

Introduction

The goal of this chapter is to provide a motivation for, and an introduction to, process control and instrumentation. After studying this chapter, the reader, given a process, should be able to do the following:

- Determine possible control objectives, input variables (manipulated and disturbance) and output variables (measured and unmeasured), and constraints (hard or soft), as well as classify the process as continuous, batch, or semicontinuous
- Assess the importance of process control from safety, environmental, and economic points of view
- Sketch a process instrumentation and control diagram
- Draw a simplified control block diagram
- Understand the basic idea of feedback control
- Understand basic sensors (measurement devices) and actuators (manipulated inputs)
- Begin to develop intuition about characteristic timescales of dynamic behavior

The major sections of this chapter are as follows:

- 1.1 Introduction
- 1.2 Instrumentation
- 1.3 Process Models and Dynamic Behavior
- 1.4 Control Textbooks and Journals
- 1.5 A Look Ahead
- 1.6 Summary

1.1 Introduction

Process engineers are often responsible for the operation of chemical processes. As these processes become larger scale and/or more complex, the role of process automation becomes more and more important. The objective of this textbook is to teach process engineers how to design and tune feedback controllers for the automated operation of chemical processes.

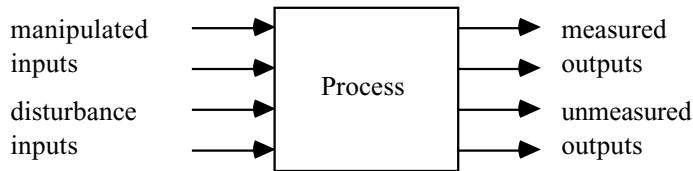
A conceptual process block diagram for a chemical process is shown in Figure 1–1. Notice that the *inputs* are classified as either manipulated or disturbance variables and the *outputs* are classified as measured or unmeasured in Figure 1–1a. To automate the operation of a process, it is important to use measurements of process outputs or disturbance inputs to make decisions about the proper values of manipulated inputs. This is the purpose of the controller shown in Figure 1–1b; the measurement and control signals are shown as dashed lines. These initial concepts probably seem very vague or abstract to you at this point. Do not worry, because we present a number of examples in this chapter to clarify these ideas.

The development of a control strategy consists of formulating or identifying the following.

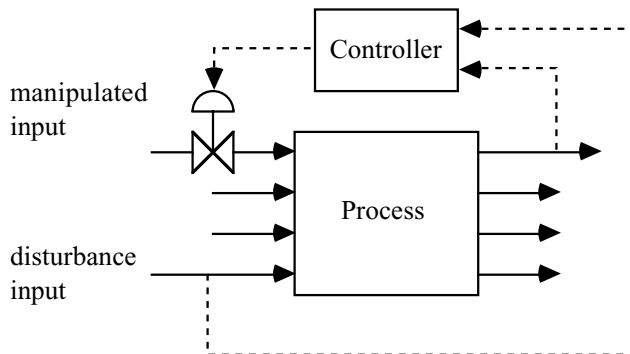
1. Control objective(s).
2. Input variables—classify these as (a) manipulated or (b) disturbance variables; inputs may change continuously, or at discrete intervals of time.
3. Output variables—classify these as (a) measured or (b) unmeasured variables; measurements may be made continuously or at discrete intervals of time.
4. Constraints—classify these as (a) hard or (b) soft.
5. Operating characteristics—classify these as (a) continuous, (b) batch, or (c) semicontinuous (or semibatch).
6. Safety, environmental, and economic considerations.
7. Control structure—the controllers can be feedback or feed forward in nature.

Here we discuss each of the steps in formulating a control problem in more detail.

1. The first step of developing a control strategy is to formulate the control *objective(s)*. A chemical-process operating unit often consists of several unit operations. The control of an operating unit is generally reduced to considering the control of each unit operation separately. Even so, each unit operation may have multiple, sometimes conflicting objectives, so the development of control objectives is not a trivial problem.



a. Input/Output representation



b. Control representation

Figure 1–1 Conceptual process input/output block diagram.

2. Input variables can be classified as *manipulated* or *disturbance* variables. A manipulated input is one that can be adjusted by the control system (or process operator). A disturbance input is a variable that affects the process outputs but that cannot be adjusted by the control system. Inputs may change *continuously* or at *discrete* intervals of time.
3. Output variables can be classified as *measured* or *unmeasured* variables. Measurements may be made *continuously* or at *discrete* intervals of time.
4. Any process has certain operating *constraints*, which are classified as hard or soft. An example of a hard constraint is a minimum or maximum flow rate—a valve operates between the extremes of fully closed or fully open. An example of a soft constraint is a product composition—it may be desirable to specify a composition between certain values to sell a product, but it is possible to violate this specification without posing a safety or environmental hazard.
5. Operating characteristics are usually classified as *continuous*, *batch*, or *semi-continuous* (*semibatch*). Continuous processes operate for long periods of time

under relatively constant operating conditions before being “shut down” for cleaning, catalyst regeneration, and so forth. For example, some processes in the oil-refining industry operate for 18 months between shutdowns. Batch processes are dynamic in nature—that is, they generally operate for a short period of time and the operating conditions may vary quite a bit during that period of time. Example batch processes include beer or wine fermentation, as well as many specialty chemical processes. For a batch reactor, an initial charge is made to the reactor, and conditions (temperature, pressure) are varied to produce a desired product at the end of the batch time. A typical semibatch process may have an initial charge to the reactor, but feed components may be added to the reactor during the course of the batch run.

Another important consideration is the dominant timescale of a process. For continuous processes this is very often related to the residence time of the vessel. For example, a vessel with a liquid volume of 100 liters and a flow rate of 10 liters/minute would have a residence time of 10 minutes; that is, on the average, an element of fluid is retained in the vessel for 10 minutes.

6. Safety, environmental, and economic considerations are all very important. In a sense, economics is the ultimate driving force—an unsafe or environmentally hazardous process will ultimately cost more to operate, through fines paid, insurance costs, and so forth. In many industries (petroleum refining, for example), it is important to minimize energy costs while producing products that meet certain specifications. Better process automation and control allows processes to operate closer to “optimum” conditions and to produce products where variability specifications are satisfied.

The concept of “fail-safe” is always important in the selection of instrumentation. For example, a control valve needs an energy source to move the valve stem and change the flow; most often this is a pneumatic signal (usually 3–15 psig). If the signal is lost, then the valve stem will go to the 3-psig limit. If the valve is *air-to-open*, then the loss of instrument air will cause the valve to close; this is known as a *fail-closed* valve. If, on the other hand, a valve is *air-to-close*, when instrument air is lost the valve will go to its fully open state; this is known as a *fail-open* valve.

7. The two standard control types are *feed forward* and *feedback*. A feed-forward controller measures the disturbance variable and sends this value to a controller, which adjusts the *manipulated* variable. A feedback control system measures the output variable, compares that value to the desired output value, and uses this information to adjust the manipulated variable. For the first part of this textbook, we emphasize feedback control of single-input (manipulated) and single-output (measured) systems. Determining the feedback control

structure for these systems consists of deciding which manipulated variable will be adjusted to control which measured variable. The desired value of the measured process output is called the *setpoint*.

A particularly important concept used in control system design is process *gain*. The process gain is the sensitivity of a process output to a change in the process input. If an increase in a process input leads to an increase in the process output, this is known as a positive gain. If, on the other hand, an increase in the process input leads to a decrease in the process output, this is known as a negative gain. The magnitude of the process gain is also important. For example, a change in power (input) of 0.5 kW to a laboratory-scale heater may lead to a fluid temperature (output) change of 10°C; this is a process gain (change in output/change in input) of 20°C/kW. The same input power change of 0.5 kW to a larger scale heater may only yield an output change of 0.5°C, corresponding to a process gain of 1°C/kW.

Once the control structure is determined, it is important to decide on the control *algorithm*. The control algorithm uses measured output variable values (along with desired output values) to change the manipulated input variable. A control algorithm has a number of control *parameters*, which must be “tuned” (adjusted) to have acceptable performance. Often the tuning is done on a simulation model before implementing the control strategy on the actual process. A significant portion of this textbook is on the use of *model-based* control, that is, controllers that have a model of the process “built in.”

This approach is best illustrated by way of example. Since many important concepts, such as control instrumentation diagrams and control block diagrams, are introduced in the next examples, it is important that you study them thoroughly.

Example 1.1: Surge Tank

Surge tanks are often used as intermediate storage for fluid streams being transferred between process units. Consider the process flow diagram shown in Figure 1–2, where a fluid stream from process 1 is fed to the surge tank; the effluent from the surge tank is sent to process 2.

There are obvious constraints on the height in this tank. If the tank overflows it may create safety and environmental hazards, which may also have economic significance. Let us analyze this system using a step-by-step procedure.

1. Control objective: The control objective is to maintain the height within certain bounds. If it is too high it will overflow and if it is too low there may be problems with the flow to process 2. Usually, a specific desired height will be selected. This desired height is known as the *setpoint*.

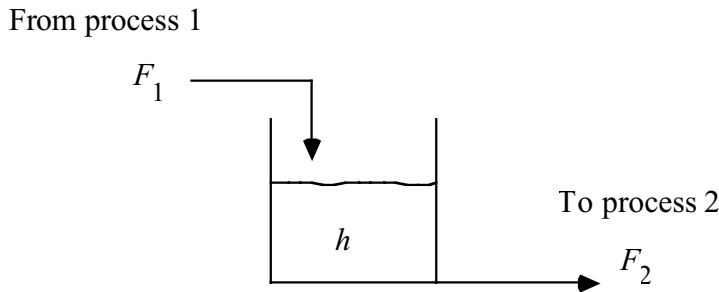


Figure 1–2 Tank level problem.

2. Input variables: The input variables are the flow from process 1 and the flow to process 2. Notice that an outlet flow rate is considered an input to this problem. The question is which input is manipulated and which is a disturbance? That depends. We discuss this problem further in a moment.
3. Output variables: The most important output variable is the liquid level. We assume that it is measured.
4. Constraints: There are a number of constraints in this problem. There is a maximum liquid level; if this is exceeded, the tank will overflow. There are minimum and maximum flow rates through the inlet and outlet valves.
5. Operating characteristics: We assume that this is a continuous process, that is, that there is a continuous flow in and out of the tank. It would be a semicontinuous process if, for example, there was an inlet flow with no outlet flow (if the tank was simply being filled).
6. Safety, environmental, and economic considerations: These aspects depend somewhat on the fluid characteristics. If it is a hazardous chemical, then there is a tremendous incentive from safety and environmental considerations to not allow the tank to overflow. Indeed, this is also an economic consideration, since injuries to employees or environmental cleanup costs money. Even if the substance is water, it has likely been treated by an upstream process unit, so losing water owing to overflow will incur an economic penalty. Safety considerations play an important role in the specification of control valves (fail-open or fail-closed). For this particular problem, the control-valve specification will depend on which input is manipulated. This is discussed in detail shortly.
7. Control structure: There are numerous possibilities for control of this system. We discuss first the feedback strategies, then the feed-forward strategies.

Feedback Control

The measured variable for a feedback control strategy is the tank height. Which input variable is manipulated depends on what is happening in process 1 and process 2. Let us consider two different scenarios.

Scenario 1 Process 2 regulates the flow-rate F_2 . This could happen, for example, if process 2 is a steam generation system and process 1 is a deionization process. Process 2 varies the flow rate of water (F_2) depending on the steam demand. As far as the tank process is concerned, F_2 is a “wild” (disturbance) stream because the regulation of F_2 is determined by another system. In this case we would use F_1 as the manipulated variable; that is, F_1 is adjusted to maintain a desired tank height.

The control and instrumentation diagram for a feedback control strategy for scenario 1 is shown in Figure 1–3. Notice that the level transmitter (LT) sends the measured height of liquid in the tank (h_m) to the level controller (LC). The LC compares the measured level with the desired level (h_{sp} , the height setpoint) and sends a pressure signal (P_v) to the valve. This valve top pressure moves the valve stem up and down, changing the flow rate through the valve (F_1). If the controller is designed properly, the flow rate changes to bring the tank height close to the desired setpoint. In this process and instrumentation diagram we use dashed lines to indicate signals between different pieces of instrumentation.

A simplified block diagram representing this system is shown in Figure 1–4. Each signal and device (or process) is shown on the block diagram. We use a slightly different

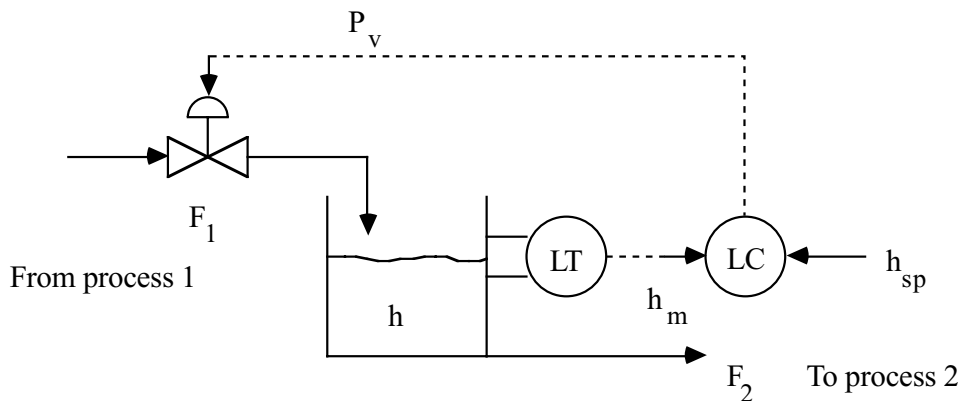


Figure 1–3 Feedback control strategy 1. The level is measured and the inlet flow rate (valve position) is manipulated.

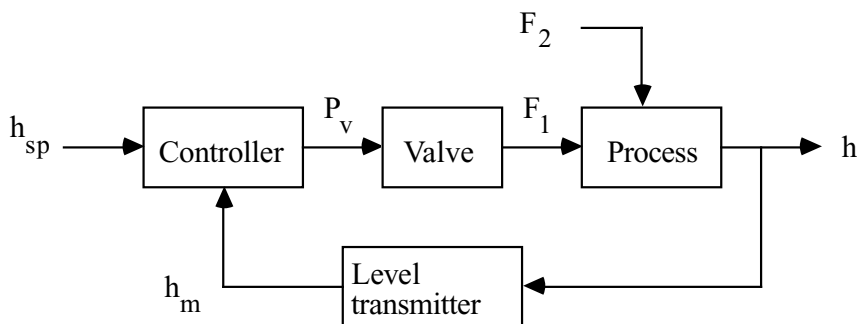


Figure 1–4 Feedback control schematic (block diagram) for scenario 1. F_1 is manipulated and F_2 is a disturbance.

form for block diagrams when we use transfer function notation for control system analysis in Chapter 5. Note that each block represents a dynamic element. We expect that the valve and LT dynamics will be much faster than the process dynamics. We also see clearly from the block diagram why this is known as a *feedback* control “loop.” The controller “decides” on the valve position, which affects the inlet flow rate (the manipulated input), which affects the level; the outlet flow rate (the disturbance input) also affects the level. The level is measured, and that value is fed back to the controller [which compares the measured level with the desired level (setpoint)].

Notice that the control valve should be specified as fail-closed or air-to-open, so that the tank will not overflow on loss of instrument air or other valve failure.

Scenario 2 Process 1 regulates flow rate F_1 . This could happen, for example, if process 1 is producing a chemical compound that must be processed by process 2. Perhaps process 1 is set to produce F_1 at a certain rate. F_1 is then considered “wild” (a disturbance) by the tank process. In this case we would adjust F_2 to maintain the tank height. Notice that the control valve should be specified as fail-open or air-to-close, so that the tank will not overflow on loss of instrument air or other valve failure.

The process and instrumentation diagram for this scenario is shown in Figure 1–5. The only difference between this and the previous instrumentation diagram (Figure 1–3) is that F_2 rather than F_1 is manipulated.

The simplified block diagram shown in Figure 1–6 differs from the previous case (Figure 1–4) only because F_2 rather than F_1 is manipulated. F_1 is a disturbance input.

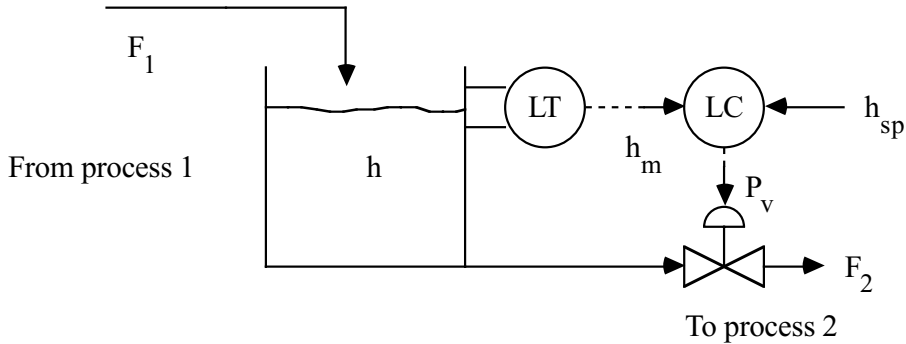


Figure 1-5 Feedback control strategy 2. Outlet flow rate is manipulated.

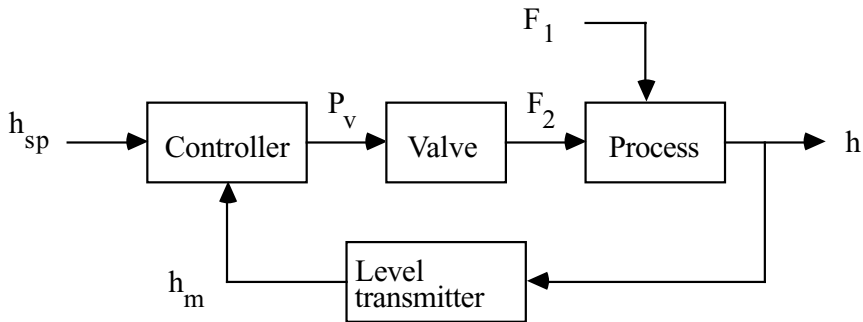


Figure 1-6 Feedback control schematic (block diagram) for scenario 2. F_2 is manipulated and F_1 is a disturbance.

Feed-Forward Control

The previous two feedback control strategies were based on measuring the output (tank height) and manipulating an input (the inlet flow rate in scenario 1 and the outlet flow rate in scenario 2). In each case the manipulated variable is changed after a disturbance affects the output. The advantage to a *feed-forward* control strategy is that a disturbance variable is measured and a manipulated variable is changed before the output is affected. Consider a case where the inlet flow rate can be changed by the upstream process unit and is therefore considered a disturbance variable. If we can measure the inlet flow rate, we can manipulate the outlet flow rate to maintain a constant tank height. This feed-forward control strategy is shown in Figure 1-7, where FM is the flow measurement device and FFC is the feed-forward controller. The corresponding control block diagram is shown in Figure 1-8. F_1 is a disturbance input that directly affects the tank height; the value of F_1 is

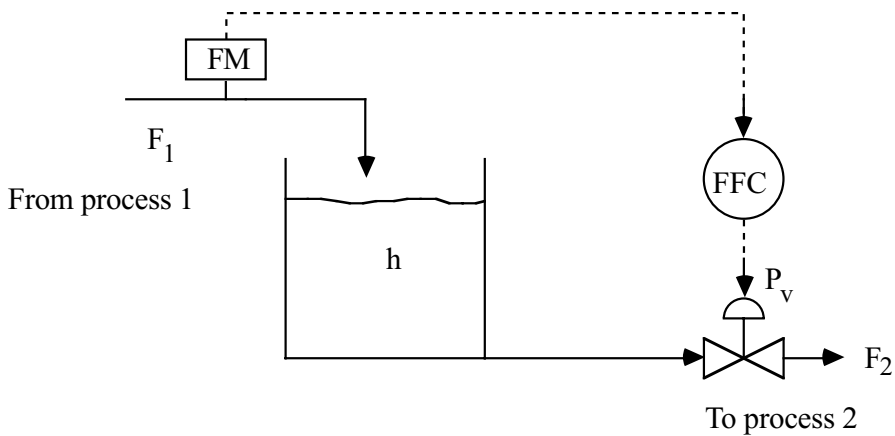


Figure 1-7 Feed-forward control strategy. Inlet flow rate is measured and outlet flow rate is manipulated.

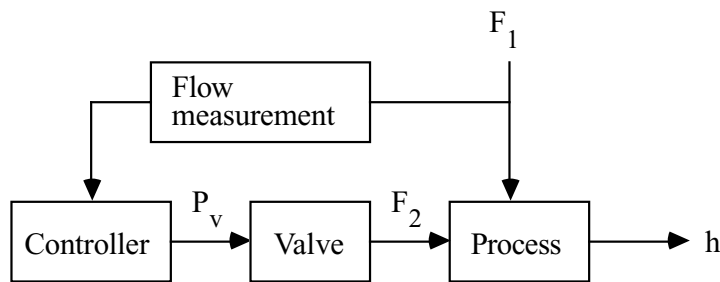


Figure 1-8 Feed-forward control schematic block diagram.

measured by the FM device, and the information is used by an FFC to change the manipulated input, F_2 .

The main disadvantage to this approach is sensitivity to uncertainty. If the inlet flow rate is not perfectly measured or if the outlet flow rate cannot be manipulated perfectly, then the tank height will not be perfectly controlled. With any small disturbance or uncertainty, the tank will eventually overflow or run dry. In practice, FFC is combined with feedback control to account for uncertainty. A feed-forward/feedback strategy is shown in Figure 1-9, and the corresponding block diagram is shown in Figure 1-10. Here, the feed-forward portion allows immediate corrective action to be taken before the disturbance (inlet flow rate) actually affects the output measurement (tank height). The feedback controller adjusts the outlet flow rate to maintain the desired tank height, even with errors in the inlet flow-rate measurement.

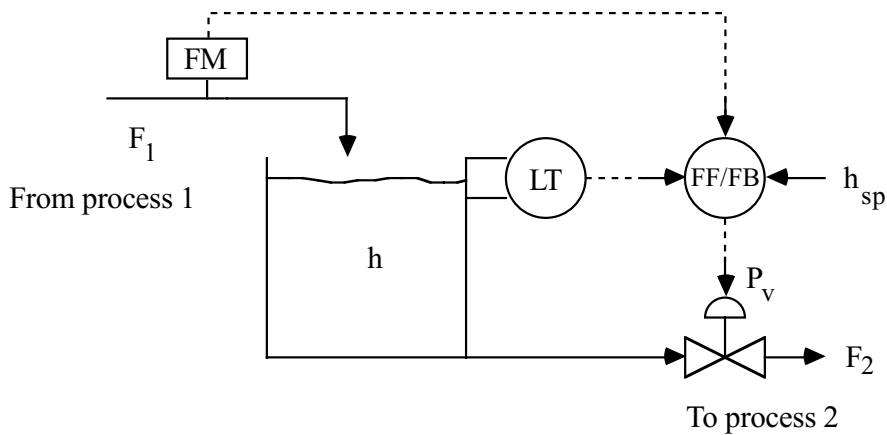


Figure 1–9 Feed-forward/feedback control strategy. The inlet flow rate is the measured disturbance, tank height is the measured output, and outlet flow rate is manipulated.

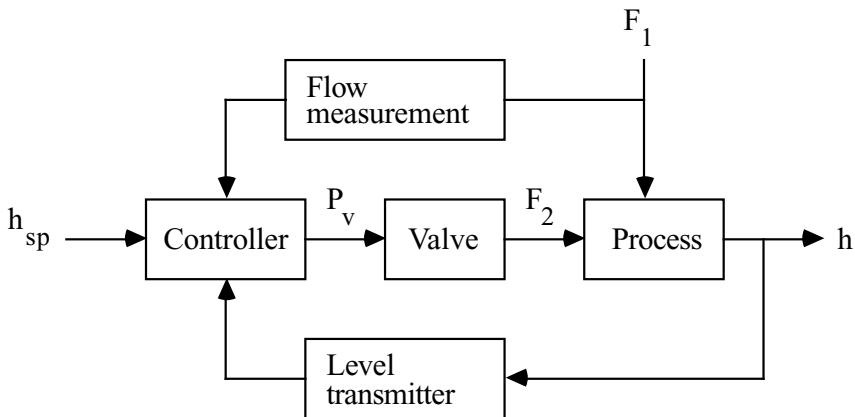


Figure 1–10 Feed-forward/feedback control schematic block diagram.

Discussion of Level Controller Tuning and the Dominant Timescale

Notice that we have not discussed the actual control algorithms; the details of control algorithms and tuning are delayed until Chapter 5. Conceptually, would you prefer to tune level controllers for “fast” or “slow” responses?

When tanks are used as surge vessels it is usually desirable to tune the controllers for a slow return to the setpoint. This is particularly true for scenario 2, where the inlet

flow rate is considered a disturbance variable. The outlet flow rate is manipulated but affects another process. In order to not upset the downstream process, we would like to change the outlet flow rate slowly, yet fast enough that the tank does not overflow or go dry.

Related to the controller tuning issue is the importance of the dominant timescale of the process. Consider the case where the maximum tank volume is 200 gallons and the steady-state operating volume is 100 gallons. If the steady-state flow rate is 100 gallons/minute, the “residence time” would be 1 minute. Assume the inlet flow rate is a disturbance and outlet flow rate is manipulated (Figure 1–5). If the feed flow rate increased to 150 gallons/minute and the outlet flow rate did not change, the tank would overflow in 2 minutes. On the other hand, if the same vessel had a steady-state flow rate of 10 gallons/minute and the inlet flow suddenly increased to 15 gallons/minute (with no change in the outlet flow), it would take 20 minutes for the tank to overflow. Clearly, controller tuning and concern about controller failure is different for these two cases.

The first example was fairly easy compared with most control-system synthesis problems in industry. Even for this simple example we found that there were many issues to be considered and a number of decisions (specification of a fail-open or fail-closed valve, etc.) that needed to be made. Often there will be many (and usually conflicting) objectives, many possible manipulated variables, and numerous possible measured variables.

It is helpful to think of common, everyday activities in the context of control, so you will become familiar with the types of control problems that can arise in practice. The following activity is just such an example.

Example 1.2: Taking a Shower

A common multivariable control problem that we face every day is taking a shower. A simplified process schematic is shown in Figure 1–11. We analyze this process step by step.

1. Control objectives: Control objectives when taking a shower include the following:
 - a. to become clean
 - b. to be comfortable (correct temperature and water velocity as it contacts the body)
 - c. to “look good” (clean hair, etc.)
 - d. to become refreshed

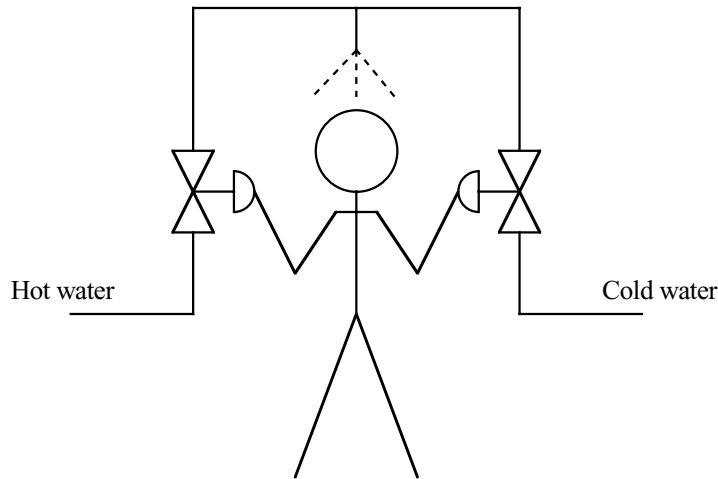


Figure 1–11 Process schematic for taking a shower.

To simplify our analysis, for the rest of the problem we discuss how we can satisfy the second objective (to maintain water temperature and flow rate at comfortable values). Similar analysis can be performed for the other objectives.

2. **Input variables:** The manipulated input variables are hot-water and cold-water valve positions. Some showers can also vary the velocity by adjustment of the shower head. Another input is body position—you can move into and out of the shower stream. Disturbance inputs include a drop in water pressure (say, owing to a toilet flushing) and changes in hot water temperature owing to “using up the hot water from the heater.”
3. **Output variables:** The “measured” output variables are the temperature and flow rate (or velocity) of the mixed stream as it contacts your body.
4. **Constraints:** There are minimum and maximum valve positions (and therefore flow rates) on both streams. The maximum mixed temperature is equal to the hot water temperature and the minimum mixed temperature is equal to the cold water temperature. The previous constraints were hard constraints—they cannot be physically violated. An example of a soft constraint is the mixed-stream water temperature—you do not want it to be above a certain value because you may get scalded. This is a soft constraint because it can physically happen, although you do not want it to happen.

5. Operating characteristics: This process is continuous while you are taking a shower but is most likely viewed as a batch process, since it is a small part of your day. It could easily be called a semicontinuous (semibatch) process.
6. Safety, environmental, and economic considerations: Too high of a temperature can scald you—this is certainly a safety consideration. Economically, if your showers are too long, more energy is consumed to heat the water, costing money. Environmentally (and economically), more water consumption means that more water and wastewater must be treated. An economic objective might be to minimize the shower time. However, if the shower time is too short, or not frequent enough, your clothes will become dirty and must be washed more often—increasing your clothes-cleaning bill.
7. Control structure: This is a multivariable control problem because adjusting either valve affects both temperature and flow rate. Control manipulations must be “coordinated,” that is, if the hot-water flow rate is increased to increase the temperature, the cold-water flow rate must be decreased to maintain the same total flow rate. The measurement signals are continuous, but the manipulated variable changes are likely to be discrete (unless your hands are continuously varying the valve positions).

Feedback control: As the body feels the temperature changing, adjustments to one or both valves is made. As the body senses a flow rate or velocity change, one or both valves are adjusted.

Feed-forward control: If you hear the toilet flush, you move your body out of the stream to avoid the higher temperature that you anticipate. Notice that you are making a manipulated variable change (moving your body) before the effect of an output (temperature or flow rate) change is actually detected.

Some showers may have a relatively large time delay (or dead time) between when a manipulated variable change is made and when the actual output change is measured. This could happen, for example, if there was a large pipe run between the mixing point and the shower head (this would be considered an input time delay). Another type of time delay is measurement dead time, for example if your body takes a while to detect a change in the temperature of the stream contacting your body.

Notice that the control strategy used has more manipulated variables (two valve positions and body movement) than measured outputs (total mixed-stream flow rate and temperature).

In the shower example, the individual taking the shower served as the controller. The measurements and manipulations for this example are somewhat qualitative (you do not know the exact temperature or flow rate, for example). Most of the rest of the textbook

consists of quantitative controller design procedures, that is, a mathematical model of the process is used to develop the control algorithm.

This chapter has covered the important first step of control system development—identifying seven basic steps in analyzing a process control problem. We have used simple examples with which you are familiar. As you learn about more chemical and environmental processes, you should get in the habit of thinking about them from a process systems point of view, just as you have with these simple systems.

1.2 Instrumentation

The example level-control problem had three critical pieces of instrumentation: a sensor (measurement device), actuator (manipulated input device), and controller. The sensor measured the tank level, the actuator changed the flow rate, and the controller determined how much to vary the actuator, based on the sensor signal.

There are many common sensors used for chemical processes. These include temperature, level, pressure, flow, composition, and pH. The most common manipulated input is the valve actuator signal (usually pneumatic).

Each device in a control loop must supply or receive a signal from another device. When these signals are continuous, such as electrical current or voltage, we use the term *analog*. If the signals are communicated at discrete intervals of time, we use the term *digital*.

Analog

Analog or continuous signals provided the foundation for control theory and design and analysis. A common measurement device might supply either a 4- to 20-mA or 0- to 5-V signal as a function of time. Pneumatic analog controllers (developed primarily in the 1930s, but used in some plants today) would use instrument air, as well as a bellows-and-springs arrangement to “calculate” a controller output based on an input from a measurement device (typically supplied as a 3- to 15-psig pneumatic signal). The controller output of 3–15 psig would be sent to an actuator, typically a control valve where the pneumatic signal would move the valve stem. For large valves, the 3- to 15-psig signal might be “amplified” to supply enough pressure to move the valve stem.

Electronic analog controllers typically receive a 4- to 20-mA or 0- to 5-V signal from a measurement device, and use an electronic circuit to determine the controller output, which is usually a 4- to 20-mA or 0- to 5-V signal. Again, the controller output is often sent to a control valve that may require a 3- to 15-psig signal for valve stem actuation. In this case the 4- to 20-mA current signal is converted to the 3- to 15-psig signal using an I/P (current-to-pneumatic) converter.

Digital

Many devices and controllers are now based on digital communication technology. A sensor may send a digital signal to a controller, which then does a discrete computation and sends a digital output to the actuator. Very often, the actuator is a valve, so there is usually a D/I (digital-to-electronic analog) converter involved. Indeed, if the valve stem is moved by a pneumatic actuator rather than electronic, then an I/P converter may also be used.

In the past few decades, digital control-system design techniques that explicitly account for the discrete (rather than continuous) nature of the control computations have been developed. If small sample times are used, the tuning and performance of the digital controllers is nearly equal to that of analog controllers.

Techniques Used in This Textbook

Most of the techniques used in this book are based on analog (continuous) control. Although many of the control computations performed on industrial processes are digital, the discrete sample time is usually small enough that virtually identical performance to analog control is obtained. Our understanding of chemical processes is based on ordinary differential equations, so it makes sense to continue to think of control in a continuous fashion. We find that controller tuning is much more intuitive in a continuous, rather than discrete, framework. In Chapter 16 we spend some time discussing techniques that are specific to digital control systems, namely model predictive control (MPC).

Control Valve Placement

In Example 1.1 and in most of the examples given in this textbook, we use a simplified representation for a control valve and signal. It should be noted that virtually all control valves are actually installed in an arrangement similar to that shown in Figure 1–12. When the control valve fails, the adjacent block valves can be closed; the control valve can then be removed and replaced. During the interim, the bypass valve can be adjusted manually to maintain the desired flow rate. Generally, these control valve “stations” are placed at ground level for easy access, even if the pipeline is in a piperack far above the ground.

1.3 Process Models and Dynamic Behavior

Thus far we have mentioned the term *model* a number of times, and you probably have a vague notion of what we mean by model. The following definition of a model is from the McGraw-Hill Dictionary of Scientific and Technical Terms:

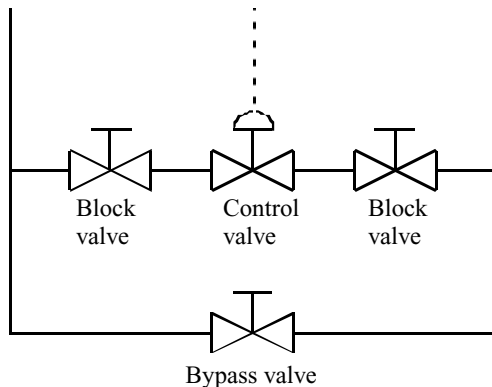


Figure 1–12 Typical control valve arrangement. When the control valve needs to be taken out of service, the two block valves are closed and the control valve is removed. The bypass valve can then be manually adjusted to control the flow.

“A mathematical or physical system, obeying certain specified conditions, whose behavior is used to understand a physical, biological, or social system to which it is analogous in some way.”

In this textbook, model will be taken to mean *mathematical model*. More specifically, we develop process models. A working definition of process model is

a set of equations (including the necessary input data to solve the equations) that allows us to predict the behavior of a chemical process.

Models play a very important role in control-system design. Models can be used to simulate expected process behavior with a proposed control system. Also, models are often “embedded” in the controller itself; in effect the controller can use a process model to anticipate the effect of a control action. We can see from Example 1.1 that we at least need to know whether an increase in the flow rate will increase or decrease the tank level. For example, an increase in the inlet flow rate increases the tank level (positive gain), while an increase in the outlet flow rate leads to a decrease in the tank level (negative gain). In order to design a controller, then, we need to know whether an increase in the manipulated input increases or decreases the process output variable; that is, we need to know whether the process gain is positive or negative.

An example of a process model is shown next. A number of other examples are developed in Chapter 2.

Example 1.3: Liquid Surge Vessel Model

In the development of a dynamic model, simplifying assumptions are often made. Also, the model requirements are a function of the end-use of the model. In this case, we are ultimately interested in designing a controller and in simulating control-system behavior. Since we have not covered control algorithms in depth, our *objective* here is to develop a model that relates the inputs (manipulated and disturbance) to measured outputs that we wish to regulate.

For this process, we first assume that the density is constant. The model we develop should allow us to determine how the volume of liquid in the vessel varies as a function of the inlet and outlet flow rates. We will list the *state variables*, *parameters*, and the *input* and *output variables*. We must also specify the required information to solve this problem (see Figure 1–2). The system is the liquid in the tank and the liquid surface is the top boundary of the system. The following notation is used in the modeling equations:

F_1 = inlet volumetric flow rate (volume/time);

F_2 = outlet volumetric flow rate;

V = volume of liquid in vessel;

h = height of liquid in vessel;

ρ = liquid density (mass/volume);

A = cross-sectional area of vessel.

Here we write the balance equations based on an instantaneous rate-of-change,

$$\begin{bmatrix} \text{rate of change of} \\ \text{total mass of fluid} \\ \text{inside the vessel} \end{bmatrix} = \begin{bmatrix} \text{mass flow rate} \\ \text{of fluid} \\ \text{into the vessel} \end{bmatrix} - \begin{bmatrix} \text{mass flow rate} \\ \text{of fluid} \\ \text{out of the vessel} \end{bmatrix} \quad (1.1)$$

where the total mass of fluid in the vessel is $V\rho$, the rate of change is $dV\rho/dt$, and the density of the outlet stream is equal to the density of the vessel contents

$$\frac{dV\rho}{dt} = F_1\rho_1 - F_2\rho \quad (1.2)$$

Notice the implicit assumption that the density of fluid in the vessel does not depend on position (the perfect mixing assumption). This assumption allows an ordinary differential equation (ODE) formulation. We refer to any system that can be modeled by ODEs as *lumped parameter systems*. Also notice that the outlet stream density was assumed to be

equal to the density of fluid in the tank. Assuming that the density of the inlet stream and fluid in the vessel are equal, this equation is then reduced to¹

$$\frac{dV}{dt} = F_1 - F_2 \quad (1.3)$$

In Equation (1.3) we refer to V as a *state variable*, and F_1 and F_2 as *input variables* (even though F_2 is an outlet stream flow rate). If density remained in the equation, we would refer to it as a *parameter*.

In order to solve this problem we must specify the inputs $F_1(t)$ and $F_2(t)$ and the initial condition $V(0)$. Direct integration of Equation (1.3) yields

$$V(t) = V(0) + \int_0^t [F_1(\sigma) - F_2(\sigma)] d\sigma \quad (1.4)$$

If, for example, the initial volume is 500 liters, the inlet flow rate is 5 liters/second and the outlet flow rate is 4.5 liters/second, we find

$$V(t) = 500 + 0.5 \cdot t$$

Example 1.3 provides an introduction to the notion of states, inputs, and parameters. Consider now the notion of an output. We may consider fluid volume to be a desired output that we wish to control, for example. In that case, volume would not only be a state, it would also be considered an output. On the other hand, we may be concerned about fluid height, rather than volume. Volume and height are related through the constant cross-sectional area, A

$$V = Ah \quad \text{or} \quad h = V/A \quad (1.5)$$

Then we have the following modeling equations,

$$\frac{dV}{dt} = F_1 - F_2, \quad h = \frac{V}{A} \quad (1.6)$$

where V is a state, F_1 and F_2 are inputs, h is an output, and A is a parameter. We could also rewrite the state variable equation to find

$$A \frac{dh}{dt} = F_1 - F_2$$

¹It might be tempting to the reader to begin to directly write a “volume balance” expression, which looks similar to Equation (1.3). We wish to make it clear that there is no such thing as a volume balance and Equation (1.3) is only correct because of the constant density assumption. It is a good idea to always write a mass balance expression, such as Equation (1.2), before making assumptions about the fluid density, which may lead to Equation (1.3).

or

$$\frac{dh}{dt} = \frac{(F_1 - F_2)}{A} \quad (1.7)$$

where fluid height is now the state variable. It should also be noted that inputs can be classified as either *manipulated* inputs (that we may regulate with a control valve, for example) or *disturbance* inputs. If we desired to measure fluid height and manipulate the flow rate of stream 1, for example, then F_1 would be a manipulated input, while F_2 would be a disturbance input.

We have found that a single process can have different modeling equations and variables, depending on assumptions and the objectives used when developing the model.

The liquid level process is an example of an *integrating* process. If the process is initially at steady state, the inlet and outlet flow rates are equal (see Equation 1.3 or 1.7). If the inlet flow rate is suddenly increased while the outlet flow rate remains constant, the liquid level (volume) will increase until the vessel overflows. Similarly, if the outlet flow rate is increased while the inlet flow rate remains constant, the tank level will decrease until the vessel is empty.

In this textbook we first develop process models based on *fundamental* or first-principles analysis, that is, models that are based on known physical-chemical relationships, such as material and energy balances, as well as reaction kinetics, transport phenomena, and thermodynamic relationships. We then develop *empirical* models. An empirical model is usually developed based on applying input changes to a process and observing the response of measured outputs. Model parameters are adjusted so that the model outputs match the observed process outputs. This technique is particularly useful for developing models that can be used for controller design.

1.4 Control Textbooks and Journals

There are a large number of undergraduate control textbooks that focus on control-system design and theory. The following books include an introduction to process modeling and dynamics, in addition to control system design.

Coughanowr, D.R., *Process Systems Analysis and Control*, 2nd ed., McGraw-Hill, New York (1991).

Luyben, M.L., and W.L. Luyben, *Essentials of Process Control*, McGraw-Hill, New York (1997).

Luyben, W.L., *Process Modeling Simulation and Control for Chemical Engineers*, 2nd ed., McGraw-Hill, New York (1990).

- Marlin, T.E., *Process Control: Designing Processes and Control Systems for Dynamic Performance*, 2nd ed., McGraw-Hill, New York (2000).
- Ogunnaike, B.A., and W.H. Ray, *Process Dynamics, Modeling and Control*, Oxford, New York (1994).
- Riggs, J.B., *Chemical Process Control*, Ferret Publishing, Lubbock, Texas (1999).
- Seborg, D.E., T.F. Edgar, and D.A. Mellichamp, *Process Dynamics and Control*, Wiley, New York (1989).
- Smith, C.A., and A.B. Corripio, *Principles and Practice of Automatic Process Control*, 2nd ed. Wiley, New York (1997).
- Stephanopoulos, G., *Chemical Process Control*, Prentice Hall, Englewood Cliffs, NJ (1984).
- Svrcek, W.Y., D.P. Mahoney, and B.R. Young, *A Real-Time Approach to Process Control*, Wiley, Chichester (2000).

The following books are generally more applied, with specific control applications detailed.

- Levine, W.S. (ed.), *The Control Handbook*, CRC Press, Boca Raton, FL (1996).
- Liptak, B.G., and K. Venczel (eds.), *Instrument Engineers Handbook, Process Control Volume*, Chilton Book Company, Radnor, PA (1985).
- Luyben, W.L., B.D. Tyreus, and M.L. Luyben, *Plantwide Process Control*, McGraw-Hill, New York (1999).
- Schork, F.J., Deshpande, P.B., and K.W. Leffew, *Control of Polymerization Reactors*, Marcel Dekker, New York (1993).
- Shinskey, F.G., *Distillation Control*, McGraw-Hill, New York (1977).
- Shunta, J.P., *Achieving World Class Manufacturing Through Process Control*, Prentice Hall, Upper Saddle River, NJ (1995).

The following sources often provide interesting process control problems and solutions.

- Advances in Instrumentation and Control (ISA Annual Conference)
- American Control Conference (ACC) Proceedings—yearly
- Chemical Engineering Magazine (McGraw-Hill)—monthly
- Chemical Engineering Progress—monthly
- Control Engineering Practice (an IFAC Journal)
- Hydrocarbon Processing (petroleum refining and petrochemicals)—monthly
- Instrumentation Technology (InTech, an instrumentation industry magazine)—monthly

IEEE Control Systems Magazine—bimonthly

ISA (Instrument Society of America) Transactions

TAPPI Journal (pulp and paper industry) —monthly

The following sources tend to be more theoretical but often have useful control-related articles.

American Institute of Chemical Engineers (AIChE) Journal

Automatica (Journal of the International Federation of Automatic Control, IFAC)

Canadian Journal of Chemical Engineering

Chemical Engineering Communications

Chemical Engineering Research and Design

Chemical Engineering Science

Computers and Chemical Engineering

Conference on Decision and Control (CDC) Proceedings—yearly

Industrial and Engineering Chemistry Research (I&EC Research)

IEEE Transactions on Automatic Control

IEEE Transactions on Biomedical Engineering

IEEE Transactions on Control System Technology

International Federation of Automatic Control (IFAC) Proceedings

International Journal of Control

International Journal of Systems Sciences

Journal of Process Control

Proceedings of the IEE (part D, Control Theory and Applications)

1.5 A Look Ahead

Chapter 2 develops fundamental models based on material and energy balances, while Chapter 3 covers dynamic analysis. Chapter 4 shows how to develop empirical models from plant tests. Chapter 5 is an introduction to feedback control and provides the first look at quantitative control-system design procedures.

The best way to understand process control is to work many problems. In particular, it is important to use simulation for complex problems. A numerical package that is

particularly useful for control-system analysis and simulation is MATLAB; the SIMULINK block-diagram simulator is particularly useful. If you are not familiar with MATLAB/SIMULINK, we recommend that you work through the MATLAB and SIMULINK tutorials (Modules 1 and 2). Simply reading the tutorials will not give you much insight into the use of MATLAB; you must sit at a computer, work through the examples, and try new ideas that you have.

1.6 Summary

You should now be able to formulate a control problem in terms of the following:

- Control objective
- Inputs (manipulated or disturbance)
- Outputs (measured or unmeasured)
- Constraints (hard or soft)
- Operating characteristics (continuous, batch, semibatch)
- Safety, environmental, and economic issues
- Control structure (feedback, feed forward)

You should also be able to sketch control and instrumentation diagrams, and control block diagrams. In addition, you should be able to recommend whether a control valve should be fail-open or fail-closed.

The following terms were introduced in this chapter:

- Actuator
- Air-to-close
- Air-to-open
- Algorithm
- Control block diagram
- Control valve
- Controller
- Deadtime or time-delay
- Digital
- Fail-closed
- Fail-open
- Gain
- Integrating process

- Model
- Process gain
- Process and instrumentation diagram
- Sensor
- Setpoint

The abstract notions of states, inputs, outputs, and parameters were introduced and are covered in more detail in Chapter 2. The examples used were as follows:

- 1.1 Surge Tank
- 1.2 Taking a Shower
- 1.3 Liquid Surge Vessel Model

Student Exercises

1. Discuss the following problems (a–g) in the context of control:
 - i. Identify control objectives;
 - ii. Identify input variables and classify as (a) manipulated or (b) disturbance;
 - iii. Identify output variables and classify these as (a) measured or (b) unmeasured;
 - iv. Identify constraints and classify as (a) hard or (b) soft;
 - v. Identify operating characteristics and classify as (a) continuous, (b) batch, (c) semicontinuous (or semibatch);
 - vi. Discuss safety, environmental, and economic considerations;
 - vii. Discuss the types of control (feed forward or feedback).

Measurements and manipulated variables can vary continuously or may be sampled discretely.

Select from the following:

- a. Driving a car
- b. Choose one of your favorite activities (skiing, basketball, making a cappuccino, etc.)
- c. A stirred tank heater
- d. Beer fermentation
- e. An activated sludge process
- f. A household thermostat
- g. Air traffic control

2. Literature Review. The process control research literature can be challenging to read, with unique notations and rigorous mathematical analyses. Find a paper from one of the magazines or journals listed in Section 1.4 that you would like to understand by the time you have completed this textbook. You will find many articles to choose from, so use some of the following criteria for your selection:

- The process is interesting to you (do not choose mainly a theory paper)
- The modeling equations and parameters are in the paper (make certain the equations are ordinary differential equations and not partial differential equations)
- There are plots that you can verify (eventually) through simulation (the plots should be based on simulation results)
- The control algorithm is clearly written
- The objectives of the paper are reasonably clear to you

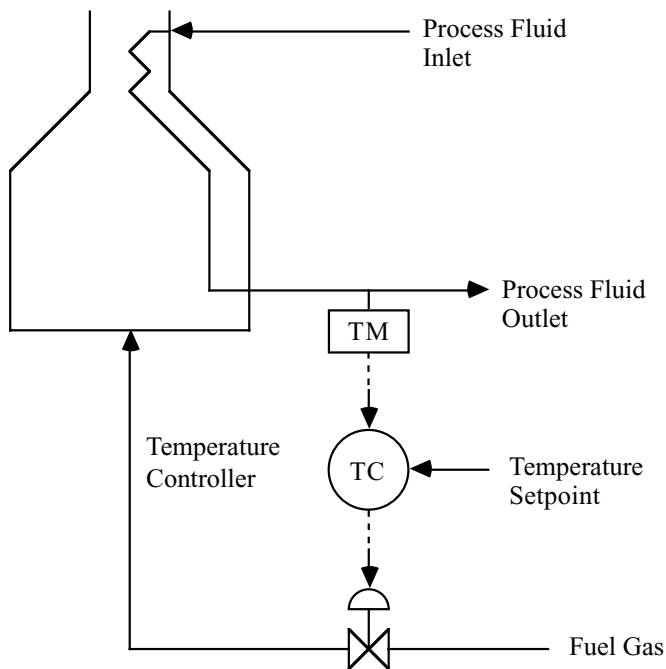
Provide the following:

- i. A short (one paragraph) summary of the overall objectives of the paper; why are you interested in the paper?
- ii. A short list of words and concepts in the paper that are familiar to you.

Suggested Topics (choose one):

- a. Fluidized catalytic cracking unit (FCCU)—petroleum refining
 - b. Reactive ion etching—semiconductor manufacturing
 - c. Rotary lime kiln—pulp and paper manufacturing
 - d. Continuous drug infusion—biomedical engineering and anesthesia
 - e. Anaerobic digester—waste treatment
 - f. Distillation—petrochemical and many other industries
 - g. Polymerization reactor—plastics
 - h. pH—waste treatment
 - i. Beer production—food and beverage
 - j. Paper machine headbox—pulp and paper manufacturing
 - k. Batch chemical reactor—pharmaceutical production
3. Instrumentation Search. Select one of the following measurement devices and use Internet resources to learn more about it. Determine what types of signals are input to or output from the device. For flow meters, what range of flow rates can be handled by a particular flow meter model?
- a. Vortex-shedding flow meters
 - b. Orifice-plate flow meters
 - c. Mass flow meters
 - d. Thermocouple-based temperature measurements

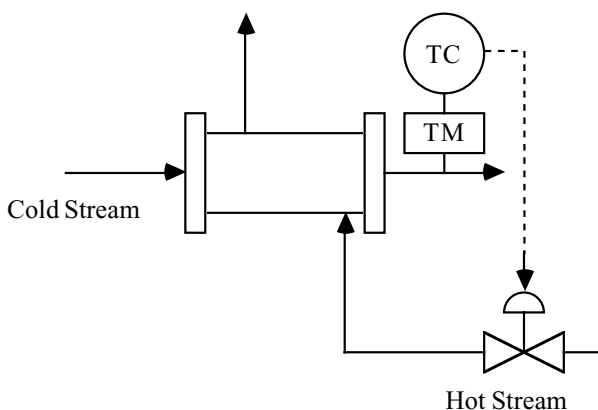
- e. Differential pressure (ΔP) measurements
 - f. Control valves
 - g. pH
4. Work through the Module 1: Introduction to MATLAB.
5. A process furnace heats a process stream from near ambient temperature to a desired temperature of 300°C. The process stream outlet temperature is regulated by manipulating the flow rate of fuel gas to the furnace, as shown below.



- a. Discuss the objectives of this control strategy.
- b. What is the measured output?
- c. What is the manipulated input?
- d. What are possible disturbances?
- e. Is this a continuous or batch process?
- f. Is this a feed-forward or feedback controller?
- g. Should the control valve fail-open or fail-closed? For the strategy you chose, is the valve gain positive or negative? Why?
- h. Discuss safety, environmental, and economic issues.

- i. Draw the control block schematic diagram and label all signals and blocks on the diagram.
6. A fluidized catalytic cracking unit (FCCU) produces a significant portion of the gasoline produced by a typical petroleum refinery. A typical FCCU processes 30,000 Bbl/day (1 Bbl = 42 gallons) of heavy gas oil from a crude oil distillation unit, producing roughly 15,000 Bbl/day of gasoline, along with streams of other components. The value of gasoline alone produced by this unit is on the order of \$500,000/day, so any improvement in yield and energy consumption owing to improved control can have a significant economic impact. *Question:* A control system revamp for a 30,000 Bbl/day FCCU is estimated to cost \$2 million. It is expected that the implementation of advanced control schemes will result in an economic increase of 2% in the value of products produced. Based on the value of gasoline alone, how many days will it take to pay back the control system investment?
7. Furnaces are often used to heat process streams to temperatures above 400°F. A typical fired furnace may have a heat duty of 100×10^6 Btu/hour, requiring roughly 1667 scfm (standard cubic feet per minute) of natural gas (methane has a fuel value of approximately 1000 Btu/scf). The cost of this fuel gas is on the order of \$5/1000 scf, yielding an annual fuel cost of \$4.4 million/year. Excess combustion air is needed to assure complete combustion; however, too much excess air wastes energy (the heated air simply goes out the exhaust stack). Too little excess air leads to incomplete combustion, wasting energy and polluting the atmosphere with unburned hydrocarbons. It is important, then, to deliver an optimum amount of combustion air to the furnace. With the large flow rates and high temperatures involved, maintaining safe operation is also very important. The control system must be designed so that excess combustion air is maintained, no matter what is happening to the fuel gas flow rate. A fired furnace control system clearly needs to satisfy safety, environmental, and economic criteria. *Question:* An advanced control scheme is estimated to save 2% in energy costs, for a fired furnace with a heat duty of 100×10^6 Btu/hour. If it is desired to have a 2-year payback period on this control system investment, what is the maximum investment allowable?
8. Consider the surge vessel process in Example 1.3. If the steady-state volume is 500 liters, and the steady-state inlet and outlet flow rates are 50 liters/minute, find how the liquid volume varies with time if the inlet flow rate is $F_1(t) = 50 + 10 \sin(0.1t)$, while the outlet flow rate remains constant at 50 liters/minute.

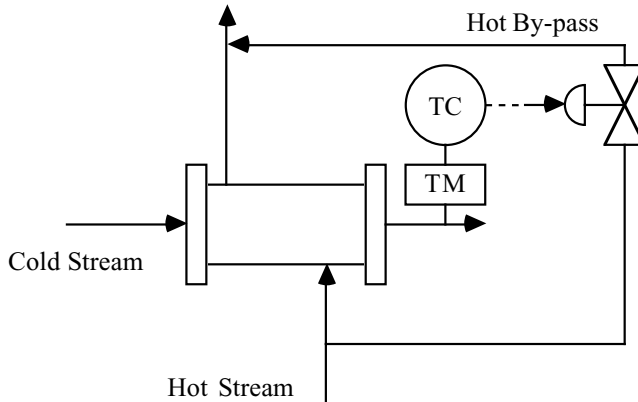
9. The human body is composed of many innate feedback and feed-forward control loops. For example, insulin is a hormone produced by the pancreas to regulate the blood glucose concentration. The pancreas in a type I (insulin dependent) diabetic has lost the ability to produce significant insulin. An insulin-dependent diabetic must monitor her/his blood glucose (accurate blood glucose strips have been on the market for years) and provide insulin injections several times per day. It is particularly important to use knowledge of the meal characteristics to determine the amount of insulin necessary to compensate for the glucose.
- Discuss the actions taken by a type I diabetic in terms of the formulation of a control problem. State the objectives and list all variables, etc.
 - It is desirable to form an automated closed-loop system, using a continuous blood glucose measurement and a continuous insulin infusion pump. Draw a “process and instrumentation” diagram and the corresponding control block diagram.
10. Consider the following three heat exchanger control instrumentation diagrams. For each diagram (a, b, and c), the objective is to maintain a desired cold stream outlet temperature. Since the cold stream exiting the exchanger is fed to a reactor, *it is important that the stream temperature never be substantially higher than the setpoint value*. Please answer the two basic questions about each strategy, then the final question (part d).
- Basic cold stream temperature control strategy.



Is the process gain relating the manipulated flow rate to the measured temperature positive or negative?

Should the control valve should be *fail-open* or *fail-closed*? Why?

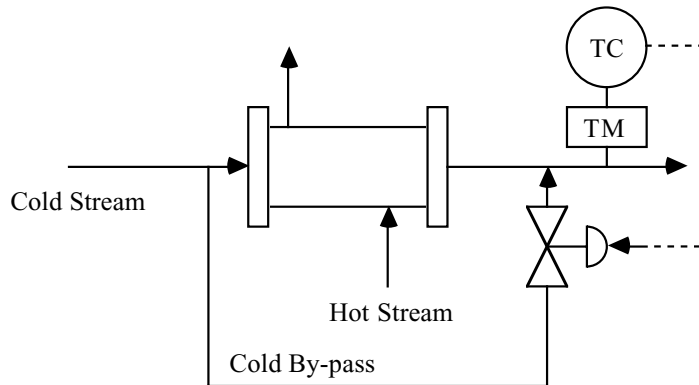
- b. Temperature control using hot stream bypass strategy.



Is the process gain relating the manipulated flow rate to the measured temperature positive or negative?

Should the control valve should be *fail-open* or *fail-closed*? Why?

- c. Temperature control using cold stream bypass strategy.



Is the process gain relating the manipulated flow rate to the measured temperature positive or negative?

Should the control valve should be *fail-open* or *fail-closed*? Why?

- d. Which strategy (a, b, or c) will have the fastest dynamic behavior? Why?

11. During surgery it is important for an anesthesiologist to regulate a patient's blood pressure to a desired value. She does this by changing the infusion rate

of vasoactive drugs to the patient. In addition to the effect of manipulated vasoactive drugs, blood pressure is affected by the level of anesthetic given to the patient. Discuss actions taken by an anesthesiologist in the context of feedback control. Sketch a control block diagram for an automated system that measures blood pressure and manipulates the infusion rate of a vasoactive drug.