

LECTURE 3: Actuators, Encoders, Relays and Switches

Actuators:

An actuator is the device that brings about the mechanical movements required for any physical process in the factory. Internally, actuators can be broken down into two separate modules: the *signal amplifier* and the *transducer*. The amplifier converts the (low power) control signal into a high power signal that is fed into the transducer; the transducer converts the energy of the amplified control signal into work; this process usually involves converting from one form of energy into another, e.g. electrical motors convert electrical energy into kinetic energy.

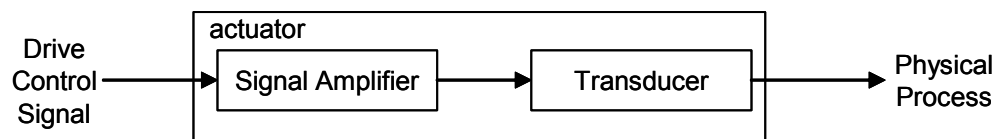


Figure 3.1. The Structure of an actuator

Examples:

Electric motors, Servo-controlled valves, pneumatic drives, hydraulic drives...

Our objective here is not to study the details of any type of actuators – this is out of the scope of any single course. However, we shall look at the basic principles behind the working of several common actuators. The goal is to get an understanding of what type of actuators are used in different applications and why, and to some extent, understand their benefits and limitations.

Everyone is familiar with electric motors – there are probably over 50 motors in any average home (e.g. inside a fan, hair-dryer, electric tooth-brush, vibrating phones, quartz watch, toys, microwave oven, fridge, computer, printer, etc.) We first look at basics of how motors work; next, we look at some simple motor types: DC, AC, Stepper and Servo-motors. Next we look at non-electrical actuators, including Hydraulic systems and Pneumatic actuators.

Electric Motors:

All electric motors use electromagnetic induction to generate a force on a rotational element called the rotor. The torque required to rotate the rotor is created due to the interaction of magnetic fields generated by the rotor, and the part surrounding it, which is fixed, and called the stator. This is easier to see if we first think in terms of magnets. Figure 3.2 shows a typical **DC**

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motor. Let's see how this motor works. A high-strength permanent magnet (field magnet) creates a magnetic field in the space occupied by the rotor. In this DC motor, the rotor is made of an axle with three radial arms fixed at equal angles around it. The axle is supported to the stator by a bearing, so it can rotate freely with respect to the stator. On each of the three arms, a conducting wire is wound in a coil, as shown; the direction of this winding is important. The coils are connected to three separate electrical contacts as shown. You can think of these contacts as a short tube of copper that has been cut to separate it into three pieces; the split ring made by these contacts is called the commutator.

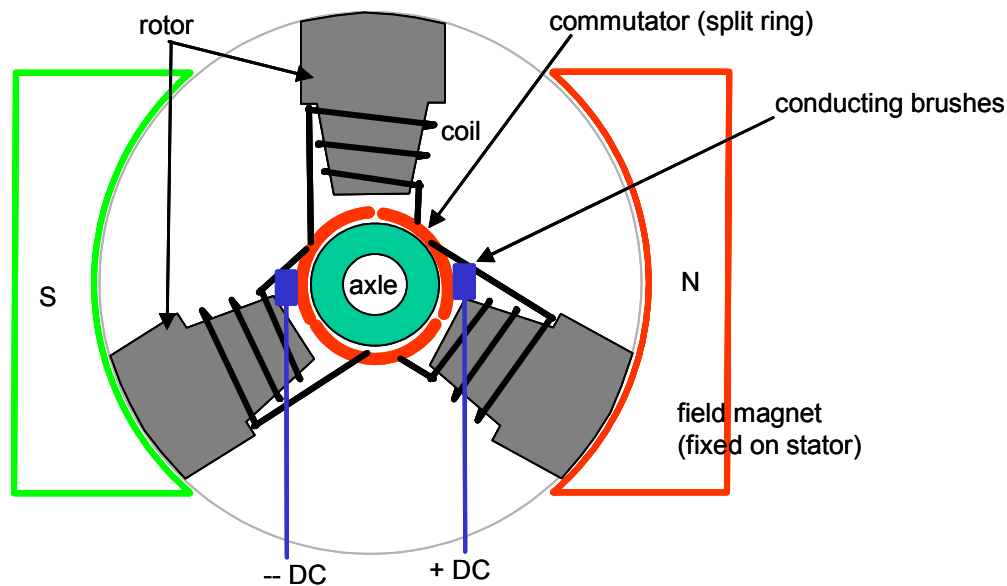


Figure 3.2. Structure of a 3-pole DC motor

Let us see how the motor works. Begin at the position as shown in Figure 3.2. A current flows through the coil on the top, inducing a magnetic field, and this arm behaves like a magnetic South pole. At the same time, the two coils in the bottom also experience a voltage drop across them. Look carefully at the positioning of the commutator; in this position, the two coils are connected in series; by the left-hand rule, both behave as magnetic North poles, but since they are in series, they are of less strength than the coil on top. In figure 3.3, we denote north poles in red color, and south poles in green. Also, half strength magnetization is shown by hashed line patterns.

[*Fleming's left hand rule*: when a current-carrying coil of wire is grasped in the left hand, the fingers curled around the coil in the direction of electron flow, from negative (-) to positive (+), the thumb will point toward the North pole of the electromagnet.]

It is clear that in the position shown, due to the magnetic forces between the field magnet and the three electromagnets in the stator, there is a torque forcing the rotor to rotate Clockwise. But as

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soon as the rotor turns a little, the connections between the input voltage and the coils change due to the commutator, changing the magnetic poles in the rotor arms. See Figure 3.3 (b) to see what the situation is like at this point – instead of reaching an equilibrium position, the rotor is still getting a torque to go Clockwise. In figure 3.3., you can see that as the rotor rotates, the commutator keeps changing the direction of the electromagnets in the rotor to maintain a continuous torque in the Clockwise direction – thus making our motor to do work.

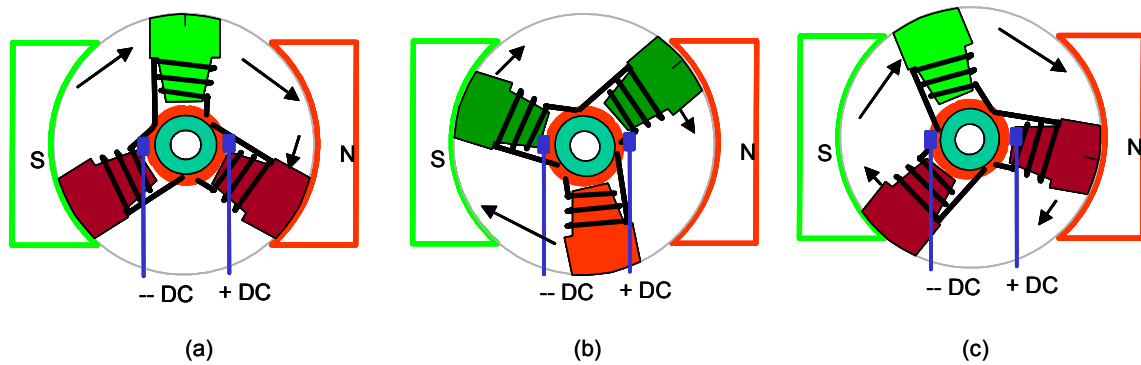


Figure 3.3. A Few stages of operation of a DC motor

Almost all small DC motors (the type that are used in most applications around your home) are a permanent magnet type; sometimes they have more than three poles, but the basic principle of operation is the same. In industrial DC motors, the electromagnetic fields in both, the rotor as well as the stator, are generated by passing the DC current through the electric wire coils in them. There are several types of large DC motors, depending on how the DC source is connected to the stator and rotor coils (namely, in series, in parallel, etc.) The table below summarizes the basic characteristics and uses of some of these. Figure 3.4 plots the basic characteristics.

Motor type	Speed regulation	Starting torque	Applications
DC series	very high	very high	Hoists, Gates, Trams, Trains, Bridges
DC shunt	low	medium	Printing press, Machine tools, Conveyors
DC compound	medium	high	Punch press, Shears, Crushers

Note: **Speed regulation** = (no load speed – full load speed)/no load speed

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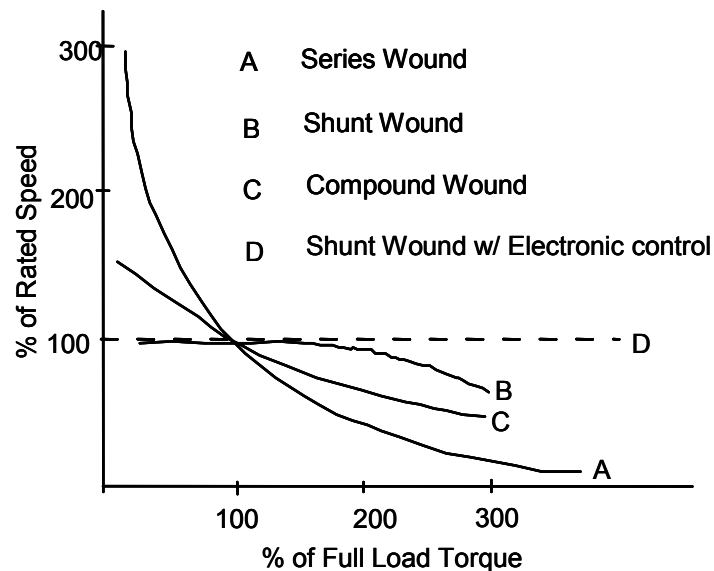


Figure 3.4. Characteristics of DC motors

In *AC motors*, only the stator has coils through which current passes. This current creates an alternating electromagnetic field, which induces an alternating current in the rotor. The interaction of the two electromagnetic fields is used to create the driving torque. The study of AC motors in more detail is out of the scope of this course. The table below summarizes the main types of AC motors, their characteristics and typical applications. AC motors are very commonly seen in machine tools in labs and workshops, since AC power sources are available everywhere.

Motor type	Speed	Power	Applications
1-phase AC induction	Nearly constant in operational range, slightly less than the synchronous speed	~ 3 KW or less	Almost all medium power pumps, fans, blowers, machines
3-phase AC induction	Nearly constant over large range of loads	High, > 1.5 KW	High power pumps, machinery

Motor Controls:

Many motor applications are not sensitive enough to require very tight accuracy of speed or control over the motion. However, from the viewpoint of manufacturing and production automation, such considerations are critical. For instance, any robot actuator requires that its motion be governable in positioning, velocity and acceleration with very high accuracy. Similarly,

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most NC machines have all their actuators controlled to provide positioning accuracy that is one order of magnitude less than the required accuracy of the part being manufactured. Considering that the typical tolerance on steel parts is 0.001 inch or less, this means that the machine controller has to be able to move the machine table to less than one-thousandths of an inch of the programmed point. How are such precise motions generated? The two most common motor types used in such applications are stepper motors, and servo-driven motors (or simply, servomotors).

Stepper Motors

Stepper motors rotate in discrete steps (e.g. 2° for each step); they have many uses, especially in motion for robots and locating or indexing tables. Their working principle is similar to DC motors, but they are controlled by digital electronics: an electronic circuit turns a series of switches ON and OFF at each electrical pulse input to the stepper motor control.

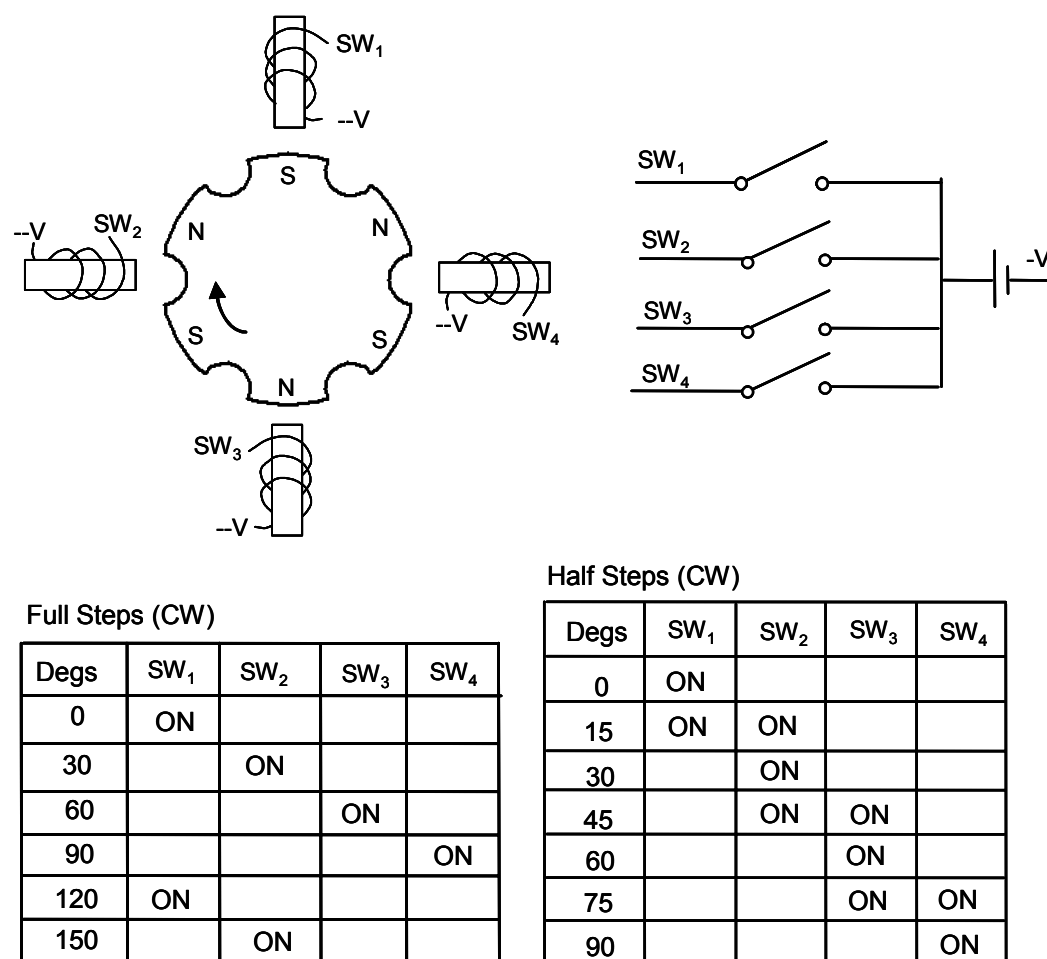


Figure 3.5. The principle of the Stepper Motor

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The stepper motor is driven by feeding it a stream of electric pulses. Each pulse makes the motor rotate by a fixed angle. Figure 3.5 shows a simple stepper motor. The rotor is a permanent magnet, configured so as to have a series of equally spaced (angularly) sets of poles along the circumference. The stator has a corresponding number of coils. The stepper motor can be operated in three different methods: full steps, half steps, and micro-steps. Depending on the method used, the step size (i.e. degrees rotated per pulse) is different. Figure 3.5 shows how the motor works in Full and Half-step modes. In full-step mode, only one of the stator coils is activated at a time, causing the rotor to align its poles in opposition to the electromagnetic poles of the energized coil. In half-step mode, a combination of coils are activated in a way so as to increase the resolution of the motor (i.e. step sizes are smaller). The third method used by stepper motor drive units is application of pulses of different voltages to different coils. By proper selection of the voltage levels applied, smaller steps can be produced; this method is called micro-stepping. Figure 3.6 shows the principle of micro-stepping.

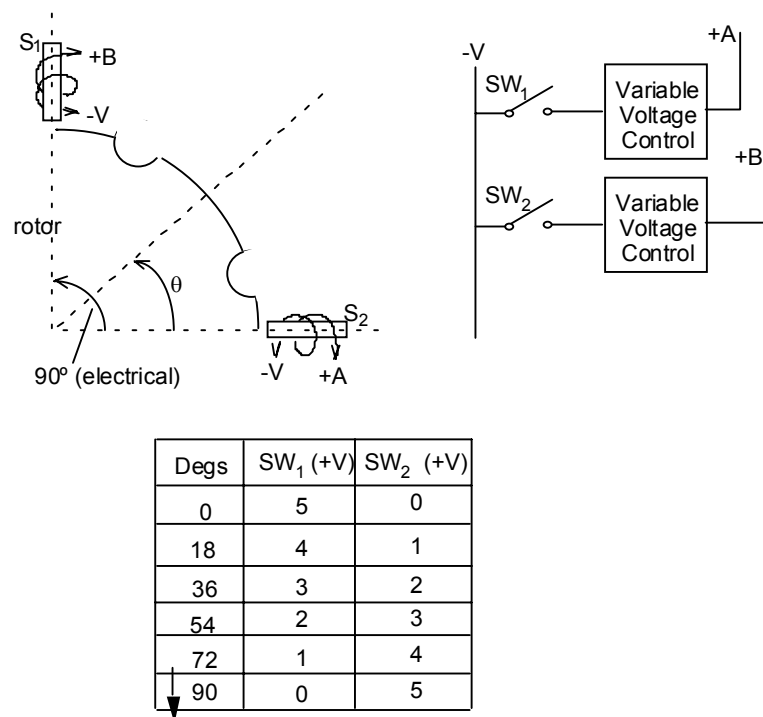


Figure 3.6. Microstepping controls for stepper motors

Stepper motors can only provide low torques. They are commonly used in laser positioning, pen positioning, disc and CDROM drives, robots, positioning tables etc.

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Servo Motors:

When higher torque *and* precise control are needed, servo motors are the best option. They provide high torque at all speeds, versatile speed control, very low drift (and therefore high repeatability), ability to reverse directions rapidly and smoothly etc. Servomotors may be AC or DC. In fact, practically any AC or DC motor can be converted to a servomotor by regulating it electronically, and using position and force feedbacks. Since the servomotors are driven through this electronic control, they are also easily interfaced with microprocessors or other high level controlling devices quite easily. The digital signal from the computer is converted to its equivalent analog level via an electronic DA converter.

Hydraulic Actuators:

Hydraulic systems are often used for driving high-power machine tools and industrial robots. They can deliver high power and forces. They also suffer from maintenance problems (e.g. leakage of the hydraulic fluid, dirt/contamination of fluid.) Hydraulic actuators may be linear, or rotary.

- Give an example of a linear actuator. What are some applications?

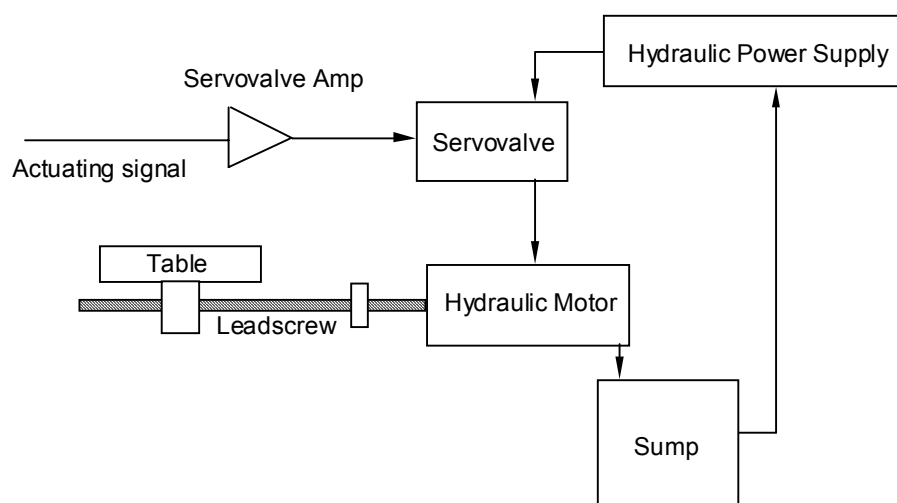


Figure 3.7. General structure of a hydraulic drive system

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Figure 3.7 shows the control system for a typical hydraulic rotary drive. The hydraulic power supply actually comprises of a pump, usually driven by a 3-phase electric motor. The pump may be a gear pump, or radial/axial displacement type. The functioning of the hydraulic motor itself is the opposite of the hydraulic pump. The servo control is exerted by applying a control voltage to a solenoid driven valve; the flow rate of oil through the valve is proportional to the voltage applied (itself proportional to the valve opening).

Pneumatic actuators

Pneumatic actuators work, in principle, similar to hydraulic actuators. The most common pneumatic controls are linear actuators, which are basically a piston-cylinder assembly connected to a supply tube of compressed air. Since air is highly compressible, pneumatic drives are frequently not used for high force transmission, nor are much good for accurate position control. Typically, they are used for fixed motion of small objects that are very common on assembly and transfer lines.

Discrete control of pneumatic systems:

Many operations on automation lines require steps like feeding of a part into a fixture, pushing the part on/off a conveyor (or between parallel conveyors, to change direction of travel), or transporting a part between several closely placed assembly or testing stations. Discrete pneumatic controls are ideally suited for such tasks. Figure 3.8 shows an example configuration for testing a part. For example, if a factory is producing high-voltage switches; each switch must be tested by applying high voltage and checking that there are no sparks. When the overhead testing machine is testing a part, all three pistons are retracted (P1, P2, and P3 are OFF). As soon as testing is over, the testing machine sends two signals to the pneumatic relay circuit: the first one indicates that the testing is complete, and the second one indicates if part is good. The first signal is used to open the relay valve for P3, which unloads the part to the out-chute. Full extension of P3 also triggers a limit switch (L1) on the chute. If the limit switch as well as the "part-is-good" signal are ON, P2 is activated, pushing the part into the collection bin. P2 then retracts. Full retraction of P3 triggers another limit switch, L2. Whenever a part is waiting on the in-chute, limit switch L3 is activated. On activation of L3 and L2, the relay valve for P1 is opened, pushing the new part onto the testing fixture.

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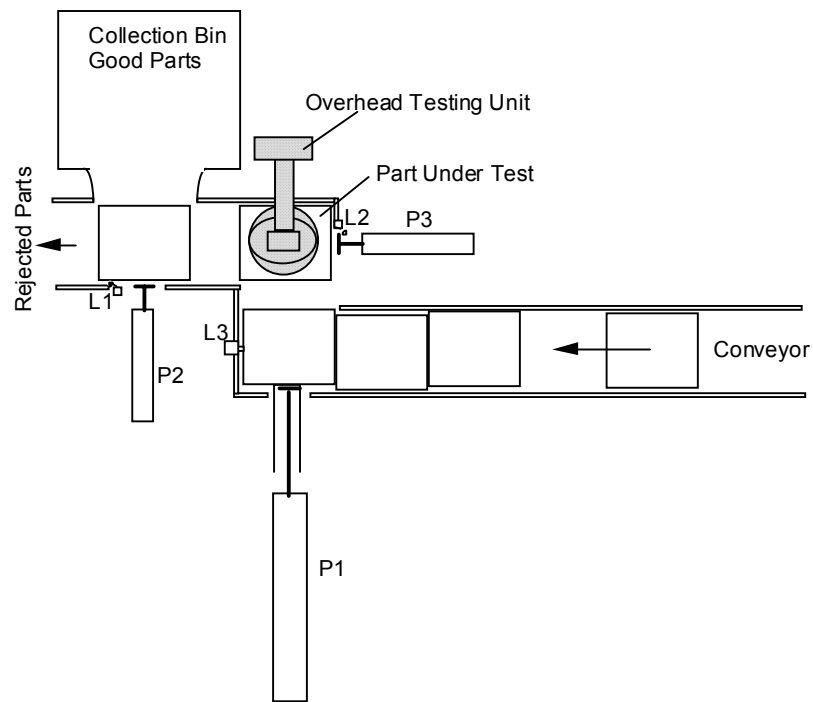


Figure 3.8. An application of pneumatic actuators for testing

Actuator characteristics:

Three major characteristics of actuators are accuracy, precision, and reliability. The definitions of these parameters are consistent with the corresponding definitions given earlier for sensors.

Switches

The most fundamental control of any equipment is the ability to turn it on/off. The easiest way to do this is using switches. Figure 3.9 shows typical configurations of switches.

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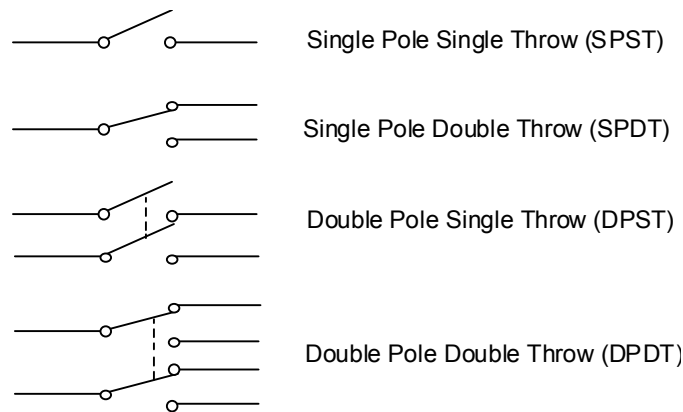


Figure 3.9. Configurations of switches

Relays

Although switches are universally used, they have their disadvantages. The biggest one is that they have to be manually (physically) turned on/off. Also, they are relatively large and occupy more space than the comparably rated alternative: relays. Relays are basically switches, which are turned on/off by application of a low voltage across the relay terminals. They are universally found in automatic control applications, since they can control equipment directly through electric signals instead of requiring physical operation. Figure 3.10 shows the structure of a simple relay. Relays may be *Normally Open*, or *Normally Closed*. In the former, the contacts are connected only when the actuation terminals are energized. In Normally Closed relays, the device is connected to the power supply when the relay actuation terminals are not connected. Relays with high current capacity (over 40Amps) are called *contactors*.

What type of relay does the figure show ?

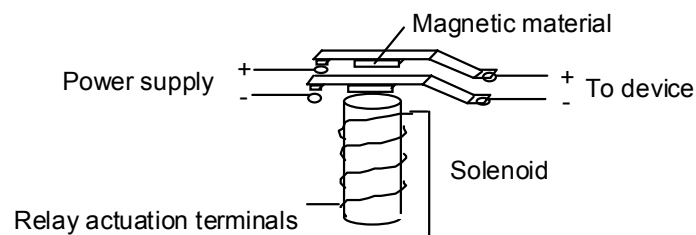


Figure 3.10. Schematic of a relay

Encoders

Encoders are sensors used to detect position. They can be linear, or rotational. The problem with linear encoders is that they have to travel the entire length of their range. Linear encoders,

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therefore, are long and expensive. Rotational encoders, on the other hand, are small and relatively cheap and less unwieldy. They are very common in many devices. The principle used in most encoders (linear or rotational) is the same: an optical device. We shall study two types of rotational encoders briefly.

Figure 3.12 shows an *incremental encoder*. The disc has three strips of opaque material which have been cut to form a binary counting pattern. At any stage, depending on the output of the three optical cells, the position of the encoder can be read off, as shown in the figure.

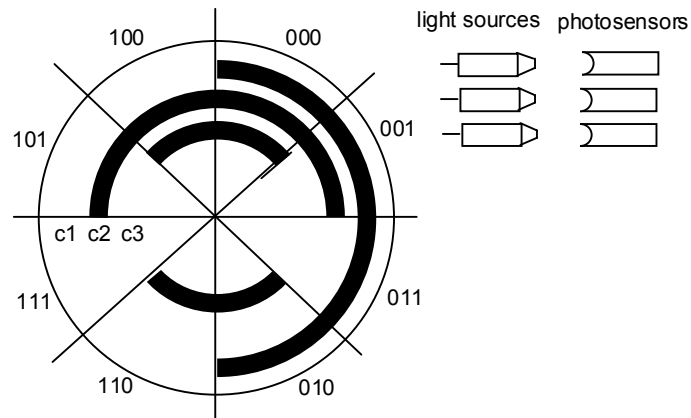


Figure 3.11. A Coded-Pattern encoder

An incremental encoder uses the same physical principle. However, since in this case there is no necessity to maintain absolute position, a simple pattern of evenly spaced opaque strips along the circumference of the disc suffice. The incremental movement (rotational) is determined by the number of cycles the photocell goes ON-OFF during the movement.

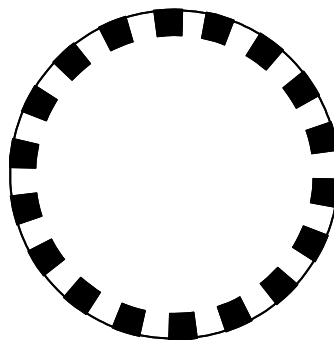


Figure 3.12. An incremental encoder

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By using two photocells instead of one, and by judiciously placing the two cells 90° out of phase with each other, the direction of movement of the encoder can easily be determined, as shown in the following figure.

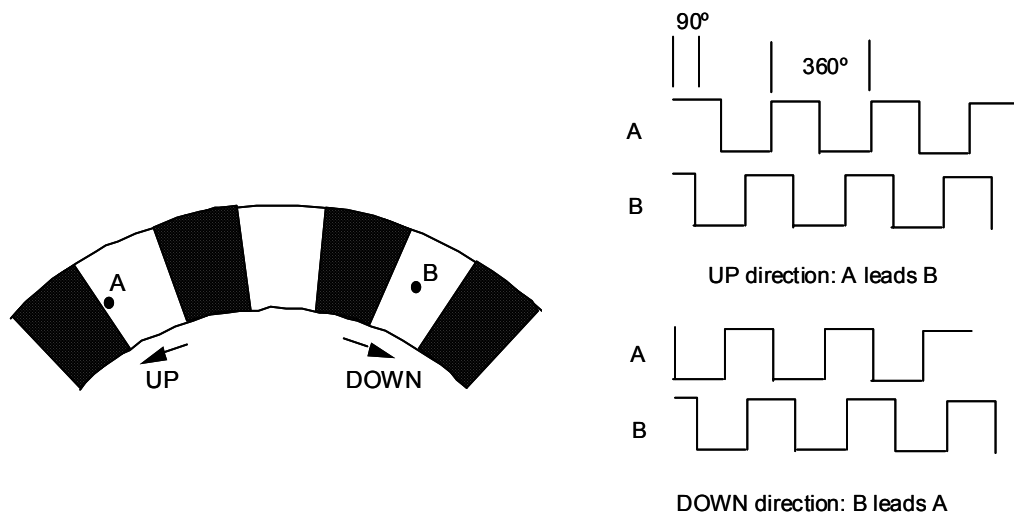


Figure 3.13. Using two sensors with 90° phase shift to sense direction

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