Process control - FE Chemical Engineering module

This part counts 5% of afternoon points based on NCEES FE Supplied-Reference Handbook, 8th edition, 2nd revision.

1. Sensors and control values.
   This section includes controls on temperature and pressure.

2. Dynamics.
   This section includes time constants, 2nd order, and underdamped.

3. Feedback and feedforward control.

4. Proportional, integral, and derivative (PID) controller concepts.

5. Cascade control.

6. Control loop design.
   This section includes matching measured and manipulated variables.

7. Tuning PID controllers and stability.
   This section includes Method of Ziegler-Nichols and Routh Test.

8. Open-loop and closed-loop transfer functions.
Instrumentation & Control

Process Control Fundamentals
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Introduction

Control in process industries refers to the regulation of all aspects of the process. Precise control of level, temperature, pressure and flow is important in many process applications. This module introduces you to control in process industries, explains why control is important, and identifies different ways in which precise control is ensured.

The following five sections are included in this module:
- The importance of process control
- Control theory basics
- Components of control loops and ISA symbology
- Controller algorithms and tuning
- Process control systems

As you proceed through the module, answer the questions in the activities column on the right side of each page. Also, note the application boxes (double-bordered boxes) located throughout the module. Application boxes provide key information about how you may use your baseline knowledge in the field. When you see the workbook exercise graphic at the bottom of a page, go to the workbook to complete the designated exercise before moving on in the module. Workbook exercises help you measure your progress toward meeting each section’s learning objectives.

Performance Objective

After completing this module, you will be able to determine needed control loop components in specific process control applications.
The Importance of Process Control

Refining, combining, handling, and otherwise manipulating fluids to profitably produce end products can be a precise, demanding, and potentially hazardous process. Small changes in a process can have a large impact on the end result. Variations in proportions, temperature, flow, turbulence, and many other factors must be carefully and consistently controlled to produce the desired end product with a minimum of raw materials and energy. Process control technology is the tool that enables manufacturers to keep their operations running within specified limits and to set more precise limits to maximize profitability, ensure quality and safety.

LEARNING OBJECTIVES

After completing this section, you will be able to:

- Define process
- Define process control
- Describe the importance of process control in terms of variability, efficiency, and safety

Note: To answer the activity questions the Hand Tool (H) should be activated.
The Importance of Process Control

**PROCESS**

*Process* as used in the terms *process control* and *process industry*, refers to the methods of changing or refining raw materials to create end products. The raw materials, which either pass through or remain in a liquid, gaseous, or slurry (a mix of solids and liquids) state during the process, are transferred, measured, mixed, heated or cooled, filtered, stored, or handled in some other way to produce the end product.

Process industries include the chemical industry, the oil and gas industry, the food and beverage industry, the pharmaceutical industry, the water treatment industry, and the power industry.

**PROCESS CONTROL**

*Process control* refers to the methods that are used to control process variables when manufacturing a product. For example, factors such as the proportion of one ingredient to another, the temperature of the materials, how well the ingredients are mixed, and the pressure under which the materials are held can significantly impact the quality of an end product. Manufacturers control the production process for three reasons:

- Reduce variability
- Increase efficiency
- Ensure safety

**Reduce Variability**

Process control can reduce variability in the end product, which ensures a consistently high-quality product. Manufacturers can also save money by reducing variability. For example, in a gasoline blending process, as many as 12 or more different components may be blended to make a specific grade of gasoline. If the refinery does not have precise control over the flow of the separate components, the gasoline may get too much of the high-octane components. As a result, customers would receive a higher grade and more expensive gasoline than they paid for, and the refinery would lose money. The opposite situation would be customers receiving a lower grade at a higher price.

**Activities**

1. Process is defined as the changing or refining of raw materials that pass through or remain in a liquid, gaseous, or slurry state to create end products.

2. Which of these industries are examples of the process industry?
   Select all options that apply.

   1. Pharmaceutical
   2. Satellite
   3. Oil and Gas
   4. Cement
   5. Power
The Importance of Process Control

Reducing variability can also save money by reducing the need for product padding to meet required product specifications. Padding refers to the process of making a product of higher-quality than it needs to be to meet specifications. When there is variability in the end product (i.e., when process control is poor), manufacturers are forced to pad the product to ensure that specifications are met, which adds to the cost. With accurate, dependable process control, the setpoint (desired or optimal point) can be moved closer to the actual product specification and thus save the manufacturer money.

Increase Efficiency

Some processes need to be maintained at a specific point to maximize efficiency. For example, a control point might be the temperature at which a chemical reaction takes place. Accurate control of temperature ensures process efficiency. Manufacturers save money by minimizing the resources required to produce the end product.

Ensure Safety

A run-away process, such as an out-of-control nuclear or chemical reaction, may result if manufacturers do not maintain precise control of all of the process variables. The consequences of a run-away process can be catastrophic.

Precise process control may also be required to ensure safety. For example, maintaining proper boiler pressure by controlling the inflow of air used in combustion and the outflow of exhaust gases is crucial in preventing boiler implosions that can clearly threaten the safety of workers.

Activities

3. What are the main reasons for manufacturers to control a process? Select all options that apply.

1. Reduce variability
2. Ensure safety
3. Reduce costs
4. Increase efficiency
5. Increase productivity

COMPLETE WORKBOOK EXERCISE - THE IMPORTANCE OF PROCESS CONTROL
Control Theory Basics

This section presents some of the basic concepts of control and provides a foundation from which to understand more complex control processes and algorithms later described in this module. Common terms and concepts relating to process control are defined in this section.

**LEARNING OBJECTIVES**

After completing this section, you will be able to:

- Define control loop
- Describe the three tasks necessary for process control to occur:
  - Measure
  - Compare
  - Adjust
- Define the following terms:
  - Process variable
  - Setpoint
  - Manipulated variable
  - Measured variable
  - Error
  - Offset
  - Load disturbance
  - Control algorithm
- List at least five process variables that are commonly controlled in process measurement industries
- At a high level, differentiate the following types of control:
  - Manual versus automatic feedback control
  - Closed-loop versus open-loop control

**Note:** To answer the activity questions the Hand Tool (H) should be activated.
The Control Loop

Imagine you are sitting in a cabin in front of a small fire on a cold winter evening. You feel uncomfortably cold, so you throw another log on the fire. This is an example of a control loop. In the control loop, a variable (temperature) fell below the setpoint (your comfort level), and you took action to bring the process back into the desired condition by adding fuel to the fire. The control loop will now remain static until the temperature again rises above or falls below your comfort level.

THREE TASKS

Control loops in the process control industry work in the same way, requiring three tasks to occur:

- Measurement
- Comparison
- Adjustment

In Figure 7.1, a level transmitter (LT) measures the level in the tank and transmits a signal associated with the level reading to a controller (LIC). The controller compares the reading to a predetermined value, in this case, the maximum tank level established by the plant operator, and finds that the values are equal. The controller then sends a signal to the device that can bring the tank level back to a lower level—a valve at the bottom of the tank. The valve opens to let some liquid out of the tank.

Many different instruments and devices may or may not be used in control loops (e.g., transmitters, sensors, controllers, valves, pumps), but the three tasks of measurement, comparison, and adjustment are always present.

A Simple Control Loop

Activities

1. The three tasks associated with any control loop are measurement, comparison, and adjustment. Is this statement true or false?
Process Control Terms

As in any field, process control has its own set of common terms that you should be familiar with and that you will use when talking about control technology.

**Process Variable**

A process variable is a condition of the process fluid (a liquid or gas) that can change the manufacturing process in some way. In the example of you sitting by the fire, the process variable was temperature. In the example of the tank in Figure 7.1, the process variable is level. Common process variables include:

- Pressure
- Flow
- Level
- Temperature
- Density
- Ph (acidity or alkalinity)
- Liquid interface (the relative amounts of different liquids that are combined in a vessel)
- Mass
- Conductivity

**Setpoint**

The setpoint is a value for a process variable that is desired to be maintained. For example, if a process temperature needs to be kept within 5 °C of 100 °C, then the setpoint is 100 °C. A temperature sensor can be used to help maintain the temperature at setpoint. The sensor is inserted into the process, and a controller compares the temperature reading from the sensor to the setpoint. If the temperature reading is 110 °C, then the controller determines that the process is above setpoint and signals the fuel valve of the burner to close slightly until the process cools to 100 °C. Set points can also be maximum or minimum values. For example, level in tank cannot exceed 20 feet.

**Activities**

2. A process variable is a condition that can change the process in some way.

3. Imagine you are in a cabin in front of a small fire on a cold winter evening. You feel uncomfortably cold, so you throw another log into the fire. In this scenario, the process variable is temperature. Is this true or false?

4. If the level of a liquid in a tank must be maintained within 5 ft of 50 ft, what is the liquid’s setpoint?

   1. 45 ft
   2. 55 ft
   3. 5 ft
   4. 50 ft
Process Control Terms

MEASURED VARIABLES, PROCESS VARIABLES, AND MANIPULATED VARIABLES

In the temperature control loop example, the measured variable is temperature, which must be held close to 100 °C. In this example and in most instances, the measured variable is also the process variable. The measured variable is the condition of the process fluid that must be kept at the designated setpoint.

Sometimes the measured variable is not the same as the process variable. For example, a manufacturer may measure flow into and out of a storage tank to determine tank level. In this scenario, flow is the measured variable, and the process fluid level is the process variable. The factor that is changed to keep the measured variable at setpoint is called the manipulated variable. In the example described, the manipulated variable would also be flow (Figure 7.2).

Variables

5. ______________ is a sustained deviation of the process variable from the setpoint.

6. A load disturbance is an undesired change in one of the factors that can affect the setpoint. Is this statement true or false?

ERROR

Error is the difference between the measured variable and the setpoint and can be either positive or negative. In the temperature control loop example, the error is the difference between the 110 °C measured variable and the 100 °C setpoint—that is, the error is +10 °C.

The objective of any control scheme is to minimize or eliminate error. Therefore, it is imperative that error be well understood. Any error can be seen as having three major components. These three components are shown in the figure on the following page

Magnitude

The magnitude of the error is simply the deviation between the values of the setpoint and the process variable. The magnitude of error at any point in time compared to the previous error provides the basis for determining the change in error. The change in error is also an important value.
Process Control Terms

**Duration**
Duration refers to the length of time that an error condition has existed.

**Rate Of Change**
The rate of change is shown by the slope of the error plot.

**Offset**
*Offset* is a sustained deviation of the process variable from the setpoint. In the temperature control loop example, if the control system held the process fluid at 100.5 °C consistently, even though the setpoint is 100 °C, then an offset of 0.5 °C exists.

**Load Disturbance**
A *load disturbance* is an undesired change in one of the factors that can affect the process variable. In the temperature control loop example, adding cold process fluid to the vessel would be a load disturbance because it would lower the temperature of the process fluid.

**Control Algorithm**
A *control algorithm* is a mathematical expression of a control function. Using the temperature control loop example, V in the equation below is the fuel valve position, and e is the error. The relationship in a control algorithm can be expressed as:
The fuel valve position \(V\) is a function \(f\) of the sign (positive or negative) of the error (Figure 7.3).

Control algorithms can be used to calculate the requirements of much more complex control loops than the one described here. In more complex control loops, questions such as “How far should the valve be opened or closed in response to a given change in setpoint?” and “How long should the valve be held in the new position after the process variable moves back toward setpoint?” need to be answered.

**MANUAL AND AUTOMATIC CONTROL**

Before process automation, people, rather than machines, performed many of the process control tasks. For example, a human operator might have watched a level gauge and closed a valve when the level reached the setpoint. Control operations that involve human action to make an adjustment are called *manual control systems*. Conversely, control operations in which no human intervention is required, such as an automatic valve actuator that responds to a level controller, are called *automatic control systems*.

Activities

7. Automatic control systems are control operations that involve human action to make adjustment. Is this statement true or false?
Process Control Terms

CLOSED AND OPEN CONTROL LOOPS

A closed control loop exists where a process variable is measured, compared to a setpoint, and action is taken to correct any deviation from setpoint. An open control loop exists where the process variable is not compared, and action is taken not in response to feedback on the condition of the process variable, but is instead taken without regard to process variable conditions. For example, a water valve may be opened to add cooling water to a process to prevent the process fluid from getting too hot, based on a pre-set time interval, regardless of the actual temperature of the process fluid.

Activities

8. Under what circumstances does an open control loop exist? Select all options that apply.

1. Process variable is not measured
2. Process variable is not compared
3. Process variable is measured and compared to a setpoint
4. Action is taken without regard to process variable conditions
5. Action is taken with regard to process variable conditions
Components of Control Loops and ISA Symbology

This section describes the instruments, technologies, and equipment used to develop and maintain process control loops. In addition, this section describes how process control equipment is represented in technical drawings of control loops.

**Learning Objectives**

After completing this section, you will be able to:
- Describe the basic function of and, where appropriate, the basic method of operation for the following control loop components:
  - Primary element/sensor
  - Transducer
  - Converter
  - Transmitter
  - Signal
  - Indicator
  - Recorder
  - Controller
  - Correcting element/final control element
  - Actuator
- List examples of each type of control loop component listed above
- State the advantages of 4–20 mA current signals when compared with other types of signals
- List at least three types of final control elements, and for each one:
  - Provide a brief explanation of its method of operation
  - Describe its impact on the control loop
  - List common applications in which it is used
- Given a piping and instrumentation drawing (P&ID), correctly label the:
  - Instrument symbols (e.g., control valves, pumps, transmitters)
  - Location symbols (e.g., local, panel-front)
  - Signal type symbols (e.g., pneumatic, electrical)
- Accurately interpret instrument letter designations used on P&IDs
The previous section described the basic elements of control as measurement, comparison, and adjustment. In practice, there are instruments and strategies to accomplish each of these essential tasks. In some cases, a single process control instrument, such as a modern pressure transmitter, may perform more than one of the basic control functions. Other technologies have been developed so that communication can occur among the components that measure, compare, and adjust.

**Primary Elements/Sensors**

In all cases, some kind of instrument is measuring changes in the process and reporting a process variable measurement. Some of the greatest ingenuity in the process control field is apparent in sensing devices. Because sensing devices are the first element in the control loop to measure the process variable, they are also called primary elements. Examples of primary elements include:

- Pressure sensing diaphragms, strain gauges, capacitance cells
- Resistance temperature detectors (RTDs)
- Thermocouples
- Orifice plates
- Pitot tubes
- Venturi tubes
- Magnetic flow tubes
- Coriolis flow tubes
- Radar emitters and receivers
- Ultrasonic emitters and receivers
- Annubar flow elements
- Vortex sheddar

Primary elements are devices that cause some change in their property with changes in process fluid conditions that can then be measured. For example, when a conductive fluid passes through the magnetic field in a magnetic flow tube, the fluid generates a voltage that is directly proportional to the velocity of the process fluid. The primary element (magnetic flow tube) outputs a voltage that can be measured and used to calculate the fluid’s flow rate. With an RTD, as the temperature of a process fluid surrounding the RTD rises or falls, the electrical resistance of the RTD increases or decreases a proportional amount. The resistance is measured, and from this measurement, temperature is determined.

**Activities**

1. Identify three examples of a primary element/sensors in process control? Select all options that apply.
   - Resistance Temperature Detectors
   - Thermocouples
   - Control Valve
   - Converter
   - Pitot tubes

2. Primary elements will not make direct contact with the process fluid. Is this statement true or false?
Control Loop Loop Equipment and Technology

**TRANSDUCERS AND CONVERTERS**

A *transducer* is a device that translates a mechanical signal into an electrical signal. For example, inside a capacitance pressure device, a transducer converts changes in pressure into a proportional change in capacitance.

A *converter* is a device that converts one type of signal into another type of signal. For example, a converter may convert current into voltage or an analog signal into a digital signal. In process control, a converter used to convert a 4–20 mA current signal into a 3–15 psig pneumatic signal (commonly used by valve actuators) is called a *current-to-pressure converter*.

**TRANSMITTERS**

A *transmitter* is a device that converts a reading from a sensor or transducer into a standard signal and transmits that signal to a monitor or controller. Transmitter types include:

- Pressure transmitters
- Flow transmitters
- Temperature transmitters
- Level transmitters
- Analytic (O₂ [oxygen], CO [carbon monoxide], and pH) transmitters

### Activities

3. A ____________ is a device that translates a mechanical signal into an electrical signal.

4. A transmitter is a device that converts a reading from a transducer into a standard signal and transmits that signal to a monitor or controller. Is this statement true or false?
CONTROL LOOP EQUIPMENT AND TECHNOLOGY

SIGNALS

There are three kinds of signals that exist for the process industry to transmit the process variable measurement from the instrument to a centralized control system.

1. Pneumatic signal
2. Analog signal
3. Digital signal

Pneumatic Signals

Pneumatic signals are signals produced by changing the air pressure in a signal pipe in proportion to the measured change in a process variable. The common industry standard pneumatic signal range is 3–15 psig. The 3 corresponds to the lower range value (LRV) and the 15 corresponds to the upper range value (URV). Pneumatic signalling is still common. However, since the advent of electronic instruments in the 1960s, the lower costs involved in running electrical signal wire through a plant as opposed to running pressurized air tubes has made pneumatic signal technology less attractive.

Analog Signals

The most common standard electrical signal is the 4–20 mA current signal. With this signal, a transmitter sends a small current through a set of wires. The current signal is a kind of gauge in which 4 mA represents the lowest possible measurement, or zero, and 20 mA represents the highest possible measurement.

For example, imagine a process that must be maintained at 100 °C. An RTD temperature sensor and transmitter are installed in the process vessel, and the transmitter is set to produce a 4 mA signal when the process temperature is at 95 °C and a 20 mA signal when the process temperature is at 105 °C. The transmitter will transmit a 12 mA signal when the temperature is at the 100 °C setpoint. As the sensor’s resistance property changes in response to changes in temperature, the transmitter outputs a 4–20 mA signal that is proportionate to the temperature changes. This signal can be converted to a temperature reading or an input to a control device, such as a burner fuel valve.

Other common standard electrical signals include the 1–5 V (volts) signal and the pulse output.

ACTIVITIES

5. Identify the signal types that are used in the process control industry?
Select all options that apply.

1. Hydraulic signals
2. Digital signals
3. Analog signals
4. Pneumatic signals
5. Electro-magnetic signals
Control Loop Equipment and Technology

Digital Signals

Digital signals are the most recent addition to process control signal technology. Digital signals are discrete levels or values that are combined in specific ways to represent process variables and also carry other information, such as diagnostic information. The methodology used to combine the digital signals is referred to as protocol.

Manufacturers may use either an open or a proprietary digital protocol. Open protocols are those that anyone who is developing a control device can use. Proprietary protocols are owned by specific companies and may be used only with their permission. Open digital protocols include the HART® (highway addressable remote transducer) protocol, FOUNDATION™ Fieldbus, Profibus, DeviceNet, and the Modbus® protocol.

(See Module 8: Communication Technologies for more information on digital communication protocols.)

INDICATORS

While most instruments are connected to a control system, operators sometimes need to check a measurement on the factory floor at the measurement point. An indicator makes this reading possible. An indicator is a human-readable device that displays information about the process. Indicators may be as simple as a pressure or temperature gauge or more complex, such as a digital read-out device. Some indicators simply display the measured variable, while others have control buttons that enable operators to change settings in the field.

Activities

6. The _________ is a human-readable device that displays information about the process or the instrument it is connected to.

7. Which of the following are examples of a digital signal? Select all options that apply.

1. Profibus
2. 4 - 20 mA
3. 1 - 5 v
4. Fieldbus
5. 3 - 15 psig
Control Loop Equipment and Technology

**Recorders**

A *recorder* is a device that records the output of a measurement devices. Many process manufacturers are required by law to provide a process history to regulatory agencies, and manufacturers use recorders to help meet these regulatory requirements. In addition, manufacturers often use recorders to gather data for trend analyses. By recording the readings of critical measurement points and comparing those readings over time with the results of the process, the process can be improved.

Different recorders display the data they collect differently. Some recorders list a set of readings and the times the readings were taken; others create a chart or graph of the readings. Recorders that create charts or graphs are called *chart recorders*.

**Controllers**

A *controller* is a device that receives data from a measurement instrument, compares that data to a programmed setpoint, and, if necessary, signals a control element to take corrective action. *Local controllers* are usually one of the three types: pneumatic, electronic or programmable. Controllers also commonly reside in a digital control system.

**Activities**

8. A recorder is a device that records the _____________ of a measurement or control device.
Controllers may perform complex mathematical functions to compare a set of data to setpoint or they may perform simple addition or subtraction functions to make comparisons. Controllers always have an ability to receive input, to perform a mathematical function with the input, and to produce an output signal. Common examples of controllers include:

- **Programmable logic controllers (PLCs)**—PLCs are usually computers connected to a set of input/output (I/O) devices. The computers are programmed to respond to inputs by sending outputs to maintain all processes at setpoint.

- **Distributed control systems (DCSs)**—DCSs are controllers that, in addition to performing control functions, provide readings of the status of the process, maintain databases and advanced man-machine-interface.

### Activities

9. Which of the following have the ability to receive input, to perform a mathematical function with the input, and produce an output signal?

1. Actuators
2. Transmitters
3. Transducers
4. Controllers

10. Which of the following is the most common final control element in process control industries?

1. Agitator
2. Pump motor
3. Valve
4. Louver

**Types of Process Controllers**
Components of Control Loops and ISA Symbology

Control Loop Equipment and Technology

Actuators

The correcting or final control element is the part of the control system that acts to physically change the manipulated variable. In most cases, the final control element is a valve used to restrict or cut off fluid flow, but pump motors, louvers (typically used to regulate air flow), solenoids, and other devices can also be final control elements. Final control elements are typically used to increase or decrease fluid flow. For example, a final control element may regulate the flow of fuel to a burner to control temperature, the flow of a catalyst into a reactor to control a chemical reaction, or the flow of air into a boiler to control boiler combustion.

In any control loop, the speed with which a final control element reacts to correct a variable that is out of setpoint is very important. Many of the technological improvements in final control elements are related to improving their response time.

ACTUATORS

An actuator is the part of a final control device that causes a physical change in the final control device when signalled to do so. The most common example of an actuator is a valve actuator, which opens or closes a valve in response to control signals from a controller. Actuators are often powered pneumatically, hydraulically, or electrically. Diaphragms, bellows, springs, gears, hydraulic pilot valves, pistons, or electric motors are often parts of an actuator system.

Activities

11. _______________ is a part final control device that causes a physical change in the final control device when signaled to do so.
## ISA Symbology

The Instrumentation, Systems, and Automation Society (ISA) is one of the leading process control trade and standards organizations. The ISA has developed a set of symbols for use in engineering drawings and designs of control loops (ISA S5.1 instrumentation symbol specification). You should be familiar with ISA symbology so that you can demonstrate possible process control loop solutions on paper to your customer. Figure 7.5 shows a control loop using ISA symbology. Drawings of this kind are known as *piping and instrumentation drawings* (P&ID).

### Activities

12. What does the acronym P&ID stand for?

1. Piping and Instrument Designing
2. Piping and Instrumentation Drawing
3. Process Control and Installation Drawing
4. Proportional, Integral and Derivative control
**ISA Symbology**

**Symbols**

In a P&ID, a circle represents individual measurement instruments, such as transmitters, sensors, and detectors (Figure 7.6).

![Figure 7.6: Discrete Instruments](image)

A single horizontal line running across the center of the shape indicates that the instrument or function is located in a primary location (e.g., a control room). A double line indicates that the function is in an auxiliary location (e.g., an instrument rack). The absence of a line indicates that the function is field mounted, and a dotted line indicates that the function or instrument is inaccessible (e.g., located behind a panel board).

A square with a circle inside represents instruments that both display measurement readings and perform some control function (Figure 7.7). Many modern transmitters are equipped with microprocessors that perform control calculations and send control output signals to final control elements.

![Figure 7.7: Shared Control/Display Elements](image)

**Activities**

13. Which of the following is a symbol of a transmitter in an auxiliary location?

1. ![Diagram](image)

2. ![Diagram](image)

3. ![Diagram](image)

4. ![Diagram](image)

14. Which of the following is a symbol of a field-mounted control/display element?

1. ![Diagram](image)

2. ![Diagram](image)

3. ![Diagram](image)

4. ![Diagram](image)
ISA Symbology

Activities

15. Which of the following is a symbol of a controller located behind a panel?

1

2

3

4
ISA Symbology

A square with a diamond inside represents PLCs (Figure 7.9).

Two triangles with their apexes contacting each other (a “bow tie” shape) represent a valve in the piping. An actuator is always drawn above the valve (Figure 7.10).

Pumps
Directional arrows showing the flow direction represent a pump (Figure 7.11).

Activities

16. The symbol displayed below denotes a PLC in a primary location. Is this statement true or false?

![Symbol Image]

17. Which of the following is a symbol of a pneumatic valve?

1. ![Symbol Image]
2. ![Symbol Image]
3. ![Symbol Image]
4. ![Symbol Image]
ISA Symbology

Piping and Connections

Piping and connections are represented with several different symbols (Figure 7.12):

- A heavy solid line represents piping
- A thin solid line represents process connections to instruments (e.g., impulse piping)
- A dashed line represents electrical signals (e.g., 4–20 mA connections)
- A slashed line represents pneumatic signal tubes
- A line with circles on it represents data links

Other connection symbols include capillary tubing for filled systems (e.g., remote diaphragm seals), hydraulic signal lines, and guided electromagnetic or sonic signals.

Activities

18. The symbols displayed below represent a data link and a process connection. Is this statement true or false?

[Diagram of piping and connection symbols]

[Blank space for answer]
ISA Symbology

**IDENTIFICATION LETTERS**

Identification letters on the ISA symbols (e.g., TT for temperature transmitter) indicate:

- The variable being measured (e.g., flow, pressure, temperature)
- The device’s function (e.g., transmitter, switch, valve, sensor, indicator)
- Some modifiers (e.g., high, low, multifunction)

Table 7.1 on page 26 shows the ISA identification letter designations. The initial letter indicates the measured variable. The second letter indicates a modifier, readout, or device function. The third letter usually indicates either a device function or a modifier.

For example, “FIC” on an instrument tag represents a flow indicating controller. “PT” represents a pressure transmitter. You can find identification letter symbology information on the ISA Web site at http://www.isa.org.

**TAG NUMBERS**

Numbers on P&ID symbols represent instrument tag numbers. Often these numbers are associated with a particular control loop (e.g., flow transmitter 123). See Figure 7.13.

19. The initial letter on an ISA symbol indicates the measured variable. Is this statement true or false?

20. What does the third letter on an ISA symbol indicate?

1. Device function or a modifier
2. Measured variable
3. Readout
4. Type of process fluid
### ISA Symbology

<table>
<thead>
<tr>
<th>Measured Variable</th>
<th>Modifier</th>
<th>Readout</th>
<th>Device Function</th>
<th>Modifier</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>Analysis</td>
<td>Alarm</td>
<td>User’s choice</td>
<td>User’s choice</td>
</tr>
<tr>
<td>B</td>
<td>Burner, combustion</td>
<td>User’s choice</td>
<td>User’s choice</td>
<td>User’s choice</td>
</tr>
<tr>
<td>C</td>
<td>User’s choice</td>
<td>Differential</td>
<td>Control</td>
<td></td>
</tr>
<tr>
<td>D</td>
<td>User’s choice</td>
<td>Voltage</td>
<td>Sensor (primary element)</td>
<td></td>
</tr>
<tr>
<td>E</td>
<td>Flow rate</td>
<td>Modifier</td>
<td>Ration (fraction)</td>
<td></td>
</tr>
<tr>
<td>F</td>
<td>G</td>
<td>User’s choice</td>
<td>Glass, viewing device</td>
<td></td>
</tr>
<tr>
<td>G</td>
<td>H Hand</td>
<td>Time, time schedule</td>
<td>Time rate of change</td>
<td>Control station</td>
</tr>
<tr>
<td>H</td>
<td>I Electrical Current</td>
<td>Time</td>
<td>Indicator</td>
<td></td>
</tr>
<tr>
<td>I</td>
<td>J Power</td>
<td>Scan</td>
<td>User’s choice</td>
<td></td>
</tr>
<tr>
<td>K</td>
<td>L Level</td>
<td>Light</td>
<td>User’s choice</td>
<td>User’s choice</td>
</tr>
<tr>
<td>M</td>
<td>N User’s choice</td>
<td>User’s choice</td>
<td>User’s choice</td>
<td>User’s choice</td>
</tr>
<tr>
<td>O</td>
<td>P Pressure, vacuum</td>
<td>Orifice, restriction</td>
<td>Point, test connection</td>
<td></td>
</tr>
<tr>
<td>P</td>
<td>Q Quantity</td>
<td>Integrate, totalizer</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Q</td>
<td>R Radiation</td>
<td></td>
<td></td>
<td>Record</td>
</tr>
<tr>
<td>R</td>
<td>S Speed, frequency</td>
<td>Safety</td>
<td>Switch</td>
<td></td>
</tr>
<tr>
<td>S</td>
<td>T Temperature</td>
<td></td>
<td>Transmit</td>
<td></td>
</tr>
<tr>
<td>T</td>
<td>U Multivariable</td>
<td>Multifunction</td>
<td>Multifunction</td>
<td>Multifunction</td>
</tr>
<tr>
<td>U</td>
<td>V Vibration, mechanical analysis</td>
<td></td>
<td>Valve, damper, louver</td>
<td></td>
</tr>
<tr>
<td>V</td>
<td>W Weight, force</td>
<td>Well</td>
<td></td>
<td></td>
</tr>
<tr>
<td>W</td>
<td>X Unclassified</td>
<td>X axis</td>
<td>Unclassified</td>
<td>Unclassified</td>
</tr>
<tr>
<td>X</td>
<td>Y Event, state, or presence</td>
<td>Y axis</td>
<td>Relay, compute, convert</td>
<td></td>
</tr>
<tr>
<td>Y</td>
<td>Z Position, dimension</td>
<td>Z axis</td>
<td>Driver, actuator</td>
<td></td>
</tr>
</tbody>
</table>

ISA Identification Letters

www.PAControl.com
ISA Symbology

ISA SYMBOLOGY REVIEW

Figure 7.14 shows the elements of ISA symbology used in a P&ID.

![P&ID with ISA Symbology](image)

Activities

21. In Figure 7.14, what kind of signal is transmitted out from the temperature transmitter?

1. Data link
2. Mechanical signal
3. Electrical signal
4. Pneumatic signal
Controller Algorithms and Tuning

The previous sections of this module described the purpose of control, defined individual elements within control loops, and demonstrated the symbology used to represent those elements in an engineering drawing. The examples of control loops used thus far have been very basic. In practice, control loops can be fairly complex. The strategies used to hold a process at setpoint are not always simple, and the interaction of numerous setpoints in an overall process control plan can be subtle and complex. In this section, you will be introduced to some of the strategies and methods used in complex process control loops.

**LEARNING OBJECTIVES**

After completing this section, you will be able to:
- Differentiate between discrete, multistep, and continuous controllers
- Describe the general goal of controller tuning.
- Describe the basic mechanism, advantages and disadvantages of the following mode of controller action:
  - Proportional action
  - Integral action
  - Derivative action
- Give examples of typical applications or situations in which each mode of controller action would be used.
- Identify the basic implementation of P, PI and PID control in the following types of loops:
  - Pressure loop
  - Flow loop
  - Level loop
  - Temperature loop

**Note:** To answer the activity questions the Hand Tool (H) should be activated.
Controller Algorithms

The actions of controllers can be divided into groups based upon the functions of their control mechanism. Each type of controller has advantages and disadvantages and will meet the needs of different applications. Grouped by control mechanism function, the three types of controllers are:

- Discrete controllers
- Multistep controllers
- Continuous controllers

**DISCRETE CONTROLLERS**

_Discrete controllers_ are controllers that have only two modes or positions: on and off. A common example of a discrete controller is a home hot water heater. When the temperature of the water in the tank falls below setpoint, the burner turns on. When the water in the tank reaches setpoint, the burner turns off. Because the water starts cooling again when the burner turns off, it is only a matter of time before the cycle begins again. This type of control doesn’t actually hold the variable at setpoint, but keeps the variable within proximity of setpoint in what is known as a _dead zone_ (Figure 7.15).

Activities

1. Which one of the following is an everyday example of a discrete controller?
   - Refrigerator
   - Electric iron
   - Air conditioner
   - Rice cooker

---

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Controller Algorithms

MULTISTEP CONTROLLERS

Multistep controllers are controllers that have at least one other possible position in addition to on and off. Multistep controllers operate similarly to discrete controllers, but as setpoint is approached, the multistep controller takes intermediate steps. Therefore, the oscillation around setpoint can be less dramatic when multistep controllers are employed than when discrete controllers are used (Figure 7.16).

CONTINUOUS CONTROLLERS

Controllers automatically compare the value of the PV to the SP to determine if an error exists. If there is an error, the controller adjusts its output according to the parameters that have been set in the controller. The tuning parameters essentially determine:

How much correction should be made? The magnitude of the correction (change in controller output) is determined by the proportional mode of the controller.

How long should the correction be applied? The duration of the adjustment to the controller output is determined by the integral mode of the controller.

How fast should the correction be applied? The speed at which a correction is made is determined by the derivative mode of the controller.

Activities

2. A controller with three or more set positions is called a continuous controller. Is this statement true or false?
Controller Algorithms

When there is an error, the controller makes a change in its output. It determines:
- How much? Proportional Mode
- How long? Integral Mode
- How fast? Derivative Mode

Automatic Feedback Control
Why Controllers Need Tuning?

Controllers are tuned in an effort to match the characteristics of the control equipment to the process so that two goals are achieved:

- The system responds quickly to errors.
- The system remains stable (PV does not oscillate around the SP).

**Gain**

Controller tuning is performed to adjust the manner in which a control valve (or other final control element) responds to a change in error. In particular, we are interested in adjusting the gain of the controller such that a change in controller input will result in a change in controller output that will, in turn, cause sufficient change in valve position to eliminate error, but not so great a change as to cause instability or cycling.

Gain is defined simply as the change in output divided by the change in input.

**Examples:**

- **Change in Input to Controller - 10%**
  - **Change in Controller Output - 20%**
  - Gain = \( \frac{20\%}{10\%} = 2 \)

- **Change in Input to Controller - 10%**
  - **Change in Controller Output - 5%**
  - Gain = \( \frac{5\%}{10\%} = 0.5 \)

Gain conveys measurements and instructions to other instruments in a control loop to maintain the highest level of safety and efficiency.

The next three sections in this module discuss electricity, circuits, transmitters, and signals in greater detail so you can understand the importance of electricity in process control.

**Activities**

3. The change in the controller output divided by the change in the input to the controller is known as __________.
Why Controllers Need Tuning?

Gain Plot - The Figure below is simply another graphical way of representing the concept of gain.

\[ \text{Gain } K_c = \frac{\Delta \text{Output } \%}{\Delta \text{Input } \%} \]

Examples - The following examples help to illustrate the purpose of setting the controller gain to different values.

Controllers May be Tuned to Help Match the Valve to the Process

- Fast Process May Require Less Gain To Achieve Stability
- Slow Process May Require Higher Gain To Achieve Responsiveness

Fast and Slow Processes May Require Different Controller Gain Settings

Activities

4. Fast or slow processes have no impact on controller gain settings. Is this statement true or false?
Proportional Mode

Proportional Action

The proportional mode is used to set the basic gain value of the controller. The setting for the proportional mode may be expressed as either:
1. Proportional Gain
2. Proportional Band

Proportional Gain (Kc) answers the question: "What is the percentage change of the controller output relative to the percentage change in controller input?"

Proportional Gain is expressed as:
\[
\text{Gain, } (Kc) = \frac{\Delta \text{Output}\%}{\Delta \text{Input}\%}
\]

Proportional Band (PB) is another way of representing the same information and answers this question: "What percentage of change of the controller input span will cause a 100% change in controller output?"

\[
\text{PB} = \frac{\Delta \text{Input} (\% \text{Span})}{\Delta \text{Output}} \text{ For 100}\%\Delta \text{Output}
\]

Converting Between PB and Gain

A simple equation converts gain to proportional band:

\[
\text{PB} = \frac{100}{\text{Gain}}
\]

Also recall that:

\[
\text{Gain} = \frac{100\%}{\text{PB}}
\]

Proportional Gain, \( (Kc) = \frac{\Delta \text{Output}\%}{\Delta \text{Input}\%} \)

\[
\text{PB} = \frac{\Delta \text{Input}(\%\text{Span})}{\Delta \text{Output}} \text{ For 100}\%\Delta \text{Output}
\]

Activities

5. Identify the major disadvantage of proportional action.

1. Tends to leave an offset
2. Reset windup during shutdown
3. Possible overshoot during startup
4. Can cause cycling in fast process by amplifying noisy signals
**Proportional Mode**

- **Controller Algorithms and Tuning**

**Activities**

6. If proportional gain is 0.5, and a level reading is 5% above setpoint, a proportional controller will signal the outflow control valve to open by <1 / 2.5 / 5> % of its full range.

---

**Proportional Mode**

- **Controller Output** - In a proportional only controller, the output is a function of the change in error and controller gain.

\[
\text{Output Change, } \% = (\text{Error Change, } \%) \times \text{Gain}
\]

**Example:** If the setpoint is suddenly changed 10% with a proportional band setting of 50%, the output will change as follows:

### Calculating Controller Output

\[\Delta \text{Controller Output} = \Delta \text{Input, } \% \times \text{Gain} \]

**Example:**

\[\Delta \text{Input} = 10\%\]

\[\text{PB} = 50\%, \text{ so Gain} = 100\%/50\% = 2\]

---

**Limits of Proportional Action**

- **Responds Only to a Change in error** - Proportional action responds *only* to a change in the magnitude of the error.

- **Does Not Return the PV to Setpoint** - Proportional action will *not* return the PV to setpoint. It will, however, return the PV to a value that is within a defined span (PB) around the PV.

---

**Determining the Controller Output**

- **Controller Output** - In a proportional only controller, the output is a function of the change in error and controller gain.

\[\Delta \text{Controller Output} = \Delta \text{Input, } \% \times \text{Gain} \]

**Example:** If the setpoint is suddenly changed 10% with a proportional band setting of 50%, the output will change as follows:

**Calculating Controller Output**

\[\Delta \text{Controller Output} = \Delta \text{Input, } \% \times \text{Gain} \]

**Example**

\[\Delta \text{Input} = 10\%\]

\[\text{PB} = 50\%, \text{ so Gain} = 100\%/50\% = 2\]
**Proportional Mode**

\[ \Delta \text{Controller Output} = \Delta \text{Input} \times \text{Gain} \]

\[ \Delta \text{Controller Output} = 10\% \times 2 = 20\% \]

**Expressed in Units:**

Controller Output Change = (0.2)(12 psi span) = 2.4 psi OR
(0.2)(16 mA span) = 3.2 mA

**PROPORTIONAL ACTION - CLOSED LOOP**

**Loop Gain** - Every loop has a critical or natural frequency. This is the frequency at which cycling may exist. This critical frequency is determined by all of the loop components. If the loop gain is too high at this frequency, the PV will cycle around the SP; i.e., the process will become unstable.

**Low Gain Example** - In the example below, the proportional band is high (gain is low). The loop is very stable, but an error remains between SP and PV.

![Proportional Control Closed Loop - Low Gain Example](image)

**High Gain Example** - In the example, the proportional band is small resulting in high gain, which is causing instability. Notice that the process variable is still not on set point.
Proportional Mode

Proportional Summary - For the proportional mode, controller output is a function of a change in error. Proportional band is expressed in terms of the percentage change in error that will cause 100% change in controller output. Proportional gain is expressed as the percentage change in output divided by the percentage change in input.

\[ \text{PB} = \left( \frac{\Delta \text{Input}, \%}{\Delta \text{Output}, \%} \right) \times 100 = 100 / \text{Gain} \]

\[ \text{Gain} = \frac{\Delta \text{Input} \%, \%}{\Delta \text{Output} \%, \%} \]

\[ \Delta \text{Controller Output} = (\text{Change in Error})(\text{Gain}) \]

1. Proportional Mode Responds only to a change in error
2. Proportional mode alone will not return the PV to SP.

Advantages - Simple

Disadvantages - Error

Settings - PB settings have the following effects:

- Small PB (%): Minimize Offset
- High Gain (%): Possible cycling
- Large PB (%): Large Offset
- Low Gain: Stable Loop

Tuning - reduce PB (increase gain) until the process cycles following a disturbance, then double the PB (reduce gain by 50%).

Activities

7. What will be the result if the proportional gain is set too high?
   Select all options that apply.

1. Large offset
2. Minimized offset
3. Possible cycling
4. Stable loop
Integral Mode

INTEGRAL ACTION

Duration of Error and Integral Mode - Another component of error is the duration of the error, i.e., how long has the error existed? The controller output from the integral or reset mode is a function of the duration of the error.

OPEN LOOP ANALYSIS

Purpose - The purpose of integral action is to return the PV to SP. This is accomplished by repeating the action of the proportional mode as long as an error exists. With the exception of some electronic controllers, the integral or reset mode is always used with the proportional mode.

Setting - Integral, or reset action, may be expressed in terms of:

- **Repeats Per Minute** - How many times the proportional action is repeated each minute.
- **Minutes Per Repeat** - How many minutes are required for 1 repeat to occur.

Activities

8. ________ action is the type of control algorithm that eliminates offset.
Integral Mode

CLOSED LOOP ANALYSIS

Closed Loop With Reset - Adding reset to the controller adds one more gain component to the loop. The faster the reset action, the greater the gain.

Slow Reset Example - In this example the loop is stable because the total loop gain is not too high at the loop critical frequency. Notice that the process variable does reach set point due to the reset action.

Fast Reset Example - In the example the rest is too fast and the PV is cycling around the SP.

Activities

9. Which of the following are integral or reset actions expressed in terms of?

Select all options that apply.

1. Repeats per setting
2. Repeats per minute
3. Repeats per loop
4. Minutes per repeat
**Integral Mode**

**RESET WINDUP**

**Defined** - Reset windup is described as a situation where the controller output is driven from a desired output level because of a large difference between the set point and the process variable.

**Shutdown** - Reset windup is common on shut down because the process variable may go to zero but the set point has not changed, therefore this large error will drive the output to one extreme.

**Startup** - At start up, large process variable overshoot may occur because the reset speed prevents the output from reaching its desired value fast enough.

**Anti Reset Windup** - Controllers can be modified with an anti-reset

---

**Activities**

10. Identify the major disadvantages of integral action. Select all options that apply.

1. Tends to leave an offset
2. Reset windup during shutdown
3. Possible overshoot during start up
4. Can cause cycling in fast process by amplifying noisy signals
Integral Mode

windup (ARW) device. The purpose of an anti-reset option is to allow the output to reach its desired value quicker, therefore minimizing the overshoot.

**SUMMARY**

Integral (Reset) Summary - Output is a repeat of the proportional action as long as error exists. The units are in terms of repeats per minute or minutes per repeat.

**Advantages** - Eliminates error

**Disadvantages** - Reset windup and possible overshoot

| Fast Reset | 1. High Gain |
| Large Repeats/Min., Small Min./Repeat | 2. Fast Return To Setpoint |
| Slow Reset | 3. Possible Cycling |
| Small Repeats/Min., Large Min./Repeats | 2. Slow Return To Setpoint |
| | 3. Stable Loop |

**Trailing and Error Tuning** - Increase repeats per minute until the PV cycles following a disturbance, then slow the reset action to a value that is 1/3 of the initial setting.
**Derivative Mode**

**DERIVATIVE ACTION**

**Derivative Mode Basics** - Some large and/or slow process do not respond well to small changes in controller output. For example, a large liquid level process or a large thermal process (a heat exchanger) may react very slowly to a small change in controller output. To improve response, a large initial change in controller output may be applied. This action is the role of the derivative mode.

The derivative action is initiated whenever there is a *change in the rate of change of the error* (the slope of the PV). The magnitude of the derivative action is determined by the setting of the derivative. The mode of a PID controller and the rate of change of the PV. The Derivative setting is expressed in terms of *minutes*. In operation, the controller first compares the current PV with the last value of the PV. If there is a change in the slope of the PV, the controller determines what its output would be at a future point in time (the future point in time is determined by the value of the derivative setting, in minutes). The derivative mode *immediately* increases the output by that amount.

**Activities**

11. _______ action is a control algorithm that is tied to the rate of change in the error.

12. Which of the following are derivative or rate actions expressed in terms of?
   1. Repeats per minute
   2. Hours
   3. Seconds
   4. Minutes
   5. Milliseconds
Derivative Mode

Example - Let's start a closed loop example by looking at a temperature control system. In this example, the time scale has been lengthened to help illustrate controller actions in a slow process. Assume a proportional band setting of 50%. There is no reset at this time. The proportional gain of 2 acting on a 10% change in set point results in a change in controller output of 20%. Because temperature is a slow process the setting time after a change in error is quite long. And, in this example, the PV never becomes equal to the SP because there is no reset.

Rate Effect - To illustrate the effect of rate action, we will add the rate mode with a setting of 1 minute. Notice the very large controller output at time 0. The output spike is the result of rate action. Recall that the change in output due to rate action is a function of the speed (rate) of change of error, which in a step is nearly infinite. The addition of rate alone will not cause the process variable to match the set point.

13. The addition of derivative or rate alone to a close loop control can cause the process variable to match the set point. Is this statement true or false?
### Derivative Mode

**Effect of Fast Rate** - Let's now increase the rate setting to 10 minutes. The controller gain is now much higher. As a result, both the IVP (controller output) and the PV are cycling. The point here is that increasing the rate setting will not cause the PV to settle at the SP.

**Need for Reset Action** - It is now clear that reset must be added to bring process variable back to set point.

**Applications** - Because this component of the controller output is dependent on the speed of change of the input or error, the output will be very erratic if rate is used on fast process or one with noisy signals. The controller output, as a result of rate, will have the greatest change when the input changes rapidly.

**Controller Option to Ignore Change in SP** - Many controllers, especially digital types, are designed to respond to changes in the PV only, and to ignore changes in SP. This feature eliminates a major upset upset that would occur following a change in the setpoint.
**Derivative Mode**

**SUMMARY**

**Derivative (Rate) Summary** - Rate action is a function of the *speed of change* of the error. The units are *minutes*. The action is to apply an immediate response that is equal to the proportional plus reset action that would have occurred some number of minutes in the future.

**Advantages** - Rapid output reduces the time that is required to return PV to SP in slow process.

**Disadvantage** - Dramatically amplifies noisy signals; can cause cycling in fast processes.

**Settings**

<table>
<thead>
<tr>
<th>Large (Minutes)</th>
<th>Settings</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. High Gain</td>
<td></td>
</tr>
<tr>
<td>2. Large Output Change</td>
<td></td>
</tr>
<tr>
<td>3. Possible Cycling</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Small (Minutes)</th>
<th>Settings</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Low Gain</td>
<td></td>
</tr>
<tr>
<td>2. Small Output Change</td>
<td></td>
</tr>
<tr>
<td>3. Stable Loop</td>
<td></td>
</tr>
</tbody>
</table>

**Trial-and-Error Tuning**

Increase the rate setting until the process cycles following a disturbance, then reduce the rate setting to one-third of the initial value.
Controller Algorithms

Proportional, PI, and PID Control

By using all three control algorithms together, process operators can:
- Achieve rapid response to major disturbances with derivative control
- Hold the process near setpoint without major fluctuations with proportional control
- Eliminate offset with integral control

Not every process requires a full PID control strategy. If a small offset has no impact on the process, then proportional control alone may be sufficient.

PI control is used where no offset can be tolerated, where noise (temporary error readings that do not reflect the true process variable condition) may be present, and where excessive dead time (time after a disturbance before control action takes place) is not a problem.

In processes where no offset can be tolerated, no noise is present, and where dead time is an issue, customers can use full PID control. Table 7.2 shows common types of control loops and which types of control algorithms are typically used.

<table>
<thead>
<tr>
<th>Controlled Variable</th>
<th>Proportional Control</th>
<th>PI Control</th>
<th>PID Control</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flow</td>
<td>Yes</td>
<td>Yes</td>
<td>No</td>
</tr>
<tr>
<td>Level</td>
<td>Yes</td>
<td>Yes</td>
<td>Rare</td>
</tr>
<tr>
<td>Temperature</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Pressure</td>
<td>Yes</td>
<td>Yes</td>
<td>Rare</td>
</tr>
<tr>
<td>Analytical</td>
<td>Yes</td>
<td>Yes</td>
<td>Rare</td>
</tr>
</tbody>
</table>

Table 7.2: Control Loops and Control Algorithms

Activities

14. What type of control is used in an application where noise is present, but where no offset can be tolerated?

1. P only
2. PD
3. PI
4. PID

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Process Control Loops

In this section, you will learn about how control components and control algorithms are integrated to create a process control system. Because in some processes many variables must be controlled, and each variable can have an impact on the entire system, control systems must be designed to respond to disturbances at any point in the system and to mitigate the effect of those disturbances throughout the system.

Learning Objectives

After completing this section, you will be able to:

- Explain how a multivariable loop is different from a single loop.
- Differentiate feedback and feedforward control loops in terms of their operation, design, benefits, and limitations.
- Perform the following functions for each type of standard process control loop (i.e., pressure, flow, level, and temperature):
  - State the type of control typically used and explain why it is used.
  - Identify and describe considerations for equipment selection (e.g., speed, noise).
  - Identify typical equipment requirements.
  - Diagram the loop using ISA symbology.
- Explain the basic implementation process, including a description of equipment requirements and considerations, for each of the following types of control:
  - Cascade control
  - Batch control
  - Ratio control
  - Selective control
  - Fuzzy control
- Describe benefits and limitations of each type of control listed above.
- Give examples of process applications in which each type of control described in this section might be used.

Note: To answer the activity questions the Hand Tool (H) should be activated.
Control loops can be divided into two categories: Single variable loops and multi-variable loops.

**Feedback Control**

A feedback loop measures a process variable and sends the measurement to a controller for comparison to setpoint. If the process variable is not at setpoint, control action is taken to return the process variable to setpoint. Figure 7.18 illustrates a feedback loop in which a transmitter measures the temperature of a fluid and, if necessary, opens or closes a hot steam valve to adjust the fluid’s temperature.

An everyday example of a feedback loop is the cruise control system in an automobile. A setpoint is established for speed. When the car begins to climb a hill, the speed drops below setpoint and the controller adjusts the throttle to return the car’s speed to setpoint.

Feedback loops are commonly used in the process control industry. The advantage of a feedback loop is that it directly controls the desired process variable. The disadvantage to feedback loops is that the process variable must leave setpoint for action to be taken.

**Activities**

1. What type of control loop takes action in response to measured deviation from setpoint?
   - Discrete control loop
   - Multi-step control loop
   - Open loop
   - Feedback control loop
Examples of Single Control Loops

While each application has its own characteristics, some general statements can be made about pressure, flow, level, and temperature loops.

**Pressure Control Loops**

Pressure control loops vary in speed—that is, they can respond to changes in load or to control action slowly or quickly. The speed required in a pressure control loop may be dictated by the volume of the process fluid. High-volume systems (e.g., large natural gas storage facilities) tend to change more slowly than low-volume systems (Figure 7.21).

![A Pressure Loop Diagram](image)

2. How does a high-volume pressure control loop react as compared to a small-volume pressure control loop?

   1. Same rate
   2. Quicker
   3. Slower
   4. Extremely fast
Examples of Single Control Loops

FLOW CONTROL LOOPS

Generally, flow control loops are regarded as fast loops that respond to changes quickly. Therefore, flow control equipment must have fast sampling and response times. Because flow transmitters tend to be rather sensitive devices, they can produce rapid fluctuations or noise in the control signal. To compensate for noise, many flow transmitters have a damping function that filters out noise. Sometimes, filters are added between the transmitter and the control system. Because the temperature of the process fluid affects its density, temperature measurements are often taken with flow measurements and compensation for temperature is accounted for in the flow calculation. Typically, a flow sensor, a transmitter, a controller, and a valve or pump are used in flow control loops (Figure 7.22).

A Flow Loop

Activities

3. Flow control loops are generally considered to be slow responding loops. Is this statement true or false?
The speed of changes in a level control loop largely depends on the size and shape of the process vessel (e.g., larger vessels take longer to fill than smaller ones) and the flow rate of the input and outflow pipes. Manufacturers may use one of many different measurement technologies to determine level, including radar, ultrasonic, float gauge, and pressure measurement. The final control element in a level control loop is usually a valve on the input and/or outflow connections to the tank (Figure 7.23). Because it is often critical to avoid tank overflow, redundant level control systems are sometimes employed.

4. Redundant control systems are sometimes used in level applications because preventing tank overflow is often critically important. Is this statement true or false?
Temperature Control Loops

Because of the time required to change the temperature of a process fluid, temperature loops tend to be relatively slow. Feedforward control strategies are often used to increase the speed of the temperature loop response. RTDs or thermocouples are typical temperature sensors. Temperature transmitters and controllers are used, although it is not uncommon to see temperature sensors wired directly to the input interface of a controller. The final control element for a temperature loop is usually the fuel valve to a burner or a valve to some kind of heat exchanger. Sometimes, cool process fluid is added to the mix to maintain temperature (Figure 7.24).

Activities

5. What type of control strategy is often used to increase the speed of a temperature control loop?

1. Feedforward control
2. Feedback control
3. Cascade control
4. Ratio control
Multi-Variable / Advanced Control Loops

MULTIVARIABLE LOOPS

Multivariable loops are control loops in which a primary controller controls one process variable by sending signals to a controller of a different loop that impacts the process variable of the primary loop. For example, the primary process variable may be the temperature of the fluid in a tank that is heated by a steam jacket (a pressurized steam chamber surrounding the tank). To control the primary variable (temperature), the primary (master) controller signals the secondary (slave) controller that is controlling steam pressure. The primary controller will manipulate the setpoint of the secondary controller to maintain the setpoint temperature of the primary process variable (Figure 7.17).

When tuning a control loop, it is important to take into account the presence of multivariable loops. The standard procedure is to tune the secondary loop before tuning the primary loop because adjustments to the secondary loop impact the primary loop. Tuning the primary loop will not impact the secondary loop tuning.

### Activities

6. A multivariable control loop contains a primary and secondary controller assigned to different process variables? Is this statement true or false?
Feedforward control is a control system that anticipates load disturbances and controls them before they can impact the process variable. For feedforward control to work, the user must have a mathematical understanding of how the manipulated variables will impact the process variable. Figure 7.19 shows a feedforward loop in which a flow transmitter opens or closes a hot steam valve based on how much cold fluid passes through the flow sensor.

Feedforward Control

An advantage of feedforward control is that error is prevented, rather than corrected. However, it is difficult to account for all possible load disturbances in a system through feedforward control. Factors such as outside temperature, buildup in pipes, consistency of raw materials, humidity, and moisture content can all become load disturbances and cannot always be effectively accounted for in a feedforward system.

In general, feedforward systems should be used in cases where the controlled variable has the potential of being a major load disturbance on the process variable ultimately being controlled. The added complexity and expense of feedforward control may not be equal to the benefits of increased control in the case of a variable that causes only a small load disturbance.

Activities

7. What type of control loop anticipates and controls load disturbances before they can impact the process variable?

1. Feedback control loop
2. Feedforward control loop
3. Ratio control loop
4. Single variable loop
Because of the difficulty of accounting for every possible load disturbance in a feedforward system, feedforward systems are often combined with feedback systems. Controllers with summing functions are used in these combined systems to total the input from both the feedforward loop and the feedback loop, and send a unified signal to the final control element. Figure 7.20 shows a feedforward-plus-feedback loop in which both a flow transmitter and a temperature transmitter provide information for controlling a hot steam valve.

8. A controller with a summing function totals the input from both the feedforward loop and the feedback loop and sends a unified signal to the final control element. This is how a single control signal is sent to the final control element in a feedforward plus feedback system. Is this statement true or false?
Multi-Variable / Advanced Control Loops

This module has discussed specific types of control loops, what components are used in them, and some of the applications (e.g., flow, pressure, temperature) they are applied to. In practice, however, many independent and interconnected loops are combined to control the workings of a typical plant. This section will acquaint you with some of the methods of control currently being used in process industries.

CASCADE CONTROL

Cascade control is a control system in which a secondary (slave) control loop is set up to control a variable that is a major source of load disturbance for another primary (master) control loop. The controller of the primary loop determines the setpoint of the summing controller in the secondary loop (Figure 7.25).

Activities

9. Ratio control is the term used to describe a system in which the controller of the primary loop determines the setpoint of a secondary loop. Is this statement true or false?
**Batch Control**

*Batch processes* are those processes that are taken from start to finish in batches. For example, mixing the ingredients for a juice drinks is often a batch process. Typically, a limited amount of one flavor (e.g., orange drink or apple drink) is mixed at a time. For these reasons, it is not practical to have a continuous process running. Batch processes often involve getting the correct proportion of ingredients into the batch. Level, flow, pressure, temperature, and often mass measurements are used at various stages of batch processes.

A disadvantage of batch control is that the process must be frequently restarted. Start-up presents control problems because, typically, all measurements in the system are below setpoint at start-up. Another disadvantage is that as recipes change, control instruments may need to be recalibrated.

**Ratio Control**

Imagine a process in which an acid must be diluted with water in the proportion two parts water to one part acid. If a tank has an acid supply on one side of a mixing vessel and a water supply on the other, a control system could be developed to control the ratio of acid to water, even though the water supply itself may not be controlled. This type of control system is called *ratio control* (Figure 7.26). Ratio control is used in many applications and involves a controller that receives input from a flow measurement device on the unregulated (wild) flow. The controller performs a ratio calculation and signals the appropriate setpoint to another controller that sets the flow of the second fluid so that the proper proportion of the second fluid can be added.

Ratio control might be used where a continuous process is going on and an additive is being put into the flow (e.g., chlorination of water).

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**Activities**

10. Which term describes a control system in which controlled flow is added proportionately to an uncontrolled flow?

1. Selective control
2. Cascade control
3. Ratio control
4. Fuzzy control
Multi-Variable / Advanced Control Loops

**SELECTIVE CONTROL**

Selective control refers to a control system in which the more important of two variables will be maintained. For example, in a boiler control system, if fuel flow outpaces air flow, then uncombusted fuel can build up in the boiler and cause an explosion. Selective control is used to allow for an air-rich mixture, but never a fuel-rich mixture. Selective control is most often used when equipment must be protected or safety maintained, even at the cost of not maintaining an optimal process variable setpoint.

**FUZZY CONTROL**

Fuzzy control is a form of adaptive control in which the controller uses fuzzy logic to make decisions about adjusting the process. Fuzzy logic is a form of computer logic where whether something is or is not included in a set is based on a grading scale in which multiple factors are accounted for and rated by the computer. The essential idea of fuzzy control is to create a kind of artificial intelligence that will account for numerous variables, formulate a theory of how to make improvements, adjust the process, and learn from the result.

Fuzzy control is a relatively new technology. Because a machine makes process control changes without consulting humans, fuzzy control removes from operators some of the ability, but none of the responsibility, to control a process.

**Activities**

11. In which type of control system will the more important of two variables be maintained?
   1. Fuzzy control
   2. Cascade control
   3. Ratio control
   4. Selective control

12. ___________ control is the term used to describe a control system in which the controller uses computer logic to make decisions about adjusting the process.
Module 7: Workbook Exercises

EXERCISE 7.1— THE IMPORTANCE OF PROCESS CONTROL

1. Which of the following options best represents the reasons to control a process? (Select three options that apply)
   (1) Reduce variability
   (2) Increase productivity
   (3) Increase efficiency
   (4) Reduce cost
   (5) Ensure safety

2. Process is defined as the method of changing or refining raw materials to create end products. Is this statement true or false?
   (1) True
   (2) False

3. Which of the following are advantages of reducing variability in a process application?
   (1) Helps ensure a consistently high-quality end product.
   (2) Helps ensure an increase in the reaction rate of the process.
   (3) Helps ensure increase in efficiency of the process.
   (4) Helps ensure safety
Module 7: Workbook Exercises

Exercise 7.2 — Control Theory Basics

1. Which of the following tasks is associated with process control? (Select three options that apply)
   (1) Measurement
   (2) Comparison
   (3) Quality Analysis
   (4) Adjustment
   (5) Calculation

2. Which of the following variables are commonly measured or monitored in process control applications? (Select three options that apply)
   (1) Pressure
   (2) Viscosity
   (3) Nitrogen content
   (4) Flow rate
   (5) Temperature

3. A process liquid level needs to be held within 5 ft of 150 ft in a large tank. A pressure transmitter monitors the liquid’s level using a pressure reading and sends the result to a controller. The controller compares the level reading to the set point and opens or closes an inflow or outflow pipe depending on the liquid level. Keeping in mind the given scenario, match the terms in Column A with their values in Column B.

   (1) Inferred process variable       (A) 150 ft
   (2) Manipulated variable           (B) Pressure
   (3) Measured variable              (C) Flow of liquid to the tank
   (4) Set point                      (D) Level
Module 7: Workbook Exercises

4. Match each term to its correct definition.

   (1) Load disturbance
   (2) Control algorithm
   (3) Manual control
   (4) Manipulated variable
   (5) Set point

   (A) The factor that is changed to keep a measured variable at set point.
   (B) An undesired change in a factor that can affect the process variable.
   (C) A value or range of values for a process variable that must be maintained to keep the process running properly.
   (D) A control operation that directly involves human action.
   (E) A mathematical expression of a control function

5. Match each term to its correct description.

   (1) Closed-loop, automatic control
   (2) Closed-loop, manual control
   (3) Open-loop, automatic control

   (A) An operator turns off the heater coil when the temperature transmitter outputs a certain reading.
   (B) A controller turns off the heater coil at set intervals, regardless of the process temperature.
   (C) A temperature sensor measures process temperature, sends the result to a controller to compare to the setpoint, and the controller turns off the heater coil.

6. __________ is a deviation from set point due to load disturbance.

   (1) Error
   (2) Offset
   (3) Rate of change

7. __________ is a continuing error due to the inability of a control system to keep the measured variable at set point.

   (1) Load disturbance
   (2) Offset
   (3) Pressure
Module 7: Workbook Exercises

EXERCISE 7.3 — COMPONENTS OF CONTROL LOOPS AND ISA SYMBOLOGY

1. The basic function of a __________ is to convert a reading from a transducer into a standard signal and transmit that signal to a controller or computer monitor.
   (1) recorder
   (2) transmitter
   (3) converter

2. 4–20 mA is the most common standard analog signal used in the process control industry today. Is this statement true or false?
   (1) True
   (2) False

3. Match the signal type in Column A with its example/application in Column B.
   (1) Analog signal (A) 3 – 15 psig
   (2) Pneumatic signal (B) Fieldbus, Profibus and Modbus
   (3) Digital signal (C) 4–20 mA and 1 – 5 V

4. A customer would use __________ to read the temperature of a process fluid on a display.
   (1) an indicator
   (2) a volt-meter
   (3) an actuator

5. Match each control loop equipment to its correct description.
   (1) Recorder     
   (2) Controller   
   (3) Final control element 
   (4) Actuator     

6. A pump motor is the most commonly used final control element. Is this statement true or false?
   (1) True
   (2) False
Module 7: Workbook Exercises

7. Match the ISA symbols in Column A with its respective description in Column B.

(1)     (A) Programmable logic control

(2)     (B) Temperature transmitter

(3)     (C) Pneumatically actuated valve

(4)     (D) Electrically actuated valve
EXERCISE 7.4 — CONTROL ALGORITHMS AND TUNING

1. Match each term to its correct definitions.

(1) Proportional band  
(2) Proportional/integral (PI) control  
(3) Proportional control  
(4) Derivative control  
(5) Integral control

(A) A type of control that corrects error and eliminates offset.  
(B) A type of control that produce erratic output in noisy applications.  
(C) The percent change in error that will cause a 100% change in controller output.  
(D) A type of control that is prone to leaving an offset.  
(E) A type of control that repeats the action of the proportional mode as long as an error exists.

2. Identify the two effects on a process variable if the proportional gain (Pgain) is set too high? (Select all that apply)

(1) Minimize offset  
(2) Large offset  
(3) Stable loop  
(4) Possible cycling

3. Derivative gain (Dgain) is typically set to zero in flow applications since flow applications are usually noisy and derivative control will react to readings that are in fact noise, thus preventing the process from holding set point. Is this statement true or false?

(1) True  
(2) False
Module 7: Workbook Exercises

EXERCISE 7.5 — PROCESS CONTROL LOOPS

1. Which control system anticipates load disturbances and controls them before they can impact the process variable?
   (1) Selective control
   (2) Fuzzy control
   (3) Feed forward control
   (4) Cascade control

2. Match the component label in Column A to its ISA symbol representation in Column B.
   (1) Flow transmitter
   (A)
   (2) Temperature transmitter
   (B)
   (3) Flow controller
   (C)
   (4) Valve
   (D)

3. If $R_1 = 60 \, \Omega$, $R_2 = 100 \, \Omega$, and $R_3 = 100 \, \Omega$, what is the equivalent resistance ($R_{eq}$) in the circuit?
   (1) slow
   (2) fast
   (3) variable speed
Module 7: Workbook Exercises - Answers

Exercise 7.1 – The Importance of Process Control

1. 1, 3, 5
2. 1
3. 1

Exercise 7.2 – Control Theory Basics

1. 1, 2, 4
2. 1, 4, 5
3. D, C, B, A
4. B, E, D, A, C
5. C, A, B
6. 1
7. 2

Exercise 7.3 – Components of Control Loops and ISA Symbology

1. 2
2. 1
3. C, A, B
4. 1
5. C, D, B, A
6. 2
7. B, C, D, A

Exercise 7.4 – Control Algorithms and Tuning

1. C, A, D, B, E
2. 1, 4
3. 1

Exercise 7.5 – Process Control Loops

1. 3
2. B, C, D, A
3. 1
Module 7: Activity Answers

The Importance of Process Control

1. True
2. 1,3,5
3. 1,2,4

Control Theory Basics

1. True
2. True
3. True
4. 4
5. 3
6. False
7. False
8. 2,4

Components of Control Loops and ISA Symbology

1. 1,2,5
2. False
3. 3
4. True
5. 2,3,4
6. 1
7. 1,4
8. 2
9. 4
10. 3
11. 1
12. 2
13. 1
14. 2
15. 3
16. True
17. 4
18. True
19. True
20. 1
21. 3
Module 7: Activity Answers

Controller Algorithms and Tuning

1. 1,2,3,4
2. False
3. 2
4. False
5. 1
6. 2.5
7. 2,3
8. 3
9. 2,4
10. 2,3
11. 2
12. 4
13. False
14. 3

Process Control Loops

1. 4
2. 3
3. False
4. True
5. 1
6. True
7. 2
8. True
9. False
10. 3
11. 4
12. 1
Topics Covered

- Sensors & Control Valves
- Dynamics
- Feedback & Feedforward Control
- Proportional, Integral and Derivative Controllers
- Cascade Control
- Control Loop Design
- Tuning PID Controllers & Stability
- Open- and Closed-Loop Transfer Functions
Sensor

- Device that measures a process variable
- Report system conditions and activate controller as necessary
- Must be placed properly in the system to achieve the desired result
Controls

• Valves control the operation
• Sometimes manual, usually mechanical
• Have various operations to adjust the system when the steady-state process is interrupted
Control Diagram Symbols

- AC - analyzer controller
- AT - analyzer transmitter
- DPC - differential pressure controller
- DPT - differential pressure sensor/transmitter
- FC - flow controller
- FT - flow sensor/transmitter
- HS - high select
- LC - level controller
- LT - level sensor/transmitter
- PC - pressure controller
- pHC - pH controller
- pHT - pH sensor/transmitter
- RSP - remote setpoint
- S - select controller
- TC - temperature controller
- TT - temperature sensor/transmitter
- + an addition function
- x multiplication function
Feedback & FeedForward
Feedback Control

- Sensor reading and setpoint value used to select the level for the manipulated process variable
- Water temperature example
Feedforward Control

• Controller makes adjustments to manipulated variable based upon measured disturbances
• Attempts to proactively respond and absorb effect of the disturbance prior to the disturbance affecting the process
• Shower example, revisited
Feedforward/Feedback Example
• For the following heat exchanger, construct a feedback and a feedforward control configuration
Feedforward

$T_{sp}$

$+X$

$e$

$T_{c}$

$T_{H}$

$T_{T}$

$T_{S}$

$T_{C}$

$T_{H}$

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Proportional, Integral, & Derivative Controller Concepts
PID Controllers

• Most common controller
• Provides adjustments to actuator (proportional to error from setpoint, to the time integral of the error, and the time derivative of the error)
• Improve performance over manual control
• Operate using Closed- and Open-Loop Transfer Functions
Open- & Closed-loop Transfer Functions
Variables

- $G_1(s)$: controller/compensator
- $G_2(s)$: plant model
- $L_s(s)$: load disturbance
- $Y(s)$: controlled variable
- $R(s)$: reference input
- $H(s)$: measurement dynamics
- $D(s)$: denominator polynomial
- $N(s)$: numerator polynomial
- $K$: controller gain/process gain
- $\zeta$: damping ratio
- $\omega$: undamped natural
Transfer Function Example

• For the feedback control system below, what is the controller gain with a critically damped response?

A) 0.5  B) 1.25  C) 1.25  D) 12.5

\[ G(s) = \frac{0.1}{(s + 1)(2s + 1)} \]
Transfer Function Solution (1)

\[ Y(s) = \frac{K_c G(s)}{1 + G(s)K_c} = \frac{0.01K_c}{(s+1)(2s+1)} + \frac{0.01K_c}{(s+1)(2s+1)} \]

\[ = \frac{0.01K_c}{(s+1)(2s+1) + 0.01K_c} \]

\[ = \frac{0.01K_c}{2s^2 + 3s + 1 + 0.01K_c} = \frac{0.01K_c}{s^2 + \frac{3}{2}s + 1 + 0.01K_c} \]

Critically damped by the problem statement, therefore, \( \zeta = 1 \)
Transfer Function Solution (2)

\[ \frac{Y(s)}{R(s)} = \frac{K\omega}{s^2 + 2\xi\omega s + \omega^2} = \frac{0.01K_c/2}{s^2 + \frac{3}{2}s + \frac{1+0.01K_c}{2}} \]

\[ \omega = \sqrt{\frac{1+0.1K_c}{2}} \]

\[ 2 = \left(\frac{16}{9}\right)(0.1)K_c + 1 \]

\[ 2 = \frac{18}{16} - 1 = 0.1K_c \]

\[ K_c = 1.25 \]

The answer is B.
Tuning PID Controllers & Stability
Tuning PID Loops

• Select values for $K$ and $\tau$

• Objectives
  – Minimize deviations from setpoint
  – Attain good setpoint tracking performance
  – Avoid excessive variation of the manipulated variables
  – Maintain process stability for major disturbance upsets
  – Eliminate offset
Introduction

To study the subject of industrial process control effectively, you must first gain a general understanding of its basic principles. To present these control principles clearly and concisely, an intuitive approach to process control is used. First, however, some basic definitions and concepts of process control are presented.

Definition of Process Control

The operations that are associated with process control have always existed in nature. Such “natural” process control can be defined as any operation that regulates some internal physical characteristic that is important to a living organism. Examples of natural regulation in humans include body temperature, blood pressure, and heart rate.

Early humans found it necessary to regulate some of their external environmental parameters to maintain life. This regulation could be defined as “artificial process control” or more simply as “process control,” as we will refer to it in this book. This type of process control is accomplished by observing a parameter, comparing it to some desired value, and initiating a control action to bring the parameter as close as possible to the desired value. One of the first examples of such control was early man’s use of fire to maintain the temperature of his environment.

The term automatic process control came into wide use when people learned to adapt automatic regulatory procedures to manufacture products or pro-
cess material more efficiently. Such procedures are called automatic because no human (manual) intervention is required to regulate them.

All process systems consist of three main factors or terms: the manipulated variables, disturbances, and the controlled variables (Figure 1-1). Typical manipulated variables are valve position, motor speed, damper position, or blade pitch. The controlled variables are those conditions—such as temperature, level, position, pressure, pH, density, moisture content, weight, and speed—that must be maintained at some desired value. For each controlled variable there is an associated manipulated variable. The control system must adjust the manipulated variables so the desired value or “set point” of the controlled variable is maintained despite any disturbances.

Disturbances enter or affect the process and tend to drive the controlled variables away from their desired value or set point condition. Typical disturbances include changes in ambient temperature, in demand for product, or in the supply of feed material. The control system must adjust the manipulated variable so the set point value of the controlled variable is maintained despite the disturbances. If the set point is changed, the manipulated quantity must be changed to adjust the controlled variable to its new desired value.

For each controlled variable the control system operator selects a manipulated variable that can be paired with the controlled variable. Often the choice is obvious, such as manipulating the flow of fuel to a home furnace to control the temperature of the house. Sometimes the choice is not so obvious and can only be determined by someone who understands the process under control. The pairing of manipulated and controlled variables is performed as part of the process design.

Figure 1-1. Process control variables
Elements of a Process Control System

Figure 1-2 illustrates the essential elements of a process control system. In the system shown, a level transmitter (LT), a level controller (LC), and a control valve (LV) are used to control the liquid level in a process tank. The purpose of this control system is to maintain the liquid level at some prescribed height (H) above the bottom of the tank. It is assumed that the rate of flow into the tank is random. The level transmitter is a device that measures the fluid level in the tank and converts it into a useful measurement signal, which is sent to a level controller. The level controller evaluates the measurement, compares it with a desired set point (SP), and produces a series of corrective actions that are sent to the control valve. The valve controls the flow of fluid in the outlet pipe to maintain a level in the tank.

Thus, a process control system consists of four essential elements: process, measurement, evaluation, and control. A block diagram of these elements is shown in Figure 1-3. The diagram also shows the disturbances that enter or affect the process. If there were no upsets to a process, there would be no need for the control system. Figure 1-3 also shows the input and output of the process and the set point used for control.
4 Measurement and Control Basics

Process

In general, a process consists of an assembly of equipment and material that is related to some manufacturing operation or sequence. In the example presented in Figure 1-2, the process whose liquid level is placed under control includes such components as a tank, the liquid in the tank, the flow of liquid into and out of the tank, and the inlet and outlet piping. Any given process can involve many dynamic variables, and it may be desirable to control all of them. In most cases, however, controlling only one variable will be sufficient to control the process to within acceptable limits. One occasionally encounters a multivariable process in which many variables, some interrelated, require regulation.

Measurement

To control a dynamic variable in a process, you must have information about the entity or variable itself. This information is obtained by measuring the variable.

Measurement refers to the conversion of the process variable into an analog or digital signal that can be used by the control system. The device that performs the initial measurement is called a sensor or instrument. Typical measurements are pressure, level, temperature, flow, position, and speed. The result of any measurement is the conversion of a dynamic variable into some proportional information that is required by the other elements in the process control loop or sequence.

Evaluation

In the evaluation step of the process control sequence, the measurement value is examined, compared with the desired value or set point, and the amount of corrective action needed to maintain proper control is deter-
mined. A device called a controller performs this evaluation. The controller can be a pneumatic, electronic, or mechanical device mounted in a control panel or on the process equipment. It can also be part of a computer control system, in which case the control function is performed by software.

Control

The control element in a control loop is the device that exerts a direct influence on the process or manufacturing sequence. This final control element accepts an input from the controller and transforms it into some proportional operation that is performed on the process. In most cases, this final control element will be a control valve that adjusts the flow of fluid in a process. Devices such as electrical motors, pumps, and dampers are also used as control elements.

Process and Instrumentation Drawings

In the measurement and control field, a standard set of symbols is used to prepare drawings of control systems and processes. The symbols used in these drawings are based on the standard ISA-5.1-1984 (R1992) Instrumentation Symbols and Identification, which was developed by ISA. A typical application for this standard is process and instrumentation diagrams (P&IDs), which show the interconnection of the process equipment and the instrumentation used to control the process. A portion of a typical P&ID is shown in Figure 1-4.

In standard P&IDs, the process flow lines, such as process fluid and steam, are indicated with heavier solid lines than the lines that are used to represent the instrument. The instrument signal lines use special markings to indicate whether the signal is pneumatic, electric, hydraulic, and so on. Table A-1 in Appendix A lists the instrument line symbols that are used on P&IDs and other instrumentation and control drawings. In Figure 1-4, two types of instrument signals are used: double cross-hatched lines denote the pneumatic signals to the steam control valve and the process outlet flow control valve, and a dashed line is used for the electrical control lines between various instruments. In process control applications, pneumatic signals are almost always 3 to 15 psi (i.e., pounds per square inch, gauge pressure), and the electric signals are normally 4 to 20 mA (milliamperes) DC (direct current).

A balloon symbol with an enclosed letter and number code is used to represent the instrumentation associated with the process control loop. This letter and number combination is called an instrument identification or instrument tag number.
The first letter of the tag number is normally chosen so that it indicates the measured variable of the control loop. In the sample P&ID shown in Figure 1-4, T is the first letter in the tag number that is used for the instruments in the temperature control loop. The succeeding letters are used to represent a readout or passive function or an output function, or the letter can be used as a modifier. For example, the balloon in Figure 1-4 marked TE represents a temperature element and that marked TIC is a temperature-indicating controller. The line across the center of the TIC balloon symbol indicates that the controller is mounted on the front of a main control panel. No line indicates a field-mounted instrument, and two lines mean that the instrument is mounted in a local or field-mounted panel. Dashed lines indicate that the instrument is mounted inside the panel.

Normally, sequences of three- or four-digit numbers are used to identify each loop. In our process example (Figure 1-4), we used loop numbers 100 and 101. Smaller processes use three-digit loop numbers; larger processes or complex manufacturing plants may require four or more digits to identify all the control loops.

Special marks or graphics are used to represent process equipment and instruments. For example, in our P&ID example in Figure 1-4, two parallel lines represent the orifice plate that is used to detect the discharge flow from the process heater. The two control valves in the figure also use a
special symbol. See Appendix A for a more detailed discussion of the instrumentation and process symbols that are used on P&IDs.

**General Requirements of a Control System**

The primary requirement of a control system is that it be reasonably stable. In other words, its speed of response must be fairly fast, and this response must show reasonable damping. A control system must also be able to reduce the system error to zero or to a value near zero.

**System Error**

The system error is the difference between the value of the controlled variable set point and the value of the process variable maintained by the system. The system error is expressed in equation form by the following:

\[ e(t) = PV(t) - SP(t) \]  

where

- \( e(t) \) = system error as a function of time (t)
- \( PV(t) \) = the process variable as a function of time
- \( SP(t) \) = the set point as a function of time

**System Response**

The main purpose of a control loop is to maintain some dynamic process variable (pressure, flow, temperature, level, etc.) at a prescribed operating point or set point. System response is the ability of a control loop to recover from a disturbance that causes a change in the controlled process variable.

There are two general types of good response: underdamped (cyclic response) and damped. Figure 1-5 shows an underdamped or cyclic response of a system in which the process variable oscillates around the set point after a process disturbance. The wavy response line shown in the figure represents an acceptable response if the process disturbance or change in set point is large, but it will not be an acceptable response if the change from the set point is small.

Figure 1-6 shows a damped response where the control system is able to bring the process variable back to the operating point with no oscillations.
Control Loop Design Criteria

Many criteria are employed to evaluate the process control’s loop response to an input change. The most common of these include settling time, maximum error, offset error, and error area (Figure 1-7).
When there is a process disturbance or a change in set point, the *settling time* is defined as the time the process control loop needs to bring the process variable back to within an allowable error. The *maximum error* is simply the maximum allowable deviation of the dynamic variable. Most control loops have certain inherent linear and nonlinear qualities that prevent the system from returning the process variable to the set point after a system change. This condition is generally called *offset error* and will be discussed later in this chapter. The *error area* is defined as the area between the response curve and the set point line as shown by the shaded area in Figure 1-7.

These four evaluation criteria are general measures of control loop behavior that are used to determine the adequacy of the loop’s ability to perform some desired function. However, perhaps the best way to gain a clear understanding of process control is to take an intuitive approach.

**Intuitive Approach to Process Control Concepts**

The practice of process control arose long before the theory or analytical methods underlying it were developed. Processes and controllers were designed using empirical methods that were based on intuition ("feel") and extensive process experience. Most of the reasoning involved was nonmathematical. This approach was unscientific trial and error, but it was a successful control method.

Consider, for example, an operator looking into an early metal processing furnace to determine whether the product was finished. He or she used flame color, amount of smoke, and process time to make this judgment. From equally direct early methods evolved most of the control concepts and hardware used today. Only later did theories and mathematical techniques emerge to explain how and why the systems responded as they did.

In this section, we will approach the study of control fundamentals in much the same way that control knowledge developed—that is, through a step-by-step procedure starting from manual control and moving to ever-increasing automatic control.

Suppose we have a process like that shown in Figure 1-8. A source of feed liquid flows into a tank at a varying rate from somewhere else in a process plant. This liquid must be heated so that it emerges at a desired temperature, $T_d$, as a hot liquid. To accomplish this, hot water, which is available from another part of the plant, flows through heat exchanger coils in the tank. By controlling the flow of hot water, we can obtain the desired tem-
temperature, $T_d$. A further process requirement is that the level of the tank must neither overflow nor fall so low that it exposes the heater coils.

The temperature is measured in the tank, and a temperature transmitter (TT-1) converts the signal into a 4-20 mA direct current (DC) signal to drive a temperature indicator (TI-1) mounted near the hot water inlet valve. Similarly, a level indicator (LI-2) is mounted within the operator’s view of the hot feed outlet valve (HV-2).

Suppose a process operator has the task of holding the temperature, $T$, near the desired temperature, $T_d$, while making sure the tank doesn’t overflow or the level get too low. The question is how the operator would cope with this task over a period of time. He or she would manually adjust the hot water inlet valve (HV-1) to maintain the temperature and occasionally adjust the outlet valve (HV-2) to maintain the correct level in the tank.

The operator would face several problems, however. Both indicators would have to be within the operator’s view, and the manual valves would have to be close to the operator and easy to adjust.

**On/Off Control**

To make the operator’s work easier, suppose we install electrically operated solenoid valves in place of the manual valves, as shown in Figure 1-9. We can also install two hand switches (HS-1 and HS-2) so the solenoid
valves can be operated from a common location. The valves can assume two states, either fully open (on) or fully closed (off). This type of control is called two-position or on/off control.

Assume for the moment that the level is holding steady and that the main concern is controlling temperature. The operator has been told to keep the temperature of the fluid in the tank at 100°F. He or she compares the reading of the temperature indicator with the selected set point of 100°F. The operator closes the hot water valve when the temperature of the fluid in the tank rises above the set point (Figure 1-10). Because of process dead time and lags the temperature will continue to rise before reversing and moving toward the set point. When the temperature falls below 100°F, the operator opens the hot water valve. Again, dead time and lags in the process create a delay before the temperature begins to rise. As it crosses the set point, the operator again shuts off the hot water, and the cycle repeats.

This cycling is normal for a control system that uses on/off control. This limitation exists because it’s impossible for the operator to control the process exactly with only two options.

This on/off type of control can be expressed mathematically as follows:

\[ e = PV - SP \]  \hspace{1cm} (1-2)
INTRODUCTION TO PROCESS CONTROL

Introduction

Control is a science that is used in many engineering disciplines such as chemical, electrical and mechanical engineering and it is applied to a wide range of physical systems from chemical processes to electrical circuits to guided missiles to robots. The field of process control encompasses the basic principles most useful when applied to the physiochemical systems often encountered by chemical engineers such as chemical reactors, heat exchangers, and mass transfer equipment. Control engineering is not a narrow specialty but an essential topic for all chemical engineers. For example, plant designers must consider the dynamic operation of all equipment, because the plant will never operate at steady state. Engineers charged with operating plants must ensure that the proper response is made to the ever-occurring disturbances so the operation is safe and profitable.

Process control engineering involves a vast body of material, including mathematical analysis and engineering practice. Before we can begin learning the specific principles and calculations we must understand the goals of process control and how it complements other aspects of chemical engineering. This lecture introduces these issues by addressing the following control topics: what is a control system? what are the objectives of control?, why is control possible? how is control done? where is control implemented? and what is the work of the control engineer?

1. Control system

We start by discussing an example of a control system that is encountered in everyday life. Consider a simple heating system shown in Figure (1). The house, in a cold climate, can be maintained near a desired temperature by circulating hot water through a heat exchanger. The temperature in the room is determined by a thermostat, which compares the measured value of the room temperature to a desired range, say 18-22 °C. If the temperature below 18, the furnace and pump are turned on, and if the temperature is above 22, the furnace and pump are turned off. If the temperature is between 18-22 °C, the furnace and pump status remains unchanged. This approach is termed “ON/OFF” control and can be used when precise control at the desired value is not required. Based on this example we identify the following common control features:

1. Control system uses a specific value or range as the desired value for the controlled variable. The term set point is usually used for the desired value.
2. The conditions of the system are measured; that’s all control systems use sensors to measure the physical variables that are to be maintained near their desired values.
3. Each control system has a control calculation “algorithm”, which uses the measured and desired values to determine a correction to the process operations. The control calculation for the room heater is very simple (on/off) where the calculations used in other systems may be very complex.
4. The results of the control calculation are implemented by adjusting some item of equipment in the system, which is termed the final control element such as the furnace and pump switches.

![Figure 1: Feedback control for room temperature](image1)

These major components are shown schematically in Figure (2), which can be used to represent many control systems.

![Figure 2: Schematic diagram of a general feedback control system](image2)

The given control example have an additional feature that is extremely important. This is feedback, which is defined as follows: feedback control makes use of an output of a system to influence an input to the same system. In our example, the temperature of the room is used, through the thermostat on/off decision to influence the hot water flow to the exchanger. The importance of feedback can be seen by considering the alternative without feedback. For example, an alternative approach for achieving the desired room temperature would set the hot water flow based on the measured outside temperature and a model for heat loss of the house. This type of predictive approach is termed feed-forward control. The strategy without feedback would not maintain the room near the desired value if the model had errors-as it always would. Some causes of model error might be changes in external wind velocity and direction or inflows of air through open windows. On the other hand feedback control
can continually manipulate the final control element to achieve the desired value. Thus, feedback provides powerful feature of enabling a control system to maintain its desired value without requiring an exact plant model.

When used in discussing control systems the terms input and output do not necessarily refer to material moving into and out of the system. Here, the term input refers to a variable that causes an output. In the room heating example, the input is the fuel to the furnace, and the output is the room temperature. The casual relationship inherent in the physical process forces us to select the input as the manipulated variable and the output as the measured variable.

2. Reasons for Control

There are two major reasons for control, which are discussed with respect to the simple stirred tank heat exchanger shown in Figure (3). The process fluid flows into the tank from a pipe and flows out of the tank by overflow. Thus the volume of the tank is constant. The heating fluid flow can be changed by adjusting the opening valve in the heating medium line. The temperature in the tank is to be controlled.

The first reason for control is to maintain the temperature at its desired value when disturbances occur. Some typical disturbances for this process occur in the following variables: inlet process fluid flow rate and temperature, heating fluid temperature, and pressure of the heating fluid upstream of the valve. The second reason for control is to respond to changes to the desired value. For example, if the desired temperature in the stirred tank heat exchanger increased, the heating valve percent opening would be increased. The desired values are based on a through analysis of the

Figure 3: A stirred tank heater system
plant operation and objectives. This analysis will be discussed in the second part of this chapter in more detail.

3. Control Possibility

The proper design of plant equipment is essential for control to be possible and for control to provide good dynamic performance. Based on the key features of the feedback control system, the plant design must include the followings:

1. Adequate capacity of the process equipment. The equipment must have a large enough maximum capacity to respond to all expected disturbances and changes in the desired values. For the stirred tank heat exchanger (Figure 3), the maximum duty, as influenced by temperature, area, and heating medium flow rate, must be large enough to maintain the tank temperature for all anticipated disturbances. Therefore, each process must be analyzed to ensure that adequate capacity exists. The adequate equipment design for control must be calculated based on expected changes; merely adding extra capacity, say 20%, to equipment sizing is not correct. In some cases, this would result in waste; in other cases, the equipment capacity would be not adequate. If this analysis is not done properly or changes outside the assumptions occur, achieving acceptable plant operation through manipulating final control elements may not be possible.

2. Adequate sensors of plant output variables. The sensors must respond rapidly so that the control action can be taken in real time. Sensors using various physical principles are available for the basic process variables (flow, temperature, pressure, and level), composition and physical properties (e.g. density, viscosity, heat of combustion). Many of these sensors are inserted into the process equipment, with a shield protecting them from corrosive effects of the streams.

3. Appropriate final control elements. The final control elements in chemical processes are usually valves that affect fluid flows, but they could be other manipulated variables such as power to an electric motor or speed of a conveyor belt.

4. Control Implementation

Control systems are automated, which require that the key functions of sensing, calculating, and manipulating be performed by equipment and that each element communicate with other elements in the control system. Most automatic control is implemented using electronic equipment, which uses levels of current or voltages to represent values to be communicated. In some cases, control systems use pneumatic, hydraulic, or mechanical mechanisms to calculate and communicate; in these systems, the signals are represented by pressure or physical position.

For much of the history of process plants (up to 1960s), control calculations were performed by analog computation. Analog computing devices are implemented by building a physical system, such as an electrical circuit or mechanical system that obeys
the same equations as the desired control calculation. This approach was inflexible and complex calculations were not possible. With the advent of low-cost digital computers most of the control calculations and essentially all of the complex calculations are being performed by digital computers. The control is done automatically, using instrumentation and computation that perform all features of feedback control without requiring (but allowing) human intervention.

Chemical plants are physically large and complex. The people responsible for operating the plant on a minute-to-minute basis must have information from much of the plant available to them in a central location. Naturally, the sensors and levels are located in the process. Signals, usually electronic, communicate with the control room, where all information is displayed to the operating personnel and where control calculations are performed. In the control room, an individual is responsible for monitoring and operating a section of a large, complex plant, containing up to 100 controlled variables and 400 other measured variables. Generally, the plant never operates on ‘automatic pilot’; a person is always present to perform tasks not automated, to optimize operations, and intervene in case an unusual or dangerous situation occurs. Other control configurations are possible and are used when appropriate. For example, small panels with instrumentation can be placed near a critical piece of process equipment when the operator needs to have access to the control system while introducing some process adjustments.

What can engineers do so that plants can be maintained reliably and safely near desired values? Most of the engineering decisions are introduced in the following topics:

4.1 Process
A key factor in engineering is the design of the process so that it can be controlled well. A more responsive plant would be easier to control. By responsive we mean that the controlled variable responds quickly to adjustments in the manipulated variable. Also, a plant that is susceptible to few disturbances would be easier to control. Reducing the frequency and magnitude of disturbances could be achieved by many means; a simple example is placing a large mixing tank before a unit so that feed composition upsets are attenuated by the averaging effects of the tank.

4.2 Measurements
Naturally, a key decision is the selection and location of sensors, because one can control only what is measured. The engineer should select sensors that measure important variables rapidly and with sufficient accuracy.

4.3 Final Elements
The engineer must provide handles-manipulated variables that can be adjusted by the control calculation. For example, if there were no valve on the heating fluid in the stirred tank heater, it would not be possible to control the process fluid outlet temperature.

4.4 Control structure
The engineer must decide some very basic issues in designing a control system. For example, which valve should be manipulated to control which measurement? As every
day example, one could adjust either the hot or cold water valve opening to control the temperature of water in a shower.

4.5 Control Calculations
After the variables and control structure have been selected, equations are chosen that use the measurements and desired values in calculating the manipulated variable. Parameters of these equations (controller parameters) are adjusted to achieve the desired control performance of the particular process.

How is process control documented?
As with all activities in chemical engineering, the results are documented in many forms. The most common are equipment specifications and sizing, operating manuals, and technical documentation of plant experiments and control equations. In addition control engineers make extensive use of drawings that concisely represent many design calculations. Standard symbols have been developed by the Instrument Society of America for use throughout the world. Sample drawings are shown in Figure (4). All process equipment –piping, vessels, valves- are drawn in solid lines. The symbols for equipment items such as pumps, tanks, drums, and valves are simple and easily recognized. Sensors are designated by a circle connected to the point in the process where they are located. The first letter in the instrumentation symbol indicates the type of variable measured. Some of the common designations are as follows:

A  Analyzer,
F  flow,
T  temperature,
L  level,
P  pressure

The communication to the sensor is shown as a solid line. If the signal is used only for display to the operator, the second letter in the symbol is “I” for indicator. If the signal is used in the control calculations, the second letter in the symbol indicates the type of calculation. For example, if the letter C is used as a second letter, it means the signal is used for feedback control calculation. For controllers, the communication to the final element is shown as a dashed line when it is electrical, which is the mode of communication considered in most of the recent control systems.

5. Control Objectives
The control objectives are discussed in detail here, with an explanation of how each influences the control design for the example process shown in Figure 4. The process separates two components based on their different vapor pressures. The liquid feed stream, consisting of components A and B, is heated by two exchangers in series. Then the stream flows through a valve to a vessel at a lower pressure. As a result of higher temperature and lower pressure, the material forms two phases, with most of A in the vapor phase and most of B in the liquid. The exact compositions can be determined by solving the mass, energy, and equilibrium expressions. A control strategy is also shown in Figure 4. Since we have not yet studied the calculations used by feedback controllers, one can interpret the controller as a linkage between a...
measurement and a valve. Thus, the feedback pressure controller (PC) can be considered as a system that measures the pressure and maintain the pressure at its desired value by adjusting the opening of the valve in the overhead vapor pipe.

5.1. Safety

The safety of the people in the plant and in the surrounding community is of paramount importance. The typical goal is that working at industrial plant should involve much less risk than any other activity in a person’s life.

Plants are designed to operate safely at expected temperature and pressures; however, improper operation can lead to equipment failure and release of potentially hazardous materials. Therefore, the process control strategies contribute to the overall plant safety by maintaining key variables near their desired values. In Figure 4, the equipment could operate at high pressure under normal conditions. If the pressure were allowed to increase too far beyond the normal value, the vessel might burst, resulting in injuries or death. Therefore, the control strategy includes a controller labeled PC-1 that controls the pressure by adjusting the valve position in the vapor line.

Another consideration in plant safety is the proper response to major incidents such as equipment failure and excursion of variables outside of their acceptable bounds. Control strategies can not guarantee safe operation; very large disturbance could lead to unsafe operation. Therefore an additional layer of control, termed an emergency system, is applied to enforce bounds on key variables. This layer might involve either safely diverting the flow of materials or shutting down the process. For example, in the flash separation process, an emergency control might stop the feed to a vessel when the liquid level is nearly overflowing. Another example, suppose that the sensor used for measuring the pressure stopped providing a reliable measurement, the control strategy PC-1 could improperly close the overhead valve, leading to unsafe pressure. The correct control design would include an additional strategy using independent equipment. For example, the safety valve shown in Figure 4 is closed unless the pressure rises above a specified maximum; then it opens to vent the excess vapor.

5.2. Environmental Protection

Protection of the environment is critically important. This objective is mostly a process design issue, that is, the process must have the capacity to convert potentially toxic components to benign material. Control can contribute to the proper operation of the plant units, resulting in consistently low effluent concentrations. In the flash example, the environment is protected by containing the material within the process equipment. Note that safety release system directs materials for containment and subsequent neutralization, which could involve recycling to the process or combusting to benign compounds.

5.3. Equipment Protection

Much of the equipment in a plant is expensive and difficult to replace without costly delays. Therefore, operating conditions must be maintained within bounds to prevent damages. The types of control strategies for equipment protection are similar to those for personnel protections. For example in Figure 4 the pump could be damaged if no liquid were flowing through it. Therefore the liquid level controller, by ensuring a
reservoir of liquid in the bottom of vessel protects the pump from damage. Additional emergency control can be provided by shutting off the pump motor when the level decreased below a specified value.

5.4. Smooth Operation and Production Rate
A chemical plant includes a complex network of interacting processes; thus, the smooth operation of a process is desirable, because it results in few disturbances to all integrated units. Naturally, all key variables in streams leaving the process should be maintained close to their desired values to prevent disturbances to downstream units. In Figure 4 the liquid from the vessel bottoms is processed by downstream equipment. The control strategy can be designed to make slow, smooth changes to the liquid flow. Naturally, the liquid level will not remain constant, but it is not required to be constant; the level must only remain within specified limits. By use of this control design, the downstream units would experience fewer disturbances, and the overall plant would perform better.

There are additional ways for upsets to be propagated in an integral plant. For example, when the control strategy increases the steam flow to heat exchanger E102, another unit in the plant must respond by generating more steam. Clearly, smooth manipulations of the steam flow require slow adjustments in the boiler operation and better overall plant operation. Therefore, we are interested in both the controlled variables and manipulated variables. Ideally, we would like to have tight regulation of the controlled variables and slow, smooth adjustment of the manipulated variables. This is not usually possible, and some compromise is required.

5.5 Product Quality
The final products from the plant must meet demanding quality specifications set by purchasers. Process control contributes to good plant operation by maintaining the operating conditions required for excellent product quality. Improving product quality control is a major economic factor in the application of digital computers and advanced control algorithms in the process industries.

In the flash example, suppose the amount of A in the bottom stream (rich in A) is to be controlled in the liquid stream. Based on our knowledge of thermodynamics, this amount can be controlled by adjusting the flash temperature or, equivalently, the heat exchanged. Therefore a control strategy would be designed to measure the composition of A in the bottom in real time (AC) and adjust the heating medium flows that exchange heat with the feed.

5.6 Profit
Naturally, the typical goal of the plant is to return profit. In the case of a utility such as water purification, in which no income sales is involved, the equivalent goal is to provide the product at a lower cost. Before achieving the profit-oriented goal, selected independent variables are adjusted to satisfy the first five control objectives. Often, some independent operating variable are not specified after the higher objectives have been satisfied. When additional variables (degree of freedom) exist, the control strategy can increase profit while satisfying all other objectives.
In Figure 4 all other control objectives can be satisfied by using exchanger E101, exchanger E102, or a combination of the two, to heat the inlet stream. Therefore the control strategy can select the correct exchanger based on the cost of the two heating fluids.

Figure 4: Flash separation process with control strategy.
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Introduction

Control in process industries refers to the regulation of all aspects of the process. Precise control of level, temperature, pressure and flow is important in many process applications. This module introduces you to control in process industries, explains why control is important, and identifies different ways in which precise control is ensured.

The following five sections are included in this module:
- The importance of process control
- Control theory basics
- Components of control loops and ISA symbology
- Controller algorithms and tuning
- Process control systems

As you proceed through the module, answer the questions in the activities column on the right side of each page. Also, note the application boxes (double-bordered boxes) located throughout the module. Application boxes provide key information about how you may use your baseline knowledge in the field. When you see the workbook exercise graphic at the bottom of a page, go to the workbook to complete the designated exercise before moving on in the module. Workbook exercises help you measure your progress toward meeting each section’s learning objectives.

**Performance Objective**

After completing this module, you will be able to determine needed control loop components in specific process control applications.
The Importance of Process Control

Refining, combining, handling, and otherwise manipulating fluids to profitably produce end products can be a precise, demanding, and potentially hazardous process. Small changes in a process can have a large impact on the end result. Variations in proportions, temperature, flow, turbulence, and many other factors must be carefully and consistently controlled to produce the desired end product with a minimum of raw materials and energy. Process control technology is the tool that enables manufacturers to keep their operations running within specified limits and to set more precise limits to maximize profitability, ensure quality and safety.

LEARNING OBJECTIVES

After completing this section, you will be able to:

- Define process
- Define process control
- Describe the importance of process control in terms of variability, efficiency, and safety

Note: To answer the activity questions the Hand Tool (H) should be activated.
The Importance of Process Control

**PROCESS**

Process as used in the terms *process control* and *process industry*, refers to the methods of changing or refining raw materials to create end products. The raw materials, which either pass through or remain in a liquid, gaseous, or slurry (a mix of solids and liquids) state during the process, are transferred, measured, mixed, heated or cooled, filtered, stored, or handled in some other way to produce the end product.

Process industries include the chemical industry, the oil and gas industry, the food and beverage industry, the pharmaceutical industry, the water treatment industry, and the power industry.

**PROCESS CONTROL**

*Process control* refers to the methods that are used to control process variables when manufacturing a product. For example, factors such as the proportion of one ingredient to another, the temperature of the materials, how well the ingredients are mixed, and the pressure under which the materials are held can significantly impact the quality of an end product. Manufacturers control the production process for three reasons:

- Reduce variability
- Increase efficiency
- Ensure safety

**Reduce Variability**

Process control can reduce variability in the end product, which ensures a consistently high-quality product. Manufacturers can also save money by reducing variability. For example, in a gasoline blending process, as many as 12 or more different components may be blended to make a specific grade of gasoline. If the refinery does not have precise control over the flow of the separate components, the gasoline may get too much of the high-octane components. As a result, customers would receive a higher grade and more expensive gasoline than they paid for, and the refinery would lose money. The opposite situation would be customers receiving a lower grade at a higher price.

**Activities**

1. Process is defined as the changing or refining of raw materials that pass through or remain in a liquid, gaseous, or slurry state to create end products.

2. Which of these industries are examples of the process industry?

Select all options that apply.

- 1 Pharmaceutical
- 2 Satellite
- 3 Oil and Gas
- 4 Cement
- 5 Power
Reducing variability can also save money by reducing the need for product padding to meet required product specifications. Padding refers to the process of making a product of higher-quality than it needs to be to meet specifications. When there is variability in the end product (i.e., when process control is poor), manufacturers are forced to pad the product to ensure that specifications are met, which adds to the cost. With accurate, dependable process control, the setpoint (desired or optimal point) can be moved closer to the actual product specification and thus save the manufacturer money.

**Increase Efficiency**

Some processes need to be maintained at a specific point to maximize efficiency. For example, a control point might be the temperature at which a chemical reaction takes place. Accurate control of temperature ensures process efficiency. Manufacturers save money by minimizing the resources required to produce the end product.

**Ensure Safety**

A run-away process, such as an out-of-control nuclear or chemical reaction, may result if manufacturers do not maintain precise control of all of the process variables. The consequences of a run-away process can be catastrophic.

Precise process control may also be required to ensure safety. For example, maintaining proper boiler pressure by controlling the inflow of air used in combustion and the outflow of exhaust gases is crucial in preventing boiler implosions that can clearly threaten the safety of workers.
Control Theory Basics

This section presents some of the basic concepts of control and provides a foundation from which to understand more complex control processes and algorithms later described in this module. Common terms and concepts relating to process control are defined in this section.

**LEARNING OBJECTIVES**

After completing this section, you will be able to:

- Define control loop
- Describe the three tasks necessary for process control to occur:
  - Measure
  - Compare
  - Adjust
- Define the following terms:
  - Process variable
  - Setpoint
  - Manipulated variable
  - Measured variable
  - Error
  - Offset
  - Load disturbance
  - Control algorithm
- List at least five process variables that are commonly controlled in process measurement industries
- At a high level, differentiate the following types of control:
  - Manual versus automatic feedback control
  - Closed-loop versus open-loop control

**Note:** To answer the activity questions the Hand Tool (H) should be activated.
The Control Loop

Imagine you are sitting in a cabin in front of a small fire on a cold winter evening. You feel uncomfortably cold, so you throw another log on the fire. This is an example of a control loop. In the control loop, a variable (temperature) fell below the setpoint (your comfort level), and you took action to bring the process back into the desired condition by adding fuel to the fire. The control loop will now remain static until the temperature again rises above or falls below your comfort level.

**THREE TASKS**

Control loops in the process control industry work in the same way, requiring three tasks to occur:

- Measurement
- Comparison
- Adjustment

In Figure 7.1, a level transmitter (LT) measures the level in the tank and transmits a signal associated with the level reading to a controller (LIC). The controller compares the reading to a predetermined value, in this case, the maximum tank level established by the plant operator, and finds that the values are equal. The controller then sends a signal to the device that can bring the tank level back to a lower level—a valve at the bottom of the tank. The valve opens to let some liquid out of the tank.

Many different instruments and devices may or may not be used in control loops (e.g., transmitters, sensors, controllers, valves, pumps), but the three tasks of measurement, comparison, and adjustment are always present.

**Activities**

1. The three tasks associated with any control loop are measurement, comparison, and adjustment. Is this statement true or false?
Process Control Terms

As in any field, process control has its own set of common terms that you should be familiar with and that you will use when talking about control technology.

**PROCESS VARIABLE**

A *process variable* is a condition of the process fluid (a liquid or gas) that can change the manufacturing process in some way. In the example of you sitting by the fire, the process variable was temperature. In the example of the tank in Figure 7.1, the process variable is level. Common process variables include:

- Pressure
- Flow
- Level
- Temperature
- Density
- Ph (acidity or alkalinity)
- Liquid interface (the relative amounts of different liquids that are combined in a vessel)
- Mass
- Conductivity

**SETPOINT**

The *setpoint* is a value for a process variable that is desired to be maintained. For example, if a process temperature needs to kept within 5 °C of 100 °C, then the setpoint is 100 °C. A temperature sensor can be used to help maintain the temperature at setpoint. The sensor is inserted into the process, and a controller compares the temperature reading from the sensor to the setpoint. If the temperature reading is 110 °C, then the controller determines that the process is above setpoint and signals the fuel valve of the burner to close slightly until the process cools to 100 °C. Set points can also be maximum or minimum values. For example, level in tank cannot exceed 20 feet.

---

**Activities**

2. A process variable is a condition that can change the process in some way.

3. Imagine you are in a cabin in front of a small fire on a cold winter evening. You feel uncomfortably cold, so you throw another log into the fire. In this scenario, the process variable is temperature. Is this true or false?

4. If the level of a liquid in a tank must be maintained within 5 ft of 50 ft, what is the liquid’s setpoint?

   1. 45 ft
   2. 55 ft
   3. 5 ft
   4. 50 ft
Process Control Terms

**MEASURED VARIABLES, PROCESS VARIABLES, AND MANIPULATED VARIABLES**

In the temperature control loop example, the measured variable is temperature, which must be held close to 100 °C. In this example and in most instances, the measured variable is also the process variable. The *measured variable* is the condition of the process fluid that must be kept at the designated setpoint.

Sometimes the measured variable is not the same as the process variable. For example, a manufacturer may measure flow into and out of a storage tank to determine tank level. In this scenario, flow is the measured variable, and the process fluid level is the *process variable*. The factor that is changed to keep the measured variable at setpoint is called the *manipulated variable*. In the example described, the manipulated variable would also be flow (Figure 7.2).

**ERROR**

*Error* is the difference between the measured variable and the setpoint and can be either positive or negative. In the temperature control loop example, the error is the difference between the 110 °C measured variable and the 100 °C setpoint—that is, the error is +10 °C.

The objective of any control scheme is to minimize or eliminate error. Therefore, it is imperative that error be well understood. Any error can be seen as having three major components. These three components are shown in the figure on the following page.

**Magnitude**

The magnitude of the error is simply the deviation between the values of the setpoint and the process variable. The magnitude of error at any point in time compared to the previous error provides the basis for determining the change in error. The change in error is also an important value.

---

5. ____________________ is a sustained deviation of the process variable from the setpoint.

6. A load disturbance is an undesired change in one of the factors that can affect the setpoint. Is this statement true or false?
Process Control Terms

Duration
Duration refers to the length of time that an error condition has existed.

Rate Of Change
The rate of change is shown by the slope of the error plot.

Offset
Offset is a sustained deviation of the process variable from the setpoint. In the temperature control loop example, if the control system held the process fluid at 100.5 °C consistently, even though the setpoint is 100 °C, then an offset of 0.5 °C exists.

Load Disturbance
A load disturbance is an undesired change in one of the factors that can affect the process variable. In the temperature control loop example, adding cold process fluid to the vessel would be a load disturbance because it would lower the temperature of the process fluid.

Control Algorithm
A control algorithm is a mathematical expression of a control function. Using the temperature control loop example, V in the equation below is the fuel valve position, and e is the error. The relationship in a control algorithm can be expressed as:
The fuel valve position \( V \) is a function \( f \) of the sign (positive or negative) of the error (Figure 7.3).

\[
V = f(\pm e)
\]

Control algorithms can be used to calculate the requirements of much more complex control loops than the one described here. In more complex control loops, questions such as “How far should the valve be opened or closed in response to a given change in setpoint?” and “How long should the valve be held in the new position after the process variable moves back toward setpoint?” need to be answered.

**MANUAL AND AUTOMATIC CONTROL**

Before process automation, people, rather than machines, performed many of the process control tasks. For example, a human operator might have watched a level gauge and closed a valve when the level reached the setpoint. Control operations that involve human action to make an adjustment are called *manual control systems*. Conversely, control operations in which no human intervention is required, such as an automatic valve actuator that responds to a level controller, are called *automatic control systems*.

7. Automatic control systems are control operations that involve human action to make adjustment. Is this statement true or false?
Process Control Terms

CLOSED AND OPEN CONTROL LOOPS

A closed control loop exists where a process variable is measured, compared to a setpoint, and action is taken to correct any deviation from setpoint. An open control loop exists where the process variable is not compared, and action is taken not in response to feedback on the condition of the process variable, but is instead taken without regard to process variable conditions. For example, a water valve may be opened to add cooling water to a process to prevent the process fluid from getting too hot, based on a pre-set time interval, regardless of the actual temperature of the process fluid.

Activities

8. Under what circumstances does an open control loop exist?
Select all options that apply.

1. Process variable is not measured
2. Process variable is not compared
3. Process variable is measured and compared to a setpoint
4. Action is taken without regard to process variable conditions
5. Action is taken with regard to process variable conditions

COMPLETE WORKBOOK EXERCISE - CONTROL THEORY BASICS
Components of Control Loops and ISA Symbology

This section describes the instruments, technologies, and equipment used to develop and maintain process control loops. In addition, this section describes how process control equipment is represented in technical drawings of control loops.

LEARNING OBJECTIVES

After completing this section, you will be able to:

- Describe the basic function of and, where appropriate, the basic method of operation for the following control loop components:
  - Primary element/sensor
  - Transducer
  - Converter
  - Transmitter
  - Signal
  - Indicator
  - Recorder
  - Controller
  - Correcting element/final control element
  - Actuator

- List examples of each type of control loop component listed above

- State the advantages of 4–20 mA current signals when compared with other types of signals

- List at least three types of final control elements, and for each one:
  - Provide a brief explanation of its method of operation
  - Describe its impact on the control loop
  - List common applications in which it is used

- Given a piping and instrumentation drawing (P&ID), correctly label the:
  - Instrument symbols (e.g., control valves, pumps, transmitters)
  - Location symbols (e.g., local, panel-front)
  - Signal type symbols (e.g., pneumatic, electrical)

- Accurately interpret instrument letter designations used on P&IDs
Control Loop Equipment and Technology

The previous section described the basic elements of control as measurement, comparison, and adjustment. In practice, there are instruments and strategies to accomplish each of these essential tasks. In some cases, a single process control instrument, such as a modern pressure transmitter, may perform more than one of the basic control functions. Other technologies have been developed so that communication can occur among the components that measure, compare, and adjust.

**PRIMARY ELEMENTS/SENSORS**

In all cases, some kind of instrument is measuring changes in the process and reporting a process variable measurement. Some of the greatest ingenuity in the process control field is apparent in sensing devices. Because sensing devices are the first element in the control loop to measure the process variable, they are also called *primary elements*. Examples of primary elements include:

- Pressure sensing diaphragms, strain gauges, capacitance cells
- Resistance temperature detectors (RTDs)
- Thermocouples
- Orifice plates
- Pitot tubes
- Venturi tubes
- Magnetic flow tubes
- Coriolis flow tubes
- Radar emitters and receivers
- Ultrasonic emitters and receivers
- Annubar flow elements
- Vortex sheddar

Primary elements are devices that cause some change in their property with changes in process fluid conditions that can then be measured. For example, when a conductive fluid passes through the magnetic field in a magnetic flow tube, the fluid generates a voltage that is directly proportional to the velocity of the process fluid. The primary element (magnetic flow tube) outputs a voltage that can be measured and used to calculate the fluid’s flow rate. With an RTD, as the temperature of a process fluid surrounding the RTD rises or falls, the electrical resistance of the RTD increases or decreases a proportional amount. The resistance is measured, and from this measurement, temperature is determined.

**Activities**

1. Identify three examples of a primary element/sensors in process control? Select all options that apply.
   - Resistance Temperature Detectors
   - Thermocouples
   - Control Valve
   - Converter
   - Pitot tubes

2. Primary elements will not make direct contact with the process fluid. Is this statement true or false?
### Control Loop Equipment and Technology

#### Transducers and Converters

A *transducer* is a device that translates a mechanical signal into an electrical signal. For example, inside a capacitance pressure device, a transducer converts changes in pressure into a proportional change in capacitance.

A *converter* is a device that converts one type of signal into another type of signal. For example, a converter may convert current into voltage or an analog signal into a digital signal. In process control, a converter used to convert a 4–20 mA current signal into a 3–15 psig pneumatic signal (commonly used by valve actuators) is called a *current-to-pressure converter*.

#### Transmitters

A *transmitter* is a device that converts a reading from a sensor or transducer into a standard signal and transmits that signal to a monitor or controller. Transmitter types include:

- Pressure transmitters
- Flow transmitters
- Temperature transmitters
- Level transmitters
- Analytic (O₂ [oxygen], CO [carbon monoxide], and pH) transmitters

### Activities

3. A __________ is a device that translates a mechanical signal into an electrical signal.

4. A transmitter is a device that converts a reading from a transducer into a standard signal and transmits that signal to a monitor or controller. Is this statement true or false?
Control Loop Equipment and Technology

**Signals**

There are three kinds of signals that exist for the process industry to transmit the process variable measurement from the instrument to a centralized control system.

1. Pneumatic signal
2. Analog signal
3. Digital signal

**Pneumatic Signals**

Pneumatic signals are signals produced by changing the air pressure in a signal pipe in proportion to the measured change in a process variable. The common industry standard pneumatic signal range is 3–15 psig. The 3 corresponds to the lower range value (LRV) and the 15 corresponds to the upper range value (URV). Pneumatic signalling is still common. However, since the advent of electronic instruments in the 1960s, the lower costs involved in running electrical signal wire through a plant as opposed to running pressurized air tubes has made pneumatic signal technology less attractive.

**Analog Signals**

The most common standard electrical signal is the 4–20 mA current signal. With this signal, a transmitter sends a small current through a set of wires. The current signal is a kind of gauge in which 4 mA represents the lowest possible measurement, or zero, and 20 mA represents the highest possible measurement.

For example, imagine a process that must be maintained at 100 °C. An RTD temperature sensor and transmitter are installed in the process vessel, and the transmitter is set to produce a 4 mA signal when the process temperature is at 95 °C and a 20 mA signal when the process temperature is at 105 °C. The transmitter will transmit a 12 mA signal when the temperature is at the 100 °C setpoint. As the sensor’s resistance property changes in response to changes in temperature, the transmitter outputs a 4–20 mA signal that is proportionate to the temperature changes. This signal can be converted to a temperature reading or an input to a control device, such as a burner fuel valve.

Other common standard electrical signals include the 1–5 V (volts) signal and the pulse output.

**Activities**

5. Identify the signal types that are used in the process control industry?

Select all options that apply.

1. Hydraulic signals
2. Digital signals
3. Analog signals
4. Pneumatic signals
5. Electro-magnetic signals
Components of Control Loops and ISA Symbology

Control Loop Equipment and Technology

**Digital Signals**

Digital signals are the most recent addition to process control signal technology. Digital signals are discrete levels or values that are combined in specific ways to represent process variables and also carry other information, such as diagnostic information. The methodology used to combine the digital signals is referred to as protocol.

Manufacturers may use either an open or a proprietary digital protocol. Open protocols are those that anyone who is developing a control device can use. Proprietary protocols are owned by specific companies and may be used only with their permission. Open digital protocols include the HART® (highway addressable remote transducer) protocol, FOUNDATION™ Fieldbus, Profibus, DeviceNet, and the Modbus® protocol.

(See Module 8: Communication Technologies for more information on digital communication protocols.)

**Indicators**

While most instruments are connected to a control system, operators sometimes need to check a measurement on the factory floor at the measurement point. An indicator makes this reading possible. An indicator is a human-readable device that displays information about the process. Indicators may be as simple as a pressure or temperature gauge or more complex, such as a digital read-out device. Some indicators simply display the measured variable, while others have control buttons that enable operators to change settings in the field.

6. The ___________ is a human-readable device that displays information about the process or the instrument it is connected to.

7. Which of the following are examples of a digital signal? Select all options that apply.

1. Profibus
2. 4 - 20 mA
3. 1 - 5 v
4. Fieldbus
5. 3 - 15 psig
RECORDERS

A recorder is a device that records the output of a measurement devices. Many process manufacturers are required by law to provide a process history to regulatory agencies, and manufacturers use recorders to help meet these regulatory requirements. In addition, manufacturers often use recorders to gather data for trend analyses. By recording the readings of critical measurement points and comparing those readings over time with the results of the process, the process can be improved.

Different recorders display the data they collect differently. Some recorders list a set of readings and the times the readings were taken; others create a chart or graph of the readings. Recorders that create charts or graphs are called chart recorders.

CONTROLLERS

A controller is a device that receives data from a measurement instrument, compares that data to a programmed setpoint, and, if necessary, signals a control element to take corrective action. Local controllers are usually one of the three types: pneumatic, electronic or programmable. Controllers also commonly reside in a digital control system.

Activities

8. A recorder is a device that records the ______________ of a measurement or control device.
Control Loop Equipment and Technology

Controllers may perform complex mathematical functions to compare a set of data to setpoint or they may perform simple addition or subtraction functions to make comparisons. Controllers always have an ability to receive input, to perform a mathematical function with the input, and to produce an output signal. Common examples of controllers include:

- **Programmable logic controllers (PLCs)**—PLCs are usually computers connected to a set of input/output (I/O) devices. The computers are programmed to respond to inputs by sending outputs to maintain all processes at setpoint.

- **Distributed control systems (DCSs)**—DCSs are controllers that, in addition to performing control functions, provide readings of the status of the process, maintain databases and advanced man-machine-interface.

### Activities

9. Which of the following have the ability to receive input, to perform a mathematical function with the input, and produce an output signal?

1. Actuators
2. Transmitters
3. Transducers
4. Controllers

10. Which of the following is the most common final control element in process control industries?

1. Agitator
2. Pump motor
3. Valve
4. Louver
Control Loop Equipment and Technology

**Activities**

11. _______ is a part final control device that causes a physical change in the final control device when signaled to do so.

---

**Correcting Elements/Final Control Elements**

The *correcting* or *final control element* is the part of the control system that acts to physically change the manipulated variable. In most cases, the final control element is a valve used to restrict or cut off fluid flow, but pump motors, louvers (typically used to regulate air flow), solenoids, and other devices can also be final control elements.

Final control elements are typically used to increase or decrease fluid flow. For example, a final control element may regulate the flow of fuel to a burner to control temperature, the flow of a catalyst into a reactor to control a chemical reaction, or the flow of air into a boiler to control boiler combustion.

In any control loop, the speed with which a final control element reacts to correct a variable that is out of setpoint is very important. Many of the technological improvements in final control elements are related to improving their response time.

**Actuators**

An *actuator* is the part of a final control device that causes a physical change in the final control device when signalled to do so. The most common example of an actuator is a valve actuator, which opens or closes a valve in response to control signals from a controller. Actuators are often powered pneumatically, hydraulically, or electrically. Diaphragms, bellows, springs, gears, hydraulic pilot valves, pistons, or electric motors are often parts of an actuator system.
ISA Symbology

The Instrumentation, Systems, and Automation Society (ISA) is one of the leading process control trade and standards organizations. The ISA has developed a set of symbols for use in engineering drawings and designs of control loops (ISA S5.1 instrumentation symbol specification). You should be familiar with ISA symbology so that you can demonstrate possible process control loop solutions on paper to your customer. Figure 7.5 shows a control loop using ISA symbology. Drawings of this kind are known as piping and instrumentation drawings (P&ID).

Activities

12. What does the acronym P&ID stand for?

1. Piping and Instrument Designing
2. Piping and Instrumentation Drawing
3. Process Control and Installation Drawing
4. Proportional, Integral and Derivative control
**ISA Symbology**

**Symbols**

In a P&ID, a circle represents individual measurement instruments, such as transmitters, sensors, and detectors (Figure 7.6).

A single horizontal line running across the center of the shape indicates that the instrument or function is located in a primary location (e.g., a control room). A double line indicates that the function is in an auxiliary location (e.g., an instrument rack). The absence of a line indicates that the function is field mounted, and a dotted line indicates that the function or instrument is inaccessible (e.g., located behind a panel board).

A square with a circle inside represents instruments that both display measurement readings and perform some control function (Figure 7.7). Many modern transmitters are equipped with microprocessors that perform control calculations and send control output signals to final control elements.

**Activities**

13. Which of the following is a symbol of a transmitter in an auxiliary location?

1. ![Symbol 1](image1)
2. ![Symbol 2](image2)
3. ![Symbol 3](image3)
4. ![Symbol 4](image4)

14. Which of the following is a symbol of a field-mounted control/display element?

1. ![Symbol 1](image1)
2. ![Symbol 2](image2)
3. ![Symbol 3](image3)
4. ![Symbol 4](image4)
15. Which of the following is a symbol of a controller located behind a panel?

1
2
3
4
**ISA Symbology**

A square with a diamond inside represents PLCs (Figure 7.9).

Two triangles with their apexes contacting each other (a “bow tie” shape) represent a valve in the piping. An actuator is always drawn above the valve (Figure 7.10).

**Activities**

16. The symbol displayed below denotes a PLC in a primary location. Is this statement true or false?

17. Which of the following is a symbol of a pneumatic valve?

- 1
- 2
- 3
- 4
Components of Control Loops and ISA Symbology

ISA Symbology

Piping and Connections

Piping and connections are represented with several different symbols (Figure 7.12):

- A heavy solid line represents piping
- A thin solid line represents process connections to instruments (e.g., impulse piping)
- A dashed line represents electrical signals (e.g., 4–20 mA connections)
- A slashed line represents pneumatic signal tubes
- A line with circles on it represents data links

Other connection symbols include capillary tubing for filled systems (e.g., remote diaphragm seals), hydraulic signal lines, and guided electromagnetic or sonic signals.

Activities

18. The symbols displayed below represent a data link and a process connection. Is this statement true or false?

---

Piping and Connection Symbols

- Piping
- Process connection
- Electrical signal
- Pneumatic signal
- Data link
- Capillary tubing for filled systems
- Hydraulic signal line
- Guided electromagnetic or sonic signal

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ISA Symbology

IDENTIFICATION LETTERS

Identification letters on the ISA symbols (e.g., TT for temperature transmitter) indicate:

- The variable being measured (e.g., flow, pressure, temperature)
- The device’s function (e.g., transmitter, switch, valve, sensor, indicator)
- Some modifiers (e.g., high, low, multifunction)

Table 7.1 on page 26 shows the ISA identification letter designations. The initial letter indicates the measured variable. The second letter indicates a modifier, readout, or device function. The third letter usually indicates either a device function or a modifier.

For example, “FIC” on an instrument tag represents a flow indicating controller. “PT” represents a pressure transmitter. You can find identification letter symbology information on the ISA Web site at http://www.isa.org.

TAG NUMBERS

Numbers on P&ID symbols represent instrument tag numbers. Often these numbers are associated with a particular control loop (e.g., flow transmitter 123). See Figure 7.13.

Activities

19. The initial letter on an ISA symbol indicates the measured variable. Is this statement true or false?

20. What does the third letter on an ISA symbol indicate?

1  Device function or a modifier
2  Measured variable
3  Readout
4  Type of process fluid
# ISA Symbology

<table>
<thead>
<tr>
<th>Measured Variable</th>
<th>Modifier</th>
<th>Readout</th>
<th>Device Function</th>
<th>Modifier</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>Analysis</td>
<td>Alarm</td>
<td>User’s choice</td>
<td>User’s choice</td>
</tr>
<tr>
<td>B</td>
<td>Burner, combustion</td>
<td>User’s choice</td>
<td>User’s choice</td>
<td>User’s choice</td>
</tr>
<tr>
<td>C</td>
<td>User’s choice</td>
<td></td>
<td>Control</td>
<td></td>
</tr>
<tr>
<td>D</td>
<td>User’s choice</td>
<td></td>
<td>Differential</td>
<td></td>
</tr>
<tr>
<td>E</td>
<td>Voltage</td>
<td>Sensor (primary element)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>F</td>
<td>Flow rate</td>
<td>Ration (fraction)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>G</td>
<td>User’s choice</td>
<td>Glass, viewing device</td>
<td></td>
<td></td>
</tr>
<tr>
<td>H</td>
<td>Hand</td>
<td></td>
<td>High</td>
<td></td>
</tr>
<tr>
<td>I</td>
<td>Electrical Current</td>
<td></td>
<td>Indication</td>
<td></td>
</tr>
<tr>
<td>J</td>
<td>Power</td>
<td>Scan</td>
<td></td>
<td></td>
</tr>
<tr>
<td>K</td>
<td>Time, time schedule</td>
<td>Time rate of change</td>
<td>Control station</td>
<td></td>
</tr>
<tr>
<td>L</td>
<td>Level</td>
<td>Light</td>
<td></td>
<td>Low</td>
</tr>
<tr>
<td>M</td>
<td>User’s choice</td>
<td>Momentary</td>
<td></td>
<td>Middle, intermediate</td>
</tr>
<tr>
<td>N</td>
<td>User’s choice</td>
<td>User’s choice</td>
<td>User’s choice</td>
<td>User’s choice</td>
</tr>
<tr>
<td>O</td>
<td>User’s choice</td>
<td>Orifice, restriction</td>
<td>User’s choice</td>
<td>User’s choice</td>
</tr>
<tr>
<td>P</td>
<td>Pressure, vacuum</td>
<td>Point, test connection</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Q</td>
<td>Quantity</td>
<td>Integrate, totalizer</td>
<td></td>
<td></td>
</tr>
<tr>
<td>R</td>
<td>Radiation</td>
<td>Record</td>
<td></td>
<td></td>
</tr>
<tr>
<td>S</td>
<td>Speed, frequency</td>
<td>Safety</td>
<td>Switch</td>
<td></td>
</tr>
<tr>
<td>T</td>
<td>Temperature</td>
<td></td>
<td>Transmit</td>
<td></td>
</tr>
<tr>
<td>U</td>
<td>Multivariable</td>
<td>Multifunction</td>
<td>Multifunction</td>
<td>Multifunction</td>
</tr>
<tr>
<td>V</td>
<td>Vibration, mechanical analysis</td>
<td>Valve, damper, louver</td>
<td></td>
<td></td>
</tr>
<tr>
<td>W</td>
<td>Weight, force</td>
<td>Well</td>
<td></td>
<td></td>
</tr>
<tr>
<td>X</td>
<td>Unclassified</td>
<td>X axis</td>
<td>Unclassified</td>
<td>Unclassified</td>
</tr>
<tr>
<td>Y</td>
<td>Event, state, or presence</td>
<td>Y axis</td>
<td>Relay, compute, convert</td>
<td></td>
</tr>
<tr>
<td>Z</td>
<td>Position, dimension</td>
<td>Z axis</td>
<td>Driver, actuator</td>
<td></td>
</tr>
</tbody>
</table>

*ISA Identification Letters*
ISA Symbology

ISA SYMBOLOGY REVIEW

Figure 7.14 shows the elements of ISA symbology used in a P&ID.

21. In Figure 7.14, what kind of signal is transmitted out from the temperature transmitter?

1. Data link
2. Mechanical signal
3. Electrical signal
4. Pneumatic signal
Controller Algorithms and Tuning

The previous sections of this module described the purpose of control, defined individual elements within control loops, and demonstrated the symbology used to represent those elements in an engineering drawing. The examples of control loops used thus far have been very basic. In practice, control loops can be fairly complex. The strategies used to hold a process at setpoint are not always simple, and the interaction of numerous setpoints in an overall process control plan can be subtle and complex. In this section, you will be introduced to some of the strategies and methods used in complex process control loops.

LEARNING OBJECTIVES

After completing this section, you will be able to:
- Differentiate between discrete, multistep, and continuous controllers
- Describe the general goal of controller tuning.
- Describe the basic mechanism, advantages and disadvantages of the following mode of controller action:
  - Proportional action
  - Integral action
  - Derivative action
- Give examples of typical applications or situations in which each mode of controller action would be used.
- Identify the basic implementation of P, PI and PID control in the following types of loops:
  - Pressure loop
  - Flow loop
  - Level loop
  - Temperature loop

Note: To answer the activity questions the Hand Tool (H) should be activated.
Controller Algorithms

The actions of controllers can be divided into groups based upon the functions of their control mechanism. Each type of controller has advantages and disadvantages and will meet the needs of different applications. Grouped by control mechanism function, the three types of controllers are:

- Discrete controllers
- Multistep controllers
- Continuous controllers

**DISCRETE CONTROLLERS**

Discrete controllers are controllers that have only two modes or positions: on and off. A common example of a discrete controller is a home hot water heater. When the temperature of the water in the tank falls below setpoint, the burner turns on. When the water in the tank reaches setpoint, the burner turns off. Because the water starts cooling again when the burner turns off, it is only a matter of time before the cycle begins again. This type of control doesn’t actually hold the variable at setpoint, but keeps the variable within proximity of setpoint in what is known as a dead zone (Figure 7.15).

**Activities**

1. Which one of the following is an everyday example of a discrete controller?
   - Refrigerator
   - Electric iron
   - Air conditioner
   - Rice cooker

![Discrete Control Diagram]

[Figure 7.15: Discrete Control]
Controller Algorithms

MULTISTEP CONTROLLERS

Multistep controllers are controllers that have at least one other possible position in addition to on and off. Multistep controllers operate similarly to discrete controllers, but as setpoint is approached, the multistep controller takes intermediate steps. Therefore, the oscillation around setpoint can be less dramatic when multistep controllers are employed than when discrete controllers are used (Figure 7.16).

CONTINUOUS CONTROLLERS

Controllers automatically compare the value of the PV to the SP to determine if an error exists. If there is an error, the controller adjusts its output according to the parameters that have been set in the controller. The tuning parameters essentially determine:

How much correction should be made? The magnitude of the correction (change in controller output) is determined by the proportional mode of the controller.

How long should the correction be applied? The duration of the adjustment to the controller output is determined by the integral mode of the controller.

How fast should the correction be applied? The speed at which a correction is made is determined by the derivative mode of the controller.

Activities

2. A controller with three or more set positions is called a continuous controller. Is this statement true or false?
Controller Algorithms

When there is an error, the controller makes a change in its output. It determines:
- How much? Proportional Mode
- How long? Integral Mode
- How fast? Derivative Mode

Automatic Feedback Control
Why Controllers Need Tuning?

Controllers are tuned in an effort to match the characteristics of the control equipment to the process so that two goals are achieved: the foundation of process control measurement in that electricity:

- The system responds quickly to errors.
- The system remains stable (PV does not oscillate around the SP).

GAIN

Controller tuning is performed to adjust the manner in which a control valve (or other final control element) responds to a change in error. In particular, we are interested in adjusting the gain of the controller such that a change in controller input will result in a change in controller output that will, in turn, cause sufficient change in valve position to eliminate error, but not so great a change as to cause instability or cycling.

Gain is defined simply as the change in output divided by the change in input.

Examples:
Change in Input to Controller - 10%
Change in Controller Output - 20%

Gain = 20% / 10% = 2

Change in Input to Controller - 10%
Change in Controller Output - 5%

Gain = 5% / 10% = 0.5

The next three sections in this module discuss electricity, circuits, transmitters, and signals in greater detail so you can understand the importance of electricity in process control.
**Why Controllers Need Tuning?**

**Gain Plot** - The Figure below is simply another graphical way of representing the concept of gain.

\[
\text{Gain } K_c = \frac{\Delta \text{Output} \%}{\Delta \text{Input} \%}
\]

---

**Examples** - The following examples help to illustrate the purpose of setting the controller gain to different values.

- **Controllers May be Tuned to Help Match the Valve to the Process**
  - Fast process may require less gain to achieve stability
  - Slow process may require higher gain to achieve responsiveness

---

**Activities**

4. Fast or slow processes have no impact on controller gain settings. Is this statement true or false?
Proportional Mode

**PROPORTIONAL ACTION**

The proportional mode is used to set the basic gain value of the controller. The setting for the proportional mode may be expressed as either:
1. Proportional Gain
2. Proportional Band

**PROPORTIONAL GAIN**

In electronic controllers, proportional action is typically expressed as proportional gain. Proportional Gain (Kc) answers the question: "What is the percentage change of the controller output relative to the percentage change in controller input?"

Proportional Gain is expressed as:

\[
\text{Gain, (Kc)} = \frac{\Delta \text{Output}\%}{\Delta \text{Input}\%}
\]

**PROPORTIONAL BAND**

Proportional Band (PB) is another way of representing the same information and answers this question: "What percentage of change of the controller input span will cause a 100% change in controller output?"

\[
\text{PB} = \frac{\Delta \text{Input} (% \text{Span})}{100\% \Delta \text{Output}}
\]

**Converting Between PB and Gain**

A simple equation converts gain to proportional Band:

\[
\text{PB} = \frac{100}{\text{Gain}}
\]

Also recall that:

\[
\text{Gain} = \frac{100\%}{\text{PB}}
\]

Proportional Gain, (Kc) = \(\Delta \text{Output}\% / \Delta \text{Input}\%\)

\[
\text{PB} = \frac{\Delta \text{Input}(%\text{Span})}{100\% \Delta \text{Output}}
\]

**Activities**

1. Tends to leave an offset
2. Reset Windup during shutdown
3. Possible overshoot during startup
4. Can cause cycling in fast process by amplifying noisy signals

5. Identify the major disadvantage of proportional action.
Controller Algorithms and Tuning

Proportional Mode

![Graph showing the relationship between input and output percentages with different gain settings.]

**LIMITS OF PROPORTIONAL ACTION**

**Responds Only to a Change in error** - Proportional action responds only to a change in the magnitude of the error.

**Does Not Return the PV to Setpoint** - Proportional action will not return the PV to setpoint. It will, however, return the PV to a value that is within a defined span (PB) around the PV.

**DETERMINING THE CONTROLLER OUTPUT**

**Controller Output** - In a proportional only controller, the output is a function of the change in error and controller gain.

\[
\text{Output Change, } \% = (\text{Error Change, } \%) \times (\text{Gain})
\]

**Example:** If the setpoint is suddenly changed 10% with a proportional band setting of 50%, the output will change as follows:

**Calculating Controller Output**

\[
\Delta \text{Controller Output} = \Delta \text{Input, } \% \times \text{Gain}
\]

**Gain = 100%/PB**

**EXAMPLE**

\[
\Delta \text{Input} = 10\%
\]

PB = 50%, so Gain = 100%/50% = 2

6. If proportional gain is 0.5, and a level reading is 5% above setpoint, a proportional controller will signal the outflow control valve to open by <1 / 2.5 / 5> % of its full range.
Proportional Mode

\[ \Delta \text{Controller Output} = \Delta \text{Input} \times \text{Gain} \]
\[ \Delta \text{Controller Output} = 10\% \times 2 = 20\% \]

**Expressed in Units:**
Controller Output Change = 
\[ (0.2)(12 \text{ psi span}) = 2.4 \text{ psi} \]
\[ (0.2)(16 \text{ mA span}) = 3.2 \text{ mA} \]

**Proportional Action - Closed Loop**

**Loop Gain** - Every loop has a critical or natural frequency. This is the frequency at which cycling may exist. This critical frequency is determined by all of the loop components. If the loop gain is too high at this frequency, the PV will cycle around the SP; i.e., the process will become unstable.

**Low Gain Example** - In the example below, the proportional band is high (gain is low). The loop is very stable, but an error remains between SP and PV.

**High Gain Example** - In the example, the proportional band is small resulting in high gain, which is causing instability. Notice that the process variable is still not on set point.
Proportional Mode

**Activities**

7. What will be the result if the proportional gain is set too high?
   Select all options that apply.

   1. Large offset
   2. Minimized offset
   3. Possible cycling
   4. Stable loop

---

**Proportional Summary** - For the proportional mode, controller output is a function of a change in error. Proportional band is expressed in terms of the percentage change in error that will cause 100% change in controller output. Proportional gain is expressed as the percentage change in output divided by the percentage change in input.

\[
P_B = \left( \frac{\Delta \text{Input} \%, \%}{\Delta \text{Output} \%, \%} \right) \times 100 = 100/\text{Gain} \]

\[\text{Gain} = \frac{\Delta \text{Input} \%}{\Delta \text{Output} \%} \]

\[\Delta \text{Controller Output} = (\text{Change in Error})(\text{Gain})\]

1. Proportional Mode Responds only to a change in error
2. Proportional mode alone will not return the PV to SP.

**Advantages** - Simple

**Disadvantages** - Error

**Settings** - PB settings have the following effects:

- Small PB (%) Minimize Offset
- High Gain (%) Possible cycling
- Large PB (%) Large Offset
- Low Gain Stable Loop

**Tuning** - reduce PB (increase gain) until the process cycles following a disturbance, then double the PB (reduce gain by 50%).
Integral Mode

INTEGRAL ACTION

Duration of Error and Integral Mode - Another component of error is the duration of the error, i.e., how long has the error existed? The controller output from the integral or reset mode is a function of the duration of the error.

Open Loop Analysis

Purpose - The purpose of integral action is to return the PV to SP. This is accomplished by repeating the action of the proportional mode as long as an error exists. With the exception of some electronic controllers, the integral or reset mode is always used with the proportional mode.

Setting - Integral, or reset action, may be expressed in terms of:
- **Repeats Per Minute** - How many times the proportional action is repeated each minute.
- **Minutes Per Repeat** - How many minutes are required for 1 repeat to occur.

Activities

8. ______ action is the type of control algorithm that eliminates offset.
Integral Mode

CLOSED LOOP ANALYSIS

Closed Loop With Reset - Adding reset to the controller adds one more gain component to the loop. The faster the reset action, the greater the gain.

Slow Reset Example - In this example the loop is stable because the total loop gain is not too high at the loop critical frequency. Notice that the process variable does reach set point due to the reset action.

Fast Reset Example - In the example the rest is too fast and the PV is cycling around the SP.

Activities

9. Which of the following are integral or reset actions expressed in terms of?
   Select all options that apply.
   1. Repeats per setting
   2. Repeats per minute
   3. Repeats per loop
   4. Minutes per repeat
**Integral Mode**

**RESET WINDUP**

**Defined** - Reset windup is described as a situation where the controller output is driven from a desired output level because of a large difference between the set point and the process variable.

**Shutdown** - Reset windup is common on shut down because the process variable may go to zero but the set point has not changed, therefore this large error will drive the output to one extreme.

**Startup** - At start up, large process variable overshoot may occur because the reset speed prevents the output from reaching its desired value fast enough.

**Anti Reset Windup** - Controllers can be modified with an anti-reset

**Activities**

10. Identify the major disadvantages of integral action.
   Select all options that apply.

1. Tends to leave an offset
2. Reset windup during shutdown
3. Possible overshoot during start up
4. Can cause cycling in fast process by amplifying noisy signals
Integral Mode

windup (ARW) device. The purpose of an anti-reset option is to allow the output to reach its desired value quicker, therefore minimizing the overshoot.

**SUMMARY**

Integral (Reset) Summary - Output is a repeat of the proportional action as long as error exists. The units are in terms of repeats per minute or minutes per repeat.

- **Advantages** - Eliminates error
- **Disadvantages** - Reset windup and possible overshoot

<table>
<thead>
<tr>
<th>Fast Reset</th>
<th>Slow Reset</th>
</tr>
</thead>
<tbody>
<tr>
<td>(Large Repeats/Min., Small Min./Repeat)</td>
<td>(Small Repeats/Min., Large Min./Repeats)</td>
</tr>
<tr>
<td>1. High Gain</td>
<td>1. Low Gain</td>
</tr>
<tr>
<td>2. Fast Return To Setpoint</td>
<td>2. Slow Return To Setpoint</td>
</tr>
<tr>
<td>3. Possible Cycling</td>
<td>3. Stable Loop</td>
</tr>
</tbody>
</table>

**Trailing and Error Tuning** - Increase repeats per minute until the PV cycles following a disturbance, then slow the reset action to a value that is 1/3 of the initial setting.
Derivative Mode

DERIVATIVE ACTION

Derivative Mode Basics - Some large and/or slow process do not respond well to small changes in controller output. For example, a large liquid level process or a large thermal process (a heat exchanger) may react very slowly to a small change in controller output. To improve response, a large initial change in controller output may be applied. This action is the role of the derivative mode.

The derivative action is initiated whenever there is a change in the rate of change of the error (the slope of the PV). The magnitude of the derivative action is determined by the setting of the derivative. The mode of a PID controller and the rate of change of the PV. The Derivative setting is expressed in terms of minutes. In operation, the controller first compares the current PV with the last value of the PV. If there is a change in the slope of the PV, the controller determines what its output would be at a future point in time (the future point in time is determined by the value of the derivative setting, in minutes). The derivative mode immediately increases the output by that amount.

Derivative Action is based on the rate of change in Error (Y/X)

11. _________ action is a control algorithm that is tied to the rate of change in the error.

12. Which of the following are derivative or rate actions expressed in terms of?

1. Repeats per minute
2. Hours
3. Seconds
4. Minutes
5. Milliseconds
Derivative Mode

**Example** - Let's start a closed loop example by looking at a temperature control system. In this example, the time scale has been lengthened to help illustrate controller actions in a slow process. Assume a proportional band setting of 50%. There is no reset at this time. The proportional gain of 2 acting on a 10% change in set point results in a change in controller output of 20%. Because temperature is a slow process the setting time after a change in error is quite long. And, in this example, the PV never becomes equal to the SP because there is no reset.

**Rate Effect** - To illustrate the effect of rate action, we will add the rate mode with a setting of 1 minute. Notice the very large controller output at time 0. The output spike is the result of rate action. Recall that the change in output due to rate action is a function of the speed (rate) of change of error, which in a step is nearly infinite. The addition of rate alone will not cause the process variable to match the set point.

![Graph](image)

---

**Activities**

13. The addition of derivative or rate alone to a close loop control can cause the process variable to match the set point. Is this statement true or false?
Derivative Mode

Effect of Fast Rate - Let's now increase the rate setting to 10 minutes. The controller gain is now much higher. As a result, both the IVP (controller output) and the PV are cycling. The point here is that increasing the rate setting will not cause the PV to settle at the SP.

Need for Reset Action - It is now clear that reset must be added to bring process variable back to set point.

Applications - Because this component of the controller output is dependent on the speed of change of the input or error, the output will be very erratic if rate is used on fast process or one with noisy signals. The controller output, as a result of rate, will have the greatest change when the input changes rapidly.

Controller Option to Ignore Change in SP - Many controllers, especially digital types, are designed to respond to changes in the PV only, and to ignore changes in SP. This feature eliminates a major upset upset that would occur following a change in the setpoint.
Derivative Mode

**SUMMARY**

Derivative (Rate) Summary - Rate action is a function of the speed of change of the error. The units are minutes. The action is to apply an immediate response that is equal to the proportional plus reset action that would have occurred some number of minutes in the future.

**Advantages** - Rapid output reduces the time that is required to return PV to SP in slow process.

**Disadvantage** - Dramatically amplifies noisy signals; can cause cycling in fast processes.

**Settings**

**Large (Minutes)**
1. High Gain
2. Large Output Change
3. Possible Cycling

**Small (Minutes)**
1. Low Gain
2. Small Output Change
3. Stable Loop

**Trial-and-Error Tuning**

Increase the rate setting until the process cycles following a disturbance, then reduce the rate setting to one-third of the initial value.
Controller Algorithms

Proportional, PI, and PID Control

By using all three control algorithms together, process operators can:

- Achieve rapid response to major disturbances with derivative control
- Hold the process near setpoint without major fluctuations with proportional control
- Eliminate offset with integral control

Not every process requires a full PID control strategy. If a small offset has no impact on the process, then proportional control alone may be sufficient.

PI control is used where no offset can be tolerated, where noise (temporary error readings that do not reflect the true process variable condition) may be present, and where excessive dead time (time after a disturbance before control action takes place) is not a problem.

In processes where no offset can be tolerated, no noise is present, and where dead time is an issue, customers can use full PID control. Table 7.2 shows common types of control loops and which types of control algorithms are typically used.

<table>
<thead>
<tr>
<th>Controlled Variable</th>
<th>Proportional Control</th>
<th>PI Control</th>
<th>PID Control</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flow</td>
<td>Yes</td>
<td>Yes</td>
<td>No</td>
</tr>
<tr>
<td>Level</td>
<td>Yes</td>
<td>Yes</td>
<td>Rare</td>
</tr>
<tr>
<td>Temperature</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Pressure</td>
<td>Yes</td>
<td>Yes</td>
<td>Rare</td>
</tr>
<tr>
<td>Analytical</td>
<td>Yes</td>
<td>Yes</td>
<td>Rare</td>
</tr>
</tbody>
</table>

Table 7.2: Control Loops and Control Algorithms

Activities

14. What type of control is used in an application where noise is present, but where no offset can be tolerated?

1. P only
2. PD
3. PI
4. PID
Process Control Loops

In this section, you will learn about how control components and control algorithms are integrated to create a process control system. Because in some processes many variables must be controlled, and each variable can have an impact on the entire system, control systems must be designed to respond to disturbances at any point in the system and to mitigate the effect of those disturbances throughout the system.

**LEARNING OBJECTIVES**

After completing this section, you will be able to:

- Explain how a multivariable loop is different from a single loop.
- Differentiate feedback and feedforward control loops in terms of their operation, design, benefits, and limitations
- Perform the following functions for each type of standard process control loop (i.e., pressure, flow, level, and temperature):
  - State the type of control typically used and explain why it is used
  - Identify and describe considerations for equipment selection (e.g., speed, noise)
  - Identify typical equipment requirements
  - Diagram the loop using ISA symbology
- Explain the basic implementation process, including a description of equipment requirements and considerations, for each of the following types of control:
  - Cascade control
  - Batch control
  - Ratio control
  - Selective control
  - Fuzzy control
- Describe benefits and limitations of each type of control listed above
- Give examples of process applications in which each type of control described in this section might be used

**Note:** To answer the activity questions the Hand Tool (H) should be activated.
Single Control Loops

Control loops can be divided into two categories: Single variable loops and multi-variable loops.

**FEEDBACK CONTROL**

A *feedback loop* measures a process variable and sends the measurement to a controller for comparison to setpoint. If the process variable is not at setpoint, control action is taken to return the process variable to setpoint. Figure 7.18 illustrates a feedback loop in which a transmitter measures the temperature of a fluid and, if necessary, opens or closes a hot steam valve to adjust the fluid’s temperature.

An everyday example of a feedback loop is the cruise control system in an automobile. A setpoint is established for speed. When the car begins to climb a hill, the speed drops below setpoint and the controller adjusts the throttle to return the car’s speed to setpoint.

Feedback loops are commonly used in the process control industry. The advantage of a feedback loop is that it directly controls the desired process variable. The disadvantage to feedback loops is that the process variable must leave setpoint for action to be taken.

1. What type of control loop takes action in response to measured deviation from setpoint?
   1. Discrete control loop
   2. Multi-step control loop
   3. Open loop
   4. Feedback control loop
Examples of Single Control Loops

While each application has its own characteristics, some general statements can be made about pressure, flow, level, and temperature loops.

**Pressure Control Loops**

Pressure control loops vary in speed—that is, they can respond to changes in load or to control action slowly or quickly. The speed required in a pressure control loop may be dictated by the volume of the process fluid. High-volume systems (e.g., large natural gas storage facilities) tend to change more slowly than low-volume systems (Figure 7.21).

![A Pressure Loop](image)

2. How does a high-volume pressure control loop react as compared to a small-volume pressure control loop?

1. Same rate
2. Quicker
3. Slower
4. Extremely fast
Examples of Single Control Loops

FLOW CONTROL LOOPS

Generally, flow control loops are regarded as fast loops that respond to changes quickly. Therefore, flow control equipment must have fast sampling and response times. Because flow transmitters tend to be rather sensitive devices, they can produce rapid fluctuations or noise in the control signal. To compensate for noise, many flow transmitters have a damping function that filters out noise. Sometimes, filters are added between the transmitter and the control system. Because the temperature of the process fluid affects its density, temperature measurements are often taken with flow measurements and compensation for temperature is accounted for in the flow calculation. Typically, a flow sensor, a transmitter, a controller, and a valve or pump are used in flow control loops (Figure 7.22).

A Flow Loop

Activities

3. Flow control loops are generally considered to be slow responding loops. Is this statement true or false?
LEVEL CONTROL LOOPS

The speed of changes in a level control loop largely depends on the size and shape of the process vessel (e.g., larger vessels take longer to fill than smaller ones) and the flow rate of the input and outflow pipes. Manufacturers may use one of many different measurement technologies to determine level, including radar, ultrasonic, float gauge, and pressure measurement. The final control element in a level control loop is usually a valve on the input and/or outflow connections to the tank (Figure 7.23). Because it is often critical to avoid tank overflow, redundant level control systems are sometimes employed.

Activities

4. Redundant control systems are sometimes used in level applications because preventing tank overflow is often critically important. Is this statement true or false?
Because of the time required to change the temperature of a process fluid, temperature loops tend to be relatively slow. Feedforward control strategies are often used to increase the speed of the temperature loop response. RTDs or thermocouples are typical temperature sensors. Temperature transmitters and controllers are used, although it is not uncommon to see temperature sensors wired directly to the input interface of a controller. The final control element for a temperature loop is usually the fuel valve to a burner or a valve to some kind of heat exchanger. Sometimes, cool process fluid is added to the mix to maintain temperature (Figure 7.24).

**Activities**

5. What type of control strategy is often used to increase the speed of a temperature control loop?

1. Feedforward control
2. Feedback control
3. Cascade control
4. Ratio control
Multi-Variable / Advanced Control Loops

**MULTIVARIABLE LOOPS**

*Multivariable loops* are control loops in which a primary controller controls one process variable by sending signals to a controller of a different loop that impacts the process variable of the primary loop. For example, the primary process variable may be the temperature of the fluid in a tank that is heated by a steam jacket (a pressurized steam chamber surrounding the tank). To control the primary variable (temperature), the primary (master) controller signals the secondary (slave) controller that is controlling steam pressure. The primary controller will manipulate the setpoint of the secondary controller to maintain the setpoint temperature of the primary process variable (Figure 7.17).

When tuning a control loop, it is important to take into account the presence of multivariable loops. The standard procedure is to tune the secondary loop before tuning the primary loop because adjustments to the secondary loop impact the primary loop. Tuning the primary loop will not impact the secondary loop tuning.

**Activities**

6. A multivariable control loop contains a primary and secondary controller assigned to different process variables? Is this statement true or false?
Feedforward control is a control system that anticipates load disturbances and controls them before they can impact the process variable. For feedforward control to work, the user must have a mathematical understanding of how the manipulated variables will impact the process variable. Figure 7.19 shows a feedforward loop in which a flow transmitter opens or closes a hot steam valve based on how much cold fluid passes through the flow sensor.

An advantage of feedforward control is that error is prevented, rather than corrected. However, it is difficult to account for all possible load disturbances in a system through feedforward control. Factors such as outside temperature, buildup in pipes, consistency of raw materials, humidity, and moisture content can all become load disturbances and cannot always be effectively accounted for in a feedforward system.

In general, feedforward systems should be used in cases where the controlled variable has the potential of being a major load disturbance on the process variable ultimately being controlled. The added complexity and expense of feedforward control may not be equal to the benefits of increased control in the case of a variable that causes only a small load disturbance.

7. What type of control loop anticipates and controls load disturbances before they can impact the process variable?
1. Feedback control loop
2. Feedforward control loop
3. Ratio control loop
4. Single variable loop
Because of the difficulty of accounting for every possible load disturbance in a feedforward system, feedforward systems are often combined with feedback systems. Controllers with summing functions are used in these combined systems to total the input from both the feedforward loop and the feedback loop, and send a unified signal to the final control element. Figure 7.20 shows a feedforward-plus-feedback loop in which both a flow transmitter and a temperature transmitter provide information for controlling a hot steam valve.

Activities

8. A controller with a summing function totals the input from both the feedforward loop and the feedback loop and sends a unified signal to the final control element. This is how a single control signal is sent to the final control element in a feedforward plus feedback system. Is this statement true or false?
Multi-Variable / Advanced Control Loops

This module has discussed specific types of control loops, what components are used in them, and some of the applications (e.g., flow, pressure, temperature) they are applied to. In practice, however, many independent and interconnected loops are combined to control the workings of a typical plant. This section will acquaint you with some of the methods of control currently being used in process industries.

CASCADE CONTROL

Cascade control is a control system in which a secondary (slave) control loop is set up to control a variable that is a major source of load disturbance for another primary (master) control loop. The controller of the primary loop determines the setpoint of the summing controller in the secondary loop (Figure 7.25).

9. Ratio control is the term used to describe a system in which the controller of the primary loop determines the setpoint of a secondary loop. Is this statement true or false?
Batch processes are those processes that are taken from start to finish in batches. For example, mixing the ingredients for a juice drinks is often a batch process. Typically, a limited amount of one flavor (e.g., orange drink or apple drink) is mixed at a time. For these reasons, it is not practical to have a continuous process running. Batch processes often involve getting the correct proportion of ingredients into the batch. Level, flow, pressure, temperature, and often mass measurements are used at various stages of batch processes.

A disadvantage of batch control is that the process must be frequently restarted. Start-up presents control problems because, typically, all measurements in the system are below setpoint at start-up. Another disadvantage is that as recipes change, control instruments may need to be recalibrated.

Ratio control

Imagine a process in which an acid must be diluted with water in the proportion two parts water to one part acid. If a tank has an acid supply on one side of a mixing vessel and a water supply on the other, a control system could be developed to control the ratio of acid to water, even though the water supply itself may not be controlled. This type of control system is called ratio control (Figure 7.26). Ratio control is used in many applications and involves a controller that receives input from a flow measurement device on the unregulated (wild) flow. The controller performs a ratio calculation and signals the appropriate setpoint to another controller that sets the flow of the second fluid so that the proper proportion of the second fluid can be added.

Ratio control might be used where a continuous process is going on and an additive is being put into the flow (e.g., chlorination of water).

Activities

10. Which term describes a control system in which controlled flow is added proportionately to an uncontrolled flow?

1  Selective control
2  Cascade control
3  Ratio control
4  Fuzzy control
**Multi-Variable / Advanced Control Loops**

**SELECTIVE CONTROL**

Selective control refers to a control system in which the more important of two variables will be maintained. For example, in a boiler control system, if fuel flow outpaces air flow, then uncombusted fuel can build up in the boiler and cause an explosion. Selective control is used to allow for an air-rich mixture, but never a fuel-rich mixture. Selective control is most often used when equipment must be protected or safety maintained, even at the cost of not maintaining an optimal process variable setpoint.

**FUZZY CONTROL**

Fuzzy control is a form of adaptive control in which the controller uses fuzzy logic to make decisions about adjusting the process. Fuzzy logic is a form of computer logic where whether something is or is not included in a set is based on a grading scale in which multiple factors are accounted for and rated by the computer. The essential idea of fuzzy control is to create a kind of artificial intelligence that will account for numerous variables, formulate a theory of how to make improvements, adjust the process, and learn from the result.

Fuzzy control is a relatively new technology. Because a machine makes process control changes without consulting humans, fuzzy control removes from operators some of the ability, but none of the responsibility, to control a process.

11. In which type of control system will the more important of two variables be maintained?

1. Fuzzy control
2. Cascade control
3. Ratio control
4. Selective control

12. __________ control is the term used to describe a control system in which the controller uses computer logic to make decisions about adjusting the process.
Module 7: Workbook Exercises

EXERCISE 7.1— THE IMPORTANCE OF PROCESS CONTROL

1. Which of the following options best represents the reasons to control a process? (Select three options that apply)
   - Reduce variability
   - Increase productivity
   - Increase efficiency
   - Reduce cost
   - Ensure safety

2. Process is defined as the method of changing or refining raw materials to create end products. Is this statement true or false?
   - True
   - False

3. Which of the following are advantages of reducing variability in a process application?
   - Helps ensure a consistently high-quality end product.
   - Helps ensure an increase in the reaction rate of the process.
   - Helps ensure increase in efficiency of the process.
   - Helps ensure safety
Module 7: Workbook Exercises

EXERCISE 7.2 — CONTROL THEORY BASICS

1. Which of the following tasks is associated with process control? (Select three options that apply)
   
   (1) Measurement
   (2) Comparison
   (3) Quality Analysis
   (4) Adjustment
   (5) Calculation

2. Which of the following variables are commonly measured or monitored in process control applications? (Select three options that apply)
   
   (1) Pressure
   (2) Viscosity
   (3) Nitrogen content
   (4) Flow rate
   (5) Temperature

3. A process liquid level needs to be held within 5 ft of 150 ft in a large tank. A pressure transmitter monitors the liquid’s level using a pressure reading and sends the result to a controller. The controller compares the level reading to the set point and opens or closes an inflow or outflow pipe depending on the liquid level. Keeping in mind the given scenario, match the terms in Column A with their values in Column B.

   (1) Inferred process variable (A) 150 ft
   (2) Manipulated variable (B) Pressure
   (3) Measured variable (C) Flow of liquid to the tank
   (4) Set point (D) Level
Module 7: Workbook Exercises

4. Match each term to its correct definition.

<table>
<thead>
<tr>
<th>Term</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>(1) Load disturbance</td>
<td>(B) An undesired change in a factor that can affect the process variable.</td>
</tr>
<tr>
<td>(2) Control algorithm</td>
<td>(C) A value or range of values for a process variable that must be maintained</td>
</tr>
<tr>
<td>(3) Manual control</td>
<td>(D) A control operation that directly involves human action.</td>
</tr>
<tr>
<td>(4) Manipulated variable</td>
<td>(E) A mathematical expression of a control function</td>
</tr>
<tr>
<td>(5) Set point</td>
<td>(A) The factor that is changed to keep a measured variable at set point.</td>
</tr>
</tbody>
</table>

5. Match each term to its correct description.

<table>
<thead>
<tr>
<th>Term</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>(1) Closed-loop, automatic control</td>
<td>(A) An operator turns off the heater coil when the temperature transmitter outputs a certain reading.</td>
</tr>
<tr>
<td>(2) Closed-loop, manual control</td>
<td>(B) A controller turns off the heater coil at set intervals, regardless of the process temperature.</td>
</tr>
<tr>
<td>(3) Open-loop, automatic control</td>
<td>(C) A temperature sensor measures process temperature, sends the result to a controller to compare to the setpoint, and the controller turns off the heater coil.</td>
</tr>
</tbody>
</table>

6. __________ is a deviation from set point due to load disturbance.

<table>
<thead>
<tr>
<th>Term</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>(1)</td>
<td>Error</td>
</tr>
<tr>
<td>(2)</td>
<td>Offset</td>
</tr>
<tr>
<td>(3)</td>
<td>Rate of change</td>
</tr>
</tbody>
</table>

7. __________ is a continuing error due to the inability of a control system to keep the measured variable at set point.

<table>
<thead>
<tr>
<th>Term</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>(1) Load disturbance</td>
<td>(A) The factor that is changed to keep a measured variable at set point.</td>
</tr>
<tr>
<td>(2) Offset</td>
<td>(B) An undesired change in a factor that can affect the process variable.</td>
</tr>
<tr>
<td>(3) Pressure</td>
<td>(C) A value or range of values for a process variable that must be maintained to keep the process running properly.</td>
</tr>
</tbody>
</table>
Module 7: Workbook Exercises

EXERCISE 7.3 — COMPONENTS OF CONTROL LOOPS AND ISA SYMBOLOGY

1. The basic function of a __________ is to convert a reading from a transducer into a standard signal and transmit that signal to a controller or computer monitor.
   (1) recorder
   (2) transmitter
   (3) converter

2. 4–20 mA is the most common standard analog signal used in the process control industry today. Is this statement true or false?
   (1) True
   (2) False

3. Match the signal type in Column A with its example/application in Column B.
   (1) Analog signal   (A) 3 –15 psig
   (2) Pneumatic signal (B) Fieldbus, Profibus and Modbus
   (3) Digital signal     (C) 4-20 mA and 1 – 5 V

4. A customer would use __________ to read the temperature of a process fluid on a display.
   (1) an indicator
   (2) a volt-meter
   (3) an actuator

5. Match each control loop equipment to its correct description.
   (1) Recorder
   (2) Controller
   (3) Final control element
   (4) Actuator

6. A pump motor is the most commonly used final control element. Is this statement true or false?
   (1) True
   (2) False
Module 7: Workbook Exercises

7. Match the ISA symbols in Column A with its respective description in Column B.

(1)     (A) Programmable logic control

(2)     (B) Temperature transmitter

(3)     (C) Pneumatically actuated valve

(4)     (D) Electrically actuated valve
Module 7: Workbook Exercises

EXERCISE 7.4 — CONTROL ALGORITHMS AND TUNING

1. Match each term to its correct definitions.

   (1) Proportional band
   (2) Proportional/integral (PI) control
   (3) Proportional control
   (4) Derivative control
   (5) Integral control

   (A) A type of control that corrects error and eliminates offset.
   (B) A type of control that produce erratic output in noisy applications.
   (C) The percent change in error that will cause a 100% change in controller output.
   (D) A type of control that is prone to leaving an offset.
   (E) A type of control that repeats the action of the proportional mode as long as an error exists.

2. Identify the two effects on a process variable if the proportional gain (Pgain) is set too high? (Select all that apply)

   (1) Minimize offset
   (2) Large offset
   (3) Stable loop
   (4) Possible cycling

3. Derivative gain (Dgain) is typically set to zero in flow applications since flow applications are usually noisy and derivative control will react to readings that are in fact noise, thus preventing the process from holding set point. Is this statement true or false?

   (1) True
   (2) False
Module 7: Workbook Exercises

EXERCISE 7.5 — PROCESS CONTROL LOOPS

1. Which control system anticipates load disturbances and controls them before they can impact the process variable?
   (1) Selective control
   (2) Fuzzy control
   (3) Feed forward control
   (4) Cascade control

2. Match the component label in Column A to its ISA symbol representation in Column B.
   (1) Flow transmitter (A)
   (2) Temperature transmitter (B)
   (3) Flow controller (C)
   (4) Valve (D)

3. If R₁ = 60 Ω, R₂ = 100 Ω, and R₃ = 100 Ω, what is the equivalent resistance (Rₑq) in the circuit?
   (1) slow
   (2) fast
   (3) variable speed
Module 7: Workbook Exercises - Answers

Exercise 7.1 – The Importance of Process Control
1.  1, 3, 5
2.  1
3.  1

Exercise 7.2 – Control Theory Basics
1.  1, 2, 4
2.  1, 4, 5
3.  D, C, B, A
4.  B, E, D, A, C
5.  C, A, B
6.  1
7.  2

Exercise 7.3 – Components of Control Loops and ISA Symbology
1.  2
2.  1
3.  C, A, B
4.  1
5.  C, D, B, A
6.  2
7.  B, C, D, A

Exercise 7.4 – Control Algorithms and Tuning
1.  C, A, D, B, E
2.  1, 4
3.  1

Exercise 7.5 – Process Control Loops
1.  3
2.  B, C, D, A
3.  1
Module 7: Activity Answers

The Importance of Process Control

1. True
2. 1,3,5
3. 1,2,4

Control Theory Basics

1. True
2. True
3. True
4. 4
5. 3
6. False
7. False
8. 2,4

Components of Control Loops and ISA Symbology

1. 1,2,5
2. False
3. 3
4. True
5. 2,3,4
6. 1
7. 1,4
8. 2
9. 4
10. 3
11. 1
12. 2
13. 1
14. 2
15. 3
16. True
17. 4
18. True
19. True
20. 1
21. 3
Module 7: Activity Answers

Controller Algorithms and Tuning

1. 1,2,3,4
2. False
3. 2
4. False
5. 1
6. 2.5
7. 2,3
8. 3
9. 2,4
10. 2,3
11. 2
12. 4
13. False
14. 3

Process Control Loops

1. 4
2. 3
3. False
4. True
5. 1
6. True
7. 2
8. True
9. False
10. 3
11. 4
12. 1