NIKU

different types of sensors may be available for the same purpose. In all these cases, the following may be considered before a sensor is chosen:

- **Cost:** The cost of a sensor is an important consideration, especially when many sensors are needed for one machine. However, the cost must be balanced with other requirements of the design, such as reliability, importance of the data they provide, accuracy, and life.
- **Size:** Depending on the application of the sensor, the size may be of primary importance. For example, the joint displacement sensors have to be adapted into the design of the joints and move with the robot's body elements. The available space around the joint may be limited. In addition, a large sensor may limit joint ranges. Thus, it is important to ensure that there is enough room for the joint sensors.
- **Weight:** Since robots are dynamic machines, the weight of the sensors is very important. A heavy sensor adds to the inertia of the arm, as well as reduces its overall payload.
- **Type of output (digital or analog):** The output of a sensor may be digital or analog, and depending on the application, this output may be used directly, or it may have to be converted. For example, the output of a potentiometer is analog, whereas that of an encoder is digital. If an encoder is used in conjunction with a microprocessor, the output may be directly routed to the input port of the processor, while the output of a potentiometer will have to be converted to digital signal with an analog-to-digital converter (ADC). The appropriateness of the type of output must be balanced with other requirements.
- **Interfacing:** Sensors must be interfaced with other devices, such as microprocessors and controllers. The interfacing between the sensor and the device can become an important issue if they do not match or if other add-on circuits become necessary.
- **Resolution:** Resolution is the minimum step size within the range of measurement of the sensor. In a wire-wound potentiometer, it will be equal to the resistance of one turn of the wire. In a digital device with n bits, the resolution will be

  $$\text{Resolution} = \frac{\text{Full Range}}{2^n}. \tag{7.1}$$

  For example, an absolute encoder with 4 bits can report positions up to $2^4 = 16$ different levels. Thus, its resolution is $360/16 = 22.5°$.
- **Sensitivity:** Sensitivity is the ratio of a change in output in response to a change in input. Highly sensitive sensors will show larger fluctuations in output as a result of fluctuations in input, including noise.
- **Linearity:** Linearity represents the relationship between input variations and output variations. This means that in a sensor with linear output, the same change in input at any level within the range will produce the same change in output. Almost all devices in nature are somewhat nonlinear, with varying degrees of nonlinearity. Certain devices can be assumed to be linear within a cer-

tain range of their operation. Others may be linearized through assumptions. If an output is not linear, but its nonlinearity is known, the nonlinearity may be overcome by proper modeling, addition of equations, or additional electronics. For example, suppose that a displacement sensor has an output that is varying with the sine of an angle. Then to use the sensor, the designer may divide the output by the sine of the angle, either in programming or through addition of a simple electronic circuit that divides the signal by the sine of the angle. Thus, the output will be as if the sensor were linear.

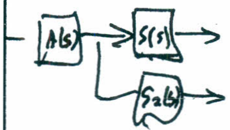
Dmax

$2^m - 1$

- **Range:** Range is the difference between the smallest and the largest outputs the sensor can produce, or the difference between the smallest and largest inputs with which it can operate properly.

$e^{-t/\tau}$

- **Response time:** Response time is the time that a sensor's output requires to reach a certain percentage of the total change. It is usually expressed in percentage of total change, such as 95%. It is also defined as the time required to observe the change in output as a result of a change in input. For example, the response time of a simple mercury thermometer is long, whereas a digital thermometer's response time, which measures temperature based on radiated heat, is short.



- **Frequency response:** Suppose that you attach a very-high-quality radio tuner to a small, cheap speaker. Although the speaker will reproduce the sound, its quality will be very low, whereas a high-quality speaker system with woofer and tweeter can reproduce the same signal with much better quality. This is because the frequency response of the two-speaker system is very different from the small, cheap speaker. For example, since the natural frequency of a small speaker is higher, it can only reproduce higher frequency sounds. On the other hand, the speaker system with at least two speakers will run the signal into both tweeter and woofer speakers, one with high natural frequency and one with low natural frequency. The summation of the two frequency responses allows the speaker system to reproduce the sound signal with much better quality. (In reality, the signals are filtered for each speaker.) All systems can resonate at around their natural frequency with little effort. As the forcing frequency decreases or increases from the natural value, the response falls off. The frequency response is the range in which the system's ability to resonate (respond) to the input remains relatively high. The larger the range of the frequency response, the better the ability of the system to respond to varying input. Similarly, it is important to consider the frequency response of a sensor and determine whether the sensor's response is fast enough under all operating conditions.

FB EXTENDS BW

- **Reliability:** Reliability is the ratio of how many times a system operates properly divided by how many times it is tried. For continuous, satisfactory operation, it is necessary to choose reliable sensors that last a long time, while considering the cost, as well as other requirements.

REAL!

- **Accuracy:** Accuracy is defined as how close the output of the sensor is to the expected value. If for a given input, the output is expected to be a certain value, the accuracy is related to how close the sensor's output is to this value.
- **Repeatability:** If the sensor's output is measured a number of times in response to the same input, the output may be different each time. Repeatability is a measure of how varied the different outputs are relative to each other.

A2D & ENCODERS

ERRORS

KLAFTER P238 – 242

A2D CONVERTER –

ACCURACY $\approx \frac{1}{2^m}$ for m-bits

10 bits $\frac{1}{1024} \times 100 \doteq 0.1\%$

IN EXAMPLE 4.5.1 HE USES 13 BITS

WOULD USE 14-bits

$2^{14} = 16384$ about 0.0061%

FOR 10V Full scale $\Delta V \approx 610\,\mu V$.

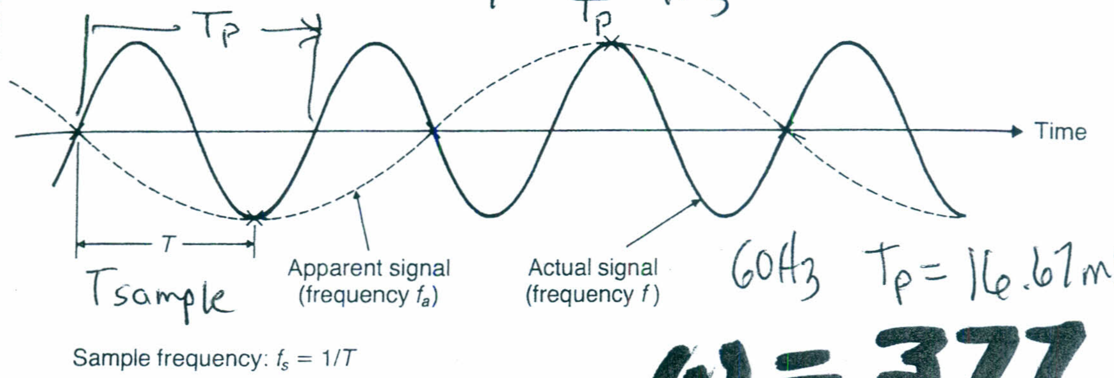
ENCODER ACCURACY

200 lines or counts / revolution

$\Delta\theta = \frac{360^\circ}{200} \doteq 1.8^\circ$ measure as θ_1

$\frac{\theta_2}{\theta_1} = \frac{1}{50}$ so $\Delta\theta_2 = \frac{1}{50}\Delta\theta_1 = \frac{1.8^\circ}{50} = 0.036^\circ$

$f = \frac{1}{T_P}$ Hz



60Hz $T_P = 16.67$ms

$\omega = 377$

Figure 6.14 Apparent low-frequency signal as a result of aliasing due to $f \geq \frac{1}{2}f_s$.

practical to eliminate the source of high frequencies in a signal to be sampled, a low-pass analog **filter** is usually placed at the input to the A/D converter as shown in Fig. 6.13. The function of this filter is to remove (ideally) all frequencies that are not less than half the sample frequency.

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Example 6.8 Aliasing Suppose that the power amplifier for a DC motor uses full-wave rectification of 60-Hz AC line voltage. Close examination of motor velocity reveals a 120-Hz ripple caused by the amplifier. Suppose further that motor velocity is to be controlled by a computer as shown in Fig. 6.15(a) via feedback from a tachometer, the output of which is sampled by an A/D converter. The sample period is to be $T = 0.008$ s.

As shown in Fig. 6.15(b), there is a 120-Hz ripple in the tachometer voltage. If no anti-aliasing filter is used, then with the sample frequency

$f_{max} = \frac{125}{2}$

$$f_s = \frac{1}{0.008\ \text{s}} = 125\ \text{Hz}$$

125 s/sec

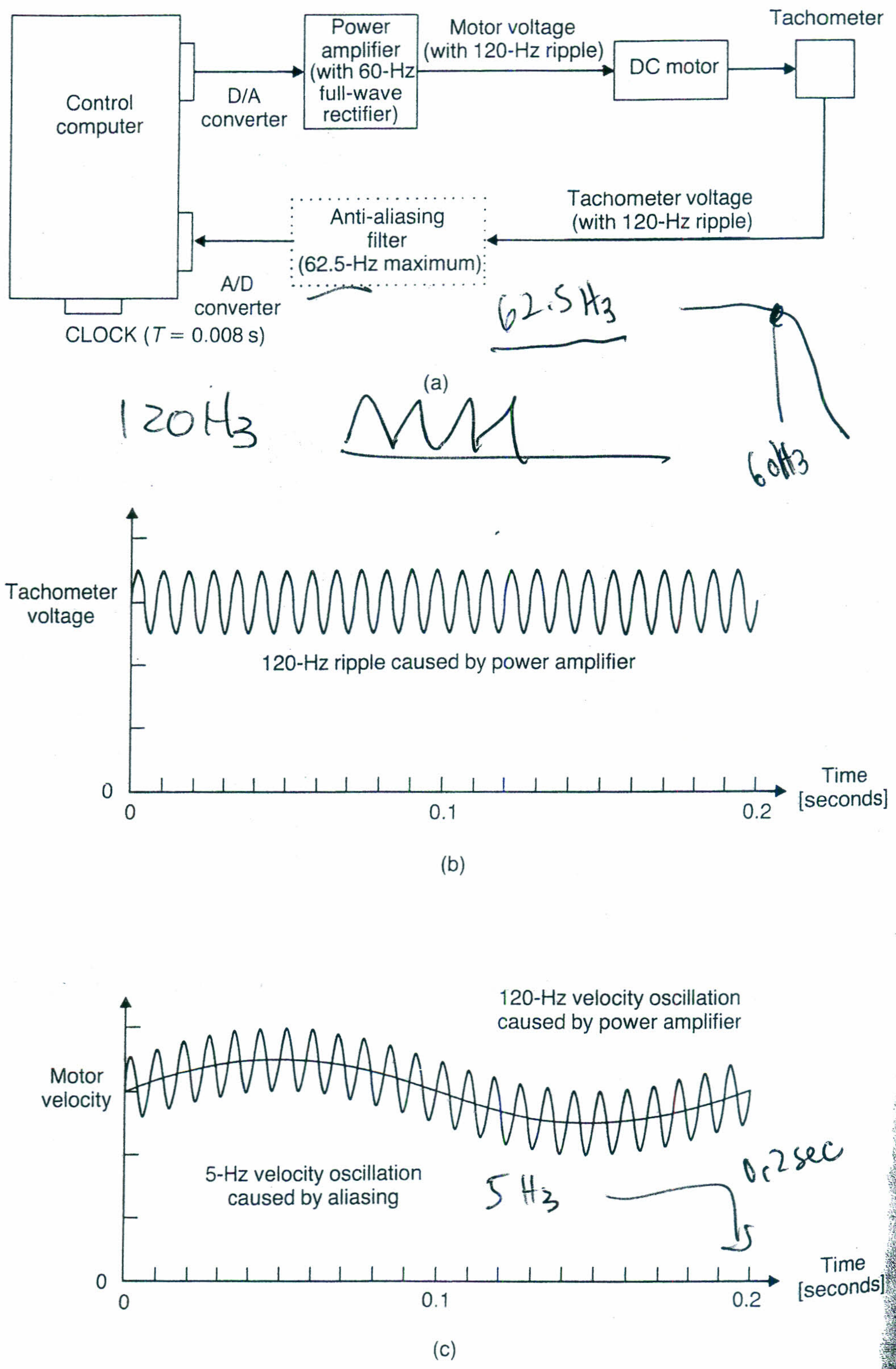
the apparent frequency of the ripple after sampling is obtained from Eq. (6.10) as

$$f_a = |120 - 125| = 5\ \text{Hz}$$

It therefore appears to the control computer that the motor velocity is oscillating at a frequency of 5 Hz. This is a relatively low frequency, and the computer corrects the perceived variation, resulting in a 5-Hz variation in actual motor velocity as shown in Fig. 6.15(c).

This aliasing problem can be prevented by filtering the feedback voltage from the tachometer to remove the ripple before it is sampled by the A/D converter. The cut-off frequency for the filter must be less than $fs/2$. That is,

$$f_c < 62.5\ \text{Hz}\ \square$$



62.5 Hz

120 Hz

60 Hz

5 Hz

0.2 sec

Figure 6.15 (a) Computer-controlled motor with 120-Hz ripple in amplifier voltage, (b) tachometer voltage with constant D/A output, and (c) motor velocity resulting from computer control when an anti-aliasing filter is not used.