Process Control

Advanced Process Control
Pressure, Flow, and Level

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Safety and Common Symbols

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Symbol	Description
⚠ DANGER	**DANGER** indicates a hazard with a high level of risk which, if not avoided, will result in death or serious injury.
⚠ WARNING	**WARNING** indicates a hazard with a medium level of risk which, if not avoided, could result in death or serious injury.
⚠ CAUTION	**CAUTION** indicates a hazard with a low level of risk which, if not avoided, could result in minor or moderate injury.
CAUTION	**CAUTION** used without the *Caution, risk of danger* sign ⚠, indicates a hazard with a potentially hazardous situation which, if not avoided, may result in property damage.
	Caution, risk of electric shock
	Caution, hot surface
	Caution, risk of danger
	Caution, lifting hazard
	Caution, hand entanglement hazard
	Notice, non-ionizing radiation
	Direct current
	Alternating current
	Both direct and alternating current
	Three-phase alternating current
	Earth (ground) terminal

Safety and Common Symbols

Symbol	Description
	Protective conductor terminal
	Frame or chassis terminal
	Equipotentiality
	On (supply)
	Off (supply)
	Equipment protected throughout by double insulation or reinforced insulation
	In position of a bi-stable push control
	Out position of a bi-stable push control

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Preface

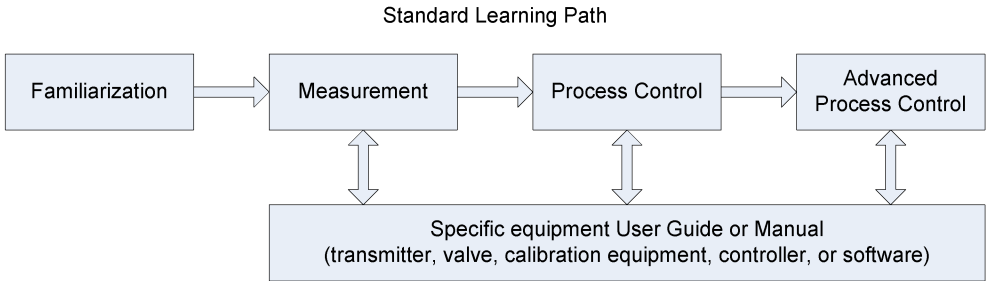
Automated process control offers so many advantages over manual control that the majority of today's industrial processes use it to some extent. Breweries, wastewater treatment plants, mining facilities, and the automotive industry are just a few industries that benefit from automated process control systems.

Maintaining process variables such as pressure, flow, level, temperature, and pH within a desired operating range is of the utmost importance when manufacturing products with a predictable composition and quality.

The Instrumentation and Process Control Training System, series 353X, is a state-of-the-art system that faithfully reproduces an industrial environment. Throughout this course, students develop skills in the installation and operation of equipment used in the process control field. The use of modern, industrial-grade equipment is instrumental in teaching theoretical and hands-on knowledge required to work in the process control industry.

The modularity of the system allows the instructor to select the equipment required to meet the objectives of a specific course. Two mobile workstations, on which all of the equipment is installed, form the basis of the system. Several optional components used in pressure, flow, level, temperature, and pH control loops are available, as well as various valves, calibration equipment, and software. These add-ons can replace basic components having the same functionality, depending on the context. During control exercises, a variety of controllers can be used interchangeably depending on the instructor's preference.

We hope that your learning experience with the Instrumentation and Process Control Training System will be the first step toward a successful career in the process control industry.



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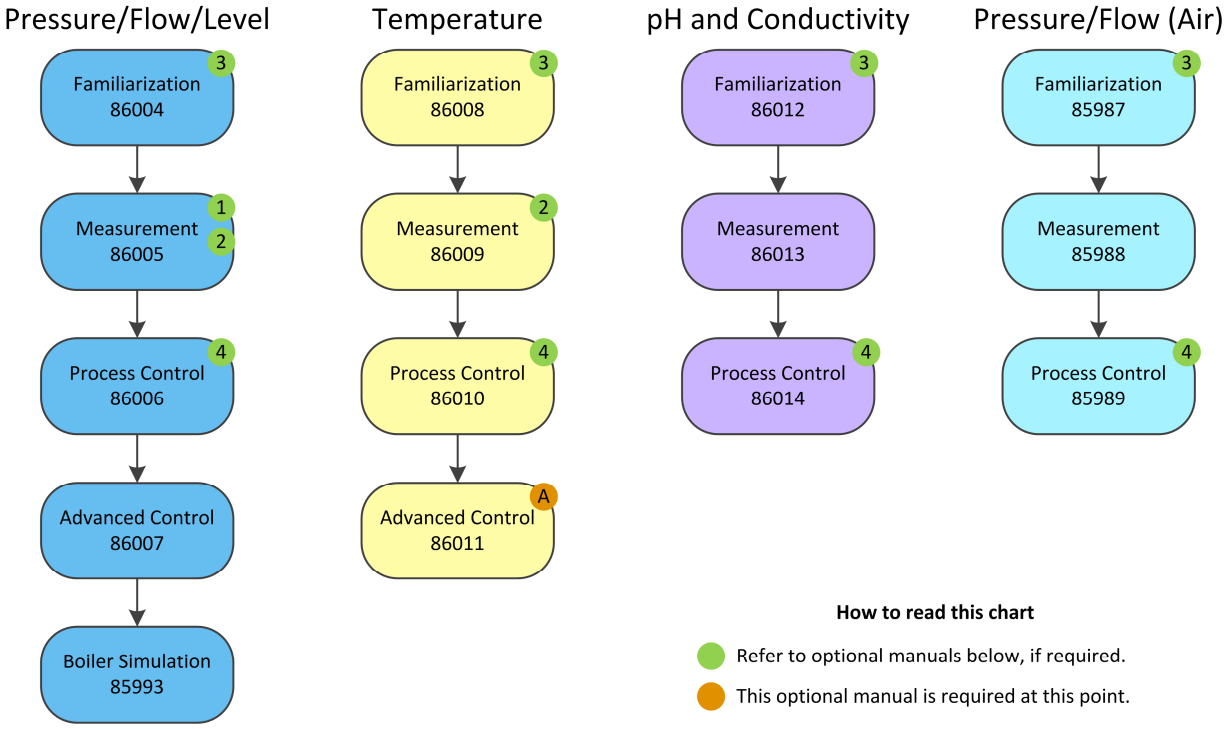

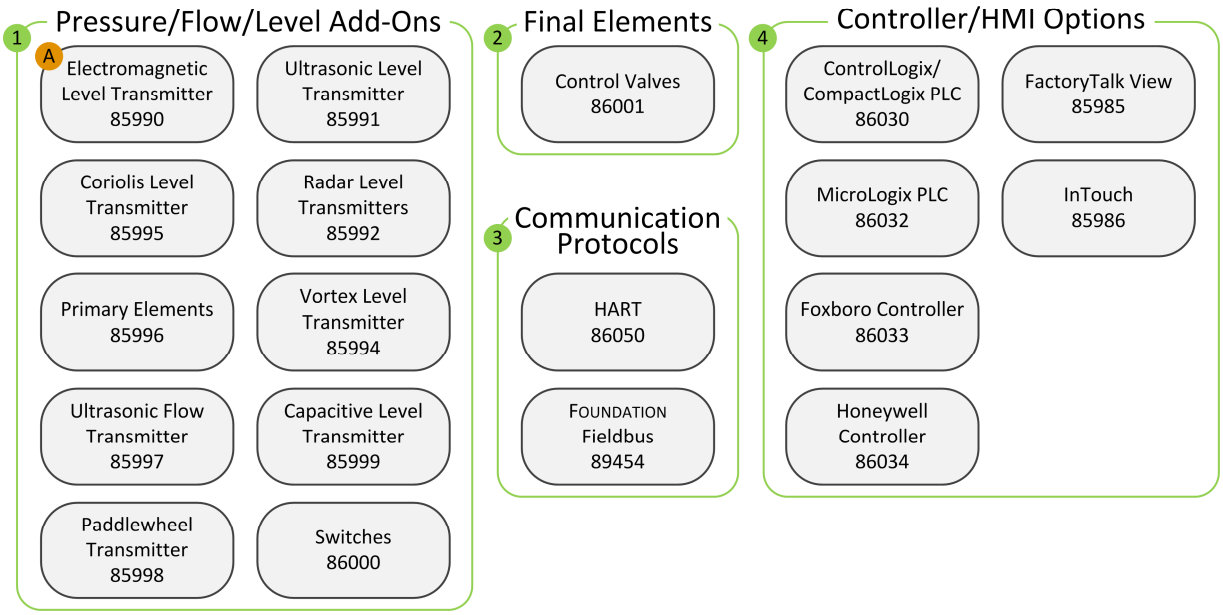

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Preface

Do you have suggestions or criticism regarding this manual?

If so, send us an e-mail at did@de.festo.com.
The authors and Festo Didactic look forward to your comments.

To the Instructor

You will find in this Instructor Guide all the elements included in the Student Manual together with the answers to all questions, results of measurements, graphs, explanations, suggestions, and, in some cases, instructions to help you guide the students through their learning process. All the information that applies to you is placed between markers and appears in red.

Accuracy of measurements

The numerical results of the hands-on exercises may differ from one student to another. For this reason, the results and answers given in this manual should be considered as a guide. Students who correctly performed the exercises should expect to demonstrate the principles involved and make observations and measurements similar to those given as answers.

Equipment installation

In order for students to be able to perform the exercises in the Student Manual, the Process Control Training Equipment – Pressure, Flow, and Level must have been properly installed, according to the instructions given in the user guide Familiarization with the Instrumentation and Process Control System – Pressure, Flow, and Level, part number 86004-E.

Sample Exercise
Extracted from
the Student Manual
and the Instructor Guide

Feedforward Control

EXERCISE OBJECTIVE

Learn the basics of feedforward control and test your knowledge on a feedforward control setup.

DISCUSSION OUTLINE

The Discussion of this exercise covers the following points:

- Feedforward control
- Block representation of a feedforward controller

DISCUSSION

Feedforward control

Feedforward control, also referred to as **predictive** control, is a type of control used to compensate for the effects of disturbances occurring upstream of a process (i.e., before the controlled variable deviates from the set point). Proper monitoring of disturbances and adequate response to each **perturbation** are essential to feedforward control. Consequently, both additional measurement devices and a model of the process (or a control equation) are required to obtain the appropriate reaction from the controller for a given perturbation.

Consider, as an example, the cruise-control system of a car. A system operating in pure feedback mode would monitor the speed of the car and adjust the throttle of the motor to match the set point. An uphill slope would start reducing the speed of the car before the controller corrects the speed by increasing the speed of revolution of the motor. We can imagine the same system equipped with an ideal feedforward component that would detect the incoming slope with an optical detector, calculate the required increase in revolution, and adjust the motor revolution before any speed reduction occurs.

Figure 1-4 presents an example of a heat-exchange process using pure feedforward control. The aim of the process is to heat the contents of a tank to a desired temperature with a heating element powered by hot steam. The temperature of the incoming liquid is approximately constant, but the incoming flow is unsteady. Those flow disturbances affect the temperature of the output flow since the mass of liquid in the tank is an important factor in the heating process. Assuming the situation can be modeled (thanks to thermal physics), a feedforward controller can be programmed to regulate the incoming flow of hot steam, and thus, diminish the effect of the disturbances.

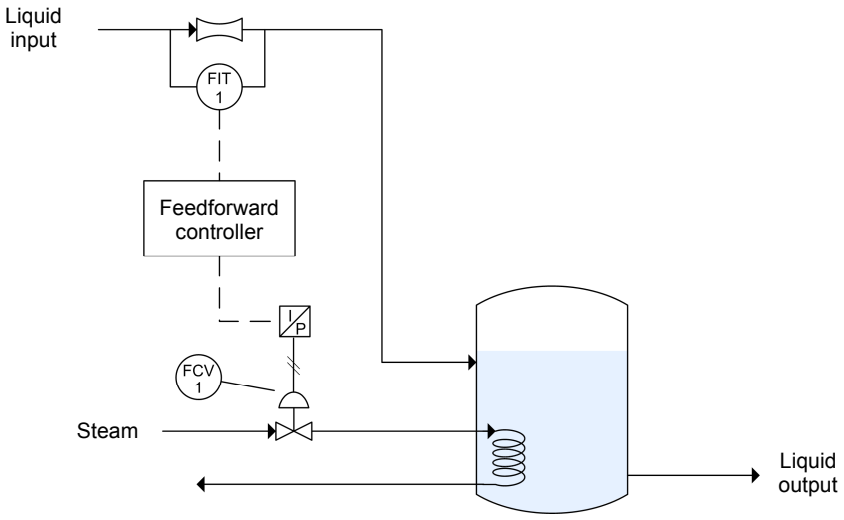

Figure 1-4. Feedforward control of the output temperature.

Unfortunately, as precise as our model and instruments can be, even the slightest error eventually creates an offset in the temperature of the output flow, which can become quite large after some time. To avoid this problem, feedforward control is usually employed in conjunction with feedback control as illustrated in Figure 1-5. In this case, the temperature at the output of the tank is monitored by a feedback loop and the predictive action of the feedforward controller is added to the signal sent to the control valve.

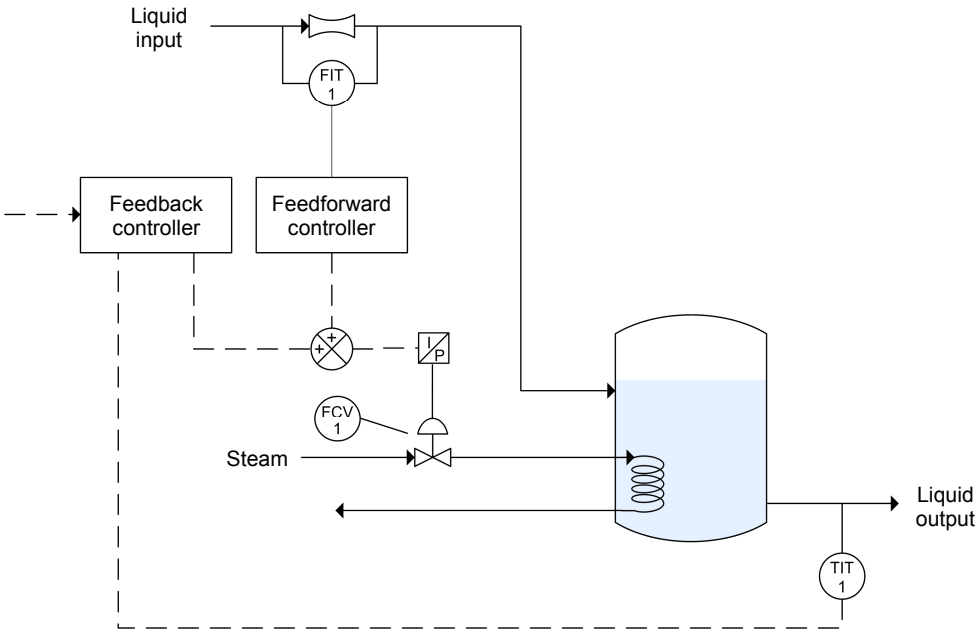

Figure 1-5. Combined feedforward and feedback control of the output temperature.

A more elaborate model of the system could have also included the temperature of the incoming liquid as one of its variables to improve the scope and accuracy of the feedforward control. Doing so would require an extra temperature measurement apparatus at the input and a more complex feedforward algorithm.

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Although they may look similar in some ways, there is a clear distinction between feedforward and **cascade** control. Both feedforward and cascade control take action before the main controlled variable deviates from the set point. Cascade control applies the corrective action before the primary controlled variable is affected, but after the disturbance has entered the process. Feedforward control, on the other hand, aims to apply its corrective action before or as the disturbance enters the process.

The following section gives mathematical details related to feedforward control. This section is not mandatory to complete the current exercise, although it may help to improve your understanding of feedforward control.

Block representation of a feedforward controller

A pure feedforward process can be modeled schematically, as shown in Figure 1-6. The process receives a series of inputs which have some effect on the dynamics of the process. Disturbances also have an impact on the process. The disturbances are measured and transmitted to a feedforward controller, which strives to find a proper way to nullify the effect of the disturbances.

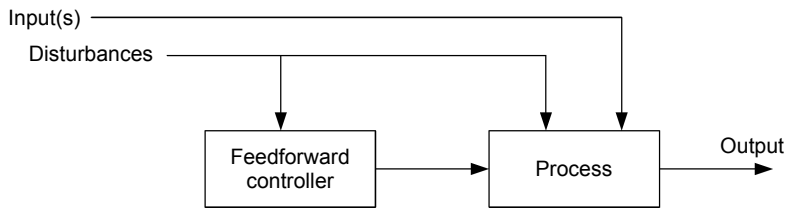

Figure 1-6. Model of a feedforward system.

This same system can be represented with a block diagram and transfer functions such as in Figure 1-7. In this example, the perturbation $P(s)$ has an effect on the process which is represented by the transfer function $G_p(s)$. The same perturbation is measured by the feedforward controller, which takes action (transfer function $G_{ff}(s)$) to produce a **manipulated variable** $M(s)$. The manipulated variable has a direct effect on the process ($G_m(s)$). The action of the other inputs on the process is modeled by $G_{input}(s)$. All of these effects are combined and have a resultant denoted by $C(s)$.

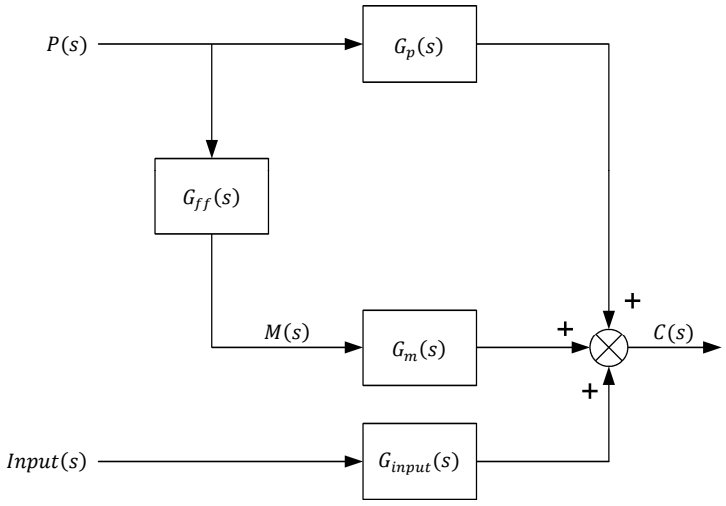

Figure 1-7. Block-function representation of a feedforward system.

Combining the different transfer functions of the block diagram shown above yields a simple equation relating the inputs and perturbations to the output of the process:

$$C(s) = \left[G_p(s) + G_{ff}(s)G_m(s)\right] \cdot P(s) + G_{input}(s) \cdot Input(s) \qquad (1\text{-}12)$$

In this case, it is straightforward to observe that, in order to make $C(s)$ independent of any perturbations $P(s)$, the following condition must be met:

$$G_p(s) + G_{ff}(s)G_m(s) = 0 \qquad (1\text{-}13)$$

or

$$G_{ff}(s) = -\frac{G_p(s)}{G_m(s)} \qquad (1\text{-}14)$$

In the simple case where the reaction of the process to a perturbation is the same as the reaction of the process to the manipulated variable (i.e., $Gp\,(s = Gm\,(s))$ the transfer function of the feedforward controller becomes $G_{ff}(s) = -1$: The controller simply injects an exact inverse of the perturbation into the process to get rid of its effects. Real-world processes are never so simple and a detailed study of the transfer functions involved may be required to optimize the feedforward control scheme.

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PROCEDURE OUTLINE

The Procedure is divided into the following sections:

- Setup and connections
- Adjusting the differential-pressure transmitters
- Controlling the flow loop
- Remote set point

PROCEDURE

Setup and connections

1. Connect the equipment according to the piping and instrumentation diagram (P&ID) shown in Figure 1-8 and use Figure 1-9 to position the equipment correctly on the frame of the training system.

Table 1-6. Material to add to the basic setup for this exercise.

Name	Model	Identification
Differential-pressure transmitter (high-pressure range)	46920	FIT 1-A
Differential-pressure transmitter (low-pressure range)	46921	FIT 1-B
Venturi tube	46911	FE 1-A
Orifice plate	46912	FE 1-B
Color paperless recorder	46972	UR
Three-valve manifolds (2)	85813	-
Controller	*	FIC 1

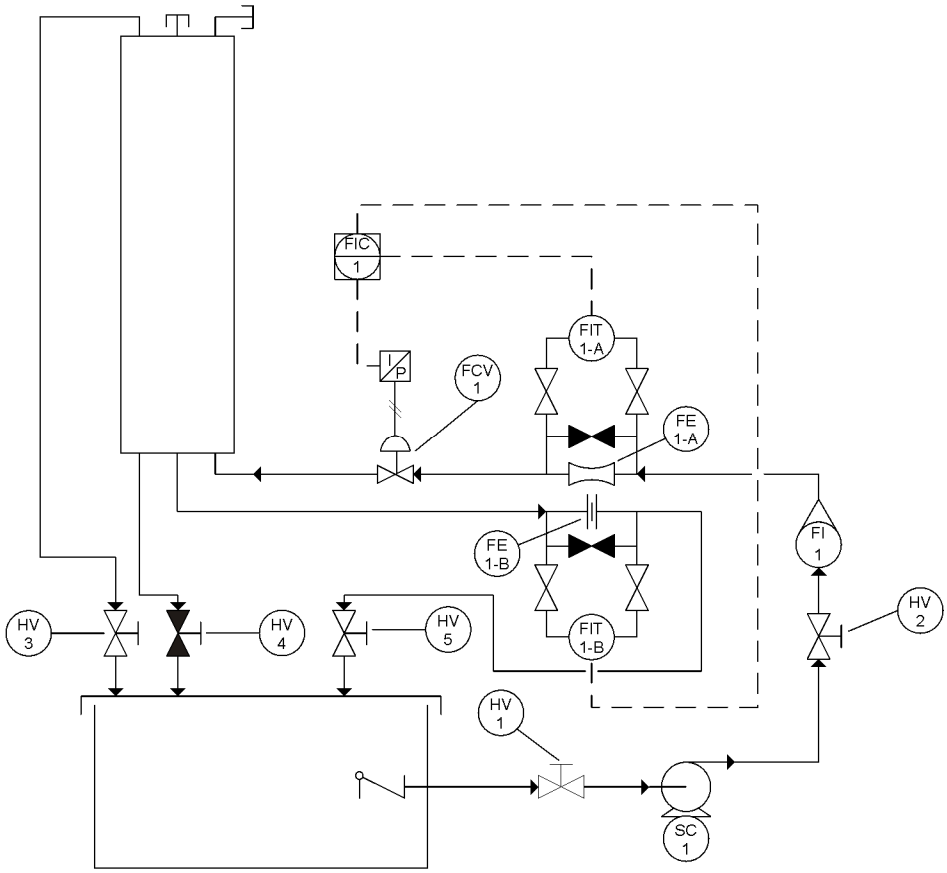

Figure 1-8. P&ID - Feedforward control loop.

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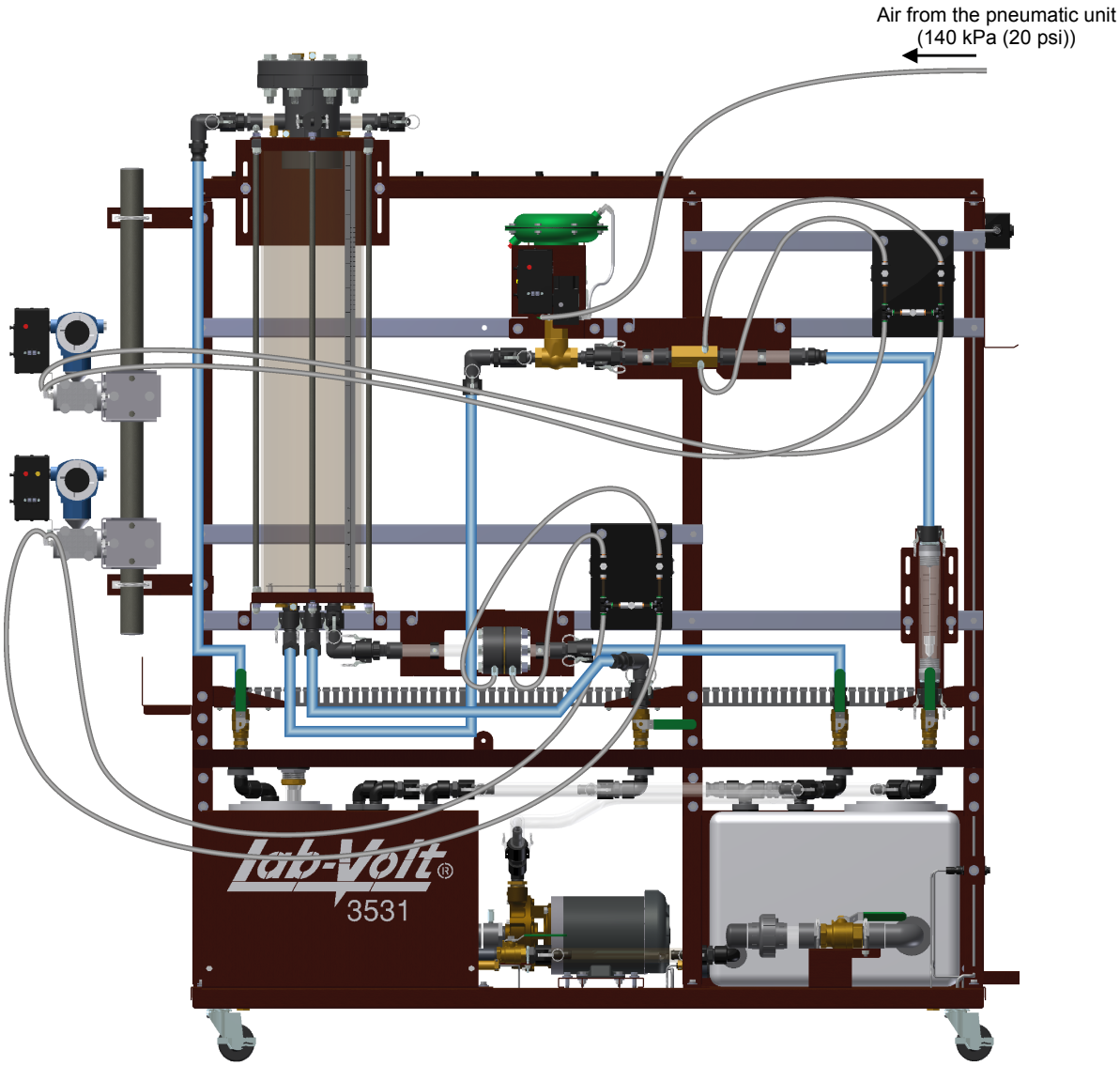

Figure 1-9. Setup - Feedforward control loop.

The paperless recorder (UR) is not displayed in the P&ID above. See Figure 1-10 for the suggested electrical connections.

2. Connect the control valve to the pneumatic unit.

3. Connect the pneumatic unit to a dry-air source with an output pressure of at least 700 kPa (100 psi).

4. Wire the emergency push-button so that you can cut power in case of emergency.

5. Do not power up the instrumentation workstation yet. You should not turn the electrical panel on before your instructor has validated your setup—that is not before step 10.

6. Connect the controller to the control valve and to the differential-pressure transmitters. You must also include the recorder in your connections. On channel 1 of the recorder, plot the output signal from the controller, on channel 2, plot the signal from the transmitter connected to the Venturi tube (FIT1-A), and on channel 3, plot the signal from the transmitter connected to the orifice plate (FIT1-B). Be sure to use the analog inputs of your controller to connect the differential-pressure transmitters.

7. Figure 1-10 shows how to connect the different devices together.

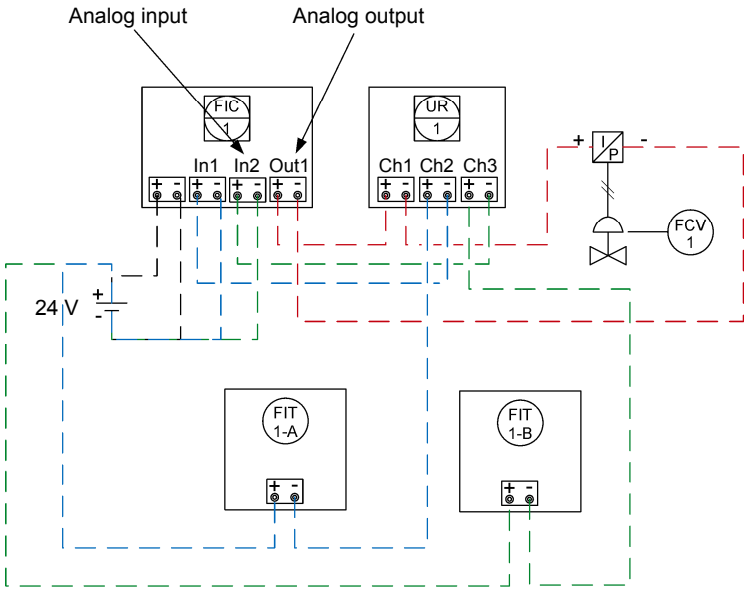

Figure 1-10. Connecting the instruments together for feedforward control.

8. Before proceeding further, complete the following checklist to make sure you have set up the system properly. The points on this checklist are crucial elements to the proper completion of this exercise. This checklist is not exhaustive, so be sure to follow the instructions in the *Familiarization with the Training System* manual as well.

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- The Venturi tube, the orifice plate ($\beta = 0.55$), and the three-valve manifolds are used according to the guidelines stated in the *Familiarization with the Training System* manual.
- The hand valves are in the positions shown in the P&ID.
- The control valve is fully open.
- The pneumatic connections are correct.
- The controller is properly connected to the differential-pressure transmitters and to the control valve.
- The paperless recorder is connected correctly to plot the appropriate signals on channel 1, channel 2, and channel 3.

9. Ask your instructor to check and approve your setup.

10. Power up the electrical unit, this starts all electrical devices as well as the pneumatic unit. Activate the control valve of the pneumatic unit to power the devices requiring compressed air.

11. With the controller in manual mode, set the output of the controller to 0%. The control valve should be fully open. If it is not, revise the electrical and pneumatic connections and be sure the calibration of the I/P converter is appropriate.

12. Test your system for leaks. Use the drive to make the pump run at low speed to produce a small flow rate. Gradually increase the flow rate, up to 50% of the maximum flow rate that the pumping unit can deliver (i.e., set the drive speed to 30 Hz). Repair any leaks and stop the pump.

Adjusting the differential-pressure transmitters

CAUTION

Be sure to connect the differential-pressure transmitter (high-pressure range), Model 46920, to the Venturi tube and the differential-pressure transmitter (low-pressure range), Model 46921, to the orifice plate.

13. Be sure to connect the impulse lines of the differential-pressure transmitters to the two three-valve manifolds. Bleed the impulse lines and configure the transmitters for flow measurement. Adjust the zero of the differential-pressure transmitter.

    Set the parameters of both transmitters so that a 4 mA signal is sent for a flow of 0 L/min (0 gal/min) and a 20 mA signal for a flow of 40 L/min (10 gal/min).

Controlling the flow loop

14. Set the pump to 30.0 Hz and close HV5 to allow the level to rise in the column up to 50 cm (about 20 inches).

15. Stop the drive, close HV2, and open HV5 to allow the water to exit the column.

16. Read the output flow on the transmitter (FIT1-B). The output flow should slightly decrease along with the height of water in the column. Why is that so?

Water exits the column under the force of gravity only. If the level of water decreases in the column, the pressure the water exerts near the column outlet decreases, thus the output flow decreases.

17. Watching both the level and the reading of the flow transmitter, record the output flow rate when the level reaches 30 cm (about 12 in).

Output flow rate: _____

The output flow rate when the level is 30 cm (about 12 in) should be around 12.5 L/min (3.3 gal/min).

18. Use the output flow rate to calculate the set point you must use to keep the level stable around 30 cm (about 12 in).

Set point: _____

The approximate set point to keep the level stable around 30 cm (about 12 in) is the measured output flow divided by the transmitter range. That is:

$$Set\ point = \frac{12.5\ \mathrm{L/min}}{40\ \mathrm{L/min}} \times 100 \approx 31\%$$

$$Set\ point = \frac{3.3\ \mathrm{gal/min}}{10\ \mathrm{gal/min}} \times 100 \approx 33\%$$

19. Open HV2, start the drive again, and use the technique of your choice to determine the tuning parameter to run your controller in PI mode.

K_c =_____

T_i =_____

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20. Configure your controller using the set point and the PI parameters found above.

21. Use the hand valves to set the level in the column to 30 cm (about 12 in).

22. Be sure the valves are set as on the P&ID and put the controller in automatic mode.

23. Is the level perfectly stable? Briefly explain your answer.

No. The level is not perfectly stable, it moves a little.

24. Is there an offset between the input flow and the output flow? Briefly explain your answer.

Yes, there is always a small offset between the input flow and the output flow. Therefore the level is not perfectly stable.

25. For a short period of time, close HV5 to allow the level to reach 40 cm (about 16 in). Once HV5 is open again, does the level return to 30 cm (about 12 in) rapidly? Why?

No. In a feedforward installation, the controller tries to compensate for the effects of disturbances occurring upstream of a process. The controlled variable is not measured. Therefore, if the controlled variable actually deviates from the set point, the controller has no way to know and it cannot compensate for the offset and return the controlled variable to its original value.

Remote set point

26. In this section, the transmitter connected to the orifice plate is used to set a remote set point on the controller. Refer to your controller manual to learn how to connect and configure it to use a remote set point. Using the output of this transmitter as the set point ensures that the input flow and output flow are equal. If a perturbation occurs, the controller changes the opening of the control valve to equilibrate the two flows.

27. Once your controller is configured to use the output of the second transmitter as its set point, adjust the level of water in the column to 30 cm (about 12 in).

28. Set the controller to the automatic mode. What are your observations?

The level becomes stable quite rapidly and it stays stable. The input flow and the output flow are equal.

29. Stop the system, turn off the power, and store the equipment.

CONCLUSION

This exercise allowed you to experiment with the basics of feedforward control and presented some approaches to study such systems. The next exercise studies a control structure closely related to feedforward control: Ratio control.

REVIEW QUESTIONS

1. Why is feedforward control sometimes called predictive control?

Because in feedforward control the measurement is made on an input parameter to try to predict changes before they occur instead of trying to compensate for the perturbation once it has already occurred.

2. Why is it that a model is required for feedforward control?

In feedforward control, an input of the system is measured and we want to infer from this measurement the reaction of the system. This cannot be done without some kind of model.

3. What happens in a system controlled by a feedforward controller if a perturbation occurs after the measurement point?

The controller cannot compensate for the perturbation.

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4. What is it that most feedforward process control systems are doomed to do?

Deviate from the set point

5. What can you add to a feedforward system to improve it?

A feedback component

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