Cascade Controllers

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Introduction

Cascade control is a strategy that in some applications improves significantly the performance provided by feedback control. This strategy is well known and has been used for a long time. The fundamentals and benefits of cascade control are explained in detail in this chapter.

Process Example

Consider the furnace/preheater and reactor process shown in Fig. 4-1.1. In this process a well-known reaction, A → B, occurs in the reactor. Reactant A is usually available at a low temperature; therefore, it must be heated before being fed to the reactor. The reaction is exothermic, and to remove the heat of reaction, a cooling jacket surrounds the reactor.

Process Example

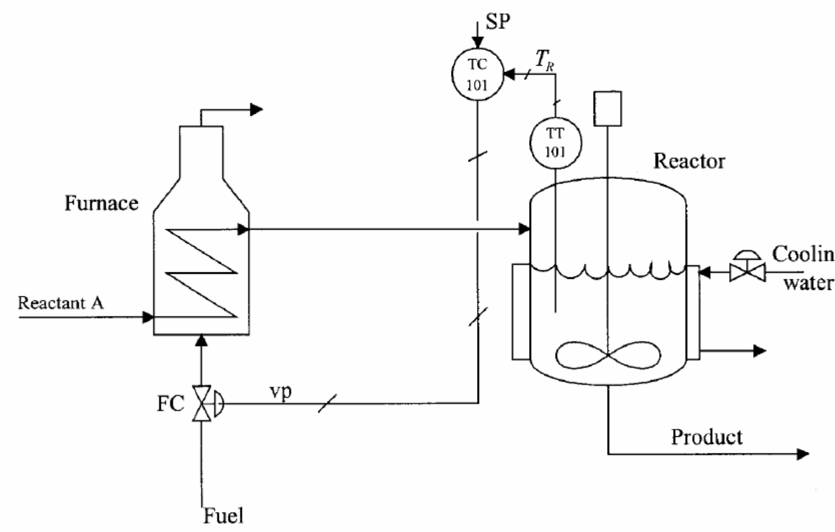


Figure 4-1.1 Feedback control of reactor.

Process Example

The important controlled variable is the temperature in the reactor, T_R. The original control strategy called for controlling this temperature by manipulating the flow of coolant to the jacket. The inlet reactant temperature to the reactor was controlled by manipulating the fuel valve. It was noted during the startup of this process that the cooling jacket could not provide the cooling capacity required. Thus it was decided to open the cooling valve completely and control the reactor temperature by manipulating the fuel to the preheater, as shown in Fig. 4-1.1. This strategy worked well enough, providing automatic control during startup.

Process Example

Once the process was “lined-out,” the process engineer noticed that every so often the reactor temperature would move from the set point enough to make offspec product. After checking the feedback controller tuning to be sure that the performance obtained was the best possible, the engineer started to look for possible process disturbances. Several upsets were found around the reactor itself (cooling fluid temperature and flow variations) and others around the preheater (variations in inlet temperature of reactant A, in the heating value of fuel, in the inlet temperature of combustion air, and so on). Furthermore, the engineer noticed that every once in a while the inlet reactant temperature to the heater would vary by as much as 25°C, certainly a major upset.

Process Example

It is fairly simple to realize that the effect of an upset in the preheater results first in a change of the reactant exit temperature from the preheater, T_H, and that this then affects the reactor temperature, T_R. Once the controller senses the error in T_R, it manipulates the signal to the fuel valve. However, with so many lags in the process, preheater plus reactor, it may take a considerable amount of time to bring the reactor temperature back to set point. Due to these lags, the simple feedback control shown in the figure will result in cycling, and in general, sluggish control.

Process Example

A superior control strategy can be designed by making use of the fact that the upsets in the preheater first affect T_H. Thus it is logical to start manipulating the fuel valve as soon as a variation in T_H is sensed, before T_R starts to change. That is, the idea is not to wait for an error in T_R to start changing the manipulated variable. This corrective action uses an intermediate variable, T_H in this case, to reduce the effect of some dynamics in the process. This is the idea behind cascade control, and it is shown in Fig. 4-1.2.

Process Example

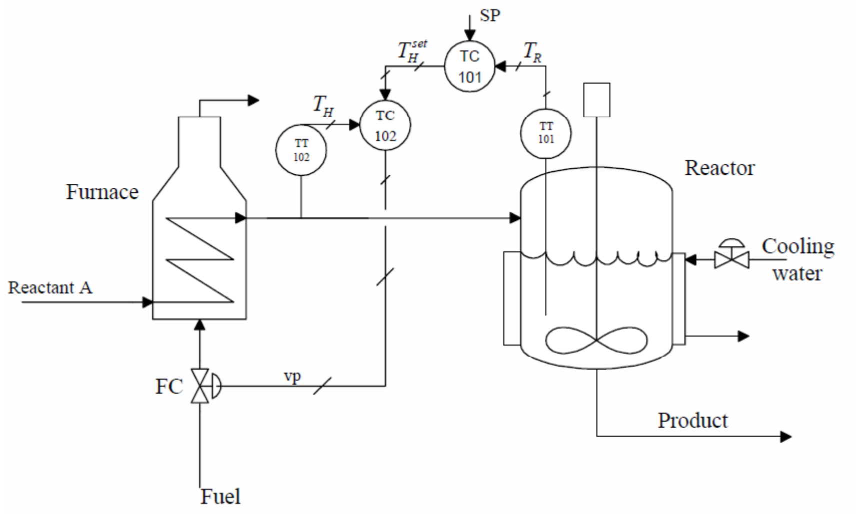


Figure 4-1.2 Cascade control of reactor.

Process Example

The strategy works as follows: Controller TC101 looks at the reactor temperature and decides how to manipulate the preheater outlet temperature to satisfy its set point. This decision is passed on to TC102 in the form of a set point. TC102, in turn, manipulates the signal to the fuel valve to maintain T_H at the set point given by TC101. If one of the upsets mentioned earlier enters the preheater, T_H deviates from the set point and TC102 takes corrective action right away, before T_R changes. Thus the dynamic elements of the process have been separated to compensate for upsets in the heater before they affect the primary controlled variable.

Process Example

In general, the controller that keeps the primary variable at set point is referred to as the *master controller, outer controller, or primary controller*. The controller used to maintain the secondary variable at the set point provided by the master controller is usually referred to as *the slave controller, inner controller, or secondary controller*. The terminology primary/secondary is commonly preferred because for systems with more than two cascaded loops it extends naturally.

Process Example

Note that the secondary controller receives a signal from the primary controller and this signal is used as the set point. To “listen” to this signal, the controller must be set in what is called remote set point or cascade. If one desires to set the set point manually, the controller must then be set in local set point or auto.

Process Example

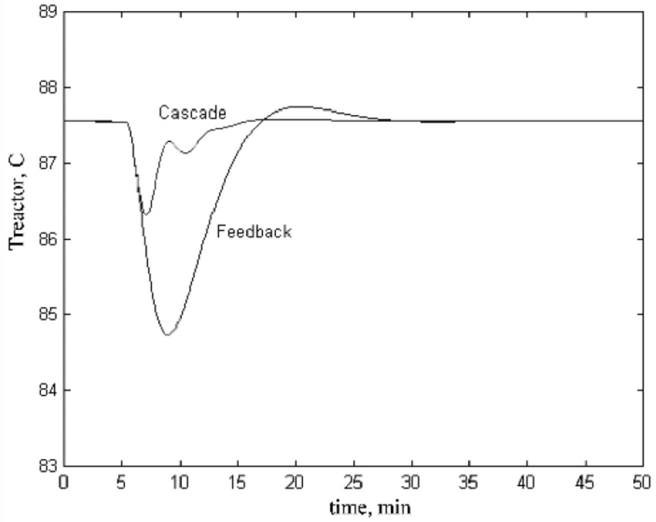


Figure 4-1.3 Response of feedback and cascade control to a –25°C change in inlet reactant temperature.

Implementation and Tuning of Controllers

Two important questions remain concerning how to put the cascade strategy into full automatic operation and how to tune the controllers. The answer to both questions is the same: from inside out. That is, the inner controller is first tuned and set into remote set-point mode while the other loops are in manual. As the inner controller is set in remote set point, it is good practice to check how it performs before proceeding to the next controller. This procedure continues outwardly until all controllers are in operation.

Implementation and Tuning of Controllers

Tuning cascade control systems is more complex than simple feedback systems if for no other reason than simply because there is more than one controller to tune. However, this does not mean that it is difficult either. We first present the methods available to tune two-level cascade systems and then proceed by discussing the tuning methods available to tune three-level cascade systems.

Two-Level Cascade Systems

The control system shown in Fig. 4-1.2 is referred to as a two-level cascade system. Realize that the inner loop by itself is a simple feedback loop. Therefore,TC102 can be tuned by any of the techniques discussed in Chapter 3. As mentioned previously, the recommendation is to tune this controller as fast as possible, avoiding instability of course. The objective is to make the inner loop fast and responsive, to minimize the effect of upsets on the primary controlled variable. Tuning this system is then reduced to tuning the primary controller.

Two-Level Cascade Systems

There are several way to obtain a first guess as to the tuning of the primary controller. Trial and error is often used by experienced personnel. The other methods available follow a "recipe" to obtain the first tuning values. The first method available is the Ziegler–Nichols oscillatory technique presented in Chapter 3.

Two-Level Cascade Systems

The second method available is the one presented by Pressler. Pressler’s method was developed assuming that the secondary controller is a proportional only and that the primary controller is a proportional integral; this P/PI combination is usually quite convenient. The method works well; however, it assumes that the inner loop does not contain dead time, which limits its application to cascade systems with flow or liquid pressure loops as the inner loop.

Two-Level Cascade Systems

The third method available is to extend the offline methods presented in Chapter 3 to both primary and secondary controllers. That is, with the secondary controller in manual, a step change in its output is introduced and the response of the temperature out of the heater (secondary variable) is recorded. From the data a gain, time constant, and dead time for the secondary loop is obtained and the controller tuned by whatever method presented in Chapter 3 the engineer desires.

Two-Level Cascade Systems

Once this is done, the secondary controller is set in remote set point. With the primary controller in manual, a step change in its output is then introduced and the response of the reactor’s temperature (primary variable) is recorded. From the data a gain, time constant, and dead time for the primary loop are obtained and the controller tuned by whatever method presented in Chapter 3 the engineer desires.

Two-Level Cascade Systems

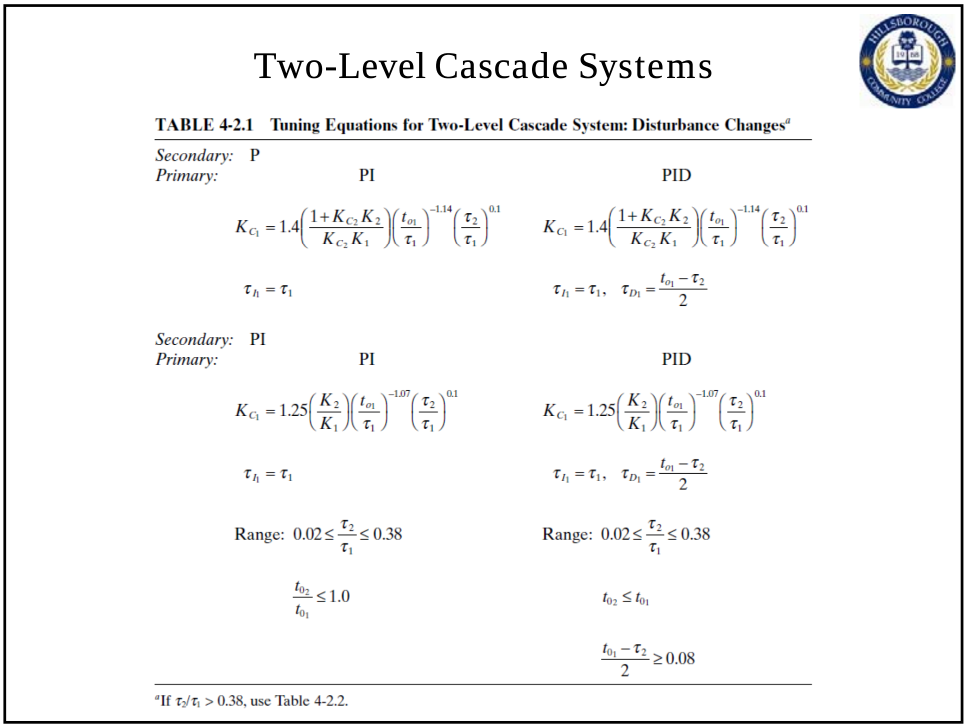
The fourth method available to tune cascade systems is the one developed by Vanessa Austin. The method provides a way to tune both the primary and secondary with only one step test. Tuning equations are provided for the primary controller, PI or PID, when the secondary controller is either P or PI. The method consists of generating a step change in signal to the control valve as explained in Chapter 3, and recording the response of the secondary and primary variables.

Two-Level Cascade Systems

The response of the secondary variable is used to calculate the gain, K_2 = %TT102/%CO, time constant t2, and dead time to2 of the inner loop. The response of the primary variable is used to calculate the gain, K_1 = %TT101/%CO, time constant t1, and dead time to1 of the primary loop. This information and the equations presented in Table 4-2.1 or 4-2.2 are used to obtain the tunings of the primary controller. Table 4-2.1 presents the equations to tune the primary controller when its set point is constant. However, when the set point to the primary controller is continuously changing with time, the equations provided in Table 4-2.2 are then used.

Two-Level Cascade Systems

Note, however, that if t2/t1 > 0.38, Table 4-2.2 should be used even if the set point to the primary controller never changes. Under this ratio condition, the equations in Table 4-2.2 provide better tunings. The t2/t1 ratio should always be checked first. Note that the term K_{C2} in the tables refers to the gain of the secondary controller.

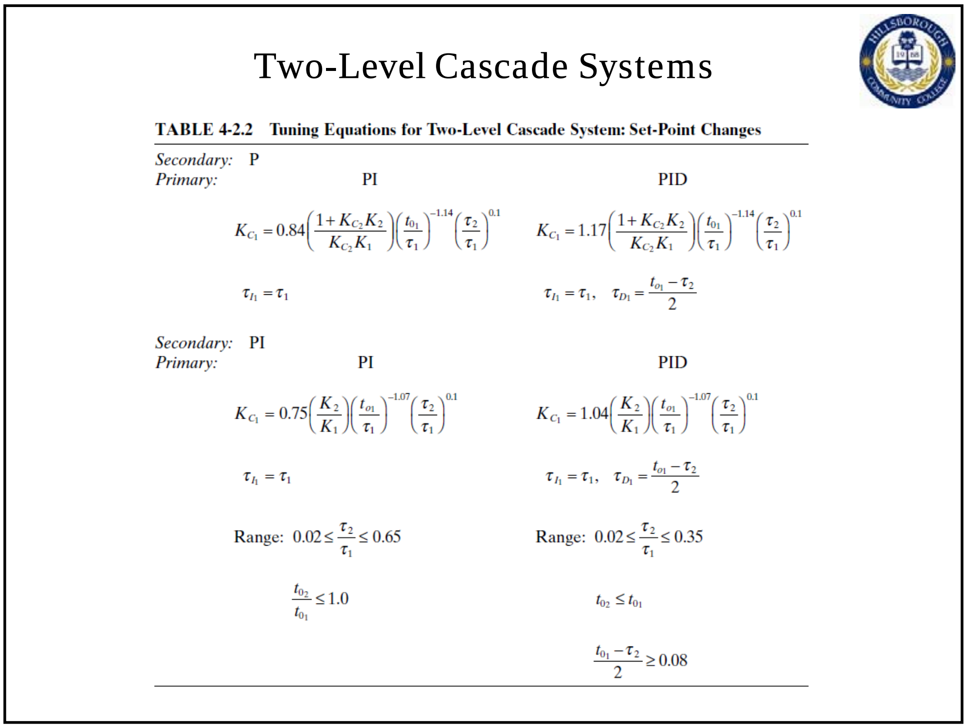


Two-Level Cascade Systems

TABLE 4-2.1 Tuning Equations for Two-Level Cascade System: Disturbance Changes[a]

Secondary: P		
Primary:	PI	PID
	$K_{C_1} = 1.4\left(\frac{1+K_{C_2}K_2}{K_{C_2}K_1}\right)\left(\frac{t_{o_1}}{\tau_1}\right)^{-1.14}\left(\frac{\tau_2}{\tau_1}\right)^{0.1}$	$K_{C_1} = 1.4\left(\frac{1+K_{C_2}K_2}{K_{C_2}K_1}\right)\left(\frac{t_{o_1}}{\tau_1}\right)^{-1.14}\left(\frac{\tau_2}{\tau_1}\right)^{0.1}$
	$\tau_{I_1} = \tau_1$	$\tau_{I_1} = \tau_1, \quad \tau_{D_1} = \frac{t_{o_1} - \tau_2}{2}$
Secondary: PI		
Primary:	PI	PID
	$K_{C_1} = 1.25\left(\frac{K_2}{K_1}\right)\left(\frac{t_{o_1}}{\tau_1}\right)^{-1.07}\left(\frac{\tau_2}{\tau_1}\right)^{0.1}$	$K_{C_1} = 1.25\left(\frac{K_2}{K_1}\right)\left(\frac{t_{o_1}}{\tau_1}\right)^{-1.07}\left(\frac{\tau_2}{\tau_1}\right)^{0.1}$
	$\tau_{I_1} = \tau_1$	$\tau_{I_1} = \tau_1, \quad \tau_{D_1} = \frac{t_{o_1} - \tau_2}{2}$
	Range: $0.02 \le \frac{\tau_2}{\tau_1} \le 0.38$	Range: $0.02 \le \frac{\tau_2}{\tau_1} \le 0.38$
	$\frac{t_{0_2}}{t_{0_1}} \le 1.0$	$t_{0_2} \le t_{0_1}$
		$\frac{t_{0_1} - \tau_2}{2} \ge 0.08$

[a] If $\tau_2/\tau_1 > 0.38$, use Table 4-2.2.



Two-Level Cascade Systems

TABLE 4-2.2 Tuning Equations for Two-Level Cascade System: Set-Point Changes

Secondary: P		
Primary:	PI	PID
	$K_{C_1} = 0.84\left(\frac{1+K_{C_2}K_2}{K_{C_2}K_1}\right)\left(\frac{t_{0_1}}{\tau_1}\right)^{-1.14}\left(\frac{\tau_2}{\tau_1}\right)^{0.1}$	$K_{C_1} = 1.17\left(\frac{1+K_{C_2}K_2}{K_{C_2}K_1}\right)\left(\frac{t_{0_1}}{\tau_1}\right)^{-1.14}\left(\frac{\tau_2}{\tau_1}\right)^{0.1}$
	$\tau_{I_1} = \tau_1$	$\tau_{I_1} = \tau_1, \quad \tau_{D_1} = \frac{t_{o_1} - \tau_2}{2}$
Secondary: PI		
Primary:	PI	PID
	$K_{C_1} = 0.75\left(\frac{K_2}{K_1}\right)\left(\frac{t_{o_1}}{\tau_1}\right)^{-1.07}\left(\frac{\tau_2}{\tau_1}\right)^{0.1}$	$K_{C_1} = 1.04\left(\frac{K_2}{K_1}\right)\left(\frac{t_{o_1}}{\tau_1}\right)^{-1.07}\left(\frac{\tau_2}{\tau_1}\right)^{0.1}$
	$\tau_{I_1} = \tau_1$	$\tau_{I_1} = \tau_1, \quad \tau_{D_1} = \frac{t_{o_1} - \tau_2}{2}$
	Range: $0.02 \le \frac{\tau_2}{\tau_1} \le 0.65$	Range: $0.02 \le \frac{\tau_2}{\tau_1} \le 0.35$
	$\frac{t_{0_2}}{t_{0_1}} \le 1.0$	$t_{0_2} \le t_{0_1}$
		$\frac{t_{0_1} - \tau_2}{2} \ge 0.08$

Three-Level Cascade Systems

Controller TC102 in the cascade system shown in Fig. 4-1.2 manipulates the valve position to maintain the preheater outlet temperature at set point. The controller manipulates the valve position, not the fuel flow. The fuel flow depends on the valve position and on the pressure drop across the valve. A change in this pressure drop, a common upset, results in a change in fuel flow. The control system, as is, will react to this upset once the outlet preheater temperature deviates from the set point. If it is important to minimize the effect of this upset, tighter control can be obtained by adding one extra level of cascade, as shown in Fig. 4-2.1. The fuel flow is then manipulated by TC102, and a change in flow, due to pressure drop changes, would then be corrected immediately by FC103. The effect of the upset on the outlet preheater temperature would be minimal.

Three-Level Cascade Systems

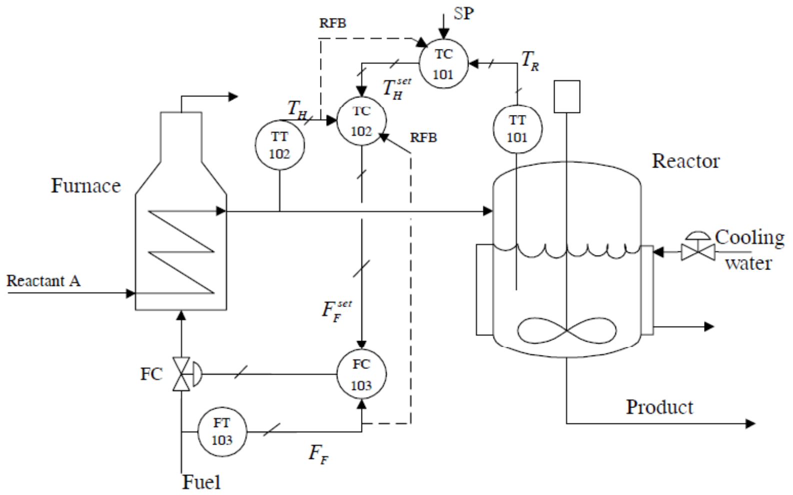


Figure 4-2.1 Three-level cascade system.

Other Process Examples

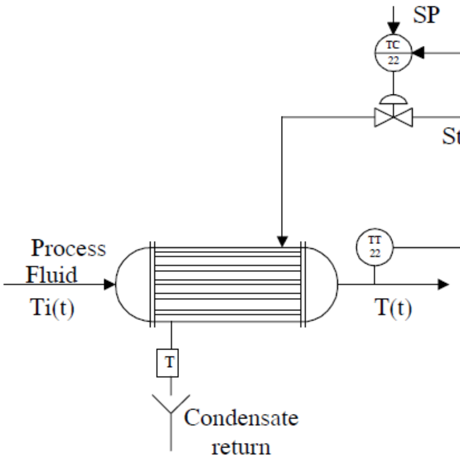
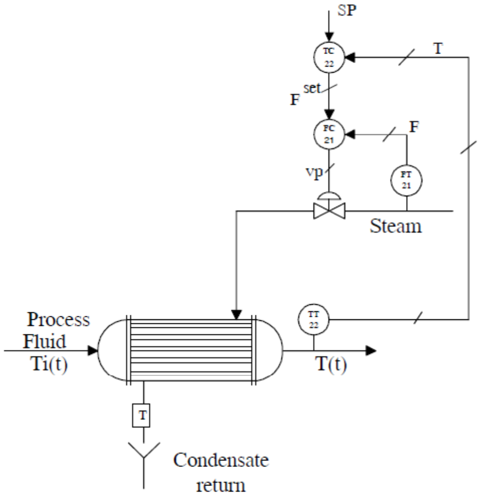


Figure 4-3.1 Temperature control.

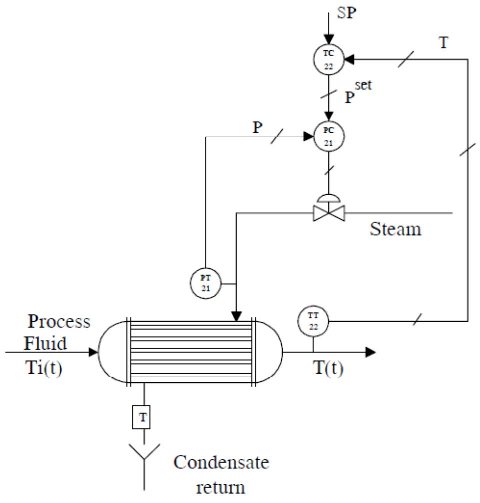
Other Process Examples



(a)

Figure 4-3.2 Cascade control schemes in heat exchanger temperature control.

Other Process Examples



(b)

Figure 4-3.2 *Continued.*

Summary

In this chapter we have presented in detail the fundamentals and benefits of cascade control, which is a simple strategy in concept and implementation, that provides improved control performance. The reader must remember that the secondary variable must respond faster to changes in the manipulated variable than the primary variable. Typical two-level cascaded loops are temperature to flow, concentration to flow, pressure to flow, level to flow, and temperature to pressure.

References

1. Automated Continuous Process Control, Carlos A. Smith, 2002, Wiley-Interscience, ISBN: 978-0471215783.
2. C. A. Smith and A. B. Corripio, Principles and Practice of Automatic Process Control, 3rd ed., Wiley, New York, 2006.