1. Fundamental Principles of Process Control

1.1 Motivation for Automatic Process Control

Safety First

Automatic control systems enable a process to be operated in a safe and profitable manner. They achieve this by continually measuring process operating parameters such as temperatures, pressures, levels, flows and concentrations, and then making decisions to, for example, open valves, slow down pumps and turn up heaters so that selected process measurements are maintained at desired values.

The overriding motivation for modern control systems is safety, which encompasses the safety of people, the environment and equipment. The safety of plant personal and people in the community is the highest priority in any plant operation. The design of a process and associated control system must always make human safety the prime objective.

The tradeoff between safety of the environment and safety of equipment is considered on a case by case basis. At the extremes, a nuclear power plant will be operated to permit as much as the entire plant to be ruined rather than allowing significant radiation to be leaked to the environment. On the other hand, a fossil fuel power plant may be operated to permit an occasional cloud of smoke to be released to the environment rather than permitting damage to a multimillion dollar process unit. Whatever the priorities for a particular plant, safety of both the environment and the equipment must be specifically addressed when defining control objectives.

The Profit Motive

When people, the environment and plant equipment are properly protected, control objectives can focus on the profit motive. Automatic control systems offer strong benefits in this regard. Plant-wide control objectives motivated by profit include meeting final product specifications, minimizing waste production, minimizing environmental impact, minimizing energy use and maximizing overall production rate.

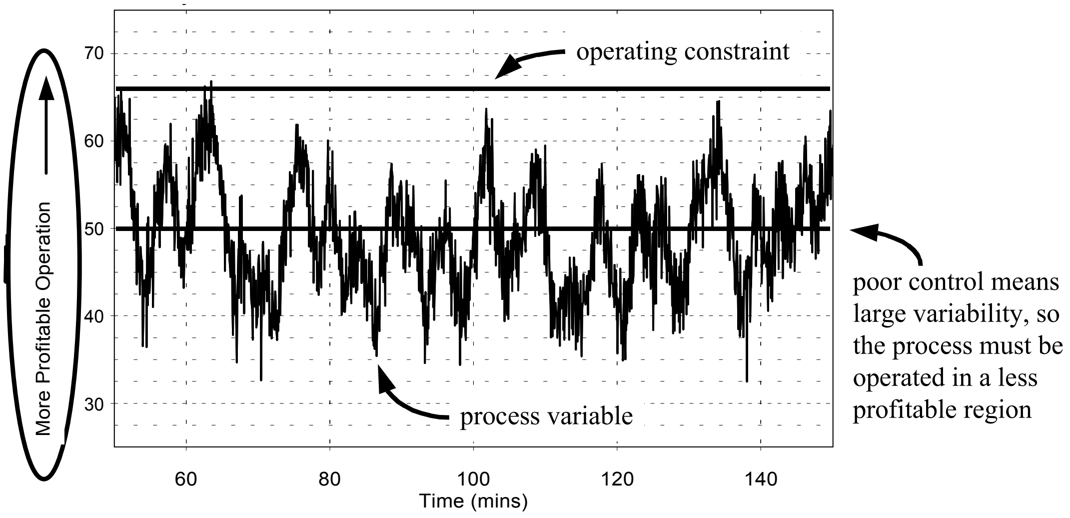


Figure 1.1 - Process variability from poor control means lost profits

Product specifications set by the marketplace (your customers) are an essential priority if deviating from these specifications lessens a product's market value. Example product specifications range from maximum or minimum values for density, viscosity or component concentration, to specifications on thickness or even color.

A common control challenge is to operate close to the minimum or maximum of a product specification, such as a minimum thickness or a maximum impurities concentration. It takes more raw material to make a product thicker than the minimum specification. Consequently, the closer an operation can come to the minimum permitted thickness constraint without going under, the greater the profit. It takes more processing effort to remove impurities, so the closer an operation can come to the maximum permitted impurities constraint without going over, the greater the profit.

All of these plant-wide objectives ultimately translate into operating the individual process units within the plant as close as possible to predetermined values of temperature, pressure, level, flow, concentration or other of the host of possible measured process variables. As shown in Fig. 1.1, a poorly controlled process can exhibit large variability in a process measurement over time. To ensure a constraint limit is not exceeded, the baseline (set point) operation of the process must be set far from the constraint, thus sacrificing profit.

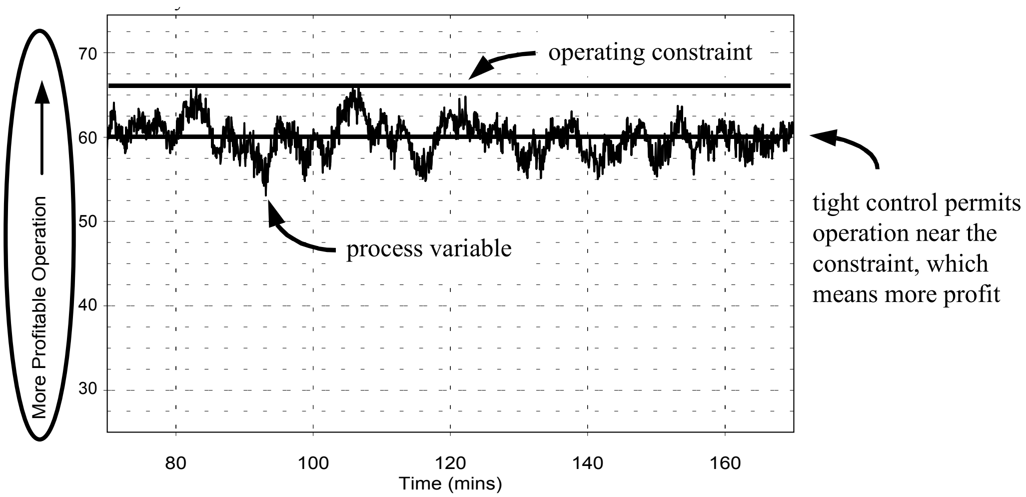


Figure 1.2 - Well controlled process has less variability in process measurements

Figure 1.2 shows that a well controlled process will have much less variability in the measured process variable. The result is improved profitability because the process can be operated closer to the operating constraint.

Automatic Process Control

Because implementation of plant-wide objectives translates into controlling a host of individual process parameters within the plant, the remainder for this text focuses on proven methods for the automatic control of individual process variables. Examples used to illustrate concepts are drawn from the Control Station® software package.

The *Case Studies* module presents industrially relevant process control challenges including level control in a tank, temperature control of a heat exchanger, purity control of a distillation column and concentration control of a jacketed reactor. These real-world challenges will provide hands-on experience as you explore and learn the concepts of process dynamics and automatic process control presented in the remainder of this book.

1.2 Terminology of Control

The first step in learning automatic process control is to learn the jargon. We introduce some basic jargon here by discussing a control system for heating a home as illustrated in Fig. 1.3. This is a rather simple automatic control example because a home furnace can only be either on or off. As we will explore later, the challenges of control system design increase greatly when process variable adjustments can assume a complete range of values between full on and full off. In any event, a home heating system is easily understood and thus provides a convenient platform for introducing the relevant terminology.

The *control objective* for the process illustrated in Fig. 1.3 is to keep the *measured process variable* (house temperature) at the *set point* value (the desired temperature set on the thermostat by the home owner) in spite of unmeasured *disturbances* (heat loss from doors and windows opening; heat being transmitted through the walls of the house).

To achieve this control objective, the measured process variable is compared to the thermostat set point. The difference between the two is the *controller error,* which is used in a computation by the controller to compute a *controller output* adjustment (an electrical or pneumatic signal).

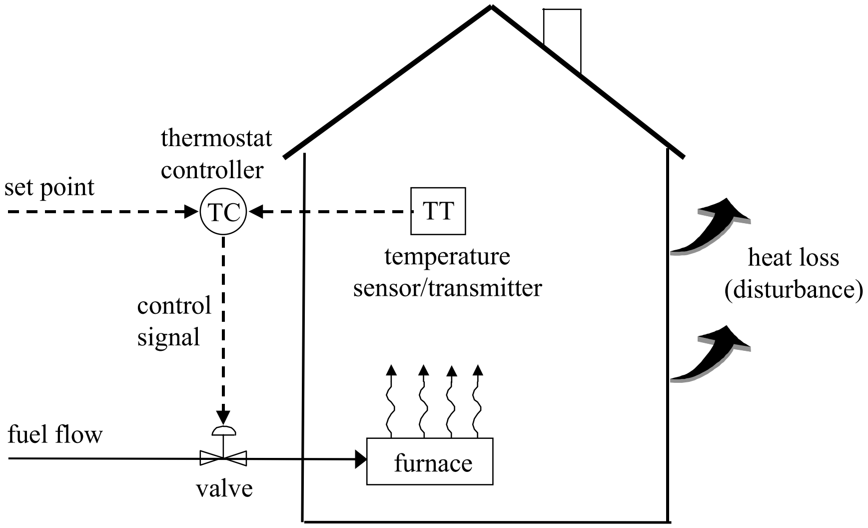


Figure 1.3 - Home heating control system

The change in the controller output signal causes a response in the *final control element* (fuel flow valve), which subsequently causes a change in the *manipulated process variable* (flow of fuel to the furnace). If the manipulated process variable is moved in the right direction and by the right amount, the measured process variable will be maintained at set point, thus satisfying the control objective. This example, like all in process control, involves a measurement, computation and action:

<u>*Measurement*</u>	<u>*Computation*</u>	<u>*Action*</u>
house temperature, T_{House}	is it colder than set point ($T_{Setpoint} - T_{House} > 0$)?	open fuel valve
	is it hotter than set point ($T_{Setpoint} - T_{House} < 0$)?	close fuel valve

Note that computing the necessary controller action is based on controller error, or the difference between the set point and the measured process variable.

1.3 Components of a Control Loop

The home heating control system of Fig. 1.3 can be organized in the form of a traditional feedback control loop block diagram as shown in Fig 1.4. Such block diagrams provide a general organization applicable to most all feedback control systems and permit the development of more advanced analysis and design methods.

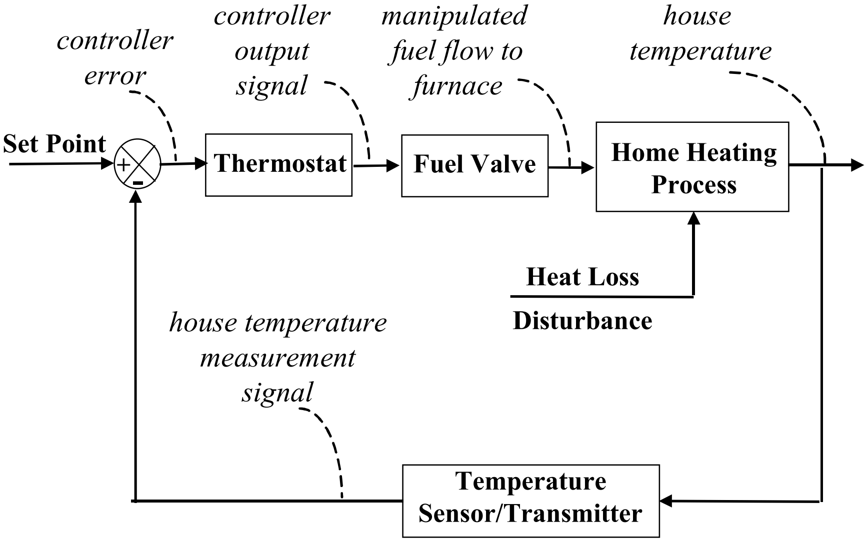


Figure 1.4 - Home heating control loop block diagram

Following the diagram of Fig. 1.4, a *sensor* measures the *measured process variable* and transmits, or feeds back, the signal to the controller. This measurement feedback signal is subtracted from the *set point* to obtain the *controller error*. The error is used by the controller to compute a *controller output* signal. The signal causes a change in the mechanical *final control element*, which in turn causes a change in the *manipulated process variable*. An appropriate change in the manipulated variable works to keep the measured process variable at set point regardless of unplanned changes in the disturbance variables.

The home heating control system of Fig. 1.4 can be further generalized into a block diagram pertinent to all *control loops* as shown in Fig. 1.5. Both these figures depict a *closed loop* system based on *negative feedback*, because the controller works to automatically counteract or oppose any drift in the measured process variable.

Suppose the measurement signal was disconnected, or opened, in the control loop so that the signal no longer feeds back to the controller. With the controller no longer in *automatic*, a person must manually adjust the controller output signal sent to the final control element if the measured process variable is to be affected.

It is good practice to adjusted controller *tuning parameters* while in this *manual,* or *open loop* mode. Switching from automatic to manual, or from closed to open loop, is also a common emergency procedure when the controller is perceived to be causing problems with process operation, ranging from an annoying cycling of the measured process variable to a dangerous trend toward unstable behavior.

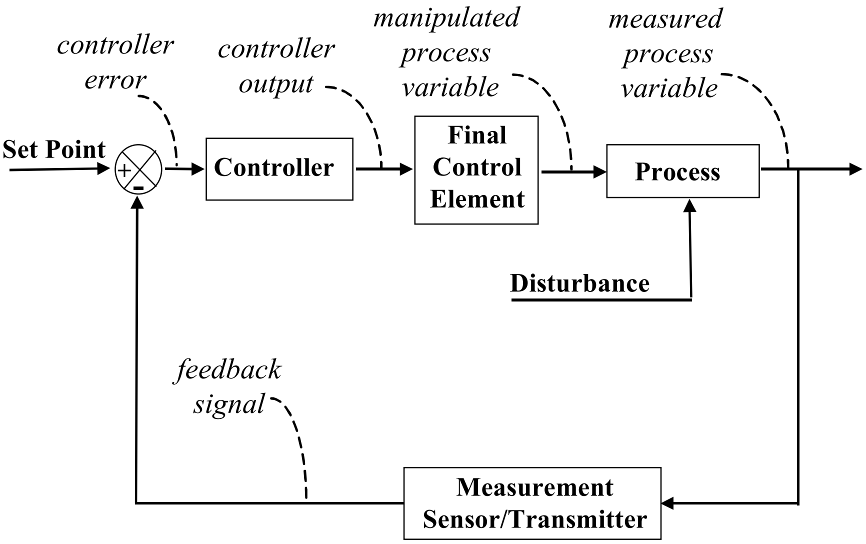


Figure 1.5 - General control loop block diagram

1.4 The Focus of This Book

Although an automatic control loop is comprised of a measurement, computation and action, details about the commercial devices available for measuring process variables and for implementing final control element actions are beyond the scope of this text. For the kinds of process control applications discussed in this book, example categories of such equipment include:

<u>Sensors to Measure</u>: temperature, pressure, pressure drop, level, flow, density, concentration

<u>Final Control Elements</u>: solenoid, valve, variable speed pump or compressor, heater or cooler

The best place to learn about the current technology for such devices is from commercial vendors, who are always happy to educate you on the items they sell. Contact several vendors and learn how their particular merchandise works. Ask about the physical principles employed, the kinds of applications the device is designed for, the accuracy and range of operation, the options available, and of course, the cost of purchase. Keep talking with different vendors, study vendor literature, visit web sites and participate in sales demonstrations until you feel educated on the subject and have gained confidence in a purchase decision. Don't forget that installation and maintenance are important variables in the final cost equation.

The third piece of instrumentation in the loop is the controller itself. The automatic controllers explored in some detail in this book include:

<u>Automatic Controllers</u>: on/off, PID, cascade, feed forward, model-based Smith predictor, multivariable, sampled data, parameter scheduled adaptive control

Although details about the many commercial products are beyond the scope of this text, fortunately, the basic computational methods employed by most all vendors for the controllers listed above are remarkably similar. Thus, the focus of this book is to help you:

- learn how to collect and analyze process data to determine the essential dynamic behavior of a process,
- learn what "good" or "best" control performance means for a particular process,
- understand the computational methods behind each of the control algorithms listed above and learn when and how to use each one to achieve this best performance,
- learn how the different adjustable or tuning parameters required for control algorithm implementation impact closed loop performance and how to determine values for these parameters,
- become aware of the limitations and pitfalls of each control algorithm and learn how to turn this knowledge to your advantage.

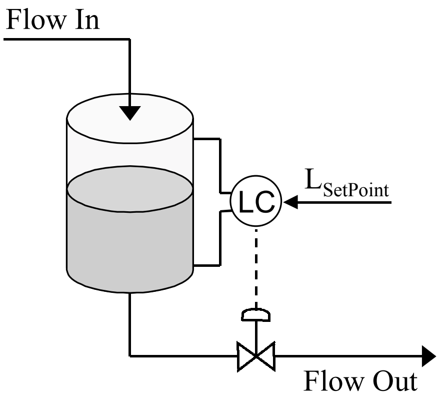
Questions

Q 1.1 New cars often come with a feature called cruise control. To activate cruise control, the driver presses a button while traveling at a desired velocity and removes his or her foot from the gas pedal. The control system then automatically maintains whatever speed the car was traveling when the button was pressed in spite of disturbances. For example, when the car starts going up (or down) a hill, the controller automatically increases (or decreases) fuel flow rate to the engine by a proper amount to maintain the set point velocity.

a) For cruise control in an automobile, identify the:
    - control objective
    - measured process variable
    - manipulated variable
    - set point
    - two different disturbances
    - measurement sensor
    - final control element

b) Draw and properly label a closed loop block diagram for the cruise control process.

Q 1.2 Below is a tank into which a liquid freely flows. The flow of liquid out of the tank is regulated by a valve in the drain line. The control objective is to maintain liquid level in the tank at a fixed or set point value. Liquid level is inferred by measuring the pressure differential across the liquid from the bottom to the top of the tank. The level sensor/controller, represented in the diagram as the LC in the circle, continually computes how much to open or close the valve in the drain line to increase or decrease the flow out as needed to maintain level at set point.



Draw and label a closed loop block diagram for this level control process.