10. SENSORS AND ACTUATORS

10.1 Introduction

The purpose of this chapter is to describe the important features of the most common sensors and actuators used in robotic systems. If you are interested in learning about sensors and actuators in greater detail please take the 4H03 Mechatronics course in Term 2. Programmable Logic Controllers (PLCs) are also covered in the Mechatronics course.

10.2 Actuators for Driving the Joints

There are three main types of actuators: hydraulic, pneumatic and electromechanical. Hydraulic actuators provide a high power to weight ratio but their power supplies (pumps, hoses, etc.) are very bulky. They are also relatively dangerous since they operate at high pressures (more than 1000 psi) and the oil used is toxic and flammable. Pneumatic actuators also have a relatively high power to weight ratio, and are safer since they use air and operate at less than 100 psi, but they are difficult to precisely control. Electromechanical actuators have the worst power to weight ratio but they are the easiest to precisely control and the easiest to interface. For these later reasons, they are the most common type of actuator used to drive robot joints.

The typical joint actuator consists of a rotary DC motor attached to a mechanical transmission. The basic structure of a brush-type DC motor is shown in Figure 10.1. It includes a stationary "stator" consisting of permanent magnets, a rotating armature or "rotor" consisting of several coils, and a "commutator". The commutator uses a split ring and metal or graphite brushes to switch the direction of current flow through the armature coils. This creates a magnetic attraction that drives the rotation. Another option is a DC brushless motor. With a brushless motor the rotor consists of permanent magnets and the stator consists of several coils that are switched using external electronics to produce the rotation. Since brushes wear out over time, brushless motors are more reliable. They can also produce higher continuous torque since the windings are attached to the motor case, producing much better heat dissipation. They are usually more expensive than brush motors.

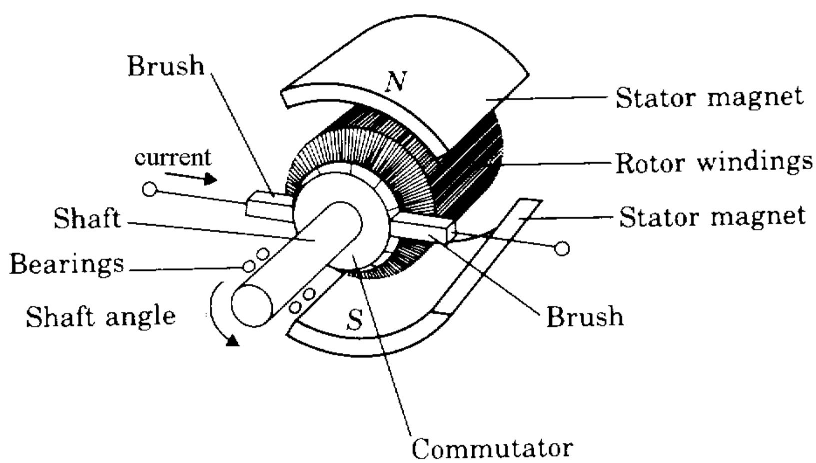

Figure 10.1 The components of a DC brush motor [1].

DC motors are relatively easy to control precisely. This is important since smooth and precise control of the motors is required for the motion of the robot's end-effector to be smooth and precise. A detailed discussion of DC motor control is beyond the scope of this course. However, two important properties of DC motors that help to make them easier to control are:

- The output torque is proportional to the armature current.
- The output speed is proportional to the armature voltage if the load is constant.

A significant disadvantage of DC motors is that they do not produce the high torques at low speeds needed for a robot, so mechanical transmission devices are necessary. These mechanical devices are used to convert the high speed, low torque motor behaviour into the desired low speed, high torque output. A typical revolute robot joint uses a gearbox with a ratio of around 300:1. Because the drives are built into the robot arm it is desirable to make the gearbox as small and lightweight as possible. For this reason, planetary gearboxes and "harmonic drive" reducers are often used. A typical planetary gearbox consists of an internal ring gear, planet gears, a planet carrier and a sun gear. The sun gear is the input and the planet carrier is the output. The internal ring gear is kept stationary. The reduction from a single stage is typically 5:1. Several such stages can be combined to produce high reduction in a small package. The disadvantage of a planetary gearbox is the gear backlash introduces positioning errors. A harmonic drive uses a completely different approach. It consists of a wave generator, a flexspline and a circular spline (see Figure 10.3). Normally the wave generator is the input, the flexspline is the output and the circular spline is kept fixed. As the elliptical shaped wave generator rotates it causes the flexspine to flex and rotate slowly relative to the fixed circular spline. A single stage harmonic drive can produce reductions of 300:1 and is lighter than a comparable planetary gearbox. Since the harmonic drive does not use gears it does not suffer from backlash, however the flexibility of the flexspline does lead to positioning errors. (If you're interested, more information on how harmonic drives work is available at: www.harmonic-drive.com).

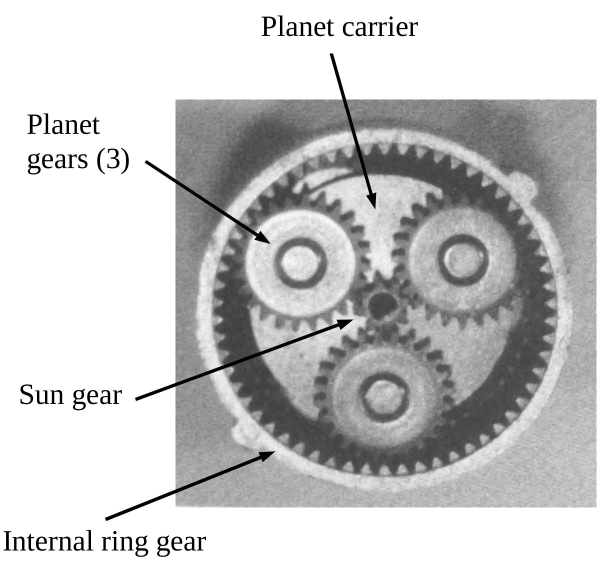

Figure 10.2 A typical planetary gearbox.

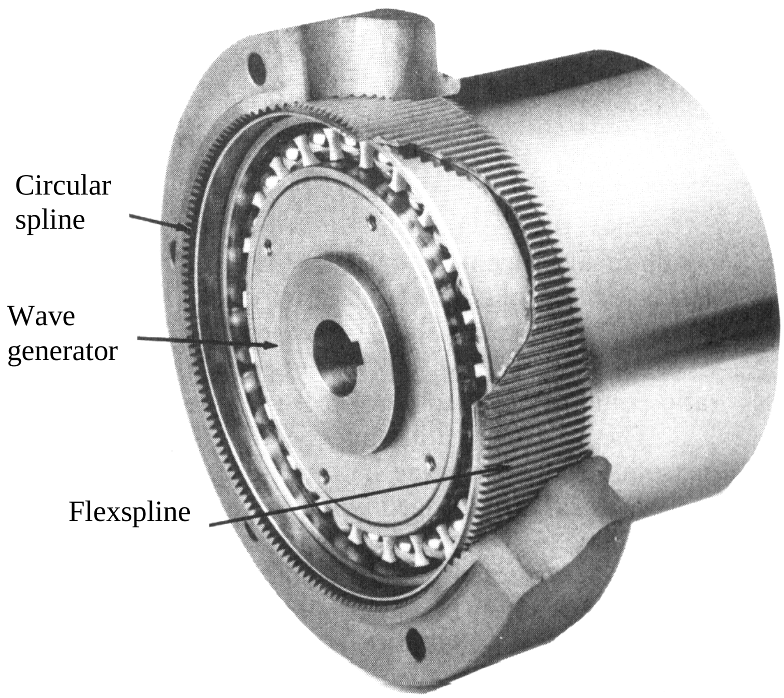

Figure 10.3 Cutaway view of a harmonic drive.

If the joint is prismatic, either the rotary motor motion must be converted to linear motion, or a linear motor must be used. Linear motors can produce faster, more precise motions but their high cost limits their industrial use. More commonly a ball screw is used. A ball screw is a mechanism consisting of a precisely ground screw and a ball nut. The ball nut and the output load are attached to a linear bearing. The ball nut is not allowed to rotate. As a result when the screw rotates the ball nut and load are made to translate. The ball nut uses ball bearings to convert the sliding action between itself and the screw into a rolling motion, reducing wear and the resulting backlash. A rack and pinion or a timing belt with pulleys are other less expensive and less precise mechanisms that are used to convert rotary to linear motion.

Examples of some actuators and transmissions will be shown in class.

10.3 Feedback Sensors for Controlling the Joints

Sensors are required to provide feedback to the robot controller so it may control the position and velocity of the joints. By far the most common type of position sensor is the rotary incremental optical encoder. One advantage of this sensor is its digital output makes it more immune to noise than sensors with analog outputs.

Its basic working principle is illustrated in Figure 10.4. The device shown will produce a single bit digital output signal. Typically an LED is used as the light source and a phototransister is used as the light sensor. The fixed disk contains a single slot, while the rotating disk contains many equal width slots. As the rotating disk is rotated the light will be sequentially blocked and unblocked, producing an ON (or high) pulse for each angular increment. The disks are made from etched glass or metal foil, and resolutions up to 10,000 pulses/revolution are available. Normally the rotating disk is attached to the output shaft of the motor (*i.e.* before the transmission mechanism).

The angle relative to where the motion started may be measured by counting the encoder output pulses using an electronic circuit. Since we require the absolute position (and not just the relative position) of the joints to control the robot, a calibrating or "homing" procedure must be performed when the robot is first powered up. Also a single output encoder is not practical since there is no way to tell if the pulse was produced by a movement in the positive or negative direction (*i.e.* should we add or subtract from the count?). A typical incremental encoder has two outputs, named Channel A and Channel B. They are created by two slots in the fixed disk that are offset by half a slot width. This offset causes the signals to be 100° out of phase as shown in the top part of Figure 10.5. If the pulse from Channel A occurs before the pulse from Channel B then the rotation is clockwise. If Channel A lags behind Channel B then the direction is counterclockwise. Using more advanced circuitry, the rising and falling edges from both channels may be counted rather than just the pulses from one. This is shown in the bottom part of Figure 10.5. This feature improves the effective resolution by four and is known as "quadrature counting". For example, if a 500 pulse/rev encoder is used with quadrature counting the resolution will be 360°/2000 counts = 0.18°/count. In addition to rotary encoders, linear incremental optical encoders are available for use with linear motors.

For speed control we also need to measure the joint velocity. A tachometer produces an analog output voltage proportional to the rotational speed. These sensors are not normally used since they are relatively expensive. Instead the position measurement obtained from the encoder is numerically differentiated. This method has the advantage that it may be done using software (for little added cost). It has the disadvantages that it amplifies noise and introduces a slight phase lag into the feedback loop. This will be discussed further in class.

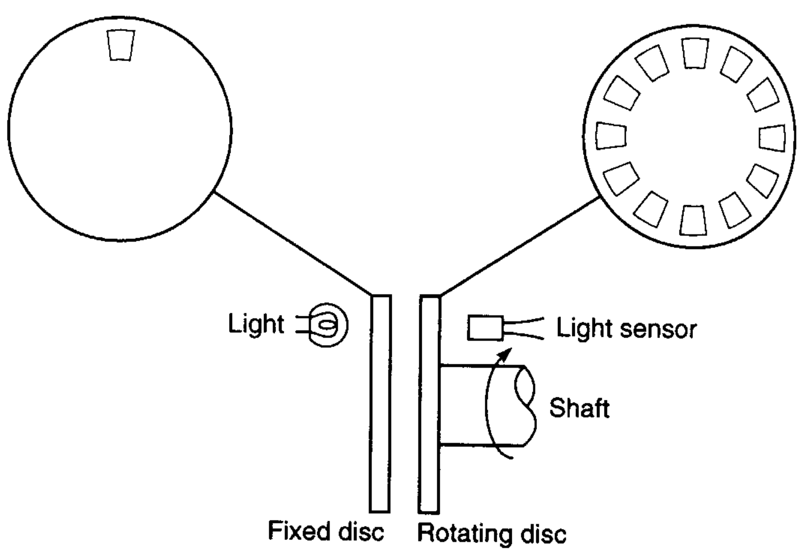

Figure 10.4 Basic working principle of a rotary incremental optical encoder [2].

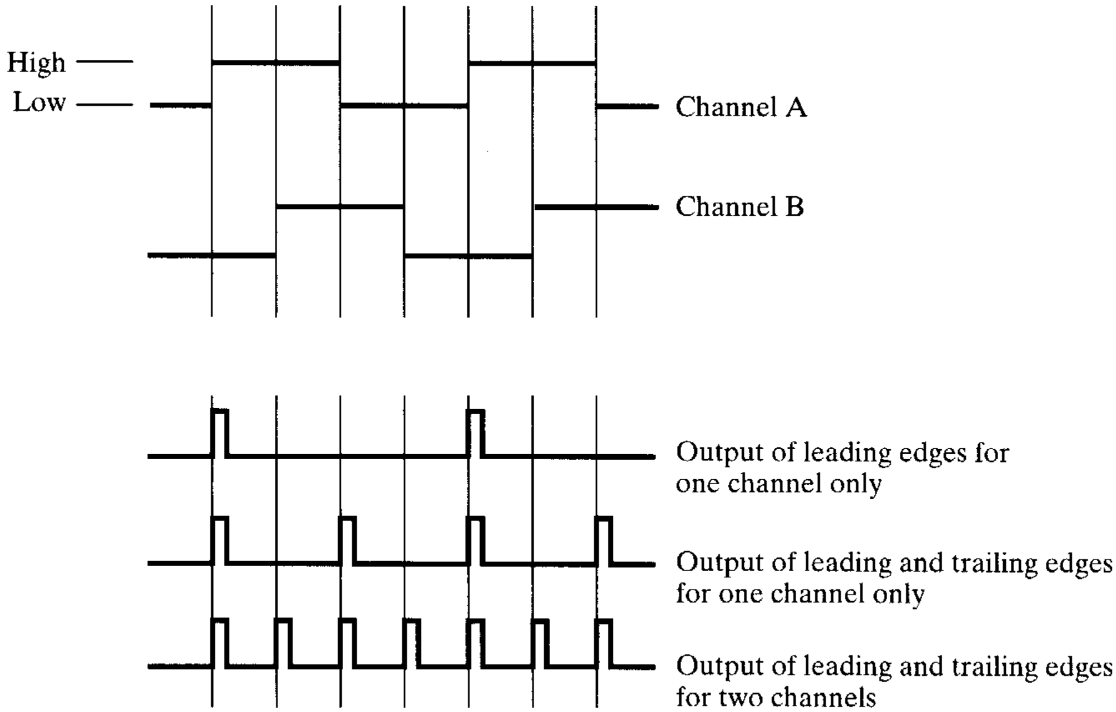

Figure 10.5 The use of quadrature counting to improve the effective resolution of an incremental encoder [3].

Examples of optical encoders will be presented in class.

References

1. J.J. Craig, “Introduction to Robotics”, Addison Wesley Longman, 110810.
2. W. Bolton, “Mechatronics”, 1st edition, Longman, 110105.
3. S.B. Niku, “Introduction to Robotics”, Pearson Education, 2001.