CHARACTERISTICS OF SENSORS AND ACTUATORS

2.0 INTRODUCTION

Mechatronic systems use a variety of sensors and actuators to measure and manipulate mechanical, electrical, and thermal systems. Sensors have many characteristics that affect their measurement capabilities and their suitability for each application. Analog sensors have an output that is continuous over a finite region of inputs. Examples of analog sensors include potentiometers, LVDTs (linear variable differential transformers), load cells, and thermistors. Digital sensors have a fixed or countable number of different output values. A common digital sensor often found in mechatronic systems is the incremental encoder. An analog sensor output conditioned by an analog-to-digital converter (ADC) has the same digital output characteristics, as seen in Fig. 2.1.

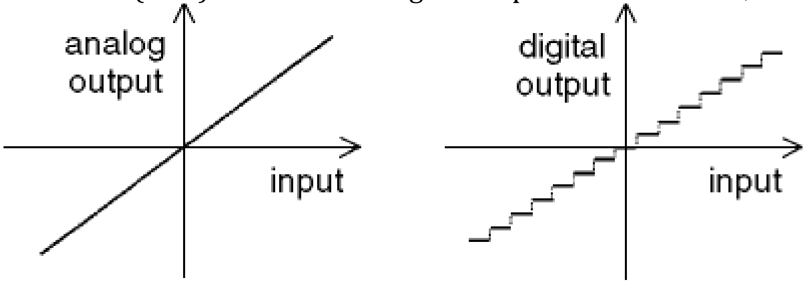


FIGURE 2.1: Analog and digital sensor outputs.

2.1 Range

The range (or span) of a sensor is the difference between the minimum (or most negative) and maximum inputs that will give a valid output. Range is typically specified by the manufacturer of the sensor. For example, a common type K thermocouple has a range of 800^{o}C (from-50^{o}C to 750^{o}C). A ten-turn potentiometer would have a range of 360^{o}degrees.

2.2 Resolution

The resolution of a sensor is the smallest increment of input that can be reliably detected. Resolution is also frequently known as the least count of the sensor. Resolution of digital sensors is easily determined.

A 1024 ppr (pulse per revolution) incremental encoder would have a resolution of

$$\frac{1\,revolution}{1024\,pulses}\times\frac{360\,degree}{1\,revolution}=0.3516\frac{degree}{pulses}$$

The resolution of analog sensors is usually limited only by low-level electrical noise and is often much better than equivalent digital sensors.

2.3 Sensitivity

Sensor sensitivity is defined as the change in output per change in input. The sensitivity of digital sensors is closely related to the resolution. The sensitivity of an analog sensor is the slope of the output versus input line. A sensor exhibiting truly linear behavior has a constant sensitivity over the entire input range.

Other sensors exhibit nonlinear behavior where the sensitivity either increases or decreases as the input is changed, as shown in Fig. 2.2.

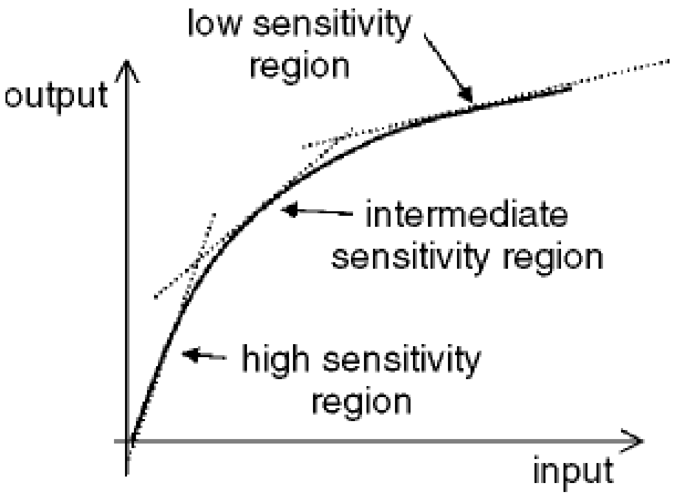


FIGURE 2.2: Sensor sensitivity.

2.4 Error

Error is the difference between a measured value and the true input value. Two classifications of errors are bias (or systematic) errors and precision (or random) errors. Bias errors are present in all measurements made with a given sensor, and cannot be detected or removed by statistical means. These bias errors can be further subdivided into:

- calibration errors (a zero or null point error is a common type of bias error created by a nonzero output value when the input is zero),
- loading errors (adding the sensor to the measured system changes the system), and
- errors due to sensor sensitivity to variables other than the desired one (e.g., temperature effects on strain gages).

2.5 Repeatability

Repeatability (or reproducibility) refers to a sensor's ability to give identical outputs for the same input.

Precision (or random) errors cause a lack of repeatability. Fortunately, precision errors can be accounted for by averaging several measurements or other operations such as low-pass filtering. Electrical noise and hysteresis (described later) both contribute to a loss of repeatability.

2.6 Linearity and Accuracy

The accuracy of a sensor is inversely proportional to error, i.e., a highly accurate sensor produces low errors. Many manufacturers specify accuracy in terms of the sensor's linearity. A least-squares straightline fit between all output measurements and their corresponding inputs determines the nominal output of the sensor. Linearity (or accuracy) is specified as a percentage of full scale (maximum valid input), as shown in Fig. 2.3, or as a percentage of the sensor reading, as shown in Fig. 2.4.

Figures 2.3 and 2.4 show both of these specifications for 10% linearity, which is much larger than most actual sensors.

Accuracy and precision are two terms that are frequently confused. Figure 2.5 shows four sets of histograms for ten measurements of angular velocity of an actuator turning at a constant 100 rad/s. The first set of data shows a high degree of precision (low standard deviation) and repeatability, but the

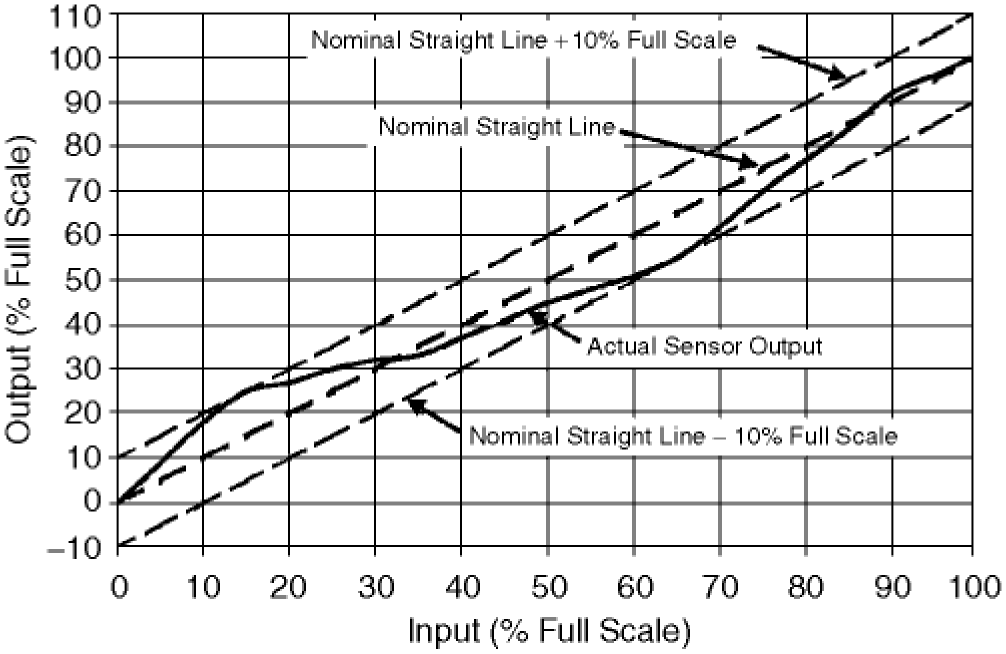


FIGURE 2.3: Linearity specified at full scale.

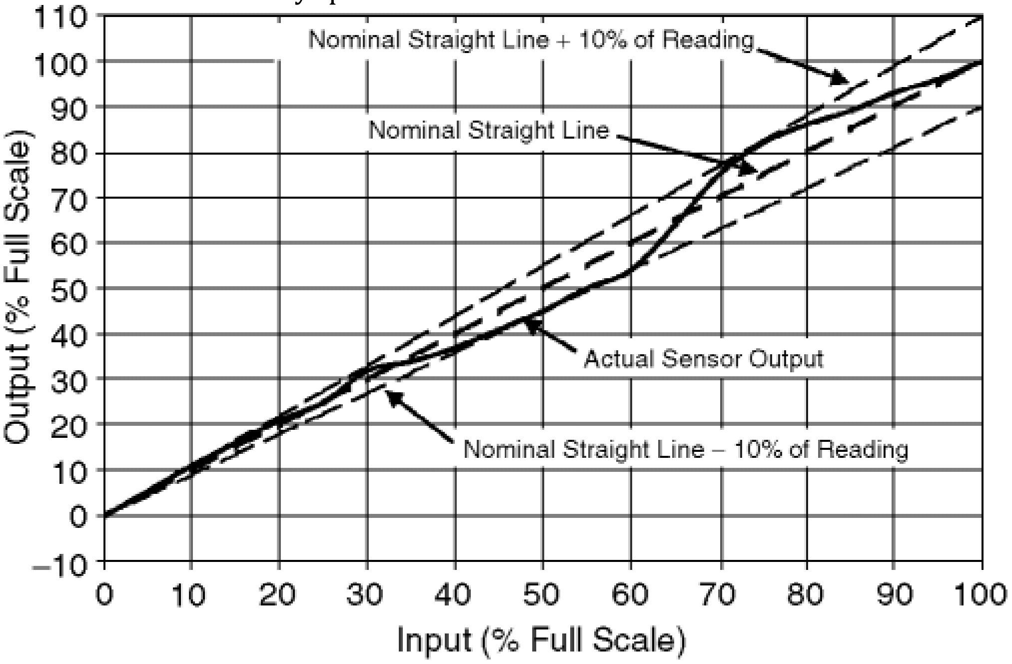
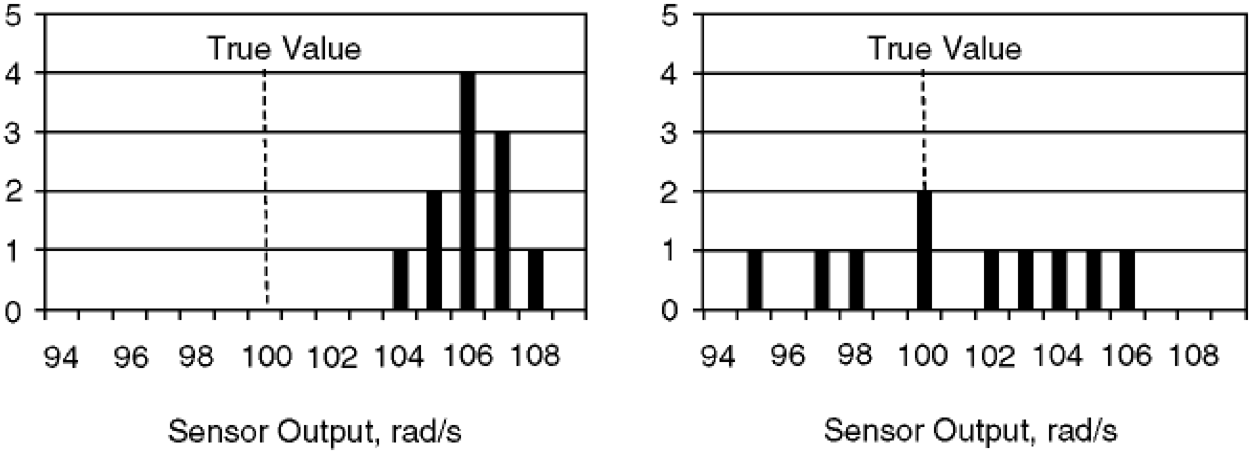
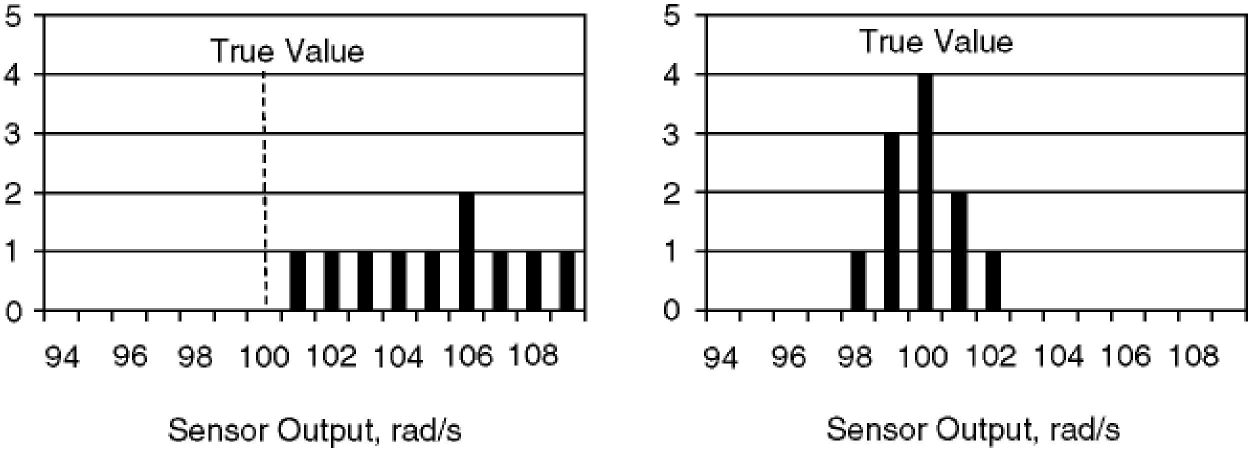


FIGURE 2.4: Linearity specified at reading.



Set 1: Precise, but not Accurate

Set 2: Accurate, but not Precise



Set 3: Neither Accurate nor Precise

Set 4: Both Accurate and Precise

FIGURE 2.5
Examples of accuracy and precision.

average accuracy is poor. The second set of data shows a low degree of precision (high standard deviation), but the average accuracy is good. The third set of data shows both low precision and low accuracy, while the fourth set of data shows both high precision, high repeatability, and high accuracy.

2.7 Impedance

Impedance is the ratio of voltage and current flow for a sensor. For a simple resistive sensor (such as a strain gage or a thermistor), the impedance *Z* is the same as the resistance *R*, which has units of ohms (Ω),

$Z_R = \frac{V}{I} = R$

For more complicated sensors, impedance includes the effects of capacitance, *C*, and inductance, *L*. Inclusion of these terms makes the impedance frequency sensitive, but the units remain ohms:

$Z_c = \frac{V}{I} = \frac{1}{jcw}$ and $Z_L = \frac{V}{I} = jLw$

where $\sqrt{-1}$ is the imaginary number and ω is the driving frequency. The impedance form is particularly nice for analyzing simple circuits, as parallel and series inductances can be treated just like resistances. Two types of impedance are important in sensor applications: input impedance and output impedance. Input impedance is a measure of how much current must be drawn to power a sensor (or signal conditioning circuit). Input impedance is frequently modeled as a resistor in parallel with the input terminals. High input impedance is desirable, since the device will then draw less current from the source. Oscilloscopes and data acquisition equipment frequently have input impedances of 1 MW or more to minimize this current draw. Output impedance is a measure of a sensor's (or signal conditioning circuit's) ability to provide current for the next stage of the system. Output impedance is frequently modeled as a resistor in series with the sensor output. Low output impedance is desirable, but is often not available directly from a sensor. Piezoelectric sensors in particular have high output impedances and cannot source much current (typically micro-amps or less). Op-amp circuits are frequently used to buffer sensor outputs for this reason. Op-amp circuits (especially voltage followers) provide nearly ideal circumstances for many sensors, since they have high input impedance but can substantially lower output impedance.

2.8 Nonlinearities

Linear systems have the property of superposition. If the response of the system to input A is output A, and the response to input B is output B, then the response to input C (=input A + input B) will be output C (=output A + output B). Many real systems will exhibit linear or nearly linear behavior over some range of operation. Therefore, linear system analysis is correct, at least over these portions of a system's operating envelope. Unfortunately, most real systems have nonlinearities that cause them to operate outside of this linear region, and many common assumptions about system behavior, such as superposition, no longer apply. Several nonlinearities commonly found in mechatronic systems include static and coulomb friction, eccentricity, backlash (or hysteresis), saturation, and deadband.

2.9 Static and Coulomb Friction

In classic linear system analysis, friction forces are assumed to be proportional to velocity, i.e., viscous friction. With an actuator velocity of zero, there should be no friction. In reality, a small amount of static (no velocity) or Coulomb friction is almost always present, even in roller or ball type anti-friction bearings. A typical plot of friction force vs. velocity is given in Fig. 2.6. Note that the static friction force can assume any value between some upper and lower limit at zero velocity. Static friction has two primary effects on mechatronic systems:

- Some of the actuator torque or force is wasted overcoming friction forces, which leads to inefficiency from an energy viewpoint.
- As the actuator moves the system to its final location, the velocity approaches zero and the actuator force/torque will approach a value that exactly balances frictional and gravity loads. Since static friction can assume any value at zero velocity, the actuator will come to slightly different final resting positions each time—depending on the final value of static friction. This effect contributes to some loss of repeatability in mechatronic systems.

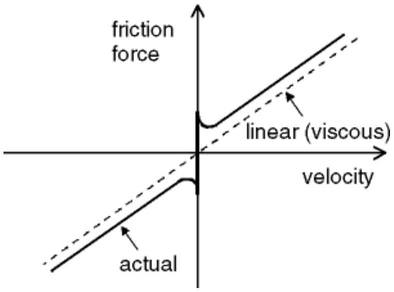


FIGURE 2.6: Static and Coulomb friction.

2.10 Eccentricity

The ideal relationships for gears, pulleys, and chain drives assume that the point of gear contact remains at a fixed distance from the center of rotation for each gear. In reality, the true center of the gears pitch circle and the center of rotation will be separated by a small amount, known as the eccentricity. Small tooth-to-tooth errors can also cause local variations in the pitch circle radius. The combination of these two effects can lead to a nonlinear geometrical relationship between two gears like that of Fig. 2.7, where the nonlinear behavior is greatly exaggerated for clarity. Eccentricity impacts the accuracy of position measurements made on the input side of the gear pair, as the output gear is not exactly where the sensor measurement indicates.

2.11 Backlash

If two otherwise perfect gears are not mounted on a center-to-center distance that exactly matches the sum of the pitch radii, there will be a small clearance, or backlash, between the teeth. When the input gear reverses direction, a small rotation is required before this clearance is removed and the output gear begins to move. Gear backlash is just one of many phenomena that can be characterized as hysteresis, as shown in Fig. 2.8. Clearance between shafts and bearings can cause hysteretic effects also. Backlash exhibits effects similar to those for eccentricity, i.e., a loss of repeatability, particularly when approaching a measured point from different directions. The gear backlash problem is so prevalent and potentially harmful that many manufacturers go to great lengths to minimize or reduce the effect:

- gears mounted closer together than the theoretically ideal spacing,
- split "anti-backlash" gears that are spring loaded to force teeth to maintain engagement at all times,
- external spring-loaded mounts for one of the gears to force engagement, or
- specially designed gears with anti-backlash features

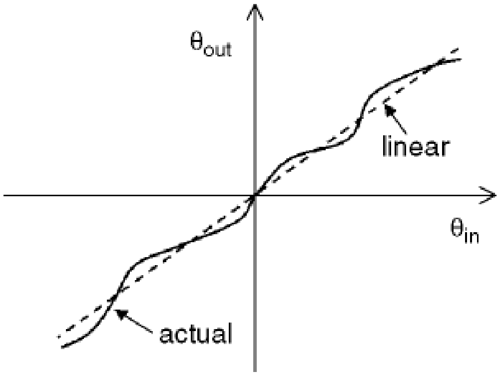


FIGURE 2.7: Gear eccentricity.

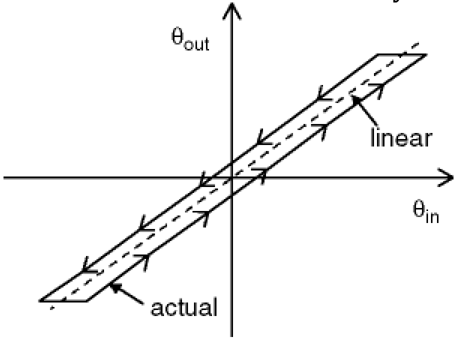


FIGURE 2.8: Gear backlash.

2.12 Saturation

All real actuators have some maximum output capability, regardless of the input. This violates the linearity assumption, since at some point the input command can be increased without significantly changing the output; see Fig. 2.9. This type of nonlinearity must be considered in mechatronic control system design, since maximum velocity and force or torque limitations affect system performance. Control systems modeled with linear system theory must be carefully tested or analyzed to determine the impact of saturation on system performance.

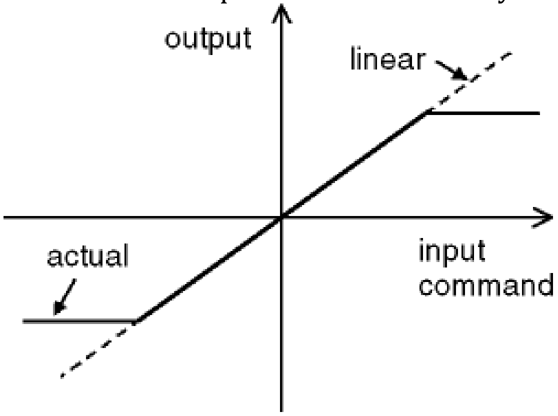


FIGURE 2.9: Saturation.

2.13 Deadband

Another nonlinear characteristic of some actuators and sensors is known as deadband. The deadband is typically a region of input close to zero at which the output remains zero. Once the input travels outside the deadband, then the output varies with input, as shown in Fig. 2.10. Analog joystick inputs frequently use a small amount of deadband to reduce the effect of noise from human inputs. A very small movement of the joystick produces no output, but the joystick acts normally with larger inputs. Deadband is also commonly found in household thermostats and other process type controllers, as shown in Fig. 2.11. When a room warms and the temperature reaches the setpoint (or desired value)

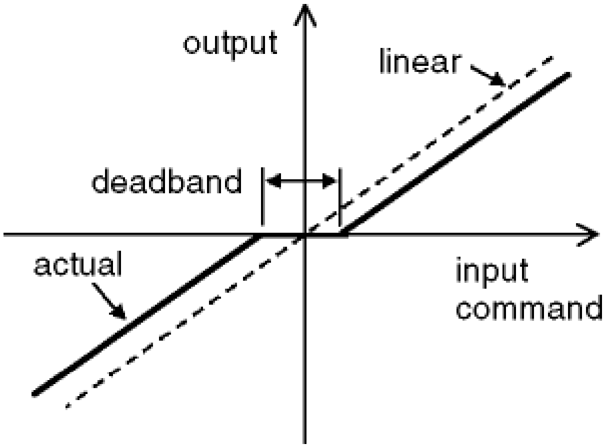


FIGURE 2.10: Deadband.

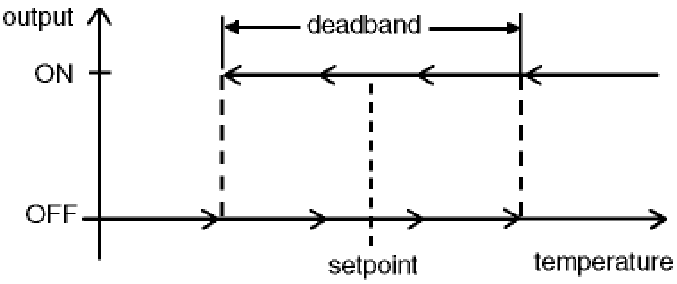


FIGURE 2.11: Thermostat deadband.

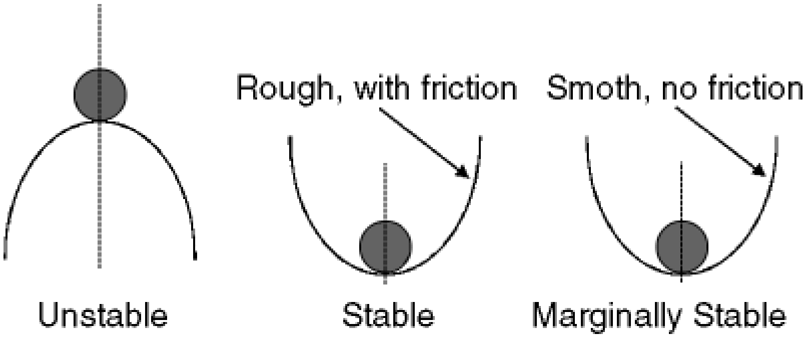


FIGURE 2.12
System stability.

on the thermostat, the output remains off. Once room temperature has increased to the setpoint plus half the deadband, then the cooling system output goes to fully on. As the room cools, the output stays fully on until the temperature reaches the setpoint minus half the deadband. At this point the cooling system output goes fully off.

2.14 System Response

Sensors and actuators respond to inputs that change with time. Any system that changes with time is considered a dynamic system. Understanding the response of dynamic systems to different types of inputs is important in mechatronic system design. The most important concept in system response is stability.

The term stability has many different definitions and uses, but the most common definition is related to equilibrium. A system in equilibrium will remain in the same state in the absence of external disturbances.

A stable system will return to an equilibrium state if a “small” disturbance moves the system away from the initial state. An unstable system will not return to an equilibrium position, and frequently will move “far” from the initial state.

Figure 2.12 illustrates three stability conditions with a simple ball and hill system. In each case an equilibrium position is easily identified—either the top of the hill or the bottom of the valley. In the unstable case, a small motion of the ball away from the equilibrium position will cause the ball to move “far” away, as it rolls down the hill. In the stable case, a small movement of the ball away from the equilibrium position will eventually result in the ball returning, perhaps after a few oscillations. In the third case, the absence of friction causes the ball to oscillate continuously about the equilibrium position once a small movement has occurred. This special case is often known as marginal stability, since the system never quite returns to the equilibrium position.

Most sensors and actuators are inherently stable. However, the addition of active control systems can cause a system of stable devices to exhibit overall unstable behavior. Careful analysis and testing is required to ensure that a mechatronic system acts in a stable manner. The complex response of stable dynamic systems is frequently approximated by much simpler systems. Understanding both first-order and second order system responses to either instantaneous (or step) changes in inputs or sinusoidal inputs will suffice for most situations.

Read about First Order System Response