STEPPER MOTORS AND DRIVE METHODS

Often a mechanical operation or function is required in an application. This may in turn require a motor or other mechanical device to position a load or device. Examples are computer peripherals (scanners,disc drives, etc), camera, telescope and satellite dish positioning systems, robotic arms, and numerically controlled machine tools. While a conventional DC or AC motor can be used, it is difficult to accurately determine the exact position of the load, motor speed, or how much total motion has been produced, unless external positioning sensors, encoders, servo loops, and controlling devices (brakes, clutches, etc) are used. Many motors run at a speed in RPM that is too high, and this involves using a gear train to reduce the speed and increase the torque to useable levels. While this may not always be a problem, conventional motors can be difficult to use for certain applications. Where very high speed is not a factor and precise control is desired, a stepper motor may be advantageous. Many applications require lower speeds, below a few hundred revolutions per minute, and often conventional type motors include integral gear speed reduction systems. A stepper motor is a device that translates an electrical signal to a change in position of a shaft or other actuator. This is usually a linear translation or rotation. Unlike a conventional DC or AC motor, this is usually a discrete quantity, and occurs when a pulse or other signal is applied. While DC or AC motors are driven continuously, a stepper motor is driven generally by pulses. Stepper motors are somewhat similar to reluctance motors, i.e. they depend on attraction or repulsion of magnetic structures and derive their torque solely on the change of reluctance of a magnetic circuit, whereby a conventional motor derives its torque from the interaction of current carrying conductors with magnetic fields. A stepper motor cannot draw a higher current in a stalled rotor condition, to rapidly accelerate a load from rest to speed. This stalled rotor condition is momentarily encountered during startup of conventional motors due to mechanical inertia. It causes an initially high current to be drawn by the motor. DC and AC motors can, within reason, draw the higher current they need to start up quickly. Stepper motors depend on reluctance torque only, so they can not start up as large a load as a comparable conventional motor. A stepper motor will move a load a certain discrete amount for each pulse applied, then stop and do nothing until another pulse is applied.

Fig 1 shows a basic stepper motor. The armature or moving part, is a magnetic structure that may be only soft iron, (reluctance type) or may be a permanent magnet itself (hybrid type). Several electromagnets (poles), called the stator, are arranged around the armature, or rotor. When the electromagnets are energized as shown, the rotor will turn until it lines up with the opposite poles. Thre figure shows the final position of the rotor as well. If two adjacent stator magnets are energized so that the polarity is the same, the rotor will tend to line up between these poles such that the magnetic circuit has minimum reluctance, which is the easiest path for the magnetic lines of force. After this occurs, nothing else will happen. The electromagnets have a steady state current now flowing in their

windings. The current flow will hold the rotor in position and a certain externally applied torque will be needed to move the rotor out of this position. This current flow acts as a brake, and therefore no external brake mechanism is needed. This force will be from several inch-ounces to several hundred inch ounces, depending on the motor. Motors with a permanent magnet rotor have a residual magnetism present and therefore a braking effect still exists with no current flow in the stator windings. Stepper motor speeds are typically from zero to a few hundred RPM, and they are best suited to low speed applications

Naturally, a stepper motor physically like the one shown would not be very useful as only large angles of rotation (45 degrees or multiples of this) could be obtained unless gearing was used. Real world stepping motors have toothed rotors that often will resemble a gear, 48 or more discrete steps, with usually 200 or sometimes 400 steps. This allows 1.8 degree or 0.9 degree increments respectively, or even smaller by using half or mini stepping methods. Common stepper motors are usually two or four phase, depending on the number of windings on the stator. Usually there are two or four, and often the windings may be connected internally, to reduce the number of external leads. This is often done with the ground connections. All stepper motors will have at least two phases, with four commonly used. There are also six phase stepper motors available. There are 3 basic types of stepper motors. The VR (variable reluctance) type has a soft iron rotor and can be turned when de-energized, since there is no holding torque. The PM (Permanentl magnet type has a radially magnetized rotor. This type has detents when deenergized, which may present a problem in some applications. It is not suitable for small step angles. The hybrid type has an axially polarized rotor with 2 sections, one with all north poles, the other with all south poles, and is a combination of the VR and PM type. The hybrid and variable reluctance types are the most commonly used.

Stepper motors have several advantages:

a) They can be operated in open loop systems
b) Position error is that of a single step.
c) Error is non-cumulative between steps
d) Discrete pulses control motor position
e) Interface well to digital and microcontroller systems
f) Mechanically simple, no brushes, highly reliable

Disadvantages are:

a) Fixed increments of motion
b) Low efficiency, driver choice important
c) High oscillation and overshoot to a step input
d) Limited power output
e) Limited ability to handle large inertial loads
f) Friction errors can increase position error.

Some basic stepping motor terms are as follows:

Step angle: Angular increment the motor shaft rotates with each activation of the windings, in degrees. The step angle divided into 360 degrees gives the number of steps per revolution

Drivers: Circuitry for interfacing stepper motors to power sources. Contains logic, power supplies, switching transistors, connections to external interfaces

Steps per second: The number of angular movements per unit time

Step accuracy: Non cumulative error expressed as a percentage of step increment. As an example, a 1.8 degree step with a 5 percent error may actually be 1.71 to 1.89 degrees.

Holding torque: The amount of externally applied torque needed to break away the motor shaft from its holding position, with rated current and voltage applied to the motor

Residual Torque: Present only in motors with a permanent magnet rotor, it is the torque present as a result of rotor magnetism under power off conditions.

Resonance: Mechanical natural frequency of a motor assembly due to mass and "spring" tension from magnetic forces. It can be controlled mechanically or electrically

Pulse rate: Rate at which windings are switched in pulses per second. If one pulse steps the motor one step it is also the stepping rate of the motor.

Damping: Control of motor overshoot, controlled electronically or mechanically

Translator: Circuitry to control motor switching sequence so one input pulse moves rotot one step

Ramping: Variation of pulse frequency to accelarate or decelarate stepping motor. Useful for high speed applications or with loads with large inertia.

Step response: Mechanical output of the motor versus time in response to a unit step input.

Start/Stop without error: Maximum step rate which a motor can start or stop without losing steps or synchronism.

Stepper motors must be interfaced with drive circuitry in order to be useful for performing a task. There are many drive schemes. The scheme chosen should be

consistent with the technical requirements, motor type, economic requirements, and available components and interfacing. Basically, the problem is to drive the stepper motor windings, which are represented by a series circuit containing resistance and inductance (R-L circuit). These windings must be driven with correct current and voltage drive levels and pulse widths. Normally, a series resistance is used to limit the current, or a constant current source can be used. The time constant of the L-R circuit is equal to L/R, which means that a low inductance, high resistance circuit will have a shorter time constant. This implies using a high voltage and a high circuit impedance, or a current source. Power supply voltages may be 12, 24, 48, or higher. The higher voltages are advantageous in allowing a larger series resistance and shorter L-R time constant.

From the driver point of view, the problem is one of driving a series L-R circuit and maintaining good control of waveforms, and avoiding damage from inductive switching transients. Either bipolar or MOS technology can be used for the drivers and the associated logic circuitry. MOS has the advantages of "rail to rail" capability, but at most reasonable voltages this is not usually a problem and bipolar devices will usually be adequate. Several approaches can be used. While discrete component circuitry can be built up from individual components, it may be simpler and more cost effective to use IC devices for this function, at least for the logic, sequencing, and control circuitry.

A basic driver circuit is shown in the figures, using a switching transistor, motor winding, and power supply, Defining quantities:

Vs = power supply voltage
Rx = external resistance (Includes that of power supply)
Rw = motor winding resistance
Rr = Leakage resistance across switch
Lw = motor winding inductance

The initial current, when the switch is open is:

$$I = I_o = V_s / (R_x + R_w + R_r)$$

When the switch is closed, the current will be:

$$I = I_o + [V_s (1 - e^{-t/T}) / (R_x + R_w)]$$

Where T = time constant = Lw / (Total Circuit Resistance)

This says the current will rise suddenly and gradually approach the value of

$$I = I_{final} = V_s / (R_x + R_w).$$

After a period of three time constants the current will be about 95 % of its final value, and after five time constants the current will approach the final steady state value within less than one percent. It is the property of an inductor that the current cannot change instantaneously in the absence of impulses. Therefore, when the switch transistor turns off, the final current keeps flowing, and flows through a total circuit resistance of (Rx + Rw + Rr), which can be very high. A very high voltage appears across the switch transistor. This could reach several thousand volts, but practical limitations such as stray capacitance and the breakdown voltage of the switch transistor limit this. Nevertheless, the switch transistor(s) must sustain this high voltage.

Note that the current takes time to reach its full value, and this time is decreased for high values of circuit resistance and lower winding inductance. But higher resistance means higher voltages must be used to obtain the necessary drive current. This makes more demands on the switching transistors with regard to voltage breakdown. For short excitation times, the current may not have time to reach the desired value unless special measures are taken. The ability to rapidly turn on and turn off the current in the windings directly affects the rate of stepping that can be achieved for a specified level of performance of the stepper motor. There are two basic drive formats used to drive stepper motors. Unipolar drive uses a bipolar motor winding, with one coil energized at a time, current flowing in only one direction. This does not fully use both windings. At low step rates torque and performance are sacrificed, but the drive circuitry is simplified, since only one switch transistor per winding is needed. The bipolar format employs a reversal of winding current to reverse the stator flux. Current flows in all windings at the same time. Full use is made of the windings, and at low and medium step rates performance is improved. However this requires more complex drive circuitry, since a bridge type driver output circuit is required. This is generally an H bridge. See figs for driver configurations. H-bridge IC drivers are available for the power stages that drive the windings. Alternatively, complete IC devices including drivers can be used if preferred.

In addition to these basic formats there are several others that can be used. They are called full step, half step, and mini or micro stepping. They differ in the energization sequence or polarity of the current in the windings, at various times. An illustration of these stepping methods is shown in the figures. Fig XX is simply one phase at a time, in a 1-2-3-4 sequence. The shaft rotation direction is controlled by the sequence, reversal of which will reverse the direction. The sequence is called wave drive. Since one winding is energized at a time, it consumes the least power. Positional accuracy is good since the rotor and stator teeth are aligned at one time. This is a full step mode, with a step angle of 360 degrees divided by the number of steps per revolution. This method can be used with either unipolar or bipolar drive format.

Another full stepping method employs sequentially energizing two adjacent motor phases, in a 1-2, 2-3, 3-4, 4-1 overlapping sequence. This uses two windings at

a time and gives a higher torque, better damping, and better immunity to resonance effects. However, it uses twice the drive power since two phases are used at once, and can suffer from imbalance. Any variation in the windings or driver can unbalance the magnetism produced by two adjacent windings, and they may not be exactly equal. This unbalance can cause detent position errors, since the effective pole lies between the adjacent pole positions.

Another method is called half stepping or alternating drive. This method combines the two previous methods, in a 1, 1-2, 2, 2-3, 3, 3-4, 4, and 4-1, yielding double the number of steps as compared to the two previous methods. The wave drive has stable positions when the rotor teeth are aligned, and the overlapping drive has stable positions in between two rotor teeth. This effectively doubles the angular resolution, making 400 steps from a 200 step motor, for example. This produces smoother operation, is quieter, and has better accelaration characteristics. However, more complex drive and logic circuitry is needed to generate the signals for the switching transistors.

For even finer steps mini or micro stepping can be employed. Half stepping uses one or two phases fully excited. If one phase was to be fully excited, and the other only half excited, a new stable position would be generated. If, in the previous sequence, instead od 1 followed by 1-2, we would have 1 followed by 1 plus half 2, then 1-2, then half 1 plus 2, then 2, and so on. This would yield quarter steps, giving 800 stable positions for a 200-position motor, as compared to using full stepping. This can be carried even further into "micro"stepping, by varying the drive currents in four excitation levels, giving 8 positions per step, or 1600 total. As one may imagine, this can become quite complex, and more expensive. However, with LSI IC devices, this can be quite feasible. Care must be used in maintaining drive waveforms, as more steps demand more precision as to drive currents, in contrast to the simple on-off requirements of full or half stepping.

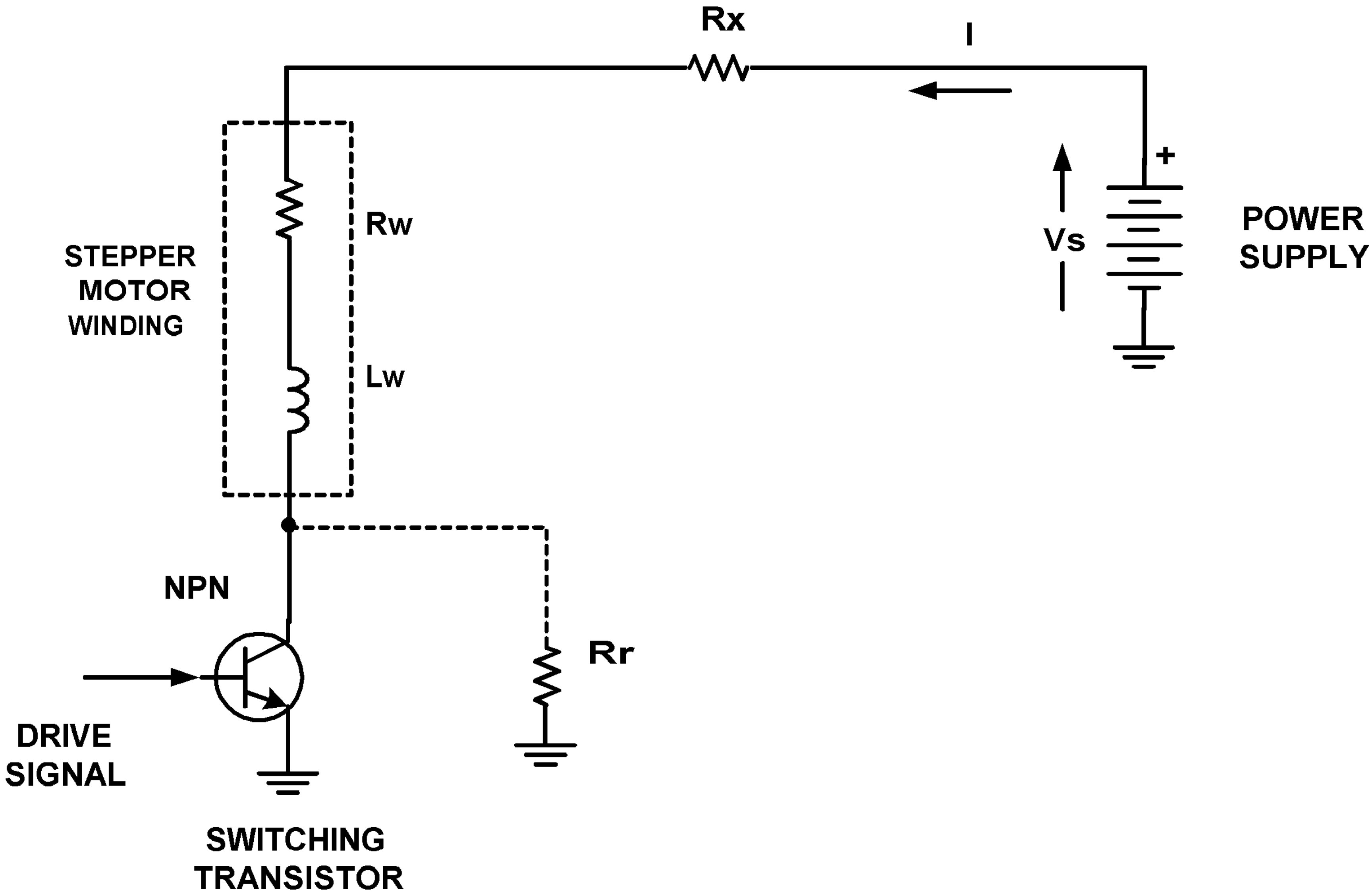
Single ended stages may be used for unipolar stepper motor drive applications. However, for bipolar applications a dual polarity driver is required. This can be achieved with the "H" bridge as was shown in the figures. This uses four transistors. Each transistor has a driver included to form Darlington pairs. This structure can easily be made in monolithic form. Q1 and Q3 are PNP, whileQ2 and Q4 are NPN devices. Care must be taken to see that Q1 and Q2 are not turned on at the same time, as this would cause a short circuit across the power supply, with large current spikes. This also applies to Q3 and Q4. In this circuit we have two voltage drops, one in each transistor pair, resulting in a loss of 1.5 to 3 volts of supply voltage, but this is usually not a problem. The use of a monolithic array for Q1 through Q4, including their drivers is a good idea, since it simplifies PC board layout and eliminates possible transistor matching problems. The design of the driver circuitry is another topic and we will not go into this aspect of stepper motors in this article. Fig XX shows a typical unipolar driver circuit using TIP32 or TIP42 plastic power transistors and a few logic gates. This circuit will drive many 4 phase

surplus stepper motors and can be used to experiment with or to test motors you may have already in your stock of parts.

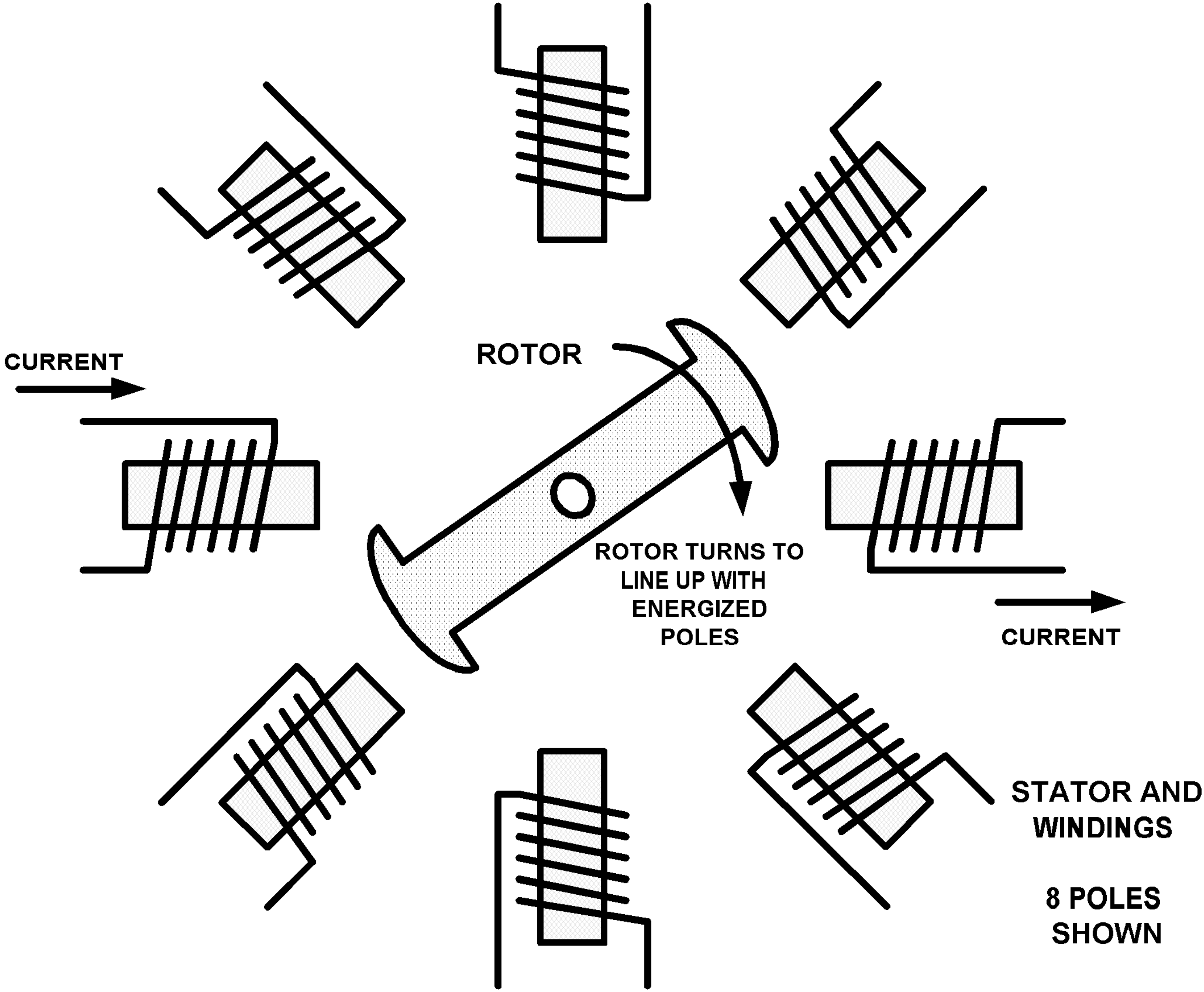
Note also that the waveforms needed can easily be generated using a microcontroller. The microcontroller can also be progranmmed to perform other necessary functions, such as on-off, positioning, counting, speed control, stepping mode (full, half, etc), speed regulation, and fault protection. The drive waveform(s) can be generated with a routine incorporated into the microcontroller firmware. From the viewpoint of the experimenter, the microcontroller approach has the advantage of programmability for specific applications and is probably the most versatile way of generating stepper motor control signals.

Stepper motors are somewhat expensive when purchased new, but you should be able to find used ones on the surplus market. The throw-away mentality plus the rapid obsolescence and disposal of so much computer and office equipment that is prevalent today should provide sources of usable stepper motors for the experimenter. Check out in particular junked scanners, fax machines, drives, and old copiers, you may find some useful stepper motors for free. You can accumulate a wide variety of hardware and components useful in robotics as well.

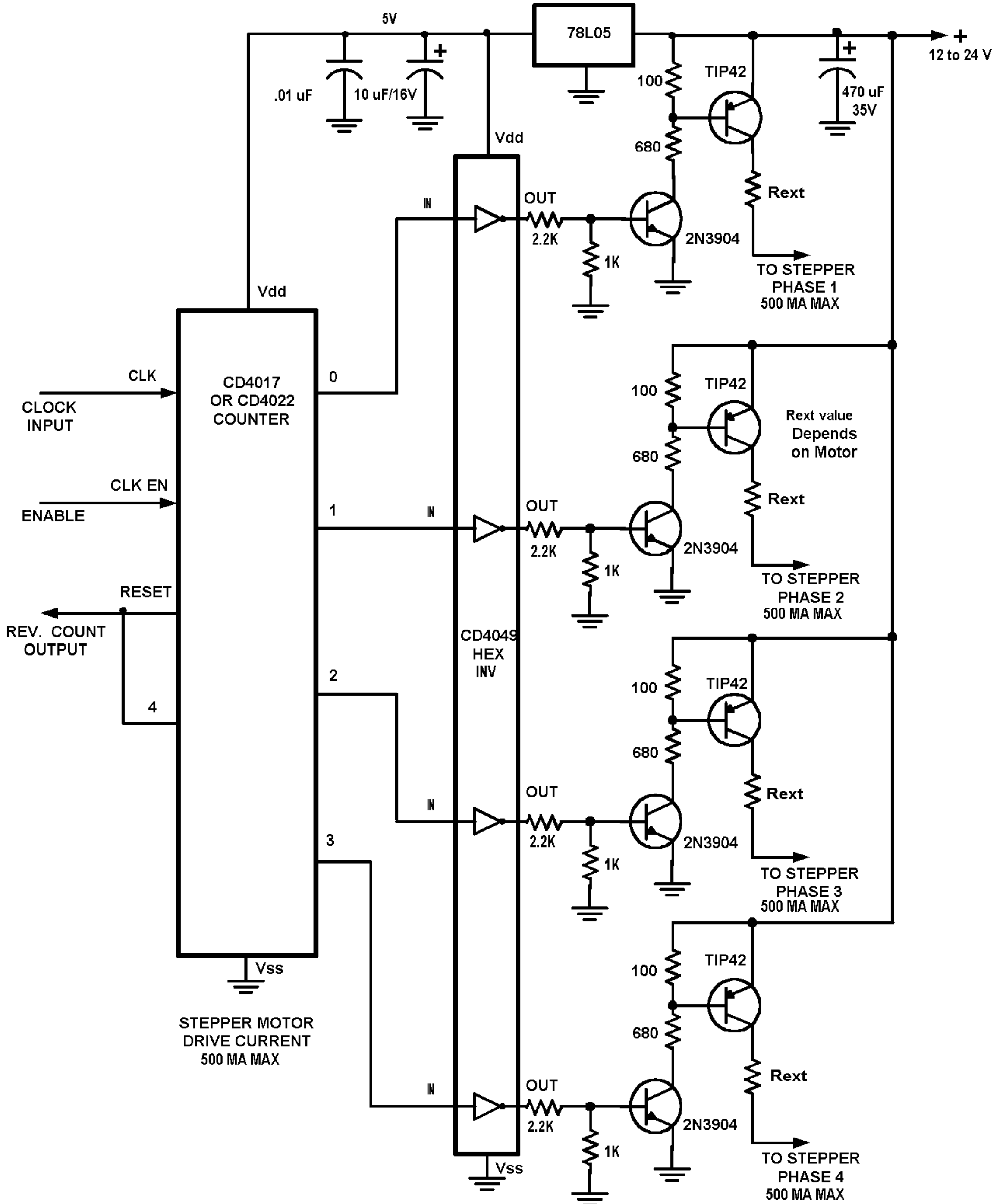
The stepper motor can be mechanically coupled to a gear train or pulley system to reduce its speed and increase torque, and/or to a cam or mechanical linkage to drive an actuator to do a required task. One such application is a positioning mechanism using a screw thread and a nut. This drives a cam and linkage that in turn positions an arm. It could also be used to position a video camera, or a steering or control linkage. This mechanism is easily assembled from hardware store components, and does not need expensive and often difficult to locate gears. It is shown in fig XX. Some mechanical applications will require speed reduction or translation of motion from linear to rotary, and vice versa. The screw thread and nut will perform a rotary to linear translation, but not the reverse. Linear to rotary translation will possibly require rack and pinion gears, pulleys, or friction drive components such as wheels and belts. Gears are commonly available from surplus houses if you do not have exacting requirements, and also can be obtained from junked machines and appliances. If you need an specific type and size, they can be obtained from vendors, but be prepared to pay. One can collect many metal and plastic gears from discarded items and appliances, but your projects must be designed around what you have. Another possible method is to use pulleys and belts. These can be salvaged from old equipment as well, and pulleys can also be homemade from wood or plastic, or obtained at hardware stores in various sizes. Friction drive components can also be obtained from junked items such as old cassette and reel to reel tape decks, discarded turntables, and also small appliances. Stepper motors can therefore be used in robotic and other applications in a number of ways and also may simplify those applications needing exact positioning without using positioning sensors and feedback techniques.



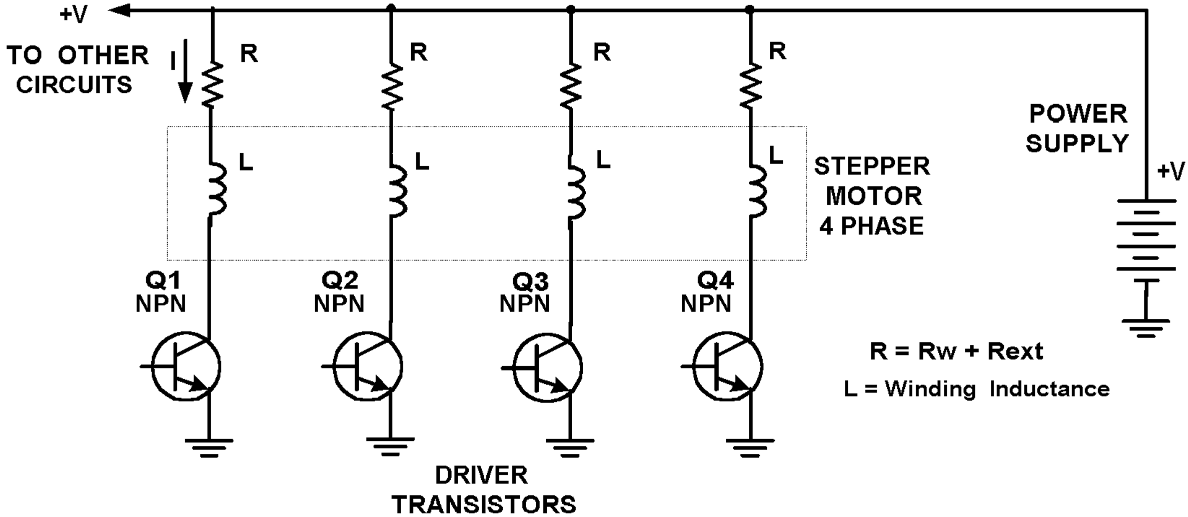
BASIC STEPPER MOTOR DRIVE CIRCUIT



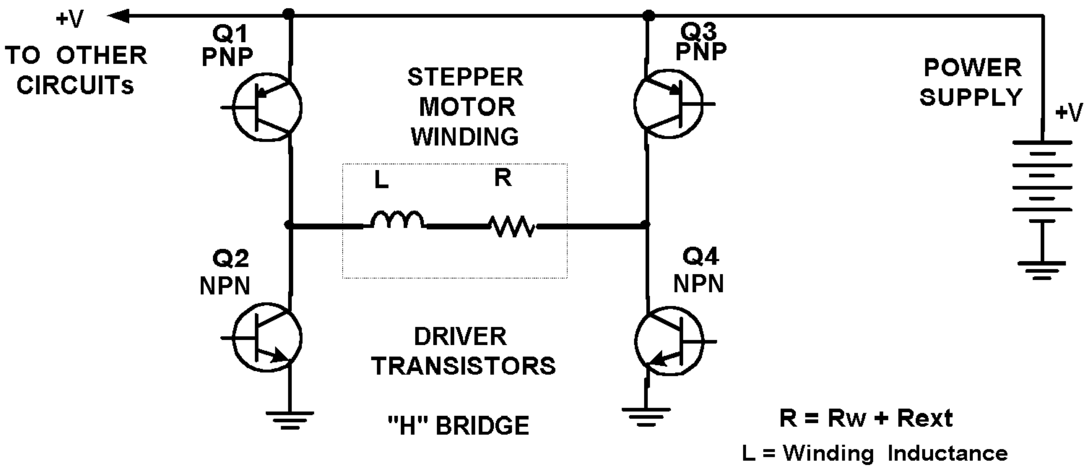
BASIC STEPPER MOTOR



STEPPER MOTOR DRIVE CIRCUIT
FULL STEPPING
4 PHASE UNIPOLAR DRIVE

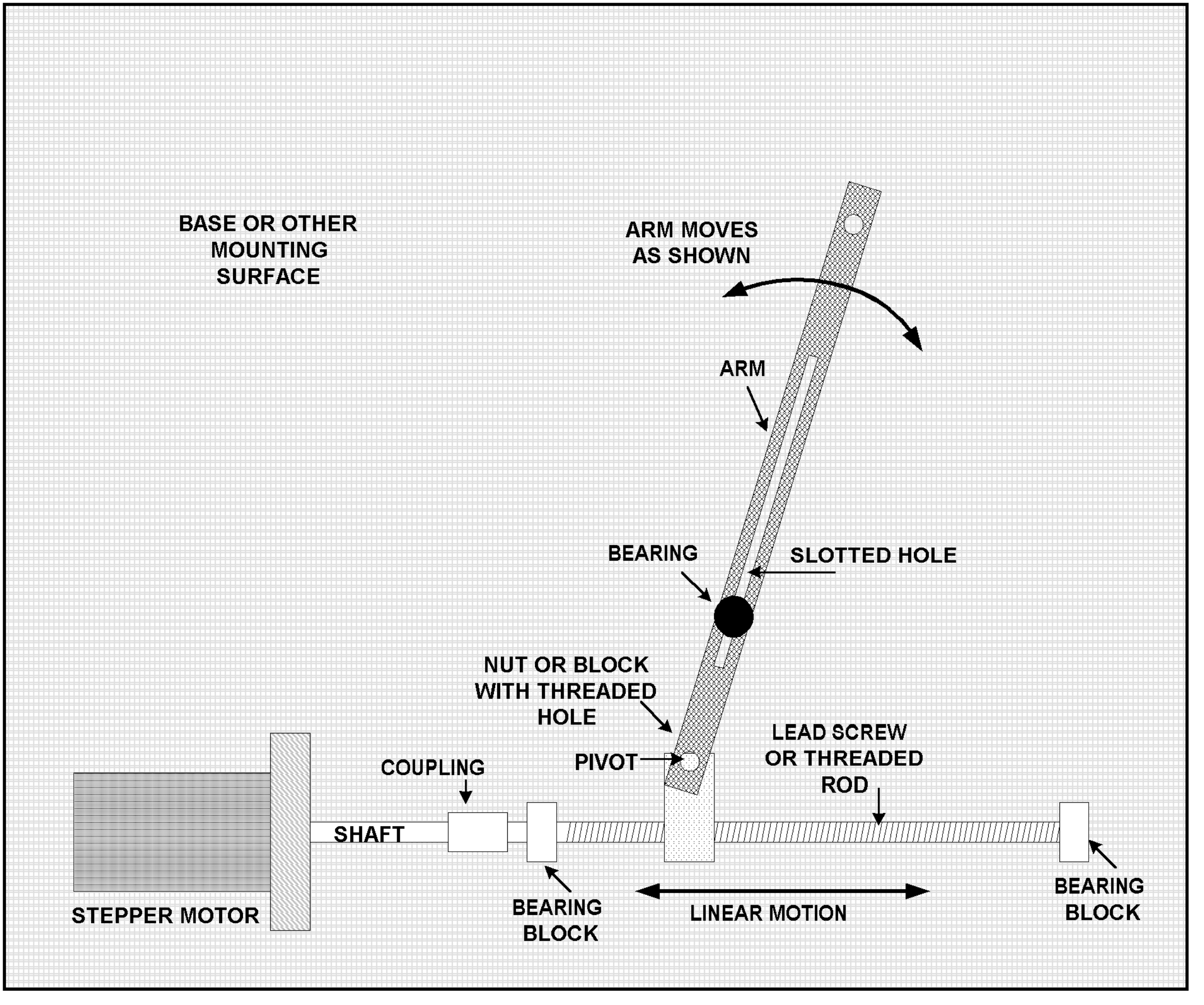


UNIPOLAR DRIVE
4 PHASE



BIPOLAR DRIVE USING "H" BRIDGE
(ONE PHASE OF STEPPER MOTOR SHOWN)

STEPPER MOTOR DRIVE CONFIGURATIONS



INTERFACING A STEPPER MOTOR TO A MECHANICAL LINKAGE AND ARM USING A LEAD SCREW

PHASE / STEP	1	2	3	4
1	ON	OFF	OFF	OFF
2	OFF	ON	OFF	OFF
3	OFF	OFF	ON	OFF
4	OFF	OFF	OFF	ON

FULL STEPPING

PHASE / STEP	1	2	3	4
1	ON	OFF	OFF	OFF
2	ON	ON	OFF	OFF
3	OFF	ON	OFF	OFF
4	OFF	ON	ON	OFF
5	OFF	OFF	ON	OFF
6	OFF	OFF	ON	ON
7	OFF	OFF	OFF	ON
8	ON	OFF	OFF	ON

HALF STEPPING

STEPPER MOTOR DRIVE MODES