Volume 2 • Issue 2
MARCH – APRIL 2001

the EXTENSION
A Technical Supplement to control NETWORK

INTRODUCTION TO CONTROL

In the next few issues of the Extension, we are going to step back quite a bit from our in-depth discussion of technology in order to explain to laymen the industry we serve. We hope that people in your organization will benefit from some basic knowledge of our industry.

When people outside our industry ask what our company does, we usually answer that we are in the industrial networking business. When we receive a blank stare we add that industrial networking is concerned with the communication between controllers and computers on the plant floor. Now we could have added that controllers could communicate with sensors and actuators as well with risking total confusion. The response we usually receive is "so you are a software company?" No we are not, although we must develop software to support our hardware when used with various operating systems. By this time, the inquiring person has usually given up trying to understand our business figuring that it is some niche business that Microsoft has not yet chosen to dominate.

The industrial networking business is indeed a niche business, and we are thankful that Microsoft has chosen to ignore us although their presence is felt. Industrial networking is a component of a much larger controls market, but before we can explain the industrial networking market we should explain the controls market first.

CONTROLS MARKET

The term *control* basically refers to the means and methods of governing the performance of an apparatus, machine or system. Using *control system* technology, we are attempting to control a process to meet a desired end. We may be interested in obtaining higher quality, higher production, repeatable production, improved safety or unattended operation. *Automatic control* or *feedback control* can meet these objectives. Feedback control is the method of regulating a physical process by comparing the value of the physical quantity that is wished to be controlled with the desired value and then making adjustments accordingly. The *controls market* refers to a very broad market of hardware, software, and service that relate to controlling a process or machine in industry. Examples of control equipment would be sensors, actuators, controllers, computers, networks, wire, cable, fittings, pipe and numerous other items that create control systems. Can a pipefitting be part of a control system? Yes it can. If you want to see the diverse equipment found in the controls industry simply attend the AHR Expo trade show hosted by ASHRAE—American Society of Heating, Refrigerating and Air-Conditioning Engineers or ISA Expo hosted by ISA—the Instrumentation, Systems, and Automation Society. This is indeed a very diverse market.

THE CONTROLS UNIVERSE

There are several terms used to describe our industry. The process industries such as chemical, petroleum, textiles, steel, paper and glass will use the term *process control*, *automatic process control* or *process automation*. The discrete manufacturing industries such as automotive or any other industry where piece parts are made (widgets) use the term *industrial control* or *industrial automation*. The environmental industries where energy and comfort are controlled use the term *building control*, *automatic building control* or *building automation*. Even with these diverse industries, the control basics are the same, although the applications are different. All control systems consist of a *controller* acting upon information from one or more *inputs* while manipulating one or more *outputs*.

GENERALIZED CONTROL MODEL

There is a branch of science called *control theory* which studies the dynamics of controlling a process. Advanced mathematics are used to predict the performance of a controlled process under various conditions but the solutions are often difficult to obtain. Attempting to characterize a process mathematically could be impossible. Much that is learned of a process is learned empirically through observation and measurement. We will not attempt to study the dynamics of a controlled process but simply gain familiarity with the concepts and terminology of control systems.

We begin with a generalized model of a control system. In figure 1, we have a block diagram of such a system. The system we are attempting to control is called the *process* and we change the character of the process by way of a *manipulated variable*. The manipulated variable results from the controller we apply to the system and the *command* we issue to the controller. This command represents the desired response from the process in the form of the *controlled variable*. The controlled variable is measured in order to determine if the response is correct. If it is not we change the value of the command accordingly. This type of system is called an *open-loop system*. Why it is called this will become obvious after reading the next paragraph.

In figure 2, the block diagram is very similar except that a significant function has been added. A summary point has been included that compares the command against the controlled variable producing an error signal equal to the difference between the two signals. If

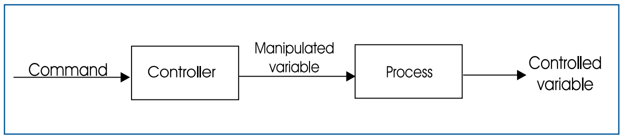

Figure 1
Open-loop control system block diagram.

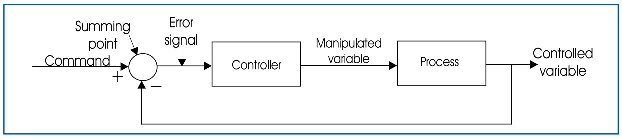

Figure 2
Closed-loop control system block diagram.

the two signals are equal, the error signal is zero meaning that the state of the process is where we want it. Using this feedback technique, the control system will automatically correct for changes in the controlled variable because the resulting error will, through the controller, manipulate the process in such a way as to drive the process back to the desired response. This is called a *closed-loop system, feedback control system* or *automatic control system.* Since the added *feedback* path creates a loop, the complete system is called a *loop* and the controller used within the loop is called a *loop controller.*

MEASUREMENT

Before we can introduce the concept of control, we need to understand the concept of measurement. *Measurement* is the determination of the magnitude or quantity by comparison to a standard. For example, heat can be quantified by its temperature which can be measured with a *thermometer.* The accuracy of a heat measurement depends upon the quality of the thermometer. A bimetallic meat thermometer will not be as accurate as a glass stem, mercury filled, laboratory grade thermometer. The point here is that you cannot control a variable more accurately than you can measure it. Therefore, measurement is fundamental to control.

In order to control a process or machine, we need to measure some variable that is indicative of the process. Examples would be pressure, level, weight, density, flow, temperature and humidity. If we are controlling motion, we may be interested in measuring speed, position (displacement), acceleration or torque. These variables would need to be measured and converted into some form of signal useful to the type of controller we are using. If we were using an electronic controller, we would need electrical signals. Therefore, we need devices that can both sense the physical variable we want to measure and convert the value of the variable into something usable by the control system.

A device that converts one form of energy into another is called a *transducer.* A mercury thermometer is a transducer that converts temperature into an equivalent length. By adding markings on the glass stem, we can read out temperature directly. This type of instrument is good for reading temperature, but it is not good as an input device to an electronic controller because the output of the thermometer is not an electronic signal.

One potential temperature transducer that is suitable for an electronic controller is the *thermocouple.* A thermocouple consists of two dissimilar metals bonded at their junction. This junction will produce minute voltages as a function of temperature. If these voltages are amplified, they could be useable by an electronic controller.

Measurement techniques are a science in itself, and there are numerous transducers to measure the various physical phenomena. The goal of a measurement is to gain enough information about the process without impacting the process by the measurement technique. There are numerous other issues.

Accuracy – Does the measurement conform to a standard?

Repeatability – Is there agreement among successive measurements?

Resolution – Can we read the measurement in acceptable detail?

Hysteresis – Is the reading of the variable returning from a higher value the same as if it had returned from a lower value?

Sensitivity – Can small changes in the variable be proportionally sensed as large changes?

Precision – Is accuracy uniform over the full range of measurement?

Reproducibility – Can results be duplicated over a relatively long period of time?

These are the issues when measuring physical quantities. The field of measurement is called *instrumentation* and it can be highly specialized.

Input Transducers

Input transducers are a class of device that measure physical variables and convert them to signals for controllers to use. If the output of the transducer is continuously variable, we call the transducer an *analog* device. A thermocouple is an analog device since its output is continuously variable with a change in temperature. A *strain gauge* used to measure pressure is an analog device. A digital device is one that has a finite number of states. The most common digital devices are binary ones which have only two states. A single pole-single throw switch has only two states—on and off. A *proximity* switch, which senses the presence of metal, has only two states. A single pole, 12-throw rotary switch has 12 states.

Instead of saying input transducers, we usually say either *sensors* or *transmitters.* An analog sensor may or may not produce the required signal for a controller. It may require what is called *signal conditioning* in order to adapt the output of the transducer into a signal suitable to the controller. Usually this involves amplification and filtering. Some sensors may even require external power in order to work. A strain gauge is an example of this.

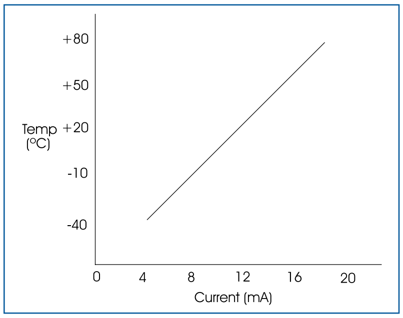

Figure 3
Calibration curve for a scaled transmitter.

The other class of input transducer is the transmitter. A transmitter has built-in sensor and signal conditioning and not only has adequate signal output, but it has a uniform signal output. In the process industry, the 4-20 mA (*milliampere*) standard is important. What this means is that all transmitters—pressure, temperature, flow, etc.—will produce 4 mA at the lowest end of their range and 20 mA at the highest. Since pressure and temperature ranges can vary per application, it is necessary to *calibrate* the transmitter. Calibration to a standard means adjusting the low end of the range of the transmitter to one temperature (or pressure) and the high end to another. For example, the transmitter could be set to -40˚C at the low end and +80˚C at the high. The temperature values in between would be proportional. In this case a 12 mA reading (1/2 scale) would translate to +20˚C. This form of calibration is called *scaling* the transmitter. See figure 3.

Output Transducers

Output transducers are a class of device that connect signals compatible with controllers to some form of mechanical movement. Examples are solenoid valves, circuit breakers, relays, pilot valves, valve positioners and motors. Some actuators control airflow or fluid flow. A solenoid valve is a digital device that can direct airflow to various ports or cutoff airflow entirely. A form of solenoid valve is called a *block valve*. A *valve positioner* is an analog device that accepts the low level signals of a controller (4-20mA) and creates a proportional pneumatic signal that controls the actual valve position on a *throttling* or *modulating valve*. This type of valve is called a *control valve*. See figure 4. This type of valve along with its valve positioner can control the amount of process flow (water, gas, waste, air, steam) depending upon the signal level sent by the controller. The valve positioner-valve combination is essentially a pneumatic closed-loop control system by itself suggesting that control loops can exist within control loops.

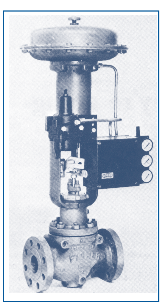

Figure 4
Typical control valve. Valve positioner is mounted on the right.

Unlike input transducers, the accuracy of output transducers is not as critical. Of course with digital devices, accuracy is not an issue. The device is either on or off. With analog output transducers, it is not critical to know the required signal level to command a valve to a desired position. This is the benefit of closed-loop control. It is only important to be able to measure the required flow accurately. The control system will automatically drive the control valve to the proper position in order to achieve the proper flow.

OPEN AND CLOSED-LOOP CONTROL

The best way of explaining control is to use an everyday experience. When we drive a car we have two hands on the steering wheel and one foot on the gas pedal. The steering wheel manipulates the angle of the front wheels in relationship to the rear wheels of the car. The direction of car travel is determined by the angle of the front wheels. The angle of the wheels is the manipulated variable. If we never turn the steering wheel, we are likely to drive off the road. Since our intention is to remain on the road, we need an indication of where the road is. Using our eyes we sense the position of the painted centerline and the edge of the road. Depending upon which country we are driving in, we stay either to the right or left of the center line while keeping centered in our lane. As the road winds we change the position of the steering wheel accordingly. The center of the lane becomes our desired position or command. The driver of the car becomes the actual controller using his eyes as sensors and hands as manipulators. The complete car-driver combination is a feedback control system since it automatically adjusts to changes in the controlled variable which is car position. This is an example of a position control loop.

The driver, using his foot, manipulates a gas pedal. The gas pedal position is linked to the amount of fuel sent to the engine. The further the gas pedal position, the more fuel sent to the engine resulting in higher revolutions of the engine and, therefore, increased road speed. The driver observes the speedometer, which monitors the actual speed of the car, and adjusts the gas pedal position in order to maintain the desired road speed. The gas pedal is the manipulated variable. This is another example of a feedback control system since the driver observes changes in the controlled variable (speed) and adjusts the gas pedal accordingly. This would be called a speed control loop.

Now let's assume that instead of driving a car, we are driving a train locomotive. Instead of having a gas pedal, the engineer has a lever that sets throttle position. This lever can only be placed in one of ten positions. So instead of having a gas pedal that can be positioned with infinite resolution, we have a lever with a finite resolution. We still have a speedometer but we need to set the throttle to a position which results in a speed near to our desired speed. We could leave the lever in this position forever and we may be able to operate at the desired speed. What happens when we approach a slight upward grade? The locomotive experiences a change in load which in control theory is called a *disturbance*. The locomotive speed will drop since more fuel would be needed to overcome the increased load, yet the throttle position is fixed. The result is a speed droop, which may or may not be acceptable to the engineer. In control theory terms, we have experienced a *deviation* from *setpoint*. See figure 5. The term setpoint is used interchangeably with command. It is possible that the grade will quickly return to a level position and the speed return to setpoint without engineer intervention. This is an example of an open-loop control system since changes in the controlled variable (speed) are not automatically compensated for but may be compensated through *operator* intervention.

Figure 5
Temperature controller. The upper display is the controlled variable and the lower is the setpoint.

Let's return to our automobile example. Attempting to maintain a constant speed of the car while navigating over hills and valleys over long distances can be tedious. Hopefully your car is equipped with a cruise control which relieves you as the controller. The cruise control becomes the controller taking over the speed control loop. It does not provide steering. First, you need to inform the cruise control the desired setpoint which you do by pressing a button once you attain the desired speed manually. The cruise control stores the setpoint and will manipulate the gas pedal (fuel flow) such that the desired road speed is maintained. You can increase the setpoint (desired speed) by holding down the acceleration button and the setpoint will slowly rise. Since you are not directly controlling the speed but the setpoint, you are performing what is called *supervisory control*. Releasing the button creates a new setpoint for the cruise control by capturing the current speed. You will notice that the gas pedal will automatically depress when going up hills and will rise going down hills. During these intervals you may notice a deviation from setpoint when observing the speedometer. This is an indication of the *tightness* of the control system. The engine may not be able to generate the required power to maintain the desired setpoint under all disturbances such as increase grade or increased wind resistance.

What happens to the cruise control when you need to brake for a traffic light or for a slower car? Once you touch the brake, immediately the cruise control is disabled and the car begins to coast. This action is equivalent to switching the control system from *automatic* to *manual*, sometimes called *hand*. While in manual mode you must take over the manipulation of the gas pedal yourself.

Once you pass the traffic light you would like to resume your normal speed. You could let the cruise control take you back to the previous setpoint by depressing the "Resume" button. When this happens, the cruise control is back in automatic operation but the controller will observe a large error signal or deviation since the setpoint is much higher than current speed. Depending upon the *gain* of the controller, this has the potential of putting the gas pedal to the floor, since the controller is attempting to zero out the error between setpoint and actual speed. This could unnerve the driver. To prevent this from occurring, output limits can be applied to the manipulated variable (gas pedal). You could restrict the gas pedal range so it never goes to the floor under automatic control. The result would be that you would not return to the desired speed as quickly as you would without the output limit, but there would be less waste of fuel and more comfort to the driver.

The above example is classified as an analog control system since all the variables are analog and the controller's output is proportional to its input signal error. However, there is another class of control system called the on/off control system that is quite popular especially for temperature loops. This type of control will be addressed in future articles.

SUMMARY

Although control theory is a complex subject, the basic underlying principles are not. In this article we introduced the reader to some of the concepts and terminology. In future articles we will explore more applications of control systems.

REFERENCES

IEEE Standard Dictionary of Electrical and Electronic Terms, Institute of Electrical and Electronics Engineers, Inc., Third Edition, John Wiley and Sons, Inc.

Direct Digital Control of Building Systems, H. Michael Newman, 1994, John Wiley and Sons

Servomechanisms, Eric R. Johnson, 1963, Prentice-Hall, Inc.

Process Control Systems, F.G. Shinskey, 1967, McGraw-Hill Book Company

Basic Instrumentation Lecture Notes and Study Guide—Measurement Fundamentals, Ralph L. Moore, 1976, Instrument Society of America