortex-M3 core is available with communication interfaces such as Ethernet and CAN.

The precision and accuracy of the PWM output along with the power components and power supply will affect the efficiency and operation of the motor. Also, it is good practice to allow some "dead time" between turning off a transistor and turning on the other transistor when changing polarity. This is especially true in multiphase motor control.

Motor control with feedback makes the job of designing a system a little more complex, but there are benefits depending upon the kind of feedback provided. For example, quadrature encoders can provide position information in addition to velocity information. Hall effect and optical sensors are two common external feedback systems. Hall effect sensors are mounted to detect the field from the electromagnets that are part of the rotor. LEDs tend to be aimed at a target on the rotor that reflects light to sensors near the LED.

Sensorless feedback refers to the use of a sensor that isn't an external device like Hall effect and optical sensors. Instead, the sensor is electronic and examines the electrical subsystem used to drive the motor. The sensors use the back EMF that is inherent in an electric motor's operation.

Sensorless feedback is normally used on multiphase motors. A similar approach can be used on a single-phase, H-bridge implementation, but it is done in a polling mode. In this case, the controlling microcontroller would stop the PWM signal train so all the transistors are off and the motor essentially acts like a generator. It then uses an analog-to-digital converter (ADC) input connected to the motor to check the output. This takes a few milliseconds, so the effect is minimal and allows a sample rate of about 50 Hz. This approach can be used with Acroname's Brainstem Moto 1.0 power control module, which is used in robotics.

A typical three-phase BLDC controller includes three ADC sensor inputs, one for each phase of the drive system *(Fig. 3)*. One way to implement this is by including a series resistor in the drive circuit and using a differential ADC to measure the voltage across it. A small resistance minimizes overhead but increases the range and precision requirements of the ADC.

The three-phase motor control also works differently from the polled H-bridge example. In a three-phase motor, only two of the coils in the rotor are powered at any one time. The power control unit has three pairs of transistors instead of the two pairs that the H-bridge has.

Timing is also key to proper operation of a motor control program. Delays are necessary at various points in algorithms to allow for motor inductance and other effects that prevent proper sensing. For example, in a three-phase BLDC application, there will be a feedback pulse when a winding is commutated at the start of open phase voltage transition.

More robust motor control algorithms need to account for a number of different factors. Likewise, control algorithms can predict the results of the sensing system and compare the predictions with the actual results. Additional optimizations can be performed when this information is available.

Finally, startup can be an issue. In three-phase BLDC motors, the rotor can be found in one of six logical positions. The position is initially unknown because there is no back EMF to detect. The trick is to assume a position, start the motor, and change the results once the motor is moving.

REFER TO THE APP NOTE

Motor control mavens can tackle motor control chores, but mere mortals need a starting point. This can be true when motor control is only part of the application being placed on a microcontroller. This is where application notes, reference designs, and development kits come in.

Development kits like Luminary Micro's RDK BLDC often include a motor and matching power circuitry *(Fig. 4)*. Luminary Micro has a three-phase version as well. These kits are great for learning about motor control. The circuit diagrams make a good starting point, especially if the end motor characteristics are close to the motor included with the kit.

Luminary Micro's kit has a 32-bit microcontroller based on ARM's Cortex M3. The latest 100-MHz incarnation uses 130-nm technology with a 4-μA hibernate mode. It has Ethernet and USB with a multiply accumulate (MAC) and physical layers (PHYs) as well as a CAN 2.0b MAC. Control-area network (CAN) PHYs are always separate chips because of the variation used in different industries.

5. The Renesas SH7286 Starter Kit module plugs into a Renesas reference design power module that is not part of the kit. Motor control platforms often don't include the power module because it must be matched to the motor being controlled.

These communication interfaces represent one way that motor control is changing. Network interfaces are becoming more common in replacing simple serial interfaces.

The Renesas SH7286 Starter Kit highlights another way vendors are delivering motor control solutions *(Fig. 5)*. The starter kit is a typical development module that plugs into a power board. Renesas will loan reference design boards and provide design services to help match power support to motors.

The 100-MHz, 32-bit SH7286 also has USB, CAN, and Ethernet support. Based on Renesas' superscaler 200 MIPS SH-2A core, it is designed for dual motors. A typical high-performance motor control overhead is 30% or about 60 MIPS/motor. This leaves a significant chunk of time available for other services, even with two motors. It has a six-channel PWM module with automatic shutdown with one fault input pin per motor. Faults can be noted by edge transition or pulse duration.

The platform can handle ac induction motors and universal motors. It also can handle three-phase BLDC motors using high-end, field-orientation control algorithms, which are designed to deliver high efficiency as well as low-noise motor control.

The module is designed for development purposes. The processor and the power elements are often built onto a single custom board. Several vendors offer modules that are used in their development kits, which are also available for deployment. For example, the Texas Instruments controlCard is a dual-inline memory module (DIMM) with a C2000 digital signal controller. It must be paired with a board that has power transistors. These host boards are found in development kits as what must be designed to address actual deployment.

Motor control algorithms can be quite complex. But once implemented, they can be simple to control. This is where the other half of mechatronics control comes into play, yet it tends to be more application-dependent. For instance, servo control is used for robotic arms while drive motors handle rolling for many robots.

These movements require precision control. Precise feedback control is also needed for balancing robots that only use a pair of wheels. The Segway PT (personal transporter) also uses this balancing inverted pendulum technique.

Motivated by hybrid cars, regenerative braking is more complicated because the motor acts as a generator but also because the system must account for the power sink. Batteries aren't created equal, and most have a limit as to how fast they can be charged, making the circuitry and control more complex.

Motor control algorithms are well supported, though regenerative braking is not. Finding a development kit that supports it will be a bit more difficult than finding one to control the same motor. Especially challenging is ac induction motor regenerative braking because the variable frequency control is key to generating current at lower speeds.

Regenerative braking is just one aspect of braking. Dynamic braking can be used to quickly stop or reverse a motor for ac motors by feeding the stator windings with dc current. It isn't possible to recoup power as in regenerative braking, but braking can be smoother and more power-efficient under microprocessor control.