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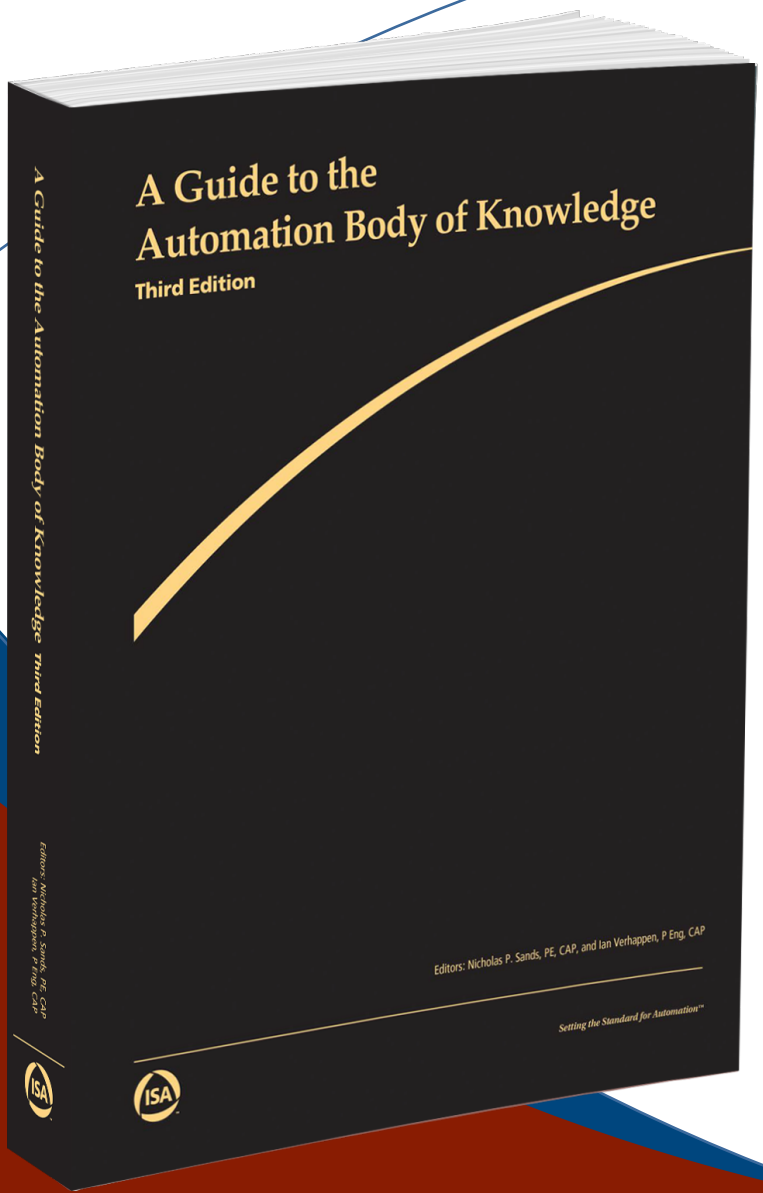

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Setting the Standard for Automation™

A Guide to the Automation Body of Knowledge

Third Edition

Editors

Nicholas P. Sands
PE, CAP, ISA Fellow

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P Eng, CAP, ISA Fellow

Setting the Standard for Automation™

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Preface to the Third Edition

It has been some years since the second edition was published in 2006. Times have changed. We have changed. Technology has changed. Standards have changed. Some areas of standards changes include; alarm management, human machine interface design, procedural automation, and intelligent device management.

Another change, in 2009, we lost the pioneer of *A Guide to the Automation Body of Knowledge* and the Certified Automation Professional (CAP) program, my friend, Vernon Trevathan. He had a vision of defining automation engineering and developing automation engineers.

With the changes in technology, it is clear that the trend of increasing automation will continue into the future. What is not clear, is how to support that trend with capable engineers and technicians. This guide is a step towards a solution. The purpose of this edition is the same as that of the first edition, to provide a broad overview of automation, broader than just instrumentation or process control, to include topics like HAZOP studies, operator training, and operator effectiveness. The chapters are written by experts who share their insights in a few pages.

The third edition was quite a project for many reasons. It was eventually successful because of the hard work and dedication of Susan Colwell and Liegh Elrod of the ISA staff, and the unstoppable force of automation that is my co-editor Ian Verhappen. Every chapter has been updated and some new chapters have been added. It is my hope that you find this guide to be a useful quick reference for the topics you know, and an overview for the topics you seek to learn. May you enjoy reading this third edition, and I hope Vernon enjoys it as well.

Nicholas P. Sands
May 2018

Control Basics

Documentation

One of the basic tenets of any project or activity is to be sure it is properly documented. Automation and control activities are no different, though they do have different and unique requirements to properly capture the requirements, outcomes, and deliverables of the work being performed. The International Society of Automation (ISA) has developed standards that are broadly accepted across the industry as the preferred method for documenting a basic control system; however, documentation encompasses more than just these standards throughout the control system life cycle.

Continuous and Process Control

Continuous processes require controls to keep them within safe operating boundaries while maximizing the utilization of the associated equipment. These basic regulatory controls are the foundation on which the automation industry relies and builds more advanced techniques. It is important to understand the different forms of basic continuous control and how to configure or tune the resulting loops—from sensor to controller then actuator—because they form the building blocks of the automation industry.

Batch Control

Not all processes are continuous. Some treat a discrete amount of material within a shorter period of time and therefore have a different set of requirements than a continuous process. The ISA standards on batch control are the accepted industry best practices in implementing control in a batch processing environment; these practices are summarized.

Discrete Control

This chapter provides examples of how to implement discrete control, which is typically used in a manufacturing facility. These systems mainly have discrete sensors and actuators, that is, sensors and actuators that have one of two values (e.g., on/off or open/closed).

1

Control System Documentation

By Frederick A. Meier and Clifford A. Meier

Reasons for Documentation

Documentation used to define control systems has evolved over the past half century as the technology used to generate it has evolved. Information formerly stored on smudged, hand-written index cards in the maintenance shop is now more likely stored in computer databases. The purpose of that documentation, however, remains largely unchanged: to impart information efficiently and clearly to a knowledgeable viewer. The information that is recorded evolves in the conceptualization, design, construction, operation, and maintenance of a facility that produces a desired product.

The documents described in this chapter form a typical set used to accomplish the goal of defining the work to be done, be it design, construction, or maintenance. The documents were developed and are commonly used for a continuous process, but they also work for other applications, such as batch processes. The authors know of no universal "standard" for documentation, but these can be considered typical. Some facilities or designs won't include all the described documents, and some designs may include documents not described, but the information provided on these documents will likely be found somewhere in any successful document suite.

All the illustrations and much of the description used in this section were published in the 2011 International Society of Automation (ISA) book *Instrumentation and Control System Documentation* by Frederick A. Meier and Clifford A. Meier. That book includes many more illustrations and a lot more explanation.

This section uses the term *automation and control* (A&C) to identify the group or discipline responsible for the design and maintenance of a process control system; the group that prepares and, hopefully, maintains these documents. Many terms are used to identify the people responsible for a process control system; the group titles differ by industry, company, and even region. In their book, the Meiers' use the term *instrument and control (I&C)* to describe

the engineers and designers who develop control system documentation; for our purposes, the terms are interchangeable.

Types of Documentation

This chapter provides descriptions and typical, albeit simple sketches for the following documents:

- Process flow diagrams (PFDs)
- Piping and instrument diagrams (P&IDs)
- Loop and tag numbering
- Instrument lists
- Specification forms
- Logic diagrams
- Location plans (instrument location drawings)
- Installation details
- Loop diagrams
- Standards and regulations
- Operating instructions

Figure 1-1 is a timeline that illustrates a sequence for document development. There are interrelationships where information developed in one document is required before a succeeding document can be developed. Data in the process flow diagram drives the design of the P&ID. P&IDs must be essentially complete before instrument specification forms can be efficiently developed. Loop diagrams are built from most of the preceding documents in the list.

The time intervals and percentage of total effort for each task will vary by industry and by designer. The intervals can be days, weeks, or months, but the sequence will likely be similar to that shown above. The documents listed are not all developed or used solely by a typical A&C group. However, the A&C group contributes to, and uses, the information contained in them.

Process Flow Diagram (PFD)

A process flow diagram is a "big picture" schematic representation of the major features of a process. These diagrams summarize the overall intent of the process using a graphical representation of the material flow and the conversion of resources into a product. Points where resources and energy combine to produce material are identified graphically. These points are then defined in more detail in associated mass balance calculations. The PFD shows how much of each resource or product a plant might make or treat; it includes descriptions and quantities of needed raw materials, as well as by-products produced. PFDs show critical pro-

2

Continuous Control

By Harold Wade

Introduction

Continuous control refers to a form of automatic process control in which the information—from sensing elements and actuating devices—can have any value between minimum and maximum limits. This is in contrast to discrete control, where the information normally is in one of two states, such as on/off, open/closed, and run/stop.

Continuous control is organized into feedback control loops, as shown in Figure 2-1. In addition to a controlled process, each control loop consists of a sensing device that measures the value of a controlled variable, a controller that contains the control logic plus provisions for human interface, and an actuating device that manipulates the rate of addition or removal of mass, energy, or some other property that can affect the controlled variable. The sensor, control and human-machine interface (HMI) station, and actuator are usually connected by some form of signal communication system, as described elsewhere in this book.

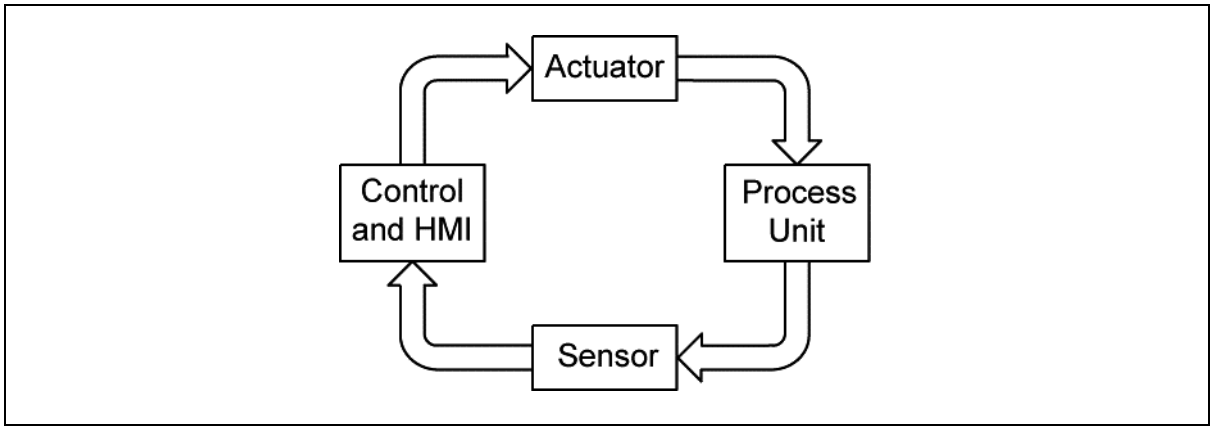

Figure 2-1. Components and Information Flow in a Feedback Control Loop

Continuous process control is used extensively in industries where the product is in a continuous, usually fluid, stream. Representative industries are petroleum refining, chemical and petrochemical, power generation, and municipal utilities. Continuous control can also be found in processes in which the final product is produced in batches, strips, slabs, or as a web in, for example, the pharmaceutical; pulp and paper; steel; and textile industries. There are also applications for continuous control in the discrete industries—for instance, a temperature controller on an annealing furnace or motion control in robotics.

The central device in a control loop, the controller, may be built as a stand-alone device or may exist as shared components in a digital system, such as a distributed control system (DCS) or programmable logic controller (PLC). In emerging technology, the control logic may be located at either the sensing or the actuating device.

Process Characteristics

In order to understand feedback control loops, one must understand the characteristics of the controlled process. Listed below are characteristics of almost all processes, regardless of the application or industry.

- Industrial processes are nonlinear; that is, they will exhibit different responses at different operating points.
- Industrial processes are subject to random disturbances, due to fluctuations in feedstock, environmental effects, and changes or malfunctions of equipment.
- Most processes contain some amount of dead time; a control action will not produce an immediate feedback of its effect.
- Many processes are interacting; a change in one controller's output may affect other process variables besides the intended one.
- Most process measurements contain some amount of random variation, called *noise*.
- Most processes are unique; processes using apparently identical equipment may have individual idiosyncrasies.

A typical response to a step change in signal to the actuating device is shown in Figure 2-2.

In addition, there are physical and environmental characteristics that must be considered when selecting equipment and installing control systems.

- The process may be toxic, requiring exceptional provisions to prevent release to the environment.
- The process may be highly corrosive, limiting the selection of materials for components that come in contact with the process.
- The process may be highly explosive, requiring special equipment housing or installation technology for electrical apparatus.

3

Control of Batch Processes

By P. Hunter Vegas, PE

What Is a Batch Process?

A batch process is generally considered one that acts on a discrete amount of material in a sequential fashion. Probably the easiest way to describe a batch process is to compare and contrast it to a continuous process, which is more common in industry today. The examples discussed below are specifically geared to continuous and batch versions of chemical processes, but these same concepts apply to a diverse range of industries. Batch manufacturing techniques can be found in wine/beer making, food and beverage production, mining, oil and gas processing, and so on.

A continuous chemical process usually introduces a constant stream of raw materials into the process, moving the material through a series of vessels to perform the necessary chemical steps to make the product. The material might pass through a fluidized bed reactor to begin the chemical reaction, pass through a water quench vessel to cool the material and remove some of the unwanted byproducts, and finally be pushed through a series of distillation columns to refine the final product before pumping it to storage. In contrast a batch chemical process usually charges the raw materials to a batch reactor, and then performs a series of chemical steps *in that same vessel* until the desired product is achieved. These steps might include mixing, heating, cooling, batch distilling, and so on. When the steps are complete, the material might be pumped to storage or it may be an intermediate material that is transferred to another batch vessel where more processing steps are performed.

Another key difference between continuous and batch processes is the typical running state of the process. A continuous process usually has a short start-up sequence and then it achieves steady state and remains in that state for days, weeks, months, and even years. The start-up and shutdown sequences are often a tiny fraction of the production run. In comparison, a batch process *rarely* achieves steady state. The process is constantly transitioning from state to state as the control system performs the processing sequence on the batch.

A third significant difference between batch and continuous processes is one of flexibility. A continuous process is specifically designed to make a large quantity of a single product (or a narrow family of products). Modification of the plant to make other products is often quite expensive and difficult to implement. In contrast, a batch process is intentionally designed to make a large number of products easily. Processing vessels are designed to handle a range of raw materials; vessels can be added (or removed) from the processing sequence as necessary; and the reactor jackets and overhead piping are designed to handle a wide range of conditions.

The flexibility of the batch process is an advantage and a disadvantage. The inherent flexibility allows a batch process to turn out a large number of very different products using the same equipment. The batch process vessels and programming can also be easily reconfigured to make completely new products with a short turn around. However, the relatively small size of the batch vessels generally limits the throughput of the product so batch processes can rarely match the volume and efficiency of a large continuous process. This is why both continuous and batch processes are extensively used in manufacturing today. Each has advantages that serve specific market needs.

Controlling a Batch Process

From a control system perspective the design of a continuous plant is usually quite straightforward. The instruments are sized and selected for the steady-state conditions, and the configuration normally consists of a large number of continuous proportional-integral-derivative (PID) controllers that keep the process at the desired steady state. The design of a batch control system is another matter entirely. The field instrumentation will often face a larger dynamic range of process conditions, and the control system must be configured to handle a large number of normal, transitional, and abnormal conditions. In addition, the control system must be easily reconfigured to address the changing process vessel sequences, recipe changes, varying product requirements, and so on. The more flexible a batch process is, the more demanding the requirements on the control system. In some cases, a single set of batch vessels might make 50 to 100 different products. Clearly such programming complexity poses quite a challenge for the automation professional.

Due to the difficulties that batch sequences posed, most batch processes were run manually for many years. As sequential controllers became available, simple batch systems were occasionally "automated" with limited sequences programmed into programmable logic controllers (PLCs) and drum programmers. Fully computerized systems that could deal with variable sequences for flexible processes were not broadly available until the mid-1980s and around that time several proprietary batch control products were introduced. Unfortunately, each had its own method of handling the complexities of batch programming and each company used different terminology adding to the confusion. The need for a common batch standard was obvious.

The first part of the ISA-88 batch control standard was published in 1995 and has had a remarkable effect on the industry. Later it was adopted by the American National Standards Institute (ANSI), it is currently named ANSI/ISA-88.00.01-2010, but it is still broadly known as *S88*. It provides a standard terminology, an internally consistent set of principles, and a set of models that can be applied to virtually any batch process. ANSI/ISA-88.00.01 can (and

4
Discrete Control

By Kelvin T. Erickson, PhD

Introduction

A discrete control system mainly has discrete sensors and actuators, that is, sensors and actuators that have one of two values (e.g., on/off or open/closed). Though Ladder Diagram (LD) is the primary language of discrete control, the industry trend is toward using the IEC 61131-3 (formerly 1131-3) standard. Besides Ladder Diagram, IEC 61131-3 defines four additional languages: Function Block Diagram (FBD), Structured Text (ST), Instruction List (IL), and Sequential Function Chart (SFC). Even though Ladder Diagram was originally developed for the programmable logic controller (PLC) and Function Block Diagram (FBD) was originally developed for the distributed control system (DCS), a PLC is not limited to ladder logic and a DCS is not limited to function block. The five IEC languages apply to all platforms for implementation of discrete control.

Ladder Logic

Early technology for discrete control used the electromechanical relays originally developed for the telegraph industry of the 1800s. Interconnections of relays implemented logic and sequential functions. The PLC was originally developed to replace relay logic control systems. By using a programming language that closely resembles the wiring diagram documentation for relay logic, the new technology was readily adopted. To introduce LD programming, simple logic circuits are converted to relay logic and then to LD (also called *ladder logic*).

Consider the simple problem of opening a valve, XV103, when pressure switches PS101 and PS102 are both closed, as in Figure 4-1a. To implement this function using relays, the switches are not connected to the valve directly but are connected to relay coils labeled PS101R and PS102R whose normally open (NO) contacts control a relay coil, XV103R, whose contacts control the valve (see Figure 4-1b). When PS101 and PS102 are both closed, the corresponding relay coils PS101R and PS102R are energized, closing two contacts and energizing

the XV103R relay coil. The contact controlled by XV103R is closed, supplying power to the XV103 valve.

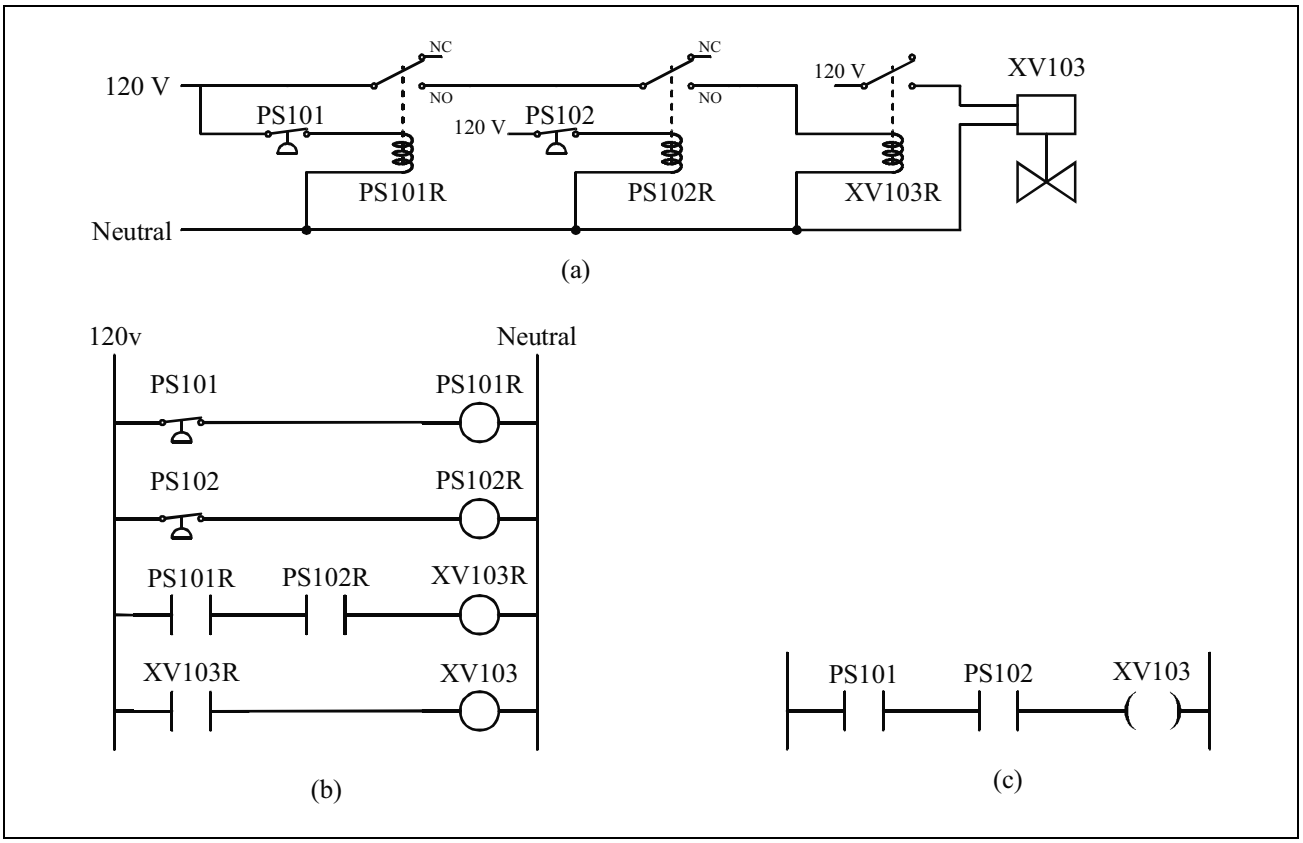

Figure 4-1. Series Switch Relay and Ladder Logic Circuits: (a) Relay Circuit; (b) Relay Ladder Logic Circuit; (c) Equivalent IEC Ladder Logic

The output (a valve in this case) is driven by the XV103R relay to provide voltage isolation from the relays implementing the logic. The need for this isolation is more obvious when the output device is a three-phase motor operating at 440 volts. The input switches, PS101 and PS102, control relay coils so that the one switch connection to an input relay can be used multiple times in the logic. A typical industrial control relay can have up to 12 poles, or sets of contacts, per coil. For example, if the PS101R relay has six poles (only one is shown), then the other five poles (contacts) are available for use in the relay logic without requiring five other connections to PS101.

The *ladder logic notation* (Figure 4-1c) is shortened from the relay wiring diagram to show only the third line, the relay contacts, and the coil of the output relay. Ladder logic notation assumes that the inputs (switches in this example) are connected to discrete input channels (equivalent to the relay coils PS101R and PS102R in Figure 4-1b). Also, the actual output (valve) is connected to a discrete output channel (equivalent to the NO contacts of XV102R in Figure 4-1b) controlled by the coil. The label shown above the contact symbol is not the contact label; it is the label of the control for the coil that drives the contact. Also, the output for the rung occurs on the extreme right side of the rung, and power is assumed to flow from left to right. The ladder logic rung is interpreted as follows: "When input (switch) PS101 is *closed* and input (switch) PS102 is *closed*, then XV103 is *on*."

11

Field Devices

Measurement Accuracy and Uncertainty

It is true that you can control well only those things that you can measure—and accuracy and reliability requirements are continually improving. Continuous instrumentation is required in many applications throughout automation, although we call it process instrumentation because the type of transmitter packaging discussed in this chapter is more widely used in process applications.

There are so many measurement principles and variations on those principles that we can only scratch the surface of all the available ones; however, this section strives to cover the more popular/common types.

Process Transmitters

The field devices, sensors, and final control elements are the most important links in process control and automation. The reason is if you are unable to measure or control your process, everything else built upon those devices cannot compensate for a poor input or the lack of ability to control the output without excessive variance.

Analytical Instrumentation

Analytical instrumentation is commonly used for process control, environmental monitoring, and related applications in a variety of industries.

Control Valves

Final control elements, such as control valves and now increasingly variable speed or variable/adjustable frequency motors, are critical components of a control loop in the process and utility industries. It has been demonstrated in nearly all types of process plants that control valve problems are a major cause of poor loop performance. A general knowledge of the impact of the control valve on loop performance is critical to process control.

Today it has become commonplace for automation professionals to delegate the selection and specification of instrumentation and control valves, as well as the tuning of controllers to technicians. However, performance in all these areas may depend on advanced technical details that require the attention of an automation professional; there are difficult issues including instrument selection, proper instrument installation, loop performance, advanced transmitter features, and valve dynamic performance. A knowledgeable automation professional could likely go into any process plant in the world and drastically improve the performance of the plant by tuning loops, redesigning the installation of an instrument for improved accuracy, or determining a needed dynamic performance improvement on a control valve—at minimal cost. More automation professionals need that knowledge.

Motor Controls

Not all final control elements are valves. Motors with adjustable speed drives are used for pumps, fans, and other powered equipment. This chapter provides a basic review of motor types and adjustable speed drive functionality.

5

Measurement Uncertainty

By Ronald H. Dieck

Introduction

All automation measurements are taken so that useful data for the decision process may be acquired. For results to be useful, it is necessary that their measurement errors be small in comparison to the changes, effects, or control process under evaluation. Measurement error is unknown but its limits may be estimated with statistical confidence. This estimate of error is called *measurement uncertainty*.

Error

Error is defined as the difference between the measured value and the true value of the measurand [1] as is shown in Equation 5-1:

$$E = (measured) - (true) \tag{5-1}$$

where

E = the measurement error
(*measured*) = the value obtained by a measurement
(*true*) = the true value of the measurand

It is only possible to estimate, with some confidence, the expected limits of error. The first major type of error with limits needing estimation is random error. The extent or limits of a random error source are usually estimated with the *standard deviation of the average*, which is written as:

$$S_{\bar{X}} = \frac{\sqrt{\dfrac{\sum_{i=1}^{N}(X_i - \bar{X})^2}{N-1}}}{\sqrt{M}} = S_X/\sqrt{M} \tag{5-2}$$

where

$S_{\overline{X}}$ = the standard deviation of the average; *the sample standard deviation of the data divided by the square root of M*

M = the number of values averaged for a measurement

S_X = the sample standard deviation

$\overline{X}$ = the sample average

Note in Equation 5-2 that N does not necessarily equal M. It is possible to obtain S_X from historical data with many degrees of freedom ([N – 1] greater than 29) and to run the test only M times. The test result, or average, would therefore be based on M measurements, and the standard deviation of the average would still be calculated with Equation 5-2.

Measurement Uncertainty (Accuracy)

One needs an estimate of the uncertainty of test results to make informed decisions. Ideally, the uncertainty of a well-run experiment will be much less than the change or test result expected. In this way, it will be known, with high confidence, that the change or result observed is real or acceptable and not a result of errors from the test or measurement process. The limits of those errors are estimated with uncertainty, and those error sources and their limit estimators, the uncertainties, may be grouped into classifications to make them easier to understand.

Classifying Error and Uncertainty Sources

There are two classification systems in use. The final uncertainty calculated at a chosen confidence is identical for the two systems no matter what classification system is used. The two classifications utilized are the International Organization for Standardization (ISO) classifications and the American Society of Mechanical Engineers (ASME)/engineering classifications. The former groups errors and their uncertainties by *type*, depending on whether or not there is data available to calculate the sample standard deviation for a particular error and its uncertainty. The latter classification groups errors and their uncertainties by their *effect* on the experiment or test. That is, the engineering classification groups errors and uncertainties by *random* and *systematic* effects, with subscripts used to denote whether there are data to calculate a standard deviation or not for a particular error or uncertainty source.

ISO Classifications

In the ISO system, errors and uncertainties are classified as Type A if there are data available to calculate a sample standard deviation and Type B if there are not [2]. In the latter case, the sample standard deviation might be obtained, for example, from engineering estimates, experience, or manufacturer's specifications.

The impact of multiple sources of error is estimated by root-sum-squaring their corresponding elemental uncertainties. The operating equations are as follows.

6

Process Transmitters

By Donald R. Gillum

Introduction

With the emphasis on improved control and control quality and with advanced control systems, the significance and importance of measurement is often overlooked. In early industrial facilities, it was soon realized that many variables needed to be measured. The first measuring devices consisted of simple pointer displays located in the processing area, a pressure gauge for example. When the observation of a variable needed to be remote from the actual point of measurement, hydraulic impulse lines were filled with a fluid and connected to a readout device mounted to a panel for local indication of a measured value.

The need for transmitting measurement signals through greater distance became apparent as the size and complexity of process units increased and control moved from the process area to a centrally located control room. Transmitters were developed to isolate the process area and material from the control room. In general terms, the transmitter is a device that is connected to the process and generates a transmitted signal proportional to the measured value. The output signal is generally 3–15 psi for pneumatic transmitters and 4–20 mA for electronic transmitters. As it has taken many years for these standard values to be adopted, other scaled output values may be used and converted to these standard units. The input to the transmitter will represent the value of the process to be measured and can be nearly any range of values. Examples can be: 0–100 psi, 0–100 in of water, 50–500^{o}F and 10–100 in of level measurement or 0–100 kPa, 0–10 mm Hg, -40–120^{o}C and 5–50 cm of level measurement. The actual value of input measurement, determined by the process requirements, is established during initial setup and calibration of the device.

Although transmitters have been referred to as transducers, this term does not define the entire function of a transmitter which usually has an input and output transducer. A transducer is a device that converts one form of energy into another form of energy that is generally more useful for a particular application.

Pressure and Differential Pressure Transmitters

The most common type of transmitters used in the processing industries measure pressure and differential pressure (d/p). These types will be discussed in greater detail in the presentation of related measurement applications. The input transducer for most process pressure and d/p transmitters is a pressure element which responds to an applied pressure and generates a proportional motion, movement, or force. Pressure is defined as force per unit area which can be expressed as $P = F/A$ where P is the pressure to be measured, F is the force, and A is the area over which the force is applied. By rearranging the expression, $F = PA$. So, the force produced by a pressure element is a function of the applied pressure acting over the area of the pressure element to which the force is applied.

Pressure elements represent a broad classification of transducers in pressure instruments. The deflection of the free end of a pressure element, the input transducer, is applied to the secondary or output transducer to generate a pneumatic or electronic signal which is the corresponding output of the transmitter. A classification of pressure instruments is called Bourdon elements and include:

- "C" tube
- Spiral
- Helical
- Bellows
- Diaphragm
- Capsule

While most of these transducers can be used on pressure gauges or transmitters, the "C" tube is predominant in pressure gauges. The diaphragm or capsule is used in d/p transmitters because of the ability to respond to the low pressure in such applications. Other types of Bourdon elements are used in most pressure transmitters.

A flapper-nozzle arrangement or a pilot-valve assembly is used for the output transducer in most pneumatic transmitters.

A variety of output transducers have been used for electronic transmitters. The list includes:

- **Potentiometers or other resistive devices** – This measurement system results in a change of resistance in the output transducer, which results in a change in current or voltage in a bridge circuit or other type of signal conditioning system.
- **Linear variable differential transformer (LVDT)** – This system is used to change the electrical energy generated in the secondary winding of a transformer as a pressure measurement changes the positioner of a movable core between the primary and secondary windings. This device can detect a very small deflection from the input transducer.
- **Variable capacitance device** – This device generates a change in capacitance as the measurement changes the relative position of capacitance plates. A capacitance

7

Analytical Instrumentation

By James F. Tatera

Introduction

Process analytical instruments are a unique category of process control instruments. They are a special class of sensors that enable the control engineer to control and/or monitor process and product characteristics in significantly more complex and various ways than traditional, more physical sensors—such as pressure, temperature, and flow—allow.

Today's safety and environmental requirements, time-sensitive production processes, inventory reduction efforts, cost reduction efforts, and process automation schemes have made process analysis a requirement for many process control strategies. Most process analyzers are providing real-time information to the control scheme that many years ago would have been the type of feedback the production process would have received from a plant's quality assurance laboratory. Today most processes require faster feedback to control the process, rather than just being advised that their process was or wasn't in control at the time the lab sample was taken, and/or that the sample was or wasn't in specification.

Various individuals have attempted to categorize the large variety of monitors typically called *process analyzers*. None of these classification schemes has been widely accepted; the result is that there are many categorization schemes in use, simultaneously. Most of these schemes are based on either the analytical/measurement technology being utilized by the monitor, the application to which the monitor is being applied, or the type of sample being analyzed. There are no hard and fast definitions for analyzer types. Consequently, most analytical instruments are classed under multiple and different groupings. Table 7-1 depicts a few of the analyzer type labels commonly used.

Table 7-1. Examples of Analyzer Types/Classifications

Compositional	Single component
Physical properties	Sulfur in oil
Oxygen	Moisture
Inferential/virtual	Auto titrators
Chromatography	Spectroscopy
Safety	Environmental
Air quality	Water quality
BTU	LEL

An example of how a single analyzer can be classified under many types would be a pH analyzer. This analyzer is designed to measure the pH (an electrochemical property of a solution—usually water-based). As such, it can be used to report the pH of the solution and may be labeled as a *pH analyzer* or *electrochemical analyzer* (its analytical technology label). It may be used to monitor the plant's water out-fall and, in this case, it may be called an *environmental-* or *water-quality analyzer* (based on its application and sample type). It may be used to monitor the acid or base concentration of a process stream, in which case it may be labeled a *single-component concentration analyzer* (based on its application and the desired result being reported). This is just an example and it is only intended to assist in understanding that there are many process analyzers that will be labeled under multiple classifications. Don't allow this to confuse or bother you.

There are too many process analyzer technologies to mention in this chapter so only a few will be used as examples. A few of the many books published on process analysis are listed in the reference summary at the end of this chapter. I recommend consulting them for further information on individual/specific technologies. The balance of this chapter will be used to introduce concepts and technical details that are important in the application of process analyzers.

Sample Point Selection

Determining which sample to analyze is usually an iterative process based on several factors and inputs. Some of these factors include regulatory requirements, product quality, process conditions, control strategies, economic justifications, and more. Usually, the final selection is a compromise that may not be optimum for any one factor, but is the overall best of the options under consideration. Too often, mistakes are made on existing processes when selections are based on a simple single guideline, like the final product or the intermediate sample that has been routinely taken to the lab. True, you usually have relatively good data regarding the composition of that sample. But, is it the best sample to use to control the process continuously to make the best product and/or manage the process safely and efficiently? Or, is it the one that will just tell you that you have or have not made good product? Both are useful information, but usually the latter is more effectively accomplished in a laboratory environment.

When you consider all the costs of procurement, engineering, installation, and maintenance, you rarely save enough money to justify installing process analyzers just to shut down or

8

Control Valves

By Hans D. Baumann

Since the onset of the electronic age, because of the concern to keep up with ever-increasing challenges by more sophisticated control instrumentation and control algorithms, instrument engineers paid less and less attention to final control elements even though all process control loops could not function without them.

> *Final control elements may be the most important part of a control loop because they control process variables, such as pressure, temperature, tank level, and so on. All these control functions involve the regulation of fluid flow in a system. The control valve is the most versatile device able to do this. Thermodynamically speaking, the moving element of a valve—may it be a plug, ball, or vane—together with one or more orifices, restricts the flow of fluid. This restriction causes the passing fluid to accelerate (converting potential energy into kinetic energy). The fluid exits the orifice into an open space in the valve housing, which causes the fluid to decelerate and create turbulence. This turbulence in turn creates heat, and at the same time reduces the flow rate or pressure.*

Unfortunately, this wastes potential energy because part of the process is irreversible. In addition, high-pressure reduction in a valve can cause cavitation in liquids or substantial aerodynamic noise with gases. One must choose special valves designed for those services.

There are other types of final control elements, such as speed-controlled pumps and variable speed drives. Speed-controlled pumps, while more efficient when flow rates are fairly constant, lack the size ranges, material choices, high pressure and temperature ratings, and wide flow ranges that control valves offer. Advertising claims touting better efficiency than valves cite as proof only the low-power consumption of the variable speed motor and omit the high-power consumption of the voltage or frequency converter that is needed.

Similarly, variable speed drives are mechanical devices that vary the speed between a motor and a pump or blower. These don't need an electric current converter because their speed is mechanically adjusted. Control valves have a number of advantages over speed-controlled pumps: they are available in a variety of materials and sizes, they have a wider rangeability

(range between maximum and minimum controllable flow), and they have a better speed of response.

To make the reader familiar with at least some of the major types of control valves (the most important final control element), here is a brief description.

Valve Types

There are two basic styles of control valves: rotary motion and linear motion. The valve shaft of rotary motion valves rotates a vane or plug following the commands of a rotary actuator. The valve stem of linear motion valves moves toward or away from the orifice driven by reciprocating actuators. Ball valves and butterfly valves are both rotary motion valves; a globe valve is a typical linear motion valve. Rotary motion valves are generally used in moderate-to-light-duty service in sizes above 2 in (50 mm), whereas linear motion valves are commonly used for more severe duty service. For the same pipe size, rotary valves are smaller and lighter than linear motion valves and are more economical in cost, particularly in sizes above 3 in (80 mm).

Globe valves are typical linear motion valves. They have less pressure recovery (higher pressure recovery factor [FL]) than rotary valves and, therefore, have less noise and fewer cavitation problems. The penalty is that they have less C_V (K_V) per diameter compared to rotary types.

Ball Valves

When a ball valve is used as a control valve, it will usually have design modifications to improve performance. Instead of a full spherical ball, it will typically have a ball segment. This reduces the amount of seal contact, thus reducing friction and allowing for more precise positioning. The leading edge of the ball segment may have a V-shaped groove to improve the control characteristic. Ball valve trim material is generally 300 series stainless steel (see Figure 8-1).

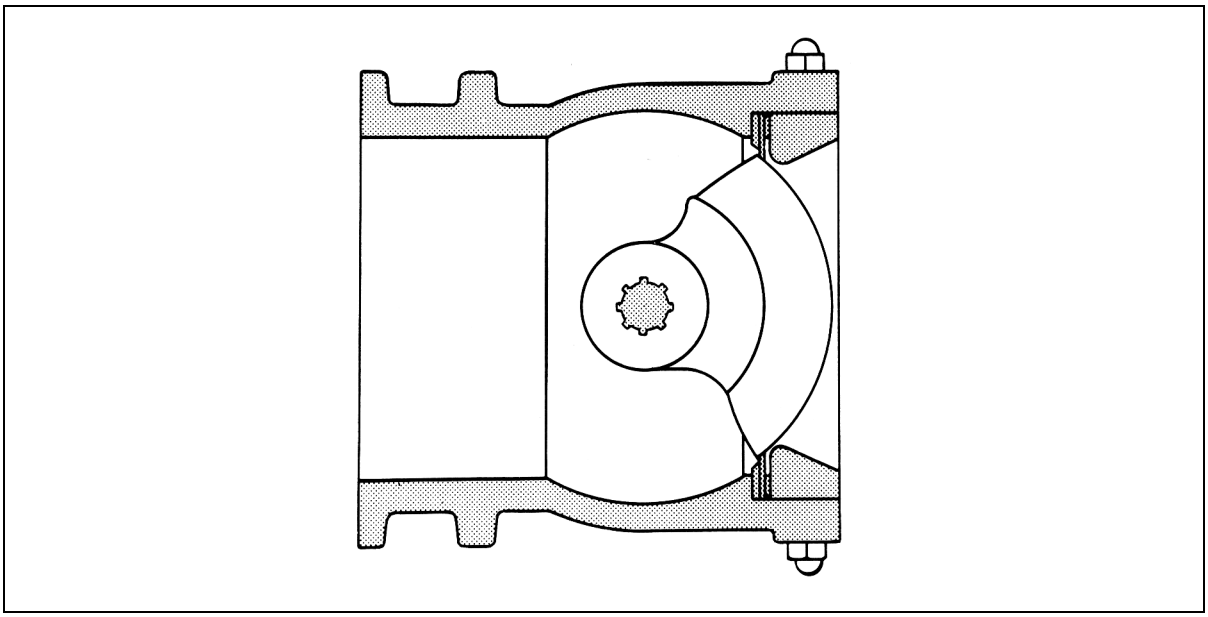

Figure 8-1. Segmental Ball Valve Cross Section
Source: Masoneilan/Dresser (MNI is a division of GE).

9

Motor and Drive Control

By Dave Polka and Donald G. Dunn

Introduction

Automation is a technique, method, or system of operating or controlling a process by highly automatic means utilizing electronic devices, which reduces human intervention to a minimum. Processes utilize mechanical devices to produce a force, which produces work within the process. Thus, a motor is a device that converts electrical energy into mechanical energy. There are both alternating current (AC) and direct current (DC) motors with the AC induction motor being the most common type utilized within most industries. It is vital that automation engineers have a basic understanding of motor and electronic drive principles. The drive is the device that controls the motor. The two interact or work together to provide the torque, speed, and horsepower (hp) necessary to operate the application or process.

The simplest concept of any motor, either direct or alternating current, is that it consists of a magnetic circuit interlinked with an electrical circuit in such a manner to produce a mechanical turning force. It was recognized long ago that a magnet could be produced by passing an electric current through a coil wound around magnetic material. Later it was established that when a current is passed through a conductor or a coil, which is situated in a magnetic field, there is a setup force tending to produce motion of the coil relative to the field.

Thus, a current flowing through a wire will create a magnetic field around the wire. The more current (or turns) in the wire, the stronger the magnetic field; by changing the magnetic field, one can induce a voltage in the conductor. Finally, a force is exerted on a current-carrying conductor when it is in a magnetic field. A magnetic flux is produced when an electric current flows through a coil of wire (referred to as a *stator*), and current is induced in a conductor (referred to as a *rotor*) adjacent to the magnetic field. A force is applied at right angles to the magnetic field on any conductor when current flows through that conductor.

DC Motors and Their Principles of Operation

There are two basic circuits in any DC motor: the *armature* (device that rotates) and the *field* (stationary part with windings). The two components magnetically interact with one another to produce rotation of the armature. Both the armature and the field are two separate circuits and are physically next to each other, in order to promote magnetic interaction.

The armature (I_A) has an integral part, called a *commutator* (see Figure 9-1). The commutator acts as an electrical switch, always changing polarity of the magnetic flux to ensure there is a "repelling" force taking place. The armature rotates as a result of the "repelling" motion created by the magnetic flux of the armature, in opposition to the magnetic flux created by the field winding (I_F).

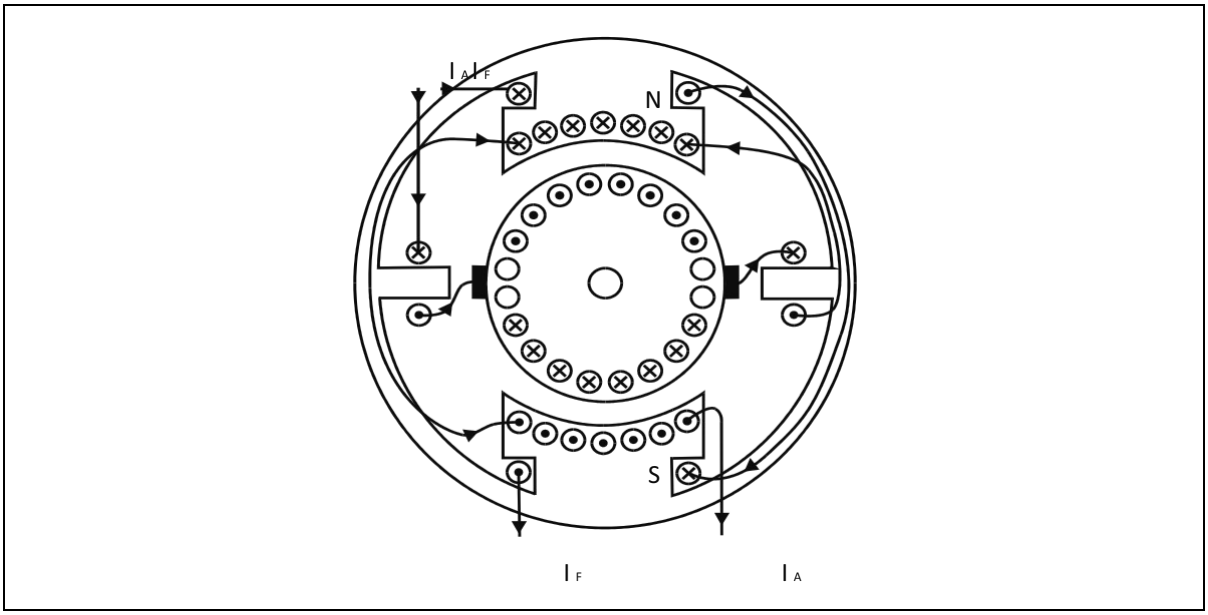

Figure 9-1. Armature and Field Connections
Source: Courtesy of ABB Inc.

The physical connection of voltage to the armature is done through "brushes." Brushes are made of a carbon material that is in constant contact with the armature's commutator plates. The brushes are typically spring loaded to provide constant pressure of the brush to the commutator plates.

Control of Speed

The speed of a DC motor is a direct result of armature voltage applied. The field receives voltage from a separate power supply, sometimes referred to as a *field exciter*. This exciter provides power to the field, which in turn generates current and magnetic flux. In a normal condition, the field is kept at maximum strength, allowing the field winding to develop maximum current and flux (known as the *armature range*). The only way to control the speed is through change in armature voltage.

III

Electrical Considerations

Electrical Installations

The chapter on electrical installations underscores the reality that the correct installation of electrical equipment is essential to implement almost any automation system. Electrical installation is an extensive topic that includes rigid codes, practices, conductor selection, distribution, grounding, interference factors, and surge protection about which this book can only scratch the surface.

This chapter is based on the U.S. codes and regulations for which—not surprisingly—other countries have similar documents.

Electrical Safety

While the safety of electrical installations is closely related to correct electrical installation in general, electrical safety is addressed separately to ensure that sufficient emphasis is placed on the safety aspects of the devices and field installations.

System Checkout

There are a variety of ways to verify the integrity of the installation, integration, and operation of control systems at the component and system levels. The objectives are to ensure the integrated system functions the way it was planned during the project's conceptual stage and specified during the design phase, and to ensure that the full system functions as intended after it is assembled.

10 Electrical Installations

By Greg Lehmann, CAP

Introduction

The successful automation professional strives to deliver a work product that will not only meet client requirements but also provide a safe and productive workplace. These efforts should be ever-present during the design, construction, checkout, start-up, and operational phases of the project. Instrumentation and control systems should be designed with diligence to assure that all electrical, hydraulic, and pneumatic installations provide safe, fault-tolerant conditions that will protect personnel, product, and the environment.

This chapter will introduce the reader to some basic premises that should be considered in the electrical installations of automated industrial facilities. While not a complete "How To," the chapter will present the fundamentals necessary to assure a safe, reliable, and practical electrical installation.

Codes, standards, and engineering practices should be viewed as minimum requirements in electrical installations and the automation professional should—within reason—attempt to go beyond simply complying with these documents. Local electrical codes and regulations should be adhered to, and as an example, the National Electrical Code (NEC) has been cited throughout the chapter to illustrate the referencing of geographically appropriate code.

Scope

The scope of this chapter is not limited to the presentation of applicable codes, standards, and practices as they relate to electrical installations. The chapter will also present some useful and significant aspects and criteria that may serve as an aid in designing a safe and dependable electrical installation. The information explained will establish the groundwork necessary for a proficient design, which will lead to a successful electrical installation.

The chapter topics include basic wiring practices, wire and cable selection, grounding, noise reduction, lightning protection, electrical circuit and surge protection, raceways, distribution equipment, and more.

The automation professional is responsible for the design and deployment of systems and equipment for many diverse industries. While these industries may share a common electrical code within their countries or jurisdictions, they will likely have differing standards and practices between their specific industries. This chapter will present a non-industry-specific, practical approach to electrical installations that will assist the automation professional working with electrical engineers in providing an installation that is safe, reliable, and productive.

Definitions

- **Ampacity** – The maximum current, in amperes, that a conductor can carry continuously under the conditions of use without exceeding its temperature rating [NEC Article 100, *Definitions*].
- **Bonded (bonding)** – Connected to establish electrical continuity and conductivity [NEC Article 100, *Definitions*].
- **Bonding of electrically conductive materials and other equipment** – Normally non-current-carrying electrically conductive materials that are likely to become energized shall be connected together and to the electrical supply source in a manner that establishes an effective ground-fault current path [NEC Article 250.4(A)(4)].
- **Bonding of electrical equipment** – Normally non-current-carrying conductive materials enclosing electrical conductors or equipment, or forming part of such equipment, shall be connected together and to the electrical supply source in a manner that establishes an effective ground-fault current path [NEC Article 250.4(A)(3)].
- **Cable** – A factory assembly of two or more conductors having an overall covering [NEC Article 800.2, *Definitions*].
- **Cable tray system** – A unit or assembly of units or sections and associated fittings forming a structural system used to securely fasten or support cables and raceways [NEC Article 392.2, *Definitions*].
- **Effective ground-fault current path** – Electrical equipment and wiring and other electrically conductive material likely to become energized shall be installed in a manner that creates a low-impedance circuit facilitating the operation of the overcurrent device or ground detector for high-impedance grounded systems [NEC Article 250.4(A)(5)].
- **Enclosure** – The case or housing of apparatus, or the fence or walls surrounding an installation to prevent personnel from accidentally contacting energized parts or to protect the equipment from physical damage [NEC Article 100, *Definitions*].
- **Ground** – The earth [NEC Article 100, *Definitions*].
- **Grounded (Grounding)** – Connected (connecting) to ground or to a conductive body that extends the ground connection [NEC Article 100, *Definitions*].

11

Safe Use and Application of Electrical Apparatus

By Ernie Magison, Updated by Ian Verhappen

Introduction

This chapter discusses ways to ensure electrical equipment does not endanger personnel or the plant. Refer to other chapters in this book for discussions on process safety and safety instrumented systems (SISs)—protecting the plant against the risk of equipment failing to perform its function in a control system or in a safety instrumented system.

Developments during the past half century have made it easier to select safe equipment. Standardization of general-purpose safety requirements has made it possible to design a single product that is acceptable with minor modifications, if any, in all nations. Worldwide adoption of common standards is progressing for constructing and selecting equipment for use in hazardous locations; but transitioning from long-accepted national practices to adopt a somewhat different international or harmonized practice is, of necessity, slowed by historical differences in philosophy. Emphasis in this chapter is on the common aspects of design and use. Present day differences in national standards, codes, and practices will be reduced in coming years. To ensure safety today, a user anywhere must select, install, and use equipment in accordance with local standards and codes.

General-purpose safety standards address construction requirements that ensure personnel will not be injured by electrical shock, hot surfaces, or moving parts—and that the equipment will not become a fire hazard. Requirements for constructing an apparatus to ensure it does not become a source of ignition of flammable gases, vapors, or dusts are superimposed on the general-purpose requirements for equipment that is to be used where potentially explosive atmospheres may be present. The practice in all industrialized countries, and in many developing countries, is that all electrical equipment must be certified as meeting these safety standards. An independent laboratory is mandated for explosion-protected apparatus but, in some cases, adherence to general-purpose requirements may be claimed by the manufacturer, subject to strict oversight by a third party. Thus, by selecting certified or approved equipment, the user can be sure that it meets the applicable construction standards and environment for the location in which it is to be installed. It is the user's duty to install and use the

equipment in a manner that ensures that safety designed into the equipment is not compromised in use.

Philosophy of General-Purpose Requirements

Protection against electrical shock is provided by construction rules that recognize that voltages below about 30 VAC, 42.4 VAC peak, or 60 VDC do not pose a danger of electrocution in normal industrial or domestic use, whereas contact with higher voltages may be life threatening. Design rules, therefore, specify insulation, minimum spacings, or partitions between low-voltage and higher-voltage circuits to prevent them from contacting each other and causing accessible extra low-voltage circuits to become hazardous. Construction must ensure higher-voltage circuits cannot be touched in normal operation or by accidental exposure of live parts. Any exposed metallic parts must be grounded or otherwise protected from being energized by hazardous voltages. Protection against contact with hot parts or moving parts is provided by an enclosure, or by guards and interlocks.

To prevent the apparatus from initiating a fire, construction standards specify careful selection of materials with respect to temperature rises of parts, minimum clearances between conductive parts to prevent short circuiting, and the enclosure itself to prevent arcs or sparks from leaving the equipment.

As part of the approval process—the approval authorities evaluate conformity to device manufacturing rules, instructions, warnings, and equipment installation diagrams. The user must install and use the apparatus in accordance with these specifications and documents to ensure safety.

Equipment for Use Where Explosive Concentrations of Gas, Vapor, or Dust Might Be Present

Equipment intended for use in hazardous locations is always marked for the hazardous locations in which use is permitted and the kind of protection incorporated. It is almost always certified by an independent approval authority. The user may depend on this marking when selecting equipment for use.

Area Classification

Any hazardous area classification system defines the *kind* of flammable material that could be present, and the *probability* that it will be present. In North America and some other locations, two nomenclatures are in use to denote type and probability: Class, Group, and Division (as summarized in Table 11-1), and the more recent international usage of Material Class and Zone. The Zone classification process is the one most commonly used around the world and is gaining broader acceptance in North America, especially for new facilities where the benefits of this system for sourcing products can be realized. Class and Group or Material Group define the nature of the hazardous material that may be present. Division or Zone indicates the probability of the location having a flammable concentration of the material.

Though not defined in a standard, a common interpretation of Division 2 or Zone 2 is that the hazardous condition can be present no more than 2 hours per year. Therefore, the overall risk

12

Checkout, System Testing, and Start-Up

By Mike Cable

Introduction

Many automation professionals are involved in planning, specifying, designing, programming, and integrating instrumentation and controls required for process automation. In this chapter, we will describe the various methods of testing the installation, integration, and operation at the component and system level. The end goal is to ensure the integrated system functions the way it was intended when everyone got together in the beginning of the project and specified what they wanted the systems to do.

In an ideal world, we could wait until the entire system is ready for operation and perform all testing at the end. This would allow a much more efficient means of testing, with everything connected, communicating, and operational. However, we all know several problems would be uncovered that would lead to long start-up delays. Uncovering the majority of these problems at the earliest opportunity eliminates many of these delays and provides the opportunity to make corrections at a much lower cost.

An efficient means of testing the system can be developed, resulting in limited duplication of effort by properly planning, communicating, and using a standardized approach to instrumentation and control system commissioning. Instrumentation and control system commissioning can be defined as a planned process by which instrumentation and control loops are methodically placed into service. Instrument commissioning can be thought of as building a case to prove the instrumentation and controls will perform as specified.

This chapter does not cover testing performed during software development, as this should be covered in the developer's software quality assurance procedures. However, a formal testing of the function blocks or program code, which will be described later in this chapter, should be performed and documented. This chapter does not cover documentation and testing required for equipment (e.g., pumps, tanks, heat exchangers, filters, and air handling units). The scope for this chapter begins at the point when instruments are received, panels

are installed, point-to-point wiring is completed, and systems have been turned over from construction.

The plan for testing described in this chapter must consider where the system is being built. There may be several suppliers building skid systems at their facility for delivery to the end user. There may be one main supplier that receives a majority of the components, some of which are used for building panels and skid systems, while others will be installed at the end user's facility. For another project, all components are delivered directly to the end user's facility. Depending on the logistics, some testing may be performed at the supplier's location, even by the supplier, if properly trained. Other testing will be performed at the end user's facility.

The flowchart in Figure 12-1 illustrates instrument commissioning activities covered in the "Instrumentation Commissioning" and "Software Testing" sections in this chapter.

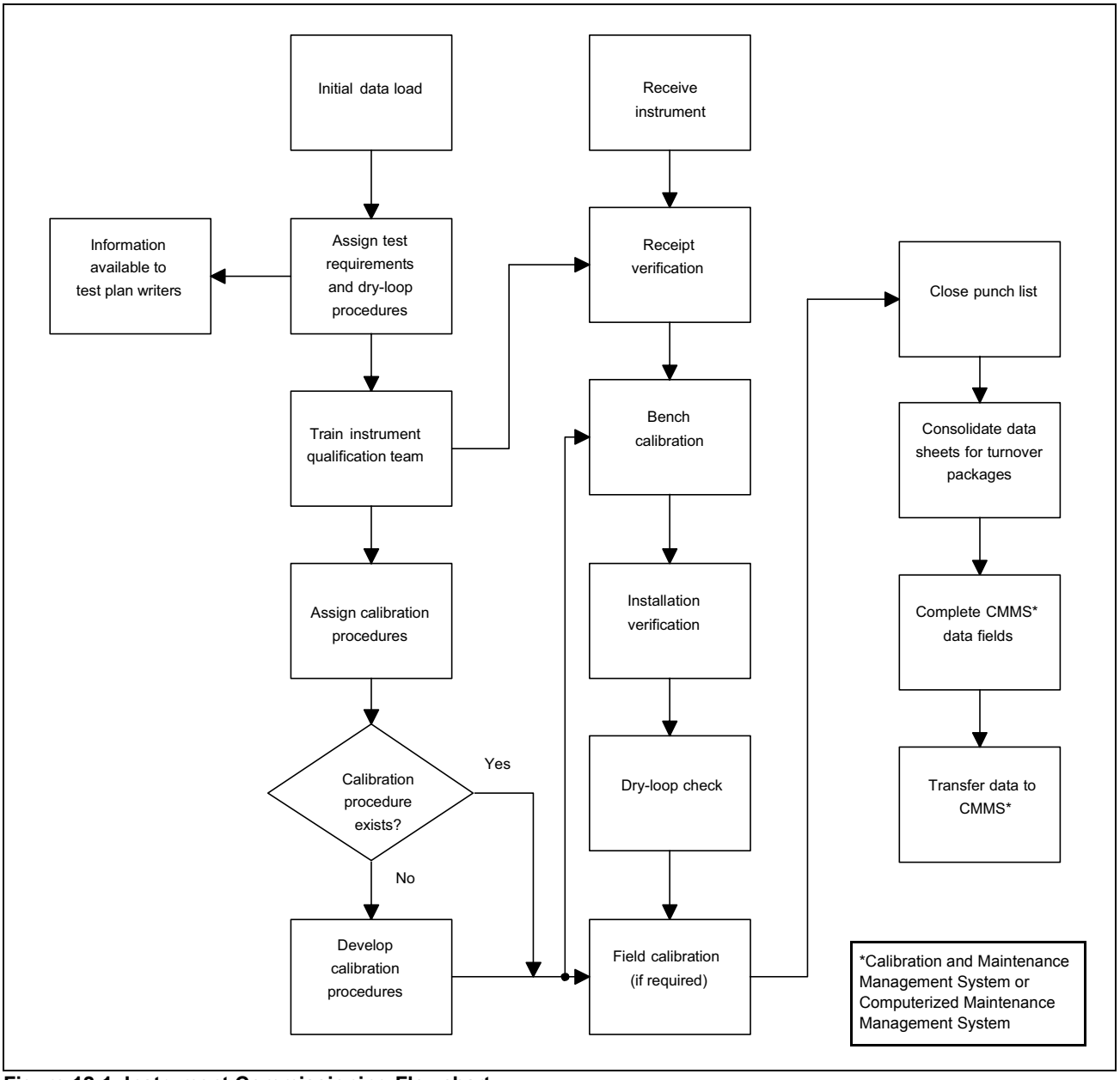

Figure 12-1. Instrument Commissioning Flowchart

IV

Control Systems

Programmable Logic Controllers

One of the most ubiquitous control platforms uses the programmable logic controller (PLC) as its hardware basis. This chapter describes the main distinguishing characteristics of the PLC, its basic hardware and software architecture, and the methods by which the program and input/output modules are scanned.

Distributed Control Systems

Distributed control systems (DCSs) are responsible for real-time management and control of major process plants and, therefore, are typically larger than PLC installations. The term "distributed" implies that various subsystem control and communication tasks are performed in different physical devices. The entire system of devices is then connected via the digital control network that provides overall communication, coordination, and monitoring.

SCADA

Supervisory control and data acquisition (SCADA) systems have been developed for geographically distributed sites requiring monitoring and control, typically from a central location or control center. This chapter describes how the three major SCADA elements—field-based controllers called remote terminal units (RTUs), a central control facility from which operations personnel monitor and control the field sites through the data-collecting master terminal unit (MTU) or a host computer system, and a wide-area communications system to link the field-based RTUs to the central control facility—are combined into a system.

13

Programmable Logic Controllers: The Hardware

By Kelvin T. Erickson, PhD

Introduction

In many respects, the architecture of the programmable logic controller (PLC) resembles a general-purpose computer with specialized input/output (I/O) modules. However, some important characteristics distinguish a PLC from a general-purpose computer. First, and most importantly, a PLC is much more reliable, designed for a mean time between failure (MTBF) measured in years. Second, a PLC can be placed in an industrial environment with its substantial amount of electrical noise, vibration, extreme temperatures, and humidity. Third, plant technicians with less than a college education can easily maintain PLCs.

This chapter describes the main distinguishing characteristics of the PLC, its basic hardware and software architecture, and the method in which the program and I/O modules are scanned.

Basic PLC Hardware Architecture

The basic architecture of a PLC is shown in Figure 13-1. The main components are the processor module, the power supply, and the I/O modules. The processor module consists of the central processing unit (CPU) and memory. In addition to a microprocessor, the CPU also contains at least an interface to a programming device and may contain interfaces to remote I/O and other communication networks. The power supply is usually a separate module and the I/O modules are separate from the processor. The types of I/O modules include discrete (on/off), analog (continuous variable), and special modules, like motion control or high-speed counters. The field devices are connected to the I/O modules.

Depending on the amount of I/O and the particular PLC processor, the I/O modules may be in the same chassis as the processor and/or in one or more other chassis. Up until the late 1980s, the I/O modules in a typical PLC system were in a chassis separate from the PLC processor. In the more typical present-day PLC, some of the I/O modules are present in the chassis that contains the processor. Some PLC systems allow more than one processor in the same

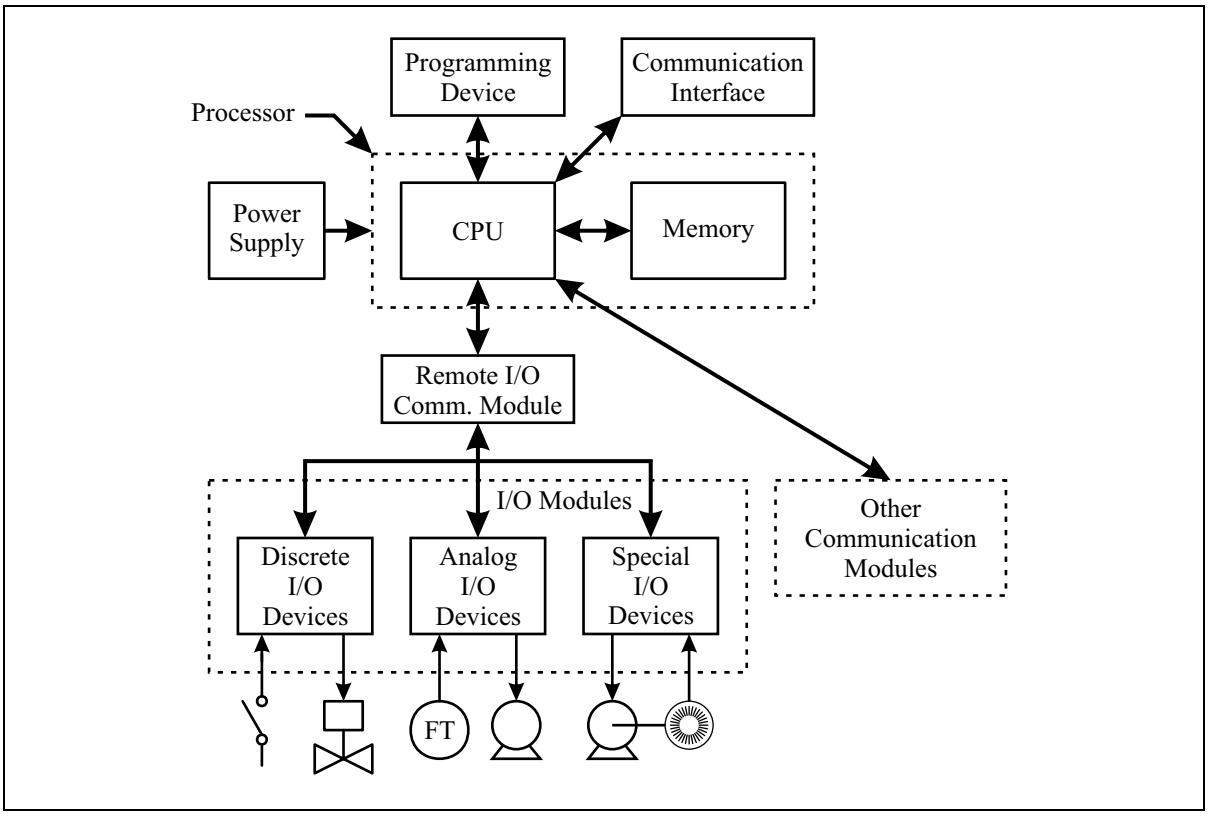

Figure 13-1. Basic PLC Architecture

chassis. Smaller PLCs are often mounted on a DIN rail. The smallest PLCs (often called *micro-PLCs* or *nano-PLCs*) include the power supply, processor, and all the I/O in one package. Some micro-PLCs contain a built-in operator-interface panel. For many micro-PLCs, the amount of I/O is limited and not expandable.

Basic Software and Memory Architecture (IEC 61131-3)

The International Electrotechnical Commission (IEC) 61131-3 programming language standard defines a memory and program model that follows modern software engineering concepts. This model incorporates such features as top-down design, structured programming, hierarchical organization, formal software interfaces, and program encapsulation. Fortunately, extensive training in software engineering techniques is not necessary to become a proficient programmer. If fully implemented, the model is reasonably complicated. The main disadvantages of the model are its complexity and its contradiction to the simplicity of the early PLCs.

Only the overall IEC 61131-3 memory program and memory model is described in this chapter. Various implementations of the standard are detailed in *Programmable Logic Controllers: An Emphasis on Design and Applications* (Erickson 2016). The IEC 61131-3 memory model (what the standard calls the *software model*) is presented in Figure 13-2. The model is layered (i.e., each layer hides many of the features of the layers beneath). Each of the main elements are described next.

- **Configuration** – The configuration is the entire body of software (program and data) that corresponds to a PLC system. Generally, a configuration equates with the

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Distributed Control Systems

By Douglas C. White

Introduction and Overview

Modern distributed control systems (DCSs) support the real-time management and control of major process plants. They provide the computing power, connectivity, and infrastructure to link measurement sensors, actuators, process control algorithms, and plant monitoring systems. They are extensively used in power generation plants and the continuous and batch process industries, and less commonly in discrete manufacturing factories.

DCSs were initially introduced in the 1970s and have subsequently been widely adopted. They convert field measurements to digital form, execute multiple control algorithms in a controller module, use computer screens and keyboards for the operator interface, and connect all components together with a single digital data network. The "distributed" in DCS implies that various sub-system control and communication tasks are performed in different physical devices. The entire system of devices is then connected via the digital control network that provides overall communication, coordination, and monitoring.

The continuing evolution of computing and communication capabilities that is evident in consumer electronics being cheaper, faster, and more reliable also impacts DCS developments. New functionality is continually being added.

The elements of a modern DCS are shown in Figure 14-1. As illustrated in the figure, DCS systems also provide the data and connectivity required for plant and corporate systems. In addition, they consolidate information from safety systems and machinery monitoring systems.

Major components of a typical system include input/output (I/O) processing and connectivity, control modules, operator stations, engineering/system workstations, application servers, and a process control network bus. These components are discussed in the following section.

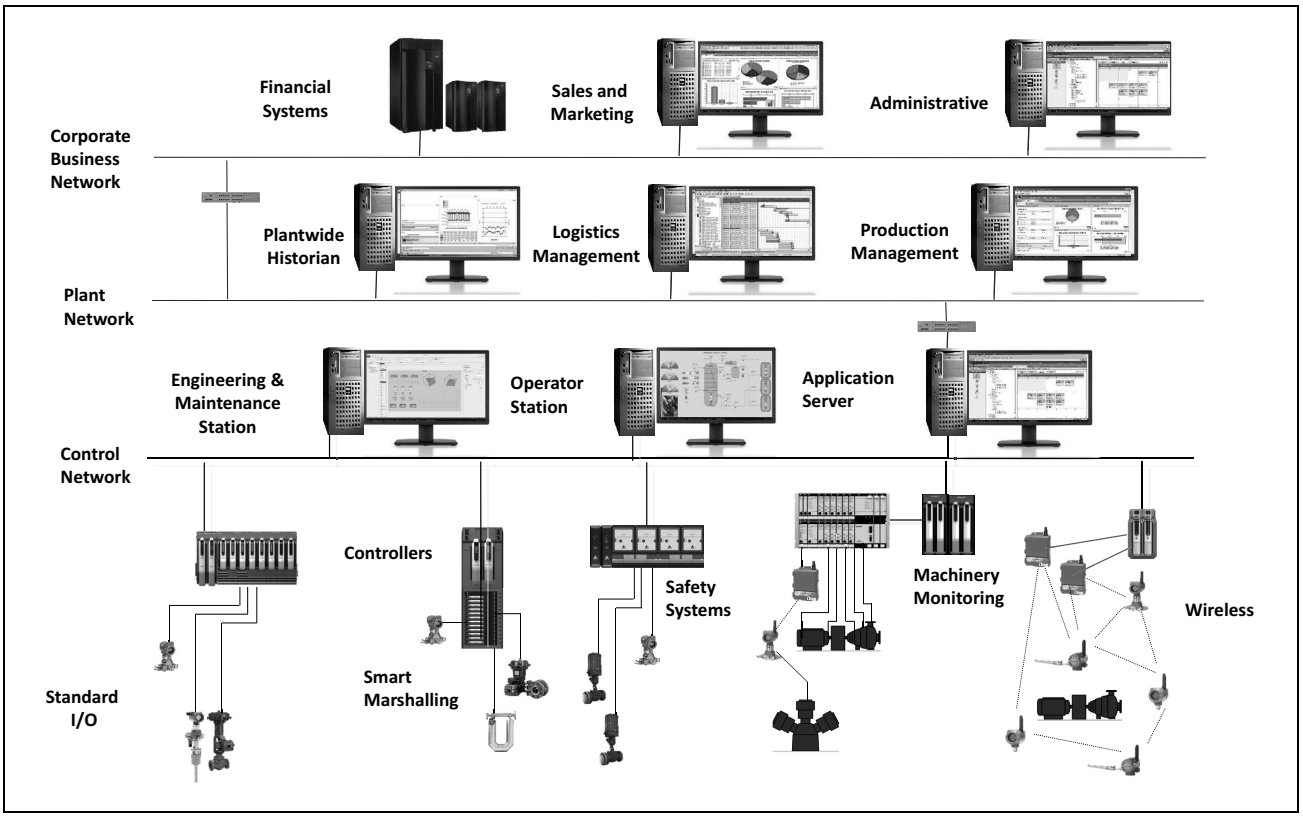

Figure 14-1. Elements of a Modern DCS
Source: Courtesy of Emerson Automation Solutions.

Input/Output Processing

The first step in control is to convert the sensed measurement into a digital value that can be evaluated by the control algorithms. It has been common in the past to bring all the input/output (I/O) in the plant to marshalling panels, perhaps located in the field, from which connections are made to the I/O terminations for the DCS controllers in the control center. Traditionally, this connection was a bundle of individual wires connecting the terminations in the marshalling panel to I/O connections at the controller and was called the *home run* cable.

Many types of equipment must be connected to a modern DCS, with different specific electronic and physical requirements for each interface. Each I/O type, discussed in the next section, requires its own specialized I/O interface that will convert the signal to the digital value used in the DCS. These interface devices are installed on an electronic bus that provides high-speed data transfer to the controller. Typically, the inputs will be accessed and converted approximately once per second with special control functions executing in the millisecond range. Modern marshalling panels can include embedded computing and communication capabilities, which are sometimes called configurable I/O. This permits the signal conversion to be done in the marshalling cabinet rather than in the DCS controller and the connection to the controller to be network wiring rather than a bundle of wires.

Large oil refineries, power stations, and chemical plants can have tens of thousands of measurements connected directly to the DCS with additional tens of thousands of readings accessed via communication links.

15

SCADA Systems: Hardware, Architecture, and Communications

By William T. (Tim) Shaw, PhD, CISSP, CPT, C|EH

In the world of industrial automation, there are processes that are geographically distributed over large areas, making it difficult, if not impossible, to interconnect all associated sites with local area network (LAN) technology. The classic examples are crude oil, refined products and gas pipelines, electric power transmission systems, water and sewage transportation and processing systems, and transportation infrastructure (e.g., highways, subways, railroads, etc.). The common theme in all these applications is the need to monitor and control large numbers of geographically distant sites, in real time, from some (distant) central location. In order to perform this task, supervisory control and data acquisition (SCADA) systems have been developed, evolving from earlier telemetry and data acquisition systems into today's powerful, computer-based systems. SCADA systems classically consist of three major elements: field-based controllers called *remote terminal units* (*RTUs*), a central control facility from which operations personnel monitor and control the field sites through the data-collecting *master terminal unit* (*MTU*, a term that predates computer-based systems) or a *host* computer system, and a wide-area communications system to link the field-based RTUs to the central control facility (as illustrated in Figure 15-1).

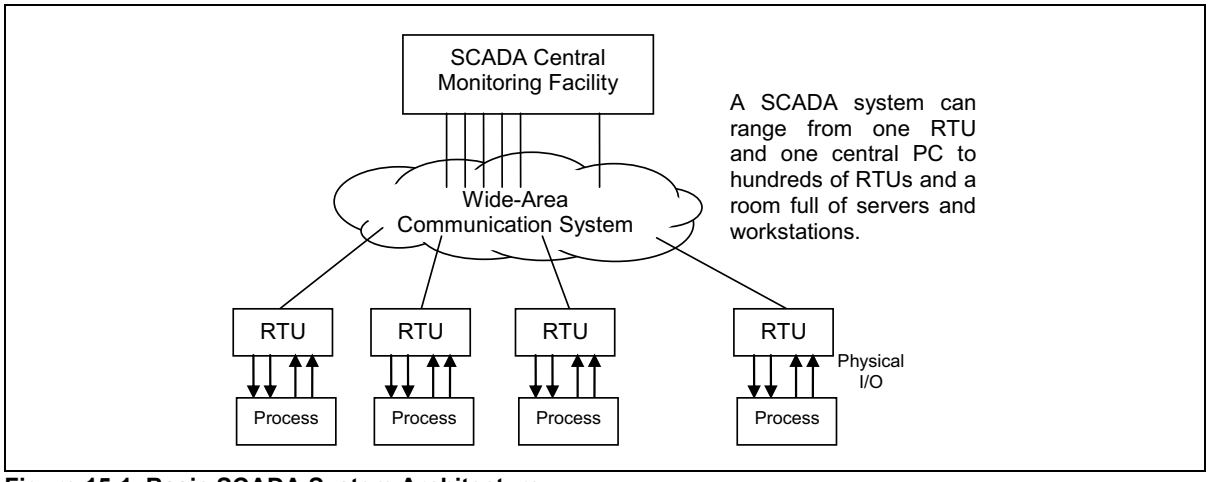

Figure 15-1. Basic SCADA System Architecture

Depending on the industry or the application, these three elements will have differences. For example, RTUs range in sophistication from "dumb" devices that are essentially just remote input/output (I/O) hardware with some form of serial communications, all the way to microprocessor-based devices capable of extensive local automatic control, sequential logic, calculations, and even wide area network (WAN) communications that are based on Internet Protocol (IP). In the water/waste industry, conventional industrial programmable logic controllers (PLCs) have become the dominant devices used as RTUs. In the pipeline industry, specialized RTUs have been developed due to a need for specialized volumetric calculations and the ability to interface with a range of analytical instruments. The electric utility RTUs have tended to be very basic, but today include units capable of direct high-speed sampling of the alternating current (AC) waveforms and the computing of real and reactive power, as well as spectral (harmonics) energy composition. One historic issue with RTUs has been the fact that every SCADA vendor tended to develop their own communication protocol as part of developing their own family of RTUs. This has led to a wide range of obsolete and ill-supported communication protocols, especially some old "bit-oriented" ones that require special communications hardware.

In the last decade, several protocols have either emerged as industry de facto standards (like Modbus, IEC 61850, and DNP3.0) or have been proposed as standards (like UCA2.0 and the various IEC protocols). There are vendors who manufacture protocol "translators" or gateways—microcomputers programmed with two or more protocols—so that old, legacy SCADA systems (that still use these legacy protocols) can be equipped with modern RTU equipment or so that new SCADA systems can communicate with an installed base of old RTUs. (If located adjacent to a field device/RTU, the typical protocol translator would support just two protocols—the one spoken by the RTU and the one spoken by the SCADA master. But if the protocol translator is located at the SCADA master, a gateway might support several protocols for the various field devices and convert them all to the one protocol used/preferred by the SCADA master.)

One of the most recent developments has been RTUs that are Internet Protocol (IP)-enabled meaning that they can connect to a Transmission Control Protocol/Internet Protocol (TCP/IP) network (usually via an Ethernet port) and offer one, or more, of the IP-based protocols like Modbus/TCP or Distributed Network Protocol/Internet Protocol (DNP/IP), or they are integrated using Inter-Control Center Communications Protocol (ICCP). RTUs with integral cellular modems or license-free industrial, scientific, and medical (or ISM) band radios (replacing the traditional licensed radios) have also come on the market.

Another recent development is the use of RTUs as data concentrators with interfaces (usually serial) to multiple smart devices at the remote site, so that all their respective data can be delivered to the SCADA system via a single communication channel. This is a variation on the master RTU concept where a given RTU polls a local set of smaller RTUs, thus eliminating the need for a communications channel to each RTU from the SCADA master. In a data concentrator application, the RTU may have little or no physical I/O, but it may have multiple serial ports and support multiple protocols. A variation often seen in the electric utility industry is RTUs that are polled by multiple SCADA masters (*multi-ported*), often using different communication protocols, as shown in Figure 15-2. This presents a unique challenge if the RTUs being shared have control outputs because some scheme is usually needed to

V

Process Control

Programming Languages

Programming languages, like any other language, describe using a defined set of instructions to put "words" together to create sentences or paragraphs to tell, in this case, the control equipment what to do. A variety of standardized programming languages, based on the programming languages in International Electrotechnical Commission (IEC) programming language standard IEC 61131-3, are recommended to ensure consistent implementation and understanding of the coding used to control the process to which the equipment is connected.

Process Modeling and Simulation

Process models can be broadly categorized as steady state and dynamic. A steady-state or dynamic model can be experimental or first principle. Steady-state models are largely used for process and equipment design and real-time optimization (RTO) of continuous processes, while dynamic models are used for system acceptance testing (SAT), operator training systems (OTS), and process control improvement (PCI).

Advanced Process Control

Advanced process control uses process knowledge to develop process models to make the control system more intelligent. The resulting quantitative process models can provide inferred controlled variables. This chapter builds on regulatory proportional-integral-derivative (PID) control to discuss both quantitative and qualitative models (such as fuzzy logic) to provide better tuning settings, set points, and algorithms for feedback and feedforward control.

16

Control System Programming Languages

By Jeremy Pollard

Introduction

Today's autonomous systems have some form of embedded intelligence that allows them to act and react, communicate and publish information in real time, and, in some cases, self-heal.

Driving this intelligence are instruction sets that have been employed in a specific programming language that a developer can use to create control programs.

Remember that *any* language is or has been created to have a core competency. English as a spoken language is different than French, for instance. However, the meaning of the spoken word is similar, if not the same.

Programming languages are much the same. They allow a developer to specify what the final functions will do, and the developer must then figure out how to put the "words" together to create a sentence or a paragraph that says and does what is needed. Also, choosing the correct hardware is key as it can sometimes limit a developer's available programming language abilities; however, a developer still needs to be able to compose that sentence or paragraph with the tools available. If a developer has a choice in which language is used, they must choose the right language for the task. That choice will affect:

- Future enhancements
- Maintenance situations
- General understanding of the task that it is performing
- Troubleshooting the system(s)
- Maintainability

When developing control system programs, a developer must be aware of the audience and the support available for the systems. A control program should not, for example, be written

in French when the team speaks only English. The task may be defined in English, however, the programming must be done in languages that the systems understand. That is what we as developers do.

Scope

This is not a programming course or a lesson on instruction sets as such. The intent is to introduce the various languages that most hardware vendors currently employ, of which there are many. Most vendors, however, use certain language standards because of their audience. Introducing these languages is the goal, along with the variants and extensions that some vendors have included in their control system offering(s).

The control system language is the translator that tells a system what to do. We will delve into the various options available for that translation to happen.

Legacy

The systems we use today may have been in operation for 10 years or more, and the systems we initiate now will be in operation for more than 10 years. The ebb and flow of technology and advancements assimilate into the industrial control space slowly because of this process longevity. The International Electrotechnical Commission (IEC) programming language standard, IEC 61131-3, for instance, was first published in 1993 and only now is beginning to gain some traction in the automation workplace. Embedded controls using IEC 61131-3 are becoming more prevalent for control systems. To quote a cliché, "The only thing that is constant is change." We need to be prepared for it at all times.

What Is a Control System?

This is a loaded question. We can make the argument that a control system is any system that controls. Profound, I know!

Think of a drink machine. The process of retrieving a can of soda is this:

- The user deposits money (or makes a payment of some sort) into the machine.
    - The system must determine if the right amount has been tendered.
- The machine gives the user a sign that it is OK to choose the type of soda.
    - It also must indicate if the chosen soda is out of stock.
- The machine delivers the can.

This process can happen in many ways. In the good old days, it was purely mechanical. But that mechanical system was still a control system. Today, most drink machines are electronic. They can accept various payment forms such as tap-and-go credit cards, cell phones, as well as cold-hard cash—coins or bills!

One of the first control systems this author ever tinkered with was a washing machine timer. It has no language as such, yet it is still a fundamental control system. It provides control for the task at hand, which is to wash clothes. These mechanical systems have given way to elec-

17 Process Modeling

By Gregory K. McMillan

Fundamentals

Process models can be broadly categorized as steady state and dynamic. Steady-state models are largely used for process and equipment design and real-time optimization (RTO) of continuous processes. Dynamic models are used for system acceptance testing (SAT), operator training systems (OTS), and process control improvement (PCI). A steady-state or dynamic model can be experimental or first principle. Experimental models are identified from process testing. First principle models are developed using the equations for charge, energy, material, and momentum balances; equilibrium relationships; and driving forces.

Steady-state models can be multivariate statistical, neural-network, or first principle models. Multivariate statistical and neural-network models are primarily used to detect abnormalities and make predictions in process operation. First principle steady-state models are widely used by process design engineers to develop process flow diagrams and, to a much lesser extent, by advanced control engineers for RTO.

Multivariate statistical and neural-network dynamic models presently rely on the insertion of dead-time blocks on process inputs to model the effect on downstream process outputs. The lack of a process time constant or integrating response means that these models cannot be used for testing feedback control systems. For batch processes, the prediction of batch endpoint conditions does not require dead-time blocks because synchronization with current values is not required.

Dynamic first principle models should include the dynamics of the automation system in addition to the process as shown in Figure 17-1. Valve and variable-speed drive (VSD) models should include the installed flow characteristic, resolution and sensitivity limits, deadband, dead time, and a velocity limited exponential response. Measurement models should include transportation delays, sensor lag and delay, signal filtering, transmitter damping, resolution and sensitivity limits, and update delays. For analyzers, the measurement models

should include sample transportation delays, cycle time, and multiplex time. Wireless devices should include the update rate and trigger level.

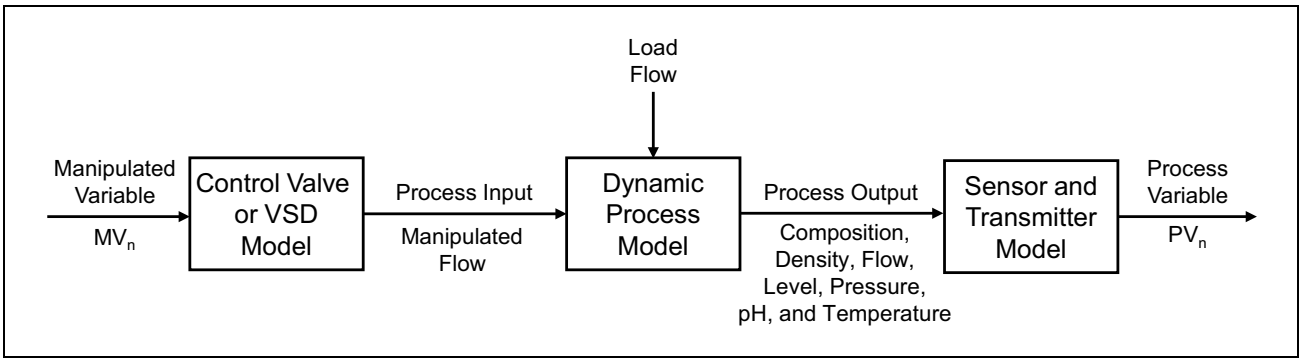

Figure 17-1. First Principle Dynamic Model

Step response models use an open-loop gain, total-loop dead time, and a primary—and possibly a secondary—time constant. The process gain is a steady-state gain for self-regulating processes. The process gain is an integrating process gain for integrating and runaway processes. The inputs and outputs of the step response model are deviation variables. The input is a change in the manipulated variable and the output is the change in the process variable (PV). The models identified by proportional-integral-derivative (PID) tuning and model predictive control (MPC) identification software take into account the controller scale ranges of the manipulated and process variables and include the effect of valve or variable speed drive and measurement dynamics. As a result, the process gain identified is really an open-loop gain that is the product of the valve or VSD gain, process gain, and measurement gain. The open-loop gain is dimensionless for self-regulating processes and has units of inverse seconds (1/sec) for integrating processes. Correspondingly, the process dead time is actually a total-loop dead time including the delays from digital components and analyzers, and equivalent dead time from small lags in the automation system. While the primary (largest) and secondary (second largest) time constants are normally in the process for composition and temperature control, they can be in the automation system for flow, level, and pressure control and for fouled sensors in all types of loops. Tieback models can be enhanced to use step response models that include the dynamics of the automation system.

Standard tieback models pass the PID output through a multiplier block for the open-loop gain and filter block for the primary time constant to create the PV input. The tieback inputs and outputs are typically in engineering units. Simple enhancements to this setup enables step response models, such as those shown in Figures 17-2a and b. These models can be used to provide a dynamic fidelity that is better than what can be achieved by first principle model, whose parameters have not been adjusted based on test runs. Not shown are the limits to prevent values from exceeding scale ranges.

The enhancement to the input of the standard tieback model is to subtract the normal operating value of the manipulated variable ($\%MV_o$) from the new value of the manipulated variable ($\%MV_n$) to create a deviation variable ($\Delta\%MV$) that is the change in the manipulated variable. The enhancement to the output is to add the normal operating value of the process variable ($\%PV_o$) to the deviation variable ($\Delta\%PV$) to provide the new value of the process variable ($\%PV_n$). A dead-time block for the total-loop dead time (θ_o) and a filter block for the

18

Advanced Process Control

By Gregory K. McMillan

Fundamentals

In advanced process control, process knowledge by way of process models is used to make the control system more intelligent. The process modeling topic (Chapter 17) shows how quantitative process models can provide process knowledge and inferential measurements, such as stream compositions, that can be less expensive, faster, and more reliable than the measurements from field analyzers. The quantitative models from Chapter 17 are used in this chapter to provide better tuning settings, set points, and models and algorithms for feedback and feedforward control.

Advanced PID Control

A fuzzy logic controller (FLC) is not detailed here, because it has recently been shown that proportional-integral-derivative (PID) tuning and various options can make a PID do as well or better than a FLC. There are some niche applications for FLC, such as in mineral processing due to indeterminate process dynamics and missing measurements.

For unmeasured disturbances, the PID has proven to provide near-optimal control minimizing the peak and integrated errors. The improvement over other control algorithms is most noticeable for processes that do not achieve a steady state in the time frame of the PID response (e.g., 4 dead times). Processes with a large time constant, known as *lag dominant* or *near-integrating*, with a true integrating response (e.g., batch, level, or gas pressure), or *runaway* response (e.g., highly exothermic reactors), need a more aggressive feedback correction by a PID to deal with the fact that the process response tends to ramp or even accelerate. For these processes, a high PID gain, derivative action, and overdriving the manipulated variable (flow) past the final resting value are essential for good control and safe operation.

If disturbances can be measured, feedforward signals whose magnitude and timing are accurate to within 10% can provide a 10:1 reduction in errors by preemptive correction and coordination of flows. When the process controller directly manipulates a control valve, the

feedforward can be integrated into the PID controller via a feedforward option in the PID. The control valve must have a linear installed characteristic or a signal characterizer must be used to provide linearization and a PID output in percent flow.

When a primary process controller manipulates a secondary flow loop set point (SP), implementing a flow feedforward is best done via a ratio and bias/gain stations to ratio a follower flow to a leader flow. Figure 18-1 shows the ratio control setup for volumes with mixing as seen in agitated vessels and in columns due to boiling and reflux. For these volumes, the process control of composition, pH, and temperature for continuous besides batch operations do not have a steady state in the PID response time frame. Increases in feed flow have an offsetting effect on PID tuning by decreasing the process gain and time constant. Correction of the ratio set point (multiplying factor) by the process controller would introduce nonlinearity. Here, the feedback correction is best done by means of a bias. The bias correction can be gradually minimized by an adaptive integral-only controller slowly correcting the ratio set point when the ratio station is in the cascade (remote set-point) mode. The operator can see the desired versus the current ratio and take over control of the ratio set point by putting the ratio station in the automatic (local set-point) mode. This feature is particularly important for the start up of distillation columns before the column has reached operating conditions (before temperature is representative of composition). A typical example is steam to feed flow and distillate to feed flow ratio control for a distillation column. Ratio control operability and visibility is important for many unit operations.

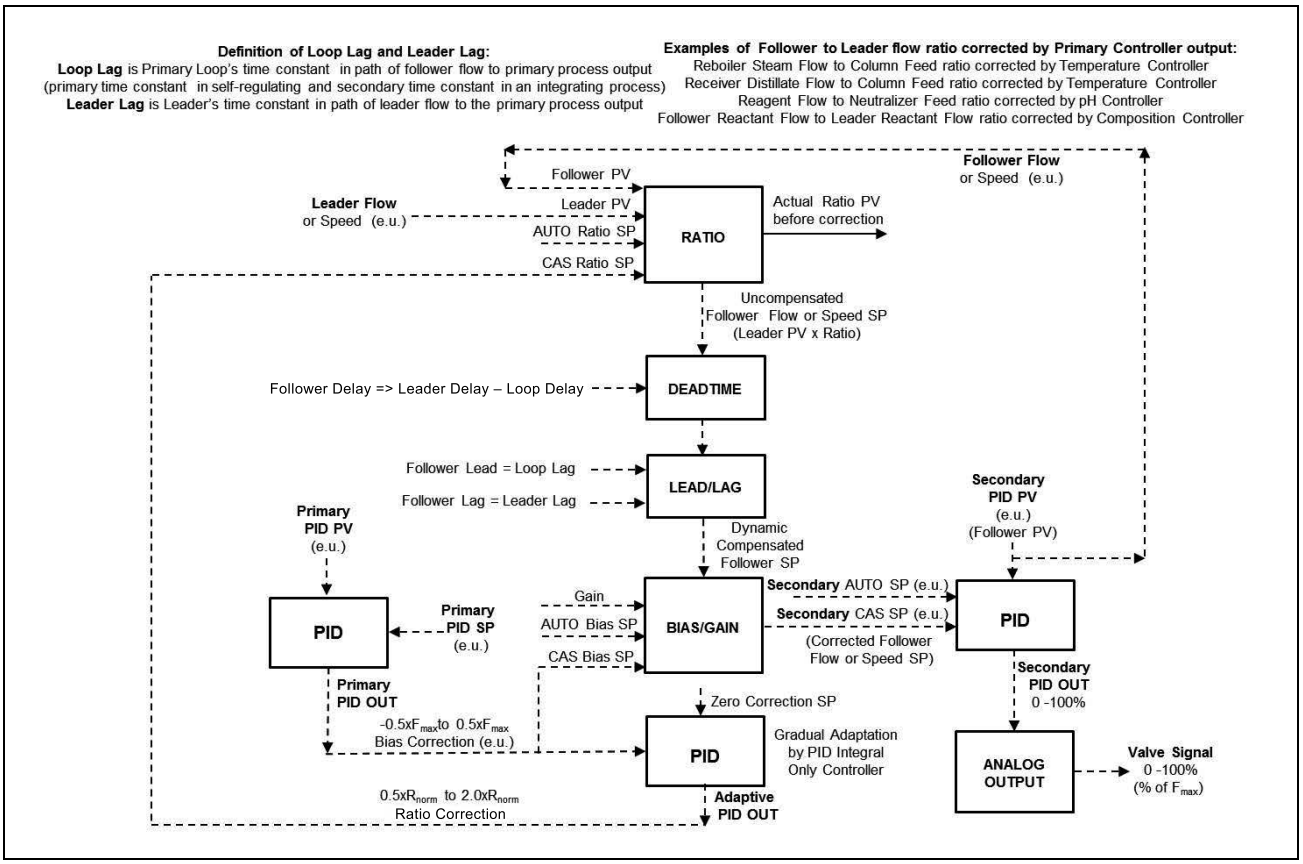

Figure 18-1. Flow Ratio Control for Vessels and Columns with a Bias for Secondary PID Flow Set Point Corrected by Primary PID and a Ratio Set Point that is Visible and Adjustable by Operator and Gradually Optimized by an Adaptive PID

VI

Operator Interaction

Operator Training

Operator training continues to increase in importance as systems become more complex, and the operator is expected to do more and more. It sometimes seems that, the more we automate, the more important it is for the operator to understand what to do when that automation system does not function as designed. This topic ties closely with the modeling topic because simulated plants allow more rigorous operator training.

Operator Interface: Human-Machine Interface (HMI) Software

Operator interfaces, data management, and other types of software are now basic topics for automation professionals, and they fit in this category better than anywhere else. Packaged automation software that is open with respect to Open Platform Communications (OPC) covers a significant portion of the needs of automation professionals; however, custom software is still needed in some cases. That custom software must be carefully designed and programmed to perform well and be easily maintained.

Alarm Management

Alarm management has become a very important topic in the safety area. The press continues to report plant incidents caused by poorly designed alarms, alarm flooding, and alarms being bypassed. Every automation professional should understand the basic concepts of this topic.

19 Operator Training

By Bridget A. Fitzpatrick

Introduction

Advances in process control and safety system technology enable dramatic improvements in process stability and overall performance. With fewer upsets, operators tend to make fewer adjustments to the process. Additionally, as the overall level of automation increases, there is less human intervention required. With less human intervention, there is less "hands on" learning.

However, even the best technology fails to capture the operators' knowledge of the real-time constraints and complex interactions between systems. The console operator remains integral to safe, efficient, and cost-effective operation. Operator training manages operator skills, knowledge, and behaviors.

Optimizing overall operations performance is a complex undertaking that includes a review of process design, safety system design, the level of automation, staffing design, shift schedules, and individual job design across the entire operations team. This chapter focuses on control room operator training.

Evolution of Training

In early control rooms, panel-board operator training was traditionally accomplished through a progression from field operator to control room operator. This progression was commonly accomplished through on-the-job training (OJT) where an experienced operator actively mentored the student worker. As process and automation technology has advanced, these early methods have been augmented with a mix of training methods. These methods and the advantages and disadvantages of each will be discussed in the following sections.

The Training Process

A successful training program is based on understanding that training is not a single pass program, but an ongoing process. This is complicated by continual changes in both human resources and the process itself. A successful program requires support for initial training and qualification, training on changes to the process and related systems, and periodic refresher training. Developing and maintaining operator skills, knowledge, and behavior is central to operational excellence.

Training Process Steps

The key steps of the training process include setting learning objectives (functional requirements), training design, materials and methods testing, metrics selection, training delivery, assessment, and continual improvement.

Learning objectives define the expected learning outcomes or identified needs for changes to student skills, knowledge, or behaviors. This applies for each segment of training, as well as for the overall training program.

Training design includes design work to define the best training delivery methods to be used to meet the functional requirements, schedule, and budget.

Materials and methods testing refines the design and includes a "dry run" testing phase to ensure that materials are effective at meeting functional requirements on a small scale. For a new program, testing all major methods on a small scale is recommended to ensure that the technologies in use and the training staff are executing successfully.

Metrics selection is important to ensure that a baseline of student performance is available prior to training and to ensure that all personnel have a clear understanding of expectations.

Training delivery is the execution phase of the training, which should include continual feedback, such as instructor-to-student, student-to-instructor, and peer feedback in the student and instructor populations.

The assessment phase includes evaluating the success of both the student learning and the training program. Student learning assessment can be formal or informal. It can be performed internally or by a third party. The proper method depends on the nature of the subject. Assessment of the training program requires feedback from the participants on training relevance, style, presentation, and perceived learning. This feedback can be gathered by anonymous post-training questionnaires or follow-up discussions.

For the training program's continuous improvement, it is recommended to include an improvement phase to refine and adjust content and work processes. If training materials are largely electronic or prepared in small batches, continual improvement is not hampered by cost concerns.

Role of the Trainer

Depending on the scope of the objectives, a range of limited part-time to multiple dedicated training staff may be required.

20

Effective Operator Interfaces

By Bill Hollifield

Introduction and History

The human-machine interface (HMI) is the collection of monitors, graphic displays, keyboards, switches, and other technologies used by the operator to monitor and interact with a modern control system (typically a distributed control system [DCS] or supervisory control and data acquisition system [SCADA]). The design of the HMI plays a vital role in determining the operator's ability to effectively manage the process, particularly in detecting and responding to abnormal situations. The primary issues with modern process HMIs are the design and content of the process graphics displayed to the operator.

As part of the changeover to digital control systems in the 1980s and 1990s, control engineers were given a new task for which they were ill prepared. The new control systems included the capability to display real-time process control graphics for the operator on cathode ray tube (CRT) screens. However, the screens were blank and it was the purchaser's responsibility to come up with graphic depictions for the operator to use to control the process.

Mostly for convenience, and in the absence of a better idea, it was chosen to depict the process as a piping and instrumentation drawing or diagram (P&ID) view covered in live numbers (Figure 20-1). Later versions added distracting 3D depictions, additional colors, and animation. The P&ID is a process design tool that was never intended to be used as an HMI, and such depictions are now known to be a suboptimal design for the purposes of overall monitoring and control of a process. However, significant inertia associated with HMI change has resulted in such depictions remaining commonplace. Poor graphics designed over 20 years ago have often been migrated, rather than improved, even as the underlying control systems were upgraded or replaced multiple times.

For many years, there were no available guidelines as to what constituted a "good" HMI for control purposes. During this time, poorly designed HMIs have been cited as significant contributing factors to major accidents. The principles for designing effective process

graphics are now available, and many industrial companies have graphic improvement efforts underway.

An effective HMI has many advantages, including significantly improved operator situation awareness; increased process surveillance; better abnormal situation detection and response; and reduced training time for new operators.

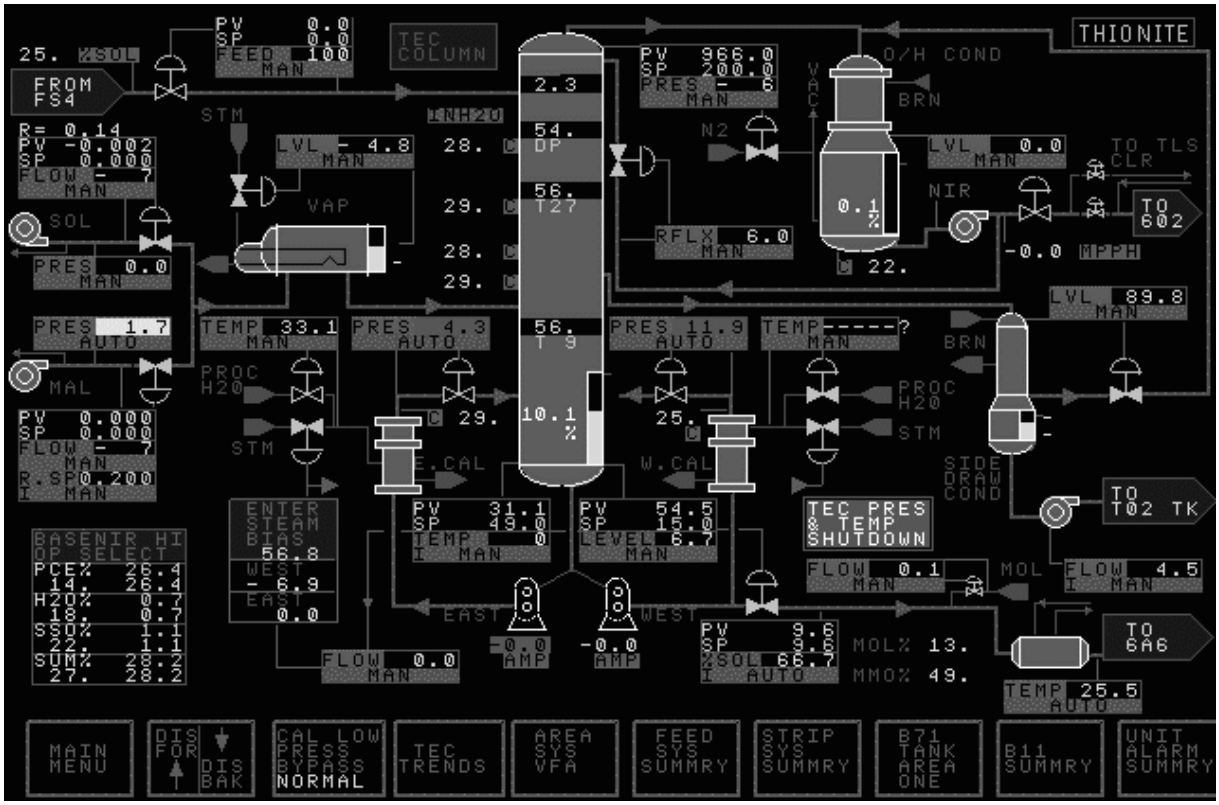

Figure 20-1. A Typical, Poor 1990s Graphic Screen Based on a P&ID

Basic Principles for an Effective HMI

This chapter provides an overview of effective practices for the creation of an improved process control HMI. The principles apply to modern, screen-based control systems and to any type of process (e.g., petrochemical, refining, power generation, pharmaceutical, mining). Application of these principles will significantly improve the operator's ability to detect and successfully resolve abnormal situations. This chapter's topics include:

- Appropriate and consistent use of color
- The display of information rather than raw data
- Depiction of alarms
- Use of embedded trends
- Implementation of a graphic hierarchy
- Embedded information in context

21
Alarm Management

By Nicholas P. Sands

Introduction

The term *alarm management* refers to the processes and practices for determining, documenting, designing, monitoring, and maintaining alarms from process automation and safety systems. The objective of alarm management is to provide the operators with a system that gives them an indication at the right time, to take the right action, to prevent an undesired consequence. The ideal alarm system is a blank banner or screen that only has an alarm for the operator when an abnormal condition occurs and clears to a blank banner or screen when the right action is taken to return to normal conditions.

Most alarm systems do not work that way in practice. The common problems of alarm management are well documented. The common solutions to those common problems are also well documented in ANSI/ISA-18.2, *Management of Alarm Systems for the Process Industries,* and the related technical reports. This chapter will describe the activities of alarm management following the alarm management life cycle, how to get started on the journey of alarm management, and which activities solve which of the common problems. The last section discusses safety alarms.

Alarm Management Life Cycle

The alarm management life cycle was developed as a framework to guide alarm management activities and map them to other frameworks like the phases of a project. A goal of the life-cycle approach to alarm management is continuous improvement, as the life-cycle activities continue for the life of the facility. The alarm management life cycle is shown in Figure 21-1 [1].

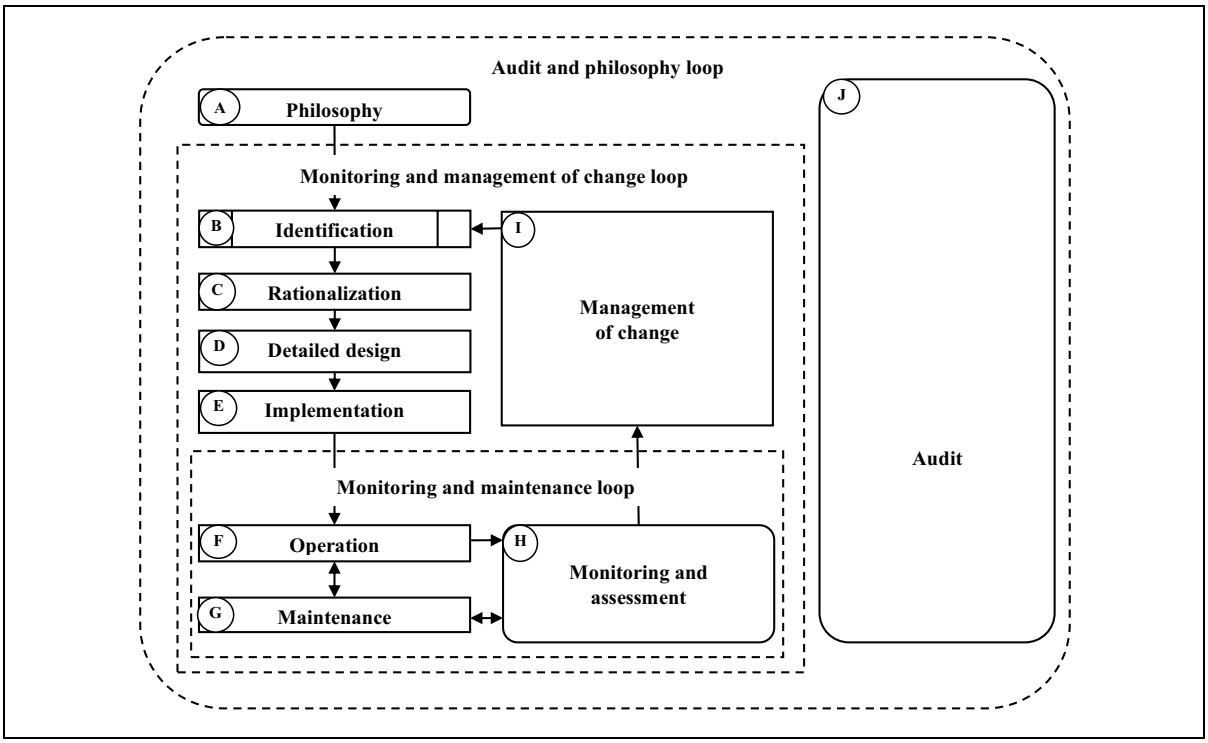

Figure 21-1. Alarm Management Life Cycle

Philosophy

A key activity in the alarm management life cycle is the development of an alarm management philosophy; a document that establishes the principles and procedures to consistently manage an alarm system over time. The philosophy does not specify the details of any one alarm, but defines each of the key processes used to manage alarm systems: rationalization, design, training, monitoring, management of change, and audit. Alarm system improvement projects can be implemented without a philosophy, but the systems tend to drift back toward the previous performance. Maintaining an effective alarm system requires the operational discipline to follow the practices in the alarm philosophy.

The philosophy includes definitions. Of those definitions, the most important is the one for alarm:

> *…audible and/or visible means of indicating to the operator an equipment malfunction, process deviation, or abnormal condition requiring a timely response* [1].

This definition clarifies that alarms are indications

- that may be audible, visible, or both,
- of abnormal conditions and not normal conditions,
- to the operator,
- that require a response, and
- that are timely.

Much of alarm management is the effort to apply this definition.

VII

Safety

HAZOP Studies

Hazard and operability studies (HAZOP), also termed HAZOP analysis or just HAZOP, are systematic team reviews of process operations to determine what can go wrong and to identify where existing safeguards are inadequate and risk-reduction actions are needed. HAZOP studies are often required to comply with regulatory requirements, such as the U.S. Occupational Safety and Health Administration's (OSHA's) Process Safety Management Standard (29?CFR 1910.119), and are also used as the first step in determining the required safety integrity level (SIL) for safety instrumented functions (SIFs) to meet a company's predetermined risk tolerance criteria.

Safety Life Cycle

A basic knowledge of reliability is fundamental to the concepts of safety and safety instrumented systems. Process safety and safety instrumented systems (SISs) are increasingly important topics. Safety is important in all industries, especially in large industrial processes, such as petroleum refineries, chemicals and petrochemicals, pulp and paper mills, and food and pharmaceutical manufacturing. Even in areas where the materials being handled are not inherently hazardous, personnel safety and property loss are important concerns. SIS is simple in concept but requires a lot of engineering to apply well.

Reliability

In the field of reliability engineering, the primary metrics employed include reliability, unreliability, availability, unavailability, and mean time to failure (MTTF). Failure modes, such as safety-instrumented function (SIF) verification, also need to be considered.

22
HAZOP Studies

By Robert W. Johnson

Application

Hazard and operability studies (HAZOPs), also termed HAZOP analyses or just HAZOPS, are systematic team reviews of process operations to determine what can go wrong and to identify where existing safeguards are inadequate and risk-reduction actions are needed. HAZOP Studies are typically performed on process operations involving hazardous materials and energies. They are conducted as one element of managing process risks, and are often performed to comply with regulatory requirements such as the U.S. Occupational Safety and Health Administration's (OSHA's) Process Safety Management Standard (29 CFR 1910.119). HAZOP Studies are also used as the first step in determining the required safety integrity level (SIL) for safety instrumented functions (SIFs) to meet a company's predetermined risk tolerance criteria in compliance with IEC 61511, *Functional Safety: Safety Instrumented Systems for the Process Industry Sector*. An international standard, IEC 61882, is also available that addresses various applications of HAZOP Studies.

Planning and Preparation

HAZOP Studies require significant planning and preparation, starting with a determination of which company standards and regulatory requirements need to be met by the study. The study scope must also be precisely determined, including not only the physical boundaries but also the operational modes to be studied (continuous operation, start-up/shutdown, etc.) and the consequences of interest (e.g., safety, health, and environmental impacts only, or operability issues as well). HAZOP Studies may be performed in less detail at the early design stages of a new facility, but are generally reserved for the final design stage or for operating facilities.

HAZOP Studies are usually conducted as team reviews, with persons having operating experience and engineering expertise being essential to the team. Depending on the process to be studied, other backgrounds may also need to be represented on the team for a thorough review, such as instrumentation and controls, maintenance, and process safety. Study teams

have one person designated as the *facilitator*, or team leader, who is knowledgeable in the HAZOP Study methodology and who directs the team discussions. Another person is designated as the *scribe* and is responsible for study documentation.

Companies often require a minimum level of training and experience for study facilitators. To be successful, management must commit to providing trained resources to facilitate the HAZOP Study and to making resources available to address the findings and recommendations in a timely manner.

A facilitator or coordinator needs to ensure all necessary meeting arrangements are made, including reserving a suitable meeting room with minimum distractions and arranging any necessary equipment. For a thorough and accurate study to be conducted, the review team will need to have ready access to up-to-date operating procedures and process safety information, including such items as safety data sheets, piping and instrumentation diagrams, equipment data, materials of construction, established operating limits, emergency relief system design and design basis, and information on safety systems and their functions.

Nodes and Design Intents

The first step in the HAZOP Study is to divide the review scope into *nodes* or *process segments*. Adjacent study nodes will generally have different relevant process parameters, with typical study nodes being vessels (with parameters of importance such as level, composition, pressure, temperature, mixing, and residence time) and transfer lines (with parameters such as source and destination locations, flow rate, composition, pressure, and temperature).

Nodes are generally studied in the same direction as the normal process flow. The HAZOP Study team begins the analysis of each node by determining and documenting its design intent, which defines the boundaries of "normal operation" for the node. This is a key step in the HAZOP Study methodology because the premise of the HAZOP approach is that loss events occur only when the facility deviates from normal operation (i.e., during abnormal situations).

The design intent should identify the equipment associated with the node including source and destination locations, the intended function(s) of the equipment, relevant parameters and their limits of safe operation, and the process materials involved including their composition limits. An example of a design intent for a chemical reactor might be to:

> Contain and control the complete reaction of 1,000 kg of 30% A and 750 kg of 98% B in EP-7 by providing mixing and external cooling to maintain 470–500°C for 2 hours, while venting off-gases to maintain < 100 kPa gauge pressure.

For procedure-based operations such as unloading or process start-up, the established operating procedure or batch procedure is an integral part of what defines "normal operation."

Scenario Development: Continuous Operations

Figure 22-1 illustrates how the HAZOP Study methodology interfaces with a typical incident sequence to develop possible incident scenarios associated with a study node. Terminology in this figure is consistent with the definitions in the *Guidelines for Hazard Evaluation Proce-*

23

Safety Instrumented Systems in the Process Industries

By Paul Gruhn, PE, CFSE

Introduction

Safety instrumented systems (SISs) are one means of maintaining the safety of process plants. These systems monitor a plant for potentially unsafe conditions and bring the equipment, or the process, to a safe state if certain conditions are violated. Today's SIS standards are performance-based, not prescriptive. In other words, they do not mandate technologies, levels of redundancy, test intervals, or system logic. Essentially, they state, "the greater the level of risk, the better the safety systems needed to control it."

Hindsight is easy. Everyone always has 20/20 hindsight. *Foresight*, however, is a bit more difficult. Foresight is required with today's large, high-risk systems. We simply cannot afford to design large petrochemical plants by trial and error. The risks are too great to learn that way. We have to try to prevent certain accidents, no matter how remote the possibility, even if they have not yet happened. This is the subject of *system safety*.

There are a number of methods for evaluating risk. There are also a variety of methods for equating risk to the performance required of a safety system. The overall design of a safety instrumented system (SIS) is not a simple, straightforward matter. The total engineering knowledge and skills required are often beyond that of any single person. An understanding is required of the process, operations, instrumentation, control systems, and hazard analysis. This typically calls for the interaction of a multidisciplined team.

Experience has shown that a detailed, systematic, methodical, well-documented design process or methodology is necessary in the design of SISs. This is the intent of the safety life cycle, as shown in Figure 23-1.

The intent of the life cycle is to leave a documented, auditable trail, and to make sure that nothing is neglected or falls between the inevitable cracks within every organization. Each phase or step of the life cycle can be defined in terms of its objectives, inputs (requirements to complete that phase), and outputs (the documentation produced). These steps and their

objectives, along with the input and output documentation required to perform them, are briefly summarized below. The steps are described in more detail later in this chapter.

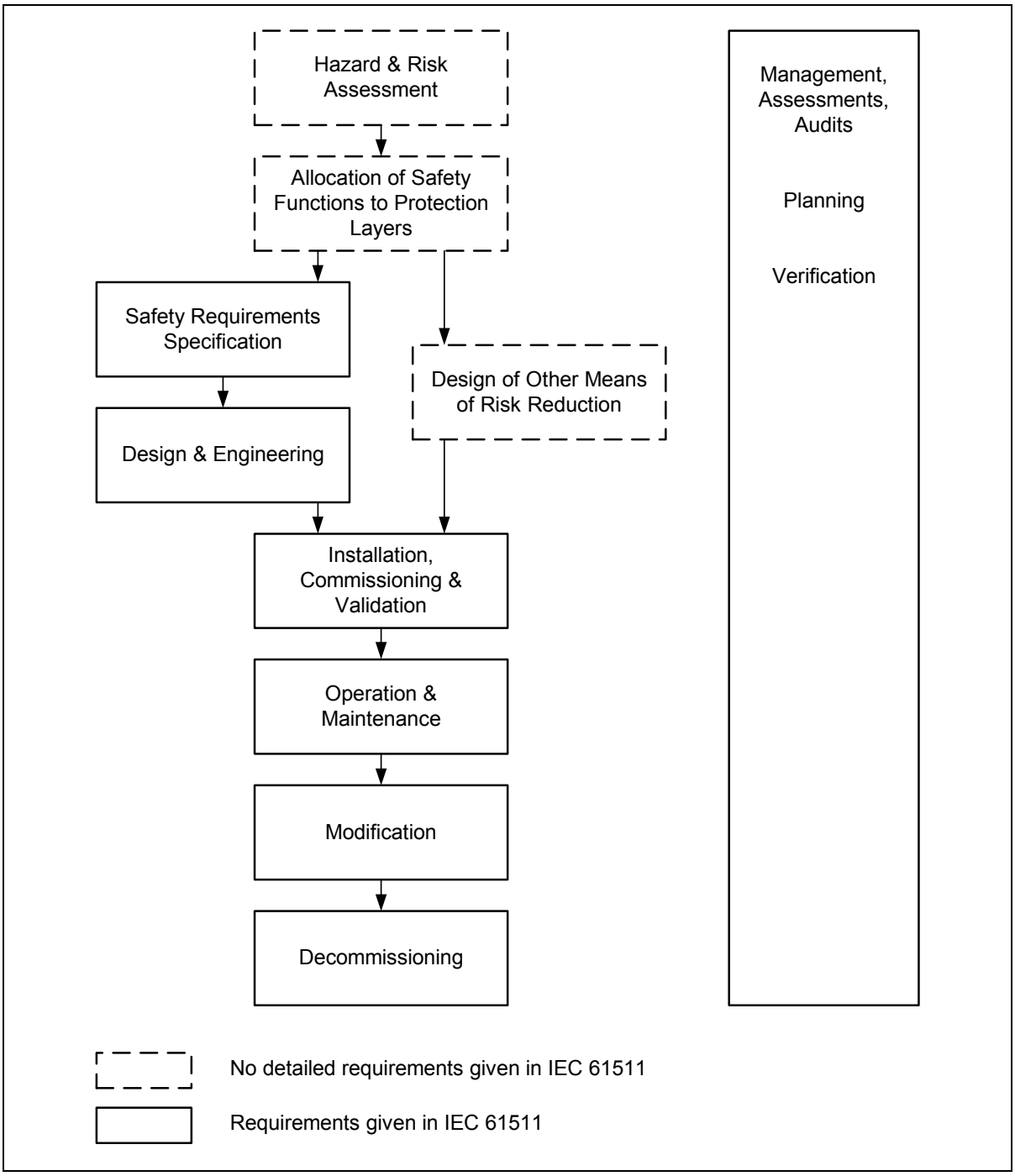

Figure 23-1. ISA 84/IEC 61511 Safety Life Cycle

24 Reliability

By William Goble

Introduction

There are several common metrics used within the field of reliability engineering. Primary ones include reliability, unreliability, availability, unavailability, and mean time to failure (MTTF). However, when different failure modes are considered, as they are when doing safety instrumented function (SIF) verification, then new metrics are needed. These include probability of failing safely (PFS), probability of failure on demand (PFD), probability of failure on demand average (PFD_{avg}), mean time to failure spurious ($MTTF^{SPURIOUS}$), and mean time to dangerous failure ($MTTF^{D}$).

Measurements of Successful Operation: No Repair

Probability of success – This is often defined as the probability that a system will perform its intended function when needed and when operated within its specified limits. The phrase at the end of the last sentence tells the user of the equipment that the published failure rates apply only when the system is not abused or otherwise operated outside of its specified limits.

Using the rules of reliability engineering, one can calculate the probability of successful operation for a particular set of circumstances. Depending on the circumstances, that probability is called *reliability* or *availability* (or, on occasion, some other name).

Reliability – A measure of successful operation for a specified interval of time. Reliability, $R(t)$, is defined as the probability that a system will perform its intended function when required to do so if operated within its specified limits for a specified operating time interval (Billinton 1983). The definition includes five important aspects:

1. The system's *intended function* must be known.
2. *When the system is required to function* must be judged.

3. *Satisfactory performance* must be determined.
4. The *specified design limits* must be known.
5. An operating time interval is specified.

Consider a newly manufactured and successfully tested component. It operates properly when put into service ($T = 0$). As the operating time interval (T) increases, it becomes less likely that the component will remain successful. Since the component will eventually fail, the probability of success for an infinite time interval is zero. Thus, all reliability functions start at a probability of one and decrease to a probability of zero (Figure 24-1).

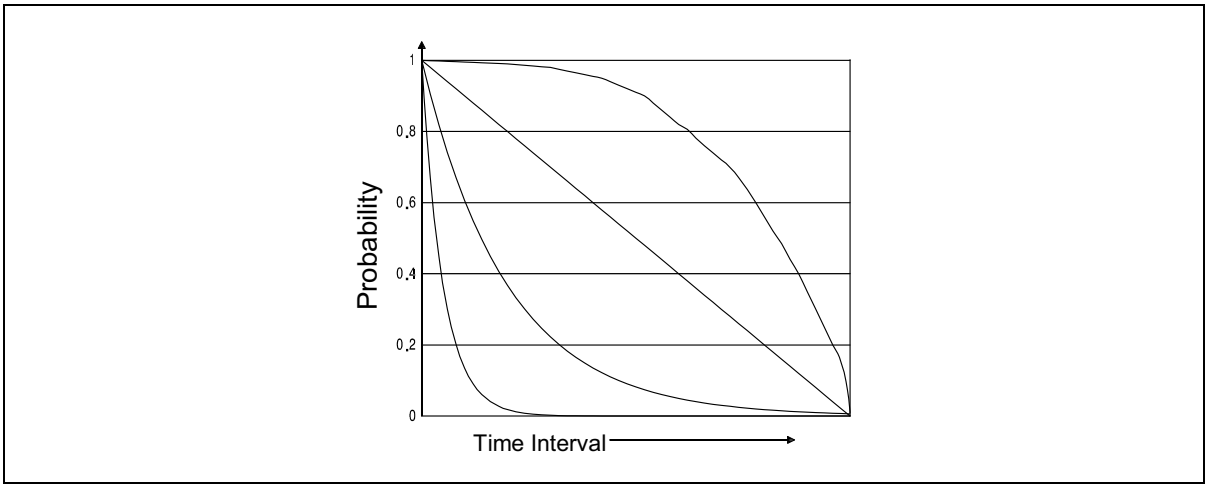

Figure 24-1. Example Reliability Plots

Reliability is a function of the operating time interval. A statement such as "system reliability is 0.95" is meaningless because the time interval is not known. The statement "the reliability equals 0.98 for a mission time of 100 hours" makes perfect sense.

A reliability function can be derived directly from probability theory. Assume the probability of successful operation for a 1-hour time interval is 0.999. What is the probability of successful operation for a 2-hour time interval? The system will be successful only if it is successful for both the first hour and the second hour. Therefore, the 2-hour probability of success equals:

$$0.999 \bullet 0.999 = 0.998 \tag{24-1}$$

The analysis can be continued for longer time intervals. For each time interval, the probability can be calculated by the equation:

$$P(t) = 0.999t \tag{24-2}$$

Figure 24-2 shows a plot of probability versus operating time using this equation. The plot is a reliability function.

Reliability is a metric originally developed to determine the probability of successful operation for a specific "mission time." For example, if a flight time is 10 hours, a logical question is, "What is the probability of successful operation for the entire flight?" The answer would be the *reliability* for the 10-hour duration. It is generally a measurement applicable to situa-

VIII

Network Communications

Analog Communications

This chapter provides an overview of the history of analog communications from direct mechanical devices to the present digital networks, and it also puts the reasons for many of the resulting analog communications standards into context through examples of the typical installations.

Wireless

Wireless solutions can dramatically reduce the cost of adding measurement points, making it feasible to include measurements that were not practical with traditional wired solutions. This chapter provides an overview of the principle field-level sensor networks and items that must be considered for their design and implementation.

Cybersecurity

Integrating systems and communications is now fundamental to automation. While some who work in a specific area of automation may have been able to avoid a good understanding of these topics, that isolation is rapidly coming to an end. With the rapid convergence of information technology (IT) and operations technology (OT), network security is a critical element in an automation professional's repertoire.

Many IT-based tools may solve the integration issue; however, they usually do not deal with the unique real-time and security issues in automation, and they often ignore the plant-floor issues. As a result, no topic is hotter today than network security—including the Internet. Automation professionals who are working in any type of integration must pay attention to the security of the systems.

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Analog Communications

By Richard H. Caro

The earliest process control instruments were mechanical devices in which the sensor was directly coupled to the control mechanism, which in turn was directly coupled to the control valve. Usually, a dial indicator was provided to enable the process variable value to be read. These devices are still being used today and are called *self-actuating controllers* or often just *regulators.* These mechanical controllers often take advantage of a physical property of some fluid to operate the final control element. For example, a fluid-filled system can take advantage of the thermal expansion of the fluid to both sense temperature and operate a control valve. Likewise, process pressure changes can be channeled mechanically or through filled systems to operate a control valve. Such controllers are proportional controllers with some gain adjustment available through mechanical linkages or some other mechanical advantage. We now know that they can exhibit some offset error.

While self-actuating controllers (see Figure 25-1) are usually low-cost devices, it was quickly recognized that it would be easier and safer for the process operator to monitor and control processes if there was an indication of the process variable in a more convenient and protected place. Therefore, a need was established to communicate the process variable from the sensor that remained in the field to a remote operator panel. The mechanism created for this communication was air pressure over the range 3–15 psi. This is called *pneumatic transmission*. Applications in countries using the metric system required the pressure in standard international units to be 20–100 kPa, which is very close to the same pressures as 3–15 psi. The value of using 3 psi (or 20 kPa) rather than zero is to detect failure of the instrument air supply. The value selected for 100% is 15 psi (or 100 kPa) because it is well below nominal pressures of the air supply for diagnostic purposes.

However, the operator still had to go to the field to change the set point of the controller. The solution was to build the controller into the display unit mounted at the operator panel using pneumatic computing relays. The panel-mounted controller could be more easily serviced than if it was in the field. The controller output was in the 3–15 psi air pressure range and piped to a control valve that was, by necessity, mounted on the process piping in the field. The control valve was operated by a pneumatic actuator or force motor using higher-pres-

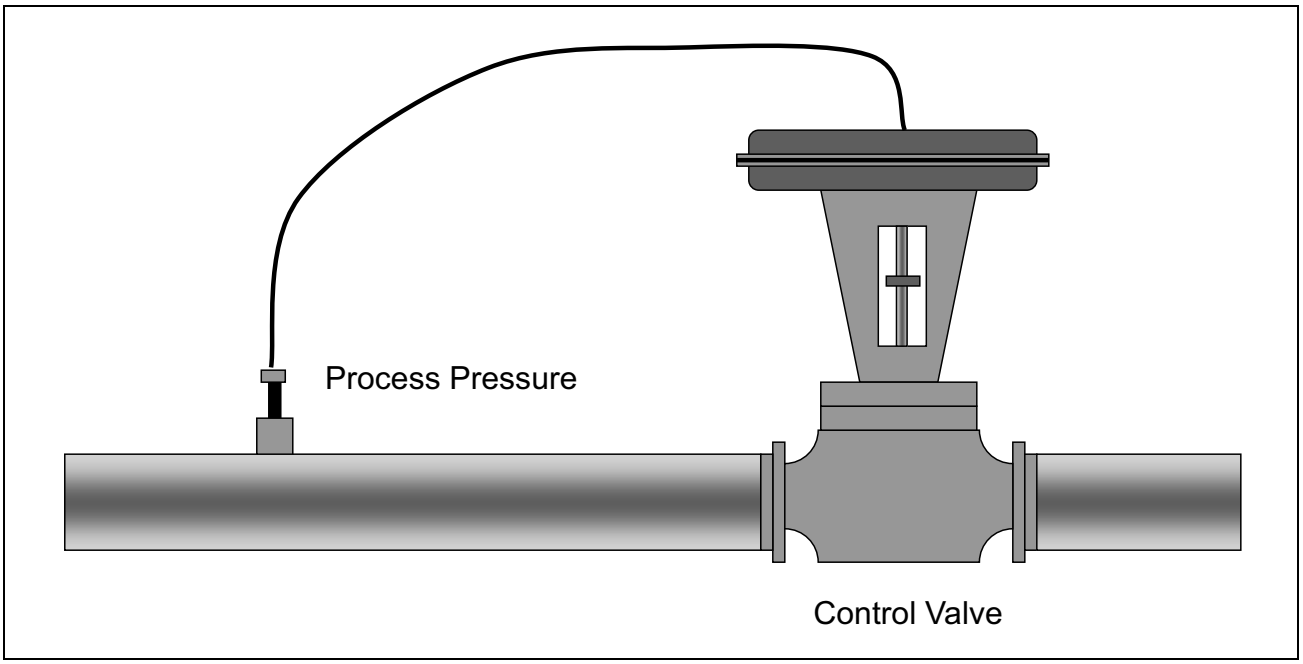

Figure 25-1. Self-Actuating Controller (Back Pressure Regulator)

sure air for operation. Once the pneumatic controller was created, innovative suppliers soon were able to add integral and derivative control to the original proportional control in order to make the control more responsive and to correct for offset error. Additionally, pneumatic valve positioners were created to provide simple feedback control for control valve position. A pneumatic control loop is illustrated in Figure 25-2.

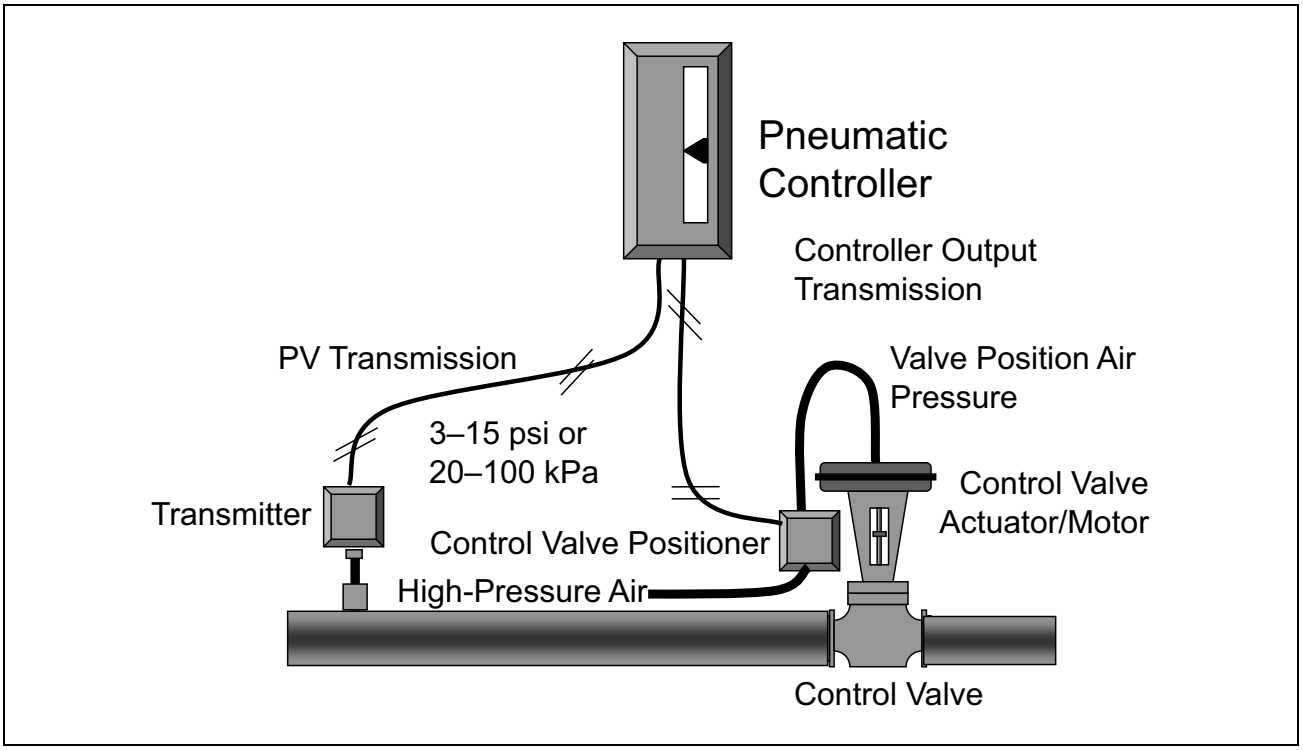

Figure 25-2. Pneumatic Analog Transmission

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Wireless Transmitters

By Richard H. Caro

Summary

Process control instrumentation has already begun the transition from bus wiring as in FOUNDATION Fieldbus and PROFIBUS, to wireless. Many wireless applications are now appearing using both ISA100 Wireless and WirelessHART, although not yet in critical control loops. As experience is gained, user confidence improves; and as microprocessors improve in speed and in reduced use of energy, it appears that wireless process control instrumentation will eventually become mainstream.

Introduction to Wireless

Most instrument engineers would like to incorporate measurement transmitters into processes without the associated complexity and cost of installing and maintaining interconnecting wiring to a host system or a distributed control system (DCS). Wireless solutions can dramatically reduce the cost of adding measurement points, making it feasible to include measurements that were not practical with traditional wired solutions.

With a wired plant, every individual wire run must be engineered, designed, and documented. Every termination must be specified and drawn so that installation technicians can perform the proper connections. Even FOUNDATION Fieldbus, in which individual point terminations are not important, must be drawn in detail since installation technicians are not permitted to make random connection decisions. Wireless has no terminations for data transmission, although sometimes it is necessary to wire-connect to a power source. Often the physical location of a wireless instrument and perhaps a detachable antenna may be very important and the antenna may need to be designed and separately installed.

Maintenance of instrumentation wiring within a plant involves ongoing costs often related to corrosion of terminations and damage from weather, construction, and other accidental sources. Wireless has a clear advantage since there are no wiring terminations and there is little likelihood of damage to the communications path from construction and accidental

sources. However, there are temporary sources of interference such as mobile large equipment blocking line-of-sight communications and random electrical noise from equipment such as an arc welder.

Wireless Network Infrastructure

Traditional distributed control systems (DCSs) use direct point-to-point wiring between field instruments and their input/output (I/O) points present on an analog input or output multiplexer card. There is no network for the I/O. If HART digital signals are present, they are either ignored, read occasionally with a handheld terminal, or routed to or from the DCS through the multiplexer card. If the field instrumentation is based on FOUNDATION Fieldbus, PROFIBUS-PA, or EtherNet/IP, then a network is required to channel the data between the field instruments and to and from the DCS. Likewise, if the field instruments are based on digital wireless technology such as ISA100 Wireless or WirelessHART, then a network is required to channel the data between the field instruments and to and from the DCS.

The nature of wired field networks is discussed in Chapter 8. The elements of the wireless portion of field networks is often referred to as the wireless network infrastructure. Unlike wired networks in which every signal is conducted by wire to its intended destination, wireless messages can be interrupted from delivery when the signals encounter obstacles or interference, or when they are not powerful enough to survive the distances involved. The wireless network infrastructure includes the following:

- Formation of mesh networks in which intermediate devices store and forward signals to overcome obstacles and lengthen reception distances
- Redundant or resilient signal paths so that messages are delivered along alternative routes for reliability
- Use of frequency shifting so that error recovery does not use the same frequency as failed messages
- Directional antennas to avoid interference and to lengthen reception distances

Wireless field networks always terminate in a gateway that may connect to a data acquisition or control system with direct wired connections, with a wired network, or with a plant-level wireless network. The cost of the wireless field networks must always include the gateway that is usually combined with the network manager, which controls the wireless network performance. The gateway almost always includes the wireless network security manager as well. Note that the incremental cost of adding wireless network field instruments does not include any additional network infrastructure devices.

ISM Band

Wireless interconnection relies on the radio frequency spectrum, a limited and crowded resource in which frequency bands are allocated by local/country governments. Governmental organizations in most nations have established license-free radio bands, the most significant of which is the industrial, scientific, and medical (ISM) band centered at 2.4 GHz. This band is widely used for cordless telephones, home and office wireless networks, and wireless process control instrumentation. It is also used by microwave ovens, which are often located

27 Cybersecurity

By Eric C. Cosman

Introduction

What is the current situation with respect to cybersecurity, and what are the trends?

Cybersecurity is a popularly used term for the protection of computer and communications systems from electronic attack. Also referred to as information security, this mature discipline is evolving rapidly to address changing threats.

Although long applied to computers and networks used for basic information processing and business needs, more recently attention has also been focused on the protection of industrial systems.[1] These systems are a combination of personnel, hardware, and software that can affect or influence the safe, secure, and reliable operation of an industrial process.

This shift has resulted in the creation of something of a hybrid discipline, bringing together elements of cybersecurity, process automation, and process safety. This combination is referred to as industrial systems cybersecurity. This is a rapidly evolving field, as evidenced by the increasing focus from a variety of communities ranging from security researchers to control engineers and policy makers.

This chapter gives a general introduction to the subject, along with references to other sources of more detailed information.

To appreciate the nature of the challenge fully, it is first necessary to understand the current situation and trends. This leads to an overview of some of the basic concepts that are the foundation of any cybersecurity program, followed by a discussion of the similarities and differences between securing industrial systems and typical information systems. There are several fundamental concepts that are specific to industrial systems cybersecurity, and some basic steps are necessary for addressing industrial systems cybersecurity in a particular situation.

1. Many terms are used to describe these systems. The ISA-62443 series of standards uses the more formal and expansive term industrial automation and control systems (IACS).

Current Situation

Industrial systems are typically employed to monitor, report on, and control the operation of a variety of different industrial processes. Quite often, these processes involve a combination of equipment and materials where the consequences of failure range from serious to severe. As a result, the routine operation of these processes consists of managing risk.

Risk is generally defined as being the combination or product of threat, vulnerability, and consequence. Increased integration of industrial systems with communication networks and general business systems has contributed to these systems becoming a more attractive target for attack, thus increasing the threat component. Organizations are increasingly sharing information between business and industrial systems, and partners in one business venture may be competitors in another.

External threats are not the only concern. Knowledgeable insiders with malicious intent or even an innocent unintended act can pose a serious security risk. Additionally, industrial systems are often integrated with other business systems. Modifying or testing operational systems has led to unintended effects on system operations. Personnel from outside the control systems area increasingly perform security testing on the systems, exacerbating the number and consequence of these effects. Combining all these factors, it is easy to see that the potential of someone gaining unauthorized or damaging access to an industrial process is not trivial.

Even without considering the possibility of deliberate attack, these systems are increasingly vulnerable to becoming collateral damage in the face of a nonspecific attack, such as the release of malicious software (viruses, worms, Trojan horses, etc.).

The vulnerability of industrial systems has changed as a result of the increased use of commodity technology, such as operating systems and network components. However, a full understanding of the level of risk is only possible after considering the consequence element. The consequence of failure or compromise of industrial systems has long been well understood by those who operate these processes.

Loss of trade secrets and interruption in the flow of information are not the only consequences of a security breach. Industrial systems commonly connect directly to physical equipment so the potential loss of production capacity or product, environmental damage, regulatory violation, compromise to operational safety, or even personal injury are far more serious consequences. These may have ramifications beyond the targeted organization; they may damage the infrastructure of the host location, region, or nation.

The identification and analysis of the cyber elements of risk, as well as the determination of the best response, is the focus of a comprehensive cybersecurity management system (CSMS). A thorough understanding of all three risk components is typically only possible by taking a multidisciplinary approach, drawing on skills and experience in areas ranging from information security to process and control engineering.

While integrated with and complementary to programs used to maintain the security of business information systems and the physical assets, the industrial system's response acknowledges and addresses characteristics and constraints unique to the industrial environment.

IX

Maintenance

Maintenance Principles

Maintenance, long-term support, and system management take a lot of work to do well. The difference in cost and effectiveness between a good maintenance operation and a poor one is easily a factor of two and may be much more. Automation professionals must understand this area so that their designs can effectively deal with life-cycle cost.

Troubleshooting Techniques

Automation professionals who only work on engineering projects in the office and leave the field work to others may not realize the tremendous amount of work required to get a system operating. Construction staff and plant technicians are doing more and more of the checkout, system testing, and start-up work today, which makes it more important that automation professionals understand these topics.

Asset Management

Asset management systems are processing and enabling information systems that support managing an organization's assets, both physical (tangible) assets and non-physical (intangible) assets. Asset management is a systematic process of cost-effectively developing, operating, maintaining, upgrading, and disposing of assets. Due to the number of elements involved, asset management is data and information intensive. Using all the information available from various assets will improve asset utilization at a lower total cost, which is the goal of asset management programs.

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Maintenance, Long-Term Support, and System Management

By Joseph D. Patton, Jr.

Maintenance Is Big Business

Maintenance is a challenging mix of art and science, where both economics and emotions have roles. Please note that *serviceability* and *supportability* parallel *maintainability*, and *maintenance* and *service* are similar for our purposes. Maintainability (i.e., *serviceability* or *supportability*) is the discipline of designing and producing equipment so it can be maintained. Maintenance and service include performing all actions necessary to restore durable equipment to, or keep it in, specified operation condition.

There are several forces changing the maintenance business. One is the technological change of electronics and optics doing what once required physical mechanics. Computers are guiding activities and interrelationships between processes instead of humans turning dials and pulling levers. Remote diagnostics using the Internet reduce the number of site visits and help improve the probability of the right technician coming with the right part. Many repairs can be handled by the equipment operator or local personnel. Robots are performing many tasks that once required humans. Many parts, such as electronic circuit boards, cannot be easily repaired and must be replaced in the field and sent out for possible repair and recycling. Fast delivery of needed parts and reverse logistics are being emphasized to reduce inventories, reuse items, reduce environmental impact, and save costs. Life-cycle costs and profits are being analyzed to consider production effects, improve system availability, reduce maintenance, repair, and operating (MRO) costs, and improve overall costs and profits. Change is continuous!

Organizations that design, produce, and support their own equipment, often on lease, have a vested interest in good maintainability. On the other hand, many companies, especially those with sophisticated high-technology products, have either gone bankrupt or sold out to a larger corporation when they became unable to maintain their creations. Then, of course, there are many organizations such as automobile service centers, computer repair shops, and many factory maintenance departments that have little, if any, say in the design of equipment they will later be called on to support. While the power of these affected organizations is

somewhat limited by their inability to do more than refuse to carry or use the product line, their complaints generally result in at least modifications and improvements to the next generation of products.

Maintenance is big business. Gartner estimates hardware maintenance and support is $120 billion per year and growing 5.36% annually. The *Northwestern University Chemical Process Design Open Textbook* places maintenance costs at 6% of fixed capital investment. U.S. Bancorp estimates that spending on spare parts costs $700 billion in the United States alone, which is 8% of the gross domestic product.

Service Technicians

Typically, maintenance people once had extensive experience with fixing things and were oriented toward repair instead of preventive maintenance. In the past, many technicians were not accustomed to using external information to guide their work. Maintenance mechanics or technicians often focused on specific equipment, usually at a single facility, which limited the broader perspective developed from working with similar situations at many other installations.

Today, service technicians are also called field engineers (FEs), customer engineers (CEs), customer service engineers (CSEs), customer service representatives (CSRs), and similar titles. This document will use the terms "technicians" or "techs." In a sense, service technicians must "fix" both equipment and customer employees. There are many situations today where technicians can solve problems over the telephone by having a cooperative customer download a software patch or perform an adjustment. The major shift today is toward remote diagnostics and self-repairs via Internet software fixes, YouTube guidance of procedures, supplier's websites, and call centers to guide the end user or technician.

Service can be used both to protect and to promote. Protective service ensures that equipment and all company assets are well maintained and give the best performance of which they are capable. Protective maintenance goals for a technician may include the following:

- Install equipment properly
- Teach the customer how to use the equipment capability effectively
- Provide functions that customers are unable to supply themselves
- Maintain quality on installed equipment
- Gain experience on servicing needs
- Investigate customer problems and rapidly solve them to the customer's satisfaction
- Preserve the end value of the product and extend its useful life
- Observe competitive activity
- Gain technical feedback to correct problems

Service techs are becoming company representatives who emphasize customer contact skills instead of being solely technical experts. In addition, the business of maintenance service is

29

Troubleshooting Techniques

By William L. Mostia, Jr.

Introduction

Troubleshooting can be defined as the method used to determine why something is not working properly or is not providing an expected result. Troubleshooting methods can be applied to physical as well as nonphysical problems. As with many practical skills, it is an art but it also has an analytical or scientific basis. As such, basic troubleshooting is a trainable skill, while advanced troubleshooting is based on experience, developed skills, information, and a bit of art. While the discussion here centers on troubleshooting instrumentation and control systems, the basic principles apply to broader classes of problems.

Troubleshooting normally begins with identifying that a problem exists and needs to be solved. The first steps typically involve applying a logical/analytical framework.

Logical/Analytical Troubleshooting Framework

A framework underlies a structure. Logical frameworks provide the basis for structured methods to troubleshoot problems. However, following a step-by-step method without first thinking through the problem is often ineffective; we also need to couple logical procedures with analytical thinking. To analyze information and determine how to proceed, we must combine logical deduction and induction with a knowledge of the system, then sort through the information we have gathered regarding the problem. Often, a logical/analytical framework does not produce the solution to a troubleshooting problem in just one pass. We usually have several iterations, which cause us to return to a previous step in the framework and go forward again. Thus, we can systematically eliminate possible solutions to our problem until we find the true solution.

Specific Troubleshooting Frameworks

Specific troubleshooting frameworks have been developed that apply to a particular instrument, class of instruments, system, or problem domain. For example, frameworks might be

developed for a particular brand of analyzer, for all types of transmitters, for pressure control systems, or for grounding problems. When these match up with your system, you have a distinct starting point for troubleshooting.

Figure 29-1 is an example of a specific troubleshooting framework (also called a *flowchart* or *tree*) for transmitters.

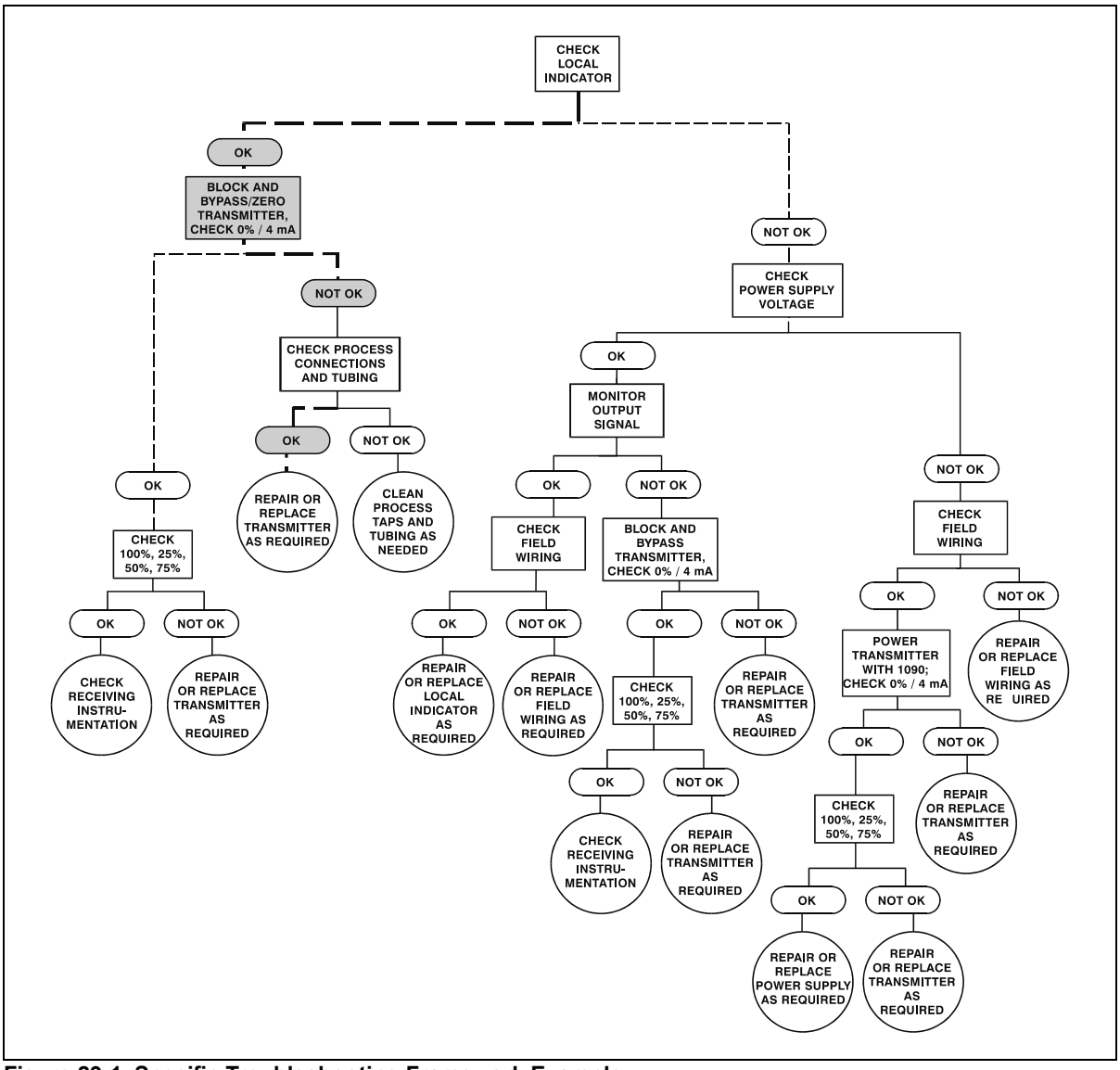

Figure 29-1. Specific Troubleshooting Framework Example

Generic Logical/Analytical Frameworks

Since we do not always have a specific structured framework available, we need a more general or generic framework that will apply to a broad class of problems. Figure 29-2 depicts this type of framework as a flowchart.

The framework shown in Figure 29-2, while efficient, leaves out some important safety-related tasks and company procedural requirements associated with or related to the troubleshooting process. As troubleshooting increases the safety risk to the troubleshooter due to

30

Asset Management

By Herman Storey and Ian Verhappen, PE, CAP

Asset management, broadly defined, refers to any system that monitors and maintains things of value to an entity or group. It may apply to both tangible assets (something you can touch) and to intangible assets, such as human capital, intellectual property, goodwill, and/or financial assets. Asset management is a systematic process of cost-effectively developing, operating, maintaining, upgrading, and disposing of assets.

Asset management systems are processing and enabling information systems that support management of an organization's assets, both physical assets, called *tangible*, and nonphysical, *intangible* assets.

Due to the number of elements involved, asset management is data and information-intensive.

What you expect the asset to do is known as the function of the asset. An important part of asset management is preserving the asset's ability to perform its function as long as required. Maintenance is how an assets function is preserved.

Maintenance usually costs money, as it consumes time and effort. Not doing maintenance has consequences. Failure of some assets to function can be expensive, harm both people and the environment, and stop the business from running, while failure of other assets may be less serious. As a result, one of the important first steps in any asset management program is understanding the importance of your assets to your operations, as well as the likelihood and consequence of their failure, so you can more effectively mitigate actions to preserve their functions. This exercise is commonly referred to as *criticality ranking*. Knowing the criticality of your assets makes it easier to determine the appropriate techniques or strategies to manage those assets.

Managing all this data requires using computer-based systems and increasingly integrating information technology (IT) and operational technology (OT) systems. Industry analyst Gartner confirms this increased integration, predicting that OT will be used to intelligently feed predictive data into enterprise asset management (EAM) IT systems in the near future. This

alerts the asset manager to potential failures, allowing effective intervention before the asset fails.

This integration promises significant improvement in asset performance and availability to operate in the near future.

Several organizations already offer asset performance management systems that straddle IT and OT, thus providing more sophistication in how these systems can be used to manage assets.

Additional guidance on how to implement asset management systems is available through recently released, and currently under development, international standards. The International Standards Organization (ISO) has developed a series of documents similar in nature to the ISO 9000 series on quality and ISO 14000 series on environmental stewardship. The ISO 55000 series of three separate voluntary asset management standards was officially released 15 January 2014.

1. ISO 55000, *Asset Management – Overview, Principles, and Terminology*
2. ISO 55001, *Asset Management – Management Systems – Requirements*
3. ISO 55002, *Asset Management – Management Systems – Guidelines for the Application of ISO 55001*

Like ISO 9000 and ISO 14000, ISO 55000 provides a generic conceptual framework—it can be applied in any industry or context.

The requirements of the ISO 55000 standards are straightforward.

An organization (such as a company, plant, mine, or school board) has a portfolio of assets. Those assets are intended (somehow) to deliver on part of the organization's objectives. The asset management system creates the link from corporate policies and objectives, through a number of interacting elements to establish policy (i.e., rules), asset management objectives, and processes through which to achieve them. Asset management itself is the activity of executing on that set of processes to realize value (as the organization defines it) from those assets.

Policies lead to objectives, which require a series of activities in order to achieve them. Like the objectives, the resulting plans must be aligned and consistent with the rest of the asset management system, including the various activities, resources, and other financing.

Similarly, risk management for assets must be considered in the organization's overall risk management approach and contingency planning.

Asset management does not exist in a vacuum. Cooperation and collaboration with other functional areas will be required to effectively manage and execute the asset management system. Resources are needed to establish, implement, maintain, and continually improve the asset management system itself, and collaboration outside of the asset management organization or functional area will be required to answer questions such as:

- What is the best maintenance program?
- What is the ideal age at which to replace the assets?

X

Factory Automation

Mechatronics

Many engineering products of the last 30 years possess integrated mechanical, electrical, and computer systems. Mechatronics has evolved significantly by taking advantage of embedded computers and supporting information technologies and software advances. The result has been the introduction of many new intelligent products into the marketplace and associated practices as described in this chapter to ensure successful implementation.

Motion Control

Motion control of machines and processes compares the desired position to the actual scale and takes whatever corrective action is necessary to bring them into agreement. Initially, machine tools were the major beneficiary of this automation. Today, packaging, material handling, food and beverage processing, and other industries that use machines with movable members are enjoying the benefits of motion control.

Vision Systems

A vision system is a perception system used for monitoring, detecting, identifying, recognizing, and gauging that provides local information useful for measurement and control. The systems consist of several separate or integrated components including cameras and lenses, illumination sources, mounting and mechanical fixturing hardware, computational or electronic processing hardware, input/output (I/O) connectivity and cabling electrical hardware, and, most importantly, the software that performs the visual sensing and provides useful information to the measurement or control system.

Building Automation

This chapter provides insight into the industry that automates large buildings. Each large building has a custom-designed heating, ventilating, and cooling (HVAC) air conditioning system to which automated controls are applied. Access control, security, fire, life safety, lighting control, and other building systems are also automated as part of the building automation system.

31 Mechatronics

By Robert H. Bishop

Basic Definitions

Modern engineering design has naturally evolved into a process that we can describe in a mechatronics framework. Since the term was first coined in the 1970s, *mechatronics* has evolved significantly by taking advantage of embedded computers and supporting information technologies and software advances. The result has been the introduction of many new intelligent products into the marketplace. But what exactly is mechatronics?

Mechatronics was originally defined by the Yasakawa Electric Company in trademark application documents [1]:

> *The word, Mechatronics, is composed of "mecha" from mechanism and "tronics" from electronics. In other words, technologies and developed products will be incorporating electronics more and more into mechanisms, intimately and organically, and making it impossible to tell where one ends and the other begins.*

The definition of mechatronics evolved after Yasakawa suggested the original definition. One of the most often quoted definitions comes from Harashima, Tomizuka, and Fukada [2]. In their words, mechatronics is defined as:

> *The synergistic integration of mechanical engineering, with electronics and intelligent computer control in the design and manufacturing of industrial products and processes.*

Other definitions include:

- Auslander and Kempf [3]
  Mechatronics is the application of complex decision-making to the operation of physical systems.
- Shetty and Kolk [4]
  Mechatronics is a methodology used for the optimal design of electromechanical products.

- Bolton [5]
  A mechatronic system is not just a marriage of electrical and mechanical systems and is more than just a control system; it is a complete integration of all of them.

These definitions of mechatronics express various aspects of mechatronics, yet each definition alone fails to capture the entirety of the subject. Despite continuing efforts to define mechatronics, to classify mechatronic products, and to develop a standard mechatronics curriculum, agreement on "what mechatronics is" eludes us. Even without a definitive description of mechatronics, engineers understand the essence of the philosophy of mechatronics from the definitions given above and from their own personal experiences.

Mechatronics is not a new concept for design engineers. Countless engineering products possess integrated mechanical, electrical, and computer systems, yet many design engineers were never formally educated or trained in mechatronics. Indeed, many so-called mechatronics programs in the United States are actually programs embedded within the mechanical engineering curriculum as minors or concentrations [6]. However, outside of the United States, for example in Korea and Japan, mechatronics was introduced in 4-year curriculum about 25 years ago. Modern concurrent engineering design practices, now formally viewed as an element of mechatronics, are natural design processes. From an educational perspective, the study of mechatronics provides a mechanism for scholars interested in understanding and explaining the engineering design process to define, classify, organize, and integrate the many aspects of product design into a coherent package. As the historical divisions between mechanical, electrical, biomedical, aerospace, chemical, civil, and computer engineering give way to more multidisciplinary structures, mechatronics can provide a roadmap for engineering students studying within the traditional structure of most engineering colleges. In fact, undergraduate and graduate courses in mechatronic engineering are now offered in many universities. Peer-reviewed journals are being published and conferences dedicated to mechatronics are very popular. However, mechatronics is not just a topic for investigative studies by academicians; it is a way of life in modern engineering practice. The introduction of the microprocessor in the early 1980s, coupled with increased performance to cost-ratio objectives, changed the nature of engineering design. The number of new products being developed at the intersection of traditional disciplines of engineering, computer science, and the natural sciences is expanding. New developments in these traditional disciplines are being absorbed into mechatronics design. The ongoing information technology revolution, advances in wireless communication, smart sensors design, the Internet of Things, and embedded systems engineering ensures that mechatronics will continue to evolve.

Key Elements of Mechatronics

The study of mechatronic systems can be divided into the following areas of specialty:

- Physical system modeling
- Sensors and actuators
- Signals and systems
- Computers and logic systems

32
Motion Control

By Lee A. Lane and Steve Meyer

What Is Motion Control?

Within the general field of automation, motion control is a special field that deals with the automatic actuation and control of mechanical systems. In the early days of the industrial revolution, many mechanical systems required a person to power and control the machinery by turning cranks or moving levers, actuating the motion as they watched a measuring scale. The brain was the control, comparing the desired position to the actual position and making corrections to get the machine to the correct position. With the introduction of automation, the scale was replaced with a feedback sensor, the human muscle was replaced with a powered actuator, and the brain was replaced with a controller. An operator would enter the desired position; the controller would compare the feedback position to the desired position and decide the direction and speed needed to achieve the desired position. The controller would send instructions to an electric motor (or other power source) until the desired position was achieved. Initially, machine tools were the major beneficiary of this automation. Today, almost every manufacturing facility—from food and beverage processing, consumer product packaging, semiconductors and electronics—all use machinery with some type of motion control.

Advantages of Motion Control

Saving time is a major benefit of motion control. It might take a person a minute or two to hand crank a machine a short distance and align it with the scale. A typical servo will do this task in a fraction of a second. A typical servo system will let the machine repeat the task accurately day after day without the need for constant manual measurement techniques.

- **Servo** – Any actuator mechanism with a feedback sensor that, when combined with a controller, can regulate position.

Coordinating two or more precision axes of motion, as is required in a metal cutting machine tool, is impossible for a human operator with manual hand cranks, but easily done with elec-

tronically controlled servos. Position regulation is another benefit. As will be seen shortly, a servo will return an axis to position when an outside force has moved the axis.

- **Axis of motion** – A principle direction along which motion occurs. A single motor coupled to a mechanical actuator and feedback device may be referred to as an axis of motion.

Feedback

The feedback device can be considered the eyes of the system; it provides information to the control system about the velocity and the position of the load in an axis of motion. Motion control systems use many different types of feedback devices, which can be analog or digital and come in both incremental and absolute configurations. Both incremental and absolute types of devices can track position changes: the difference is in how they respond to a loss of power. Absolute devices can determine their position on power up, providing the axis was calibrated during start up. Incremental devices will lose their position and need to go through a homing sequence on power up. In this chapter, we will briefly discuss several of the more popular types of feedback devices.

Resolvers

Resolvers are analog devices relying on magnetic coupling to determine position. They do this by looking at the magnetic coupling of a rotating winding, the rotor, compared to two stationary windings, stators (see Figure 32-1). This coupling varies with the angle of the shaft relative to the stators. As such, resolvers are rotary transformers and typically are interfaced with an analog-to-digital (A/D) converter to be used with a digital controller. These circuits typically provide 12 or 13 bits of resolution, although there are models with up to 16 bits of resolution. Resolvers are commonly used as velocity feedback devices in brushless DC (direct current) or ACPM (alternating current permanent magnet) machines. They are extremely rugged and provide absolute feedback for one revolution of their shafts. This makes them ideal for AC servomotors, as the absolute nature in one revolution allows the drive to know where the motor shaft is. This also allows the resolver to commutate the motor. Although this works well for commutation, it is less than ideal for absolute position feedback. Typically an axis travels over more than one revolution of a motor shaft; therefore a single resolver loses its ability to act as an absolute device. If the application allows the axis to perform a homing routine on power up, this configuration offers the advantage of using a single feedback device. You can use the resolver for the drive for commutation and the controller for position and velocity. To achieve absolute positioning over multiple turns, use a dual resolver set or master vernier resolver set. Two resolvers are connected to the load, but each resolver is geared at a different ratio. By looking at the phase shift between the two resolvers, it is possible to determine the absolute position of the axis over multiple turns.

Magnetostrictive Transducers

Magnetostrictive transducers are unique due to the noncontact nature of this type of feedback device, which makes them ideal for linear hydraulic applications. Magnetostrictive transducers operate in a manner similar to sonar. A sensing magnet is placed on or, in the case of a hydraulic cylinder, inside the actual load. The magnetostrictive transducer sends

33 Vision Systems

By David Michael

Using a Vision System

A vision system is a perception system that provides local information useful for measurement and control. It is an implementation of visual sensing used to monitor, detect, identify, recognize, and gauge objects in the vicinity of the system. Visual perception is the ability to see and interpret visual information. Fundamentally, a vision system involves generating images of the environment and then using a computer to discover from the images what objects are there, where they are, what are their dimensions, and how well the objects visually meet our expectations.

A vision system should be used when visual sensing is required or beneficial. Sensing provides data about the environment that is needed for action. Visual sensing is a powerful sensing method because it is fast, nondestructive, requires no contact, and can generate a great deal of information.

A vision system is but one way to provide perception to machines. Other methods of perception that are also nondestructive include interpreting sound, temperature, radio frequency, and electric fields, as well as detecting chemical vapor presence. Destructive sensing methods, such as touch, deep chemical analysis, or mechanical/crash testing, can perturb an object or its environment.

Visual sensing isn't just powerful, it is also popular. In 2016, the global market for machine vision systems was estimated at USD 9.1 billion and the market is estimated to grow to over USD 19 billion by 2025.[1] Its popularity is primarily due to the far-reaching and useful applications of this technology. Another reason for its popularity is that people have good intuition of what a vision system can do from what they see in the world (see Figure 33-1).

1. Grand View Research market analysis, http://www.grandviewresearch.com/industry-analysis/machine-vision-market.

Figure 33-1. Perception for Measurement and Control

Vision System Components

A vision system consists of several separate or integrated components working together. Its parts include: cameras and lenses, illumination sources, mounting and mechanical fixturing hardware, computational or electronic processing hardware, input and output (I/O) connectivity, and cabling electrical hardware. Most important, however, is its visual sensing software, which provides useful data to the measurement and control system (see Figure 33-2).

Cameras and lenses are used to form and collect images. Critical imaging parameters will be discussed later in this chapter. The illumination sources shine light to make the object under observation visible. Mechanical mounting and fixturing hardware secure the vision system in the right place and ensure that the image collection apparatus remains free from vibration, motion, or drift. Well-designed mechanical hardware allows worn parts or broken cameras to be replaced without requiring a complete system rebuild. The I/O connectivity hardware and cables provide power to components that need it, connect the cameras to the processing elements, and electrically connect the vision system's communication ports to transceivers that need to receive the visual information. The transceivers receiving the visual information are typically process control systems, factory information systems, and/or human-machine interfaces (HMIs). The vision system's most complex feature is found in the visual sensing

34 Building Automation

By John Lake, CAP

Introduction

Today's building automation systems (BASs) function to control the environment in order to maintain occupant comfort and indoor air quality, manage energy consumption, provide life-safety capability, and provide historical access. BASs are often combined with other smart systems to facilitate an interoperable control and monitoring system for the entire facility, campus, or multilocation buildings. From their humble beginnings around the turn of the last century, BASs have progressed from single-device control to fully computerized building control. This chapter is an overview of the basic structure of BASs.

Cloud computing has become more prevalent with the acceptance and implementation of open system protocols by many manufacturers. In addition, software vendors are now providing powerful display engines that can be combined with dashboards to become a powerful tool to communicate information.

With the already massive amount of cloud memory increasing every day, the wider bandwidth enables us to collect a significantly larger amount of information regarding the operation and maintenance of BASs and other connected open systems.

There are many names for building automation systems. They vary by geographical area, building type, and industry or building purpose. Here are a few examples:

- Building automation system (BAS)
- Building management system (BMS)
- Facility management system (FMS)
- Facility management and control system (FMCS)
- Energy management system (EMS)
- Energy management and control system (EMCS)

Direct Digital Controls

In the early 1980s, direct digital controls (DDCs) began using powerful microprocessors to accomplish programmed tasks; this enabled them to enter the commercial building arena. DDC controllers generally contain a library of specific algorithms to perform their intended functions, which enables them to provide an accurate, cost-effective approach to building control and management. The early DDC controllers were standalone with limited communication ability. When network capability was added to the DDC controllers at the end of the 1980s, a new path and a coordinated approach to building control and management was born.

The DDC controller is the basic building block of modern BASs. Building block components of a typical BAS of today are:

- Building-level controllers
- Equipment-level controllers
- Plant-level controllers
- Unit-level controllers

Building Level (Network) Controller

The building network controller is more of a system level router rather than a controller. It handles the network traffic and allows information sharing between other controllers. It provides global information, network real time of day, building schedules, and so on. It handles access to the BAS via high-speed Internet or dial-up.

By contrast, in legacy systems the building level controller drove the high speed (48 kb–72 kb, depending on the vendor) proprietary network traffic, and it handled the slower speed controller traffic (9,600–19,200 baud, also vendor specific). Dial-up systems are quite common.

Equipment-Level Controllers

These controllers are designed to handle built-up systems and are available with varying point counts in order to manage the various control points that may be needed on a built-up system. Equipment-level controllers are designed for larger applications and point counts than typical unit-level controllers. They most often have their own enclosure and stand-alone capability. They can be placed in original equipment manufacturers (OEM) equipment at a vendor's factory or in the field. Their point count can be expanded by adding additional input/output (I/O) modules. The controllers are backed up by a battery so they will keep time and remember their last state in the event of a loss of power to the controller. Custom applications can be built by applying combinations of built-in libraries and custom programs. These controllers can have enough capacity added to be able to do all the work of the lower-level controllers.

Plant-Level Controllers

Plant-level controllers are similar to equipment-level controllers, but they generally have a higher point capacity and routinely encompass multiple pieces of equipment to form a single

XI Integration

Data Management

Data are the lifeblood of industrial process operations. The levels of efficiency, quality, flexibility, and cost reduction needed in today's competitive environment cannot be achieved without a continuous flow of accurate, reliable information. Good data management ensures the right information is available at the right time to answer the needs of the organization. Databases store this information in a structured repository and provide for easy retrieval and presentation in various formats. Managing the data itself and associated relationships make it possible to provide meaningful interpretations and hence use of the data proper.

Manufacturing Operations Management

The automation industry needs a good coupling of information technology (IT) know-how with a broad knowledge of plant floor automation—either by having IT systems specialists learn plant floor controls or by having automation professionals learn more about integration, or both.

Functionality and integration of the shorter time frame operating systems with both plant floor controls and with company business systems is called by several names; manufacturing execution systems (MESs) is the most common.

The concepts of where functions should be performed and when data flows should occur were wrestled with for decades after the computer-integrated manufacturing (CIM) work of the 1980s. The ISA-95 series on enterprise-control system integration provided real standardization in this area. The ISA-95 standards have been adopted by some of the biggest names in manufacturing and business systems. While a large percentage of automation professionals do not know what MES is, this topic, like integration in general, cannot be ignored any longer.

Operational Performance Analysis

The phrase operational performance analysis has referred to a variety of different technologies and approaches in the field of industrial automation. There are four components to operational performance analysis that must be considered: the industrial operation under consideration, the measurement of the performance of the operation, the analysis of the performance based on the measurements and the performance expectation, and the implementation of appropriate performance improvements. All four components must continuously work in concert to have an effective operational performance analysis system.

35
Data Management

By Diana C. Bouchard

Introduction

Data are the lifeblood of industrial process operations. The levels of efficiency, quality, flexibility, and cost reductions needed in today's competitive environment cannot be achieved without a continuous flow of accurate, reliable information. Good data management ensures the right information is available at the right time to answer the needs of the organization. Databases store this information in a structured repository and provide for easy retrieval and presentation in various formats.

Database Structure

The basic structure of a typical database consists of *records* and *fields*. A *field* contains a specific type of information—for example, the readings from a particular instrument or the values of a particular laboratory test. A *record* contains a set of related field values, typically taken at one time or associated with one location in the plant. In a spreadsheet, the fields would usually be the columns (variables) and the records would be the rows (sets of readings).

In order to keep track of the information in the database as it is manipulated in various ways, it is desirable to choose a *key field* to identify each record, much as it is useful for people to have names so we can address them. Figure 35-1 shows the structure of a portion of a typical process database, with the date and time stamp as the key field.

Data Relationships

Databases describe relationships among *entities*, which can be just about anything: people, products, machines, measurements, payments, shipments, and so forth. The simplest kind of data relationship is *one-to-one*, meaning that any one of entity *a* is associated with one and only one of entity *b*. An example would be customer name and business address.

DateTime	Impeller Speed rpm	Additive Flowrate, L/min	Additive Concentration ppm	…
2005-05-20 02:00	70.1	24.0	545	…
2005-05-20 03:00	70.5	25.5	520	…
2005-05-20 04:00	71.1	25.8	495	…
2005-05-20 05:00	69.5	23.9	560	…
2005-05-20 06:00	69.8	24.2	552	…
…	…	…	…	…

Figure 35-1. Process Database Structure

In some cases, however, entities have a *one-to-many* relationship. A given customer has probably made multiple purchases from your company, so customer name and purchase order number would have a one-to-many relationship. In other cases, *many-to-many* relationships exist. A supplier may provide you with multiple products, and a given product may be obtained from multiple suppliers.

Database designers frequently use *entity-relationship diagrams* (Figure 35-2) to illustrate linkages among data entities.

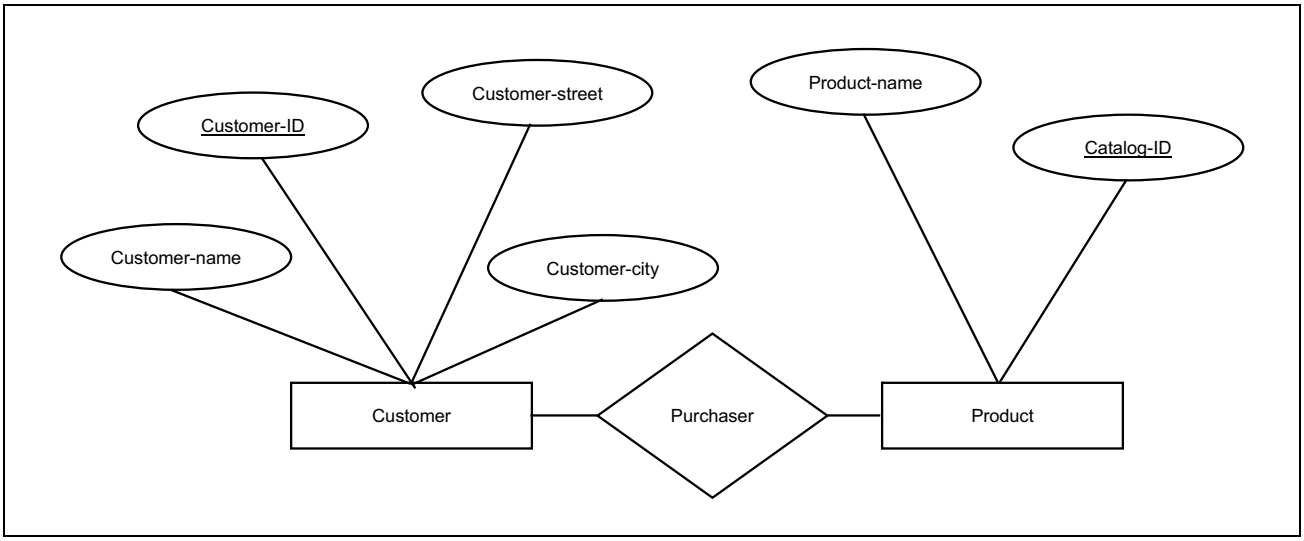

Figure 35-2. Typical Entity-Relationship Diagram

Database Types

The simplest database type is called a *flat file*, which is an electronic analog of a file drawer, with one record per folder, and no internal structure beyond the two-dimensional (row and column) tabular structure of a spreadsheet. Flat-file databases are adequate for many small applications of low complexity.

However, if the data contain one-to-many or many-to-many relationships, the flat file structure cannot adequately represent these linkages. The temptation is to reproduce information in multiple locations, wherever it is needed. However, if you do this, and you need to update the information afterwards, it is easy to do so in some places and forget to do it in others.

36

Mastering the Activities of Manufacturing Operations Management

Understanding the Functional Level above Automation and Control and below Enterprise

By Charlie Gifford

Introduction

Automation only begins with equipment control on the plant floor; it also includes higher levels of control that manage production workflows, production job orders, and resources such as personnel, equipment, and materials across production areas. Effective manufacturing in the plant and across its supply chain is only partially based on production's equipment control capability. In an environment executing as little as 20% make-to-order (MTO) orders (80% make-to-stock [MTS]), resource optimization is critical to effective low-cost order fulfillment. In the 21st century global market, manufacturing companies must be effective at coordinating and controlling resources (personnel, materials, and equipment) across production and its supporting operations activities and their control systems to reach their maximum potential. This is usually accomplished using industrialized manufacturing applications to manage and optimize operations execution and governance procedures. These operations activities are collectively called the *manufacturing operations management* (MOM) *functional domain level*. MOM defines a diverse set of functions and tasks to execute operations job orders while effectively applying resources above automation control systems; these operations management functions reside below the functional level of enterprise business systems, and they are typically local to a site or area. This chapter explains the activities and functions of the MOM level and how these functions exchange information between each other for production optimization and within the context of other corporate business systems.

The term *manufacturing execution system* (MES), described in earlier editions of this book, was defined by the Advanced Market Research (AMR, acquired by the Gartner Group in 2009) in the early 1990s and was a high-level explanation that did not describe the actual functionality

set in general or in a vertical industry way. MES did not explain the inner MOM data exchanges (Level 3 in Figure 36-1) or the business Level 4 exchanges. For the most part, MES has been a highly misunderstood term in manufacturing methods and systems. This term was primarily based on defining production management for a 20th century make-to-stock manufacturing environment. MES was focused on describing the execution and tracking of a production order route/sequence and associated material transitions—not on the execution of critical supporting operations such as quality, maintenance, and intra-plant inventory movement to effectively utilize available resource capabilities and capacity. This is key to cost effectiveness in operation manufacturing for make-to-order or lean pull supply chains. In the ANSI/ISA-95.00.03-2013 standard, *Enterprise-Control System Integration – Part 3: Activity Models of Manufacturing Operations Management* [1], the basic MES definition was incorporated into the functions of the production operations management (POM) activity model. The ISA-95 Part 3 activity models include a definition that describes the actual functions, the tasks within functions, and the data exchanges between functions. No other MES definition by industry analysts or international standards provides a more comprehensive level of definition. The Gartner Group has updated their MES definition to use the term manufacturing operations system (MOS), which is a system abstraction from ISA-95 Part 3 activities instead of their 1990s MES term. The ISA-95 Part 3 POM activity model is supported by activity models for quality operation management (QOM), inventory operations management (IOM), and maintenance operations management (MaintOM); these four activity models define all the MOM activities (functions, tasks, and data exchanges) for the *Purdue Enterprise Reference Architecture* and Level 3 of the ISA-95 Functional Hierarchy Model. Since 2006, ISA-95 Part 3 is the primary requirements definition template used by 80% of manufacturers worldwide to define their Level 3 MOM systems in their requests for proposals (RFPs).

The ISA-95 standard's Functional Hierarchy Model defines the five levels of functions and activities of a manufacturing organization as originally described in the *Purdue Enterprise Reference Architecture.* Automation and control supports Level 1 and Level 2, while Level 3 MOM supports the lower and the enterprise level to fulfill orders, as shown in Figure 36-1.

- **Level 0** defines the actual physical processes.
- **Level 1** defines the activities involved in sensing and manipulating the physical processes. Level 1 elements are the physical sensors and actuators attached to the Level 2 control functions in automation systems.
- **Level 2** defines the activities of monitoring and controlling the physical processes, and in automated systems this includes equipment control and equipment monitoring. Level 2 automation and control systems have real-time responses measured in subseconds and are typically implemented on programmable logic controllers (PLCs), distributed control systems (DCSs), and open control systems (OCSs).
- **Level 3** defines the activities that coordinate production and support resources to produce the desired end products. It includes workflow "control" and procedural "control" through recipe execution. Level 3 typically operates on time frames of days, shifts, hours, minutes, and seconds. Level 3 functions also include production, maintenance, quality, and inventory operations; these activities are collectively called

37

Operational Performance Analysis

By Peter G. Martin, PhD

The phrase *operational performance analysis* has referred to many different technologies and approaches in the industrial automation field. An overall discussion of this topic requires a functional definition of operational performance analysis that will provide a framework. Figure 37-1 illustrates a block diagram with such a framework. There are four components to operational performance analysis that must be considered. First is the industrial operation under consideration. For the purposes of this discussion, an industrial operation can range from a single process control loop to an entire plant. Second is measuring the operation's performance, which is a critical component of the model since the performance cannot be controlled if it is not measured. Third is the analysis of the performance based on the measurements and the performance expectations. This function has traditionally been thought of as the domain of engineering, but performance analysis should be conducted by every person directly involved with the operation from the operator through executive management. The final component is implementing appropriate performance improvements and determining if those improvements impact the industrial operation in the expected manner, which is revealed through changes in the measurements. All four components of this loop must continuously work in concert to have an effective operational performance analysis system.

Automation technologies are the most promising for the effective development and calculation of operational performance analytics and for their presentation to operations and management. Also, automation technologies offer one of the best ways to improve operational performance.

Operational Performance Analysis Loops

As the model in Figure 37-1 shows, operational performance analysis can be viewed almost as a control loop. In complex manufacturing operations, multiple nested loops are required for effective operations performance analysis (Figure 37-2). Effective operational performance will only be realized if these loops are both cascaded top to bottom and operate in a

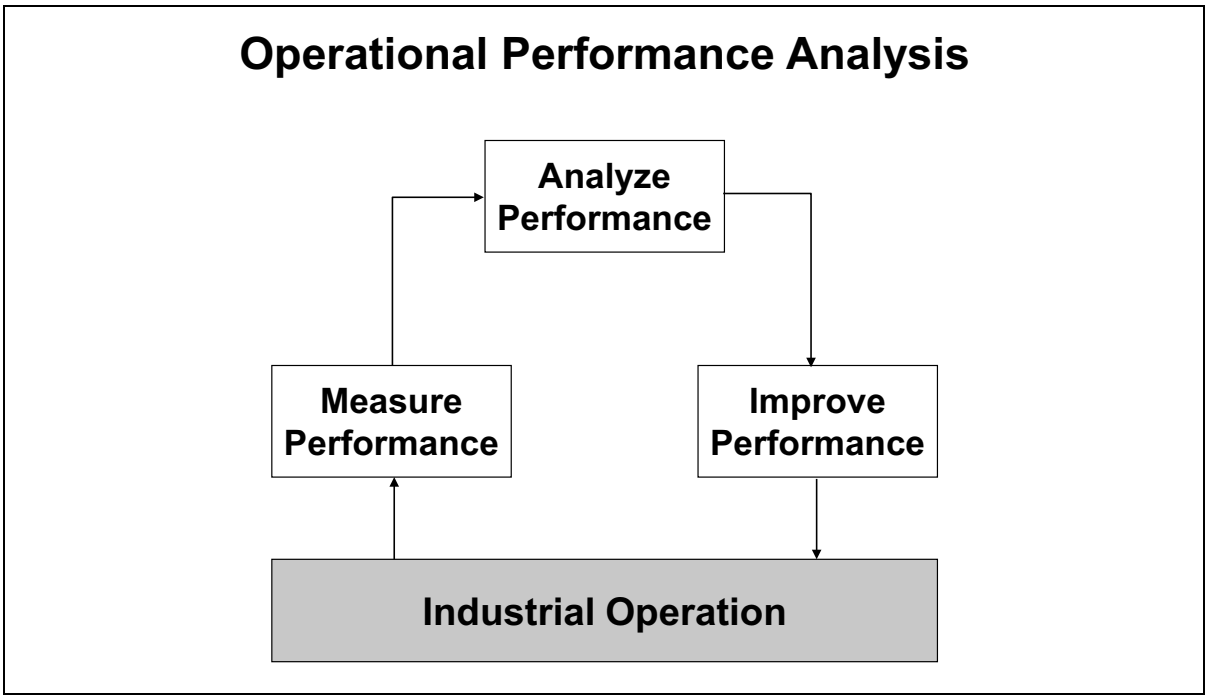

Figure 37-1. The Four Components of Operational Performance Analysis

bottom-up manner. The lowest-level loop is the classic process control loop. The next level represents an operational control loop, which drives the operational performance of a larger industrial operation than a control loop and may actually provide operational outputs that are set points to multiple process control loops. Advanced control loops utilize advanced control technologies, such as multivariable predictive control, linear optimization, or nonlinear optimization. The next level involves plant business control loops. These loops evaluate plant business measures, such as key performance indicators (KPIs) and accounting measures, and determine the most effective operational control outputs that are set-point inputs to multiple operational controllers. The fourth level involves enterprise control loops, which take current strategic set points in from the business strategy functions and provide business outputs that become set points to the plant business controllers. Although this multilevel cascade control perspective may be a simplification, fully integrated cascade control from the plant floor through the enterprise business systems has been the objective of both automation and information systems since the advent of the computer in manufacturing.

The higher levels of operational performance loops may involve much more complicated control algorithms or processes than the lower-level loops. The higher-level control mechanisms may involve recipe management, product management, production planning, resource allocation, profit analysis, and other functions not traditionally viewed as control functions. The general multiple cascade control model applies in both continuous and batch manufacturing operations with the control approach at each level adapted to the process characteristics.

This cascade operational performance analysis model provides both a bottom-up and a top-down perspective of effective operational performance analysis. The bottom-up perspective is the classic operational perspective of "doing things right" (i.e., making sure that the resources of the operation are most effectively deployed and managed to do the job at hand). The top-down perspective involves doing the "right things" (i.e., making the right products

XII

Project Management

Automation Benefits and Project Justifications

Many manufacturers felt it was important just to get new technology installed in order to have the potential to run their operations more efficiently. There are many aspects that must be understood and effectively managed when dealing with automation benefits and project justification. These include understanding business value in production processes, capital projects, life-cycle cost analysis, life-cycle economic analysis, return on investment, net present value, internal rate of return, and project-justification hurdle levels. Each of these topics is addressed in detail. Also included is a discussion on an effective way to start developing automation benefits and project justification.

Project Management and Execution

Automation professionals who work for engineering contractors and system integrators and who see the project only after it has been given some level of approval by the end-user management, may not realize the months or even years of effort that go into identifying the scope of a project and justifying its cost. In fact, even plant engineers who are responsible for performing the justifications often do not realize that good processes exist for identifying the benefits from automation.

In the process of developing the Certified Automation Professional® (CAP®) certification program, the first step was to analyze the work of an automation professional. By focusing on describing the job, it became clear how important project leadership and interpersonal skills are in the work of an automation professional. That analysis helped the CAP development team realize that these topics had to be included in any complete scope of automation.

If the job analysis team had jumped immediately into defining skills, they might have failed to recognize the importance of project leadership and interpersonal skills for automation professionals—whether those professionals are functioning in lead roles or not.

Interpersonal Skills

Interpersonal skills cover the wide range of soft skills from communicating and negotiating to motivating. Process automation professionals need interpersonal skills to communicate, work with people, and provide appropriate leadership. A balance of technical, business, and interpersonal skills is needed on every project or team.

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Automation Benefits and Project Justifications

By Peter G. Martin, PhD

Introduction

For many industrial operations, installing one of the early computer-based automation systems was taken for granted. That is, many manufacturers felt it was important just to get the new technology installed in order to have the potential to run their operations more efficiently. Little consideration seems to have been given to the actual economic impact the system would provide. A survey of manufacturing managers indicated that the primary motivators driving manufacturers to purchase automation systems included their desire to:

- Improve plant quality
- Improve safety
- Increase manufacturing flexibility
- Improve operations reliability
- Improve decision-making
- Improve regulatory compliance
- Increase product yields
- Increase productivity
- Increase production
- Reduce manufacturing costs

Although few would disagree with this list, it appears that these criteria were seldom taken into consideration either during the purchase of an automation system or over the system's life cycle. However, most of the criteria listed have a direct impact on the ongoing economic performance of the manufacturing operation.

Identifying Business Value in Production Processes

Certainly, there are many different types of production and manufacturing processes for which the effective application of automation systems may provide improved business value. Each would need to be evaluated on its own merit, but all production processes have similar basic characteristics that can help to identify the potential areas of value generation.

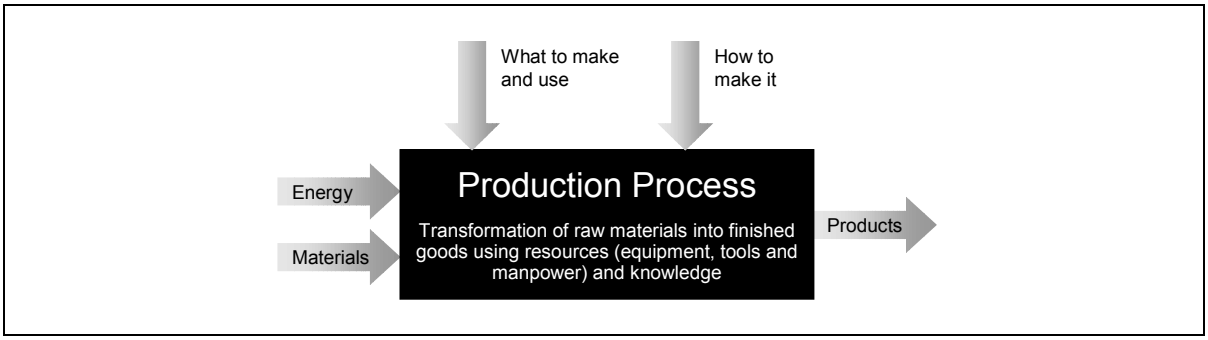

Figure 38-1. Simplified Production Process

Figure 38-1 provides a very general and high-level functional diagram of a production process. From this diagram, it is fairly straightforward to develop a discussion of at least some general areas of potential value generation from automation technology. Essentially, every production process consumes energy and raw materials, transforming them into products. Simplistically, the business value of the production process can be viewed as a function of the product value minus the energy cost, the material cost, and the transformation cost over a given time period or production run. Therefore, the potential business value improvements are energy cost reductions, material cost reductions, transformation cost reductions, and production increases. Of course, if there is not incremental market demand for the product or products being produced, an increased production rate may lead to a negative business value proposition due to the incremental storage costs required to handle the surplus inventory. It is critical to the success of any production business that the production team does not create false economics by, for example, reducing cost in one area and taking value credit for that reduction while inadvertently creating cost in other areas or negatively impacting production. Production operations have lost credibility with the financial teams in their organizations by taking too narrow a view of the business value generated. I recommend involving plant accounting personnel on the project team as early as possible to develop an appropriate analysis from a financial perspective.

Controlling costs and production can provide value to many production operations, but there are other higher-level decisions that can also drive business value. Going back to Figure 38-1, the two arrows coming into the top of the production process block represent decisions on "what to make" and "how to make it." These decisions can have a huge economic impact in a multiproduct and/or multigrade operation. Certainly, the cost and production value of each potential product and each potential grade will be different and variable. This functionality is typically referred to as production planning and scheduling. For some production operations, the most reasonable time frame for making planning and scheduling changes is daily or even weekly, but more and more operations are moving toward an Agile manufacturing approach in which changes can be made much more frequently. In some manufactur-

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Project Management and Execution

By Michael D. Whitt

Introduction

A *project* is a temporary activity with the purpose of creating a product or service. Projects have a defined beginning and end. Projects usually involve a sequence of tasks with definite starting and ending points. These points are bounded by time, resources, and end results.[1]

An engineering project is a means to an end, with a specific objective. For such a project to exist there must be a perceived need and an expectation that the need can be met with a reasonable investment. The owner must weigh the risks against the rewards and conclude the project is worthwhile. Making that risk/reward assessment is sometimes more of an art than a science. *Every project—particularly an automation project—involves some level of risk.*

> *All pilots take chances from time to time, but knowing—not guessing—about what you can risk is often the critical difference between getting away with it and drilling a fifty-foot hole in Mother Earth.* ~ Chuck Yeager, 1985[2]

More than in most endeavors, the effects of mishandling risk in an automation project can be catastrophic. Beyond the economic ramifications of a poor estimate, which are bad enough, the potential risk to the operators and the public at large can be extensive. Therefore, a well-conceived process of preliminary evaluation, short- and long-range planning, and project control is necessary. This evaluation begins with a thorough understanding of the issues. Like General Yeager, the key is to know, not to guess.

Proper project management starts with the project manager (PM). According to the Project Manager's Institute (PMI), a PM performs variations of five basic activities. The PM:

1. **Initiates** – When a project begins, the PM should identify all the project's stakeholders and determine their relative impact(s) on the project. The PM will then

1. Cockrell, Gerald W., *Practical Project Management: Learning to Manage the Professional* (Research Triangle Park, NC: ISA, 2001), 2.
2. Yeager, General Chuck and Leo Janos, *Yeager: An Autobiography* (New York: Bantam Books, 1985), 84.

develop strategies to satisfy stakeholders' needs for information. The PM will also develop a Project Charter in which he documents his rights and responsibilities, as well as his boundary limits. The Charter will also describe the project's objectives, initial risks, and acceptance criteria, among other things.

2. **Plans** – The PM creates a Project Plan by defining the scope, developing a schedule, determining the budget, and developing several subordinate plans, such as a Quality Plan, a Staffing Plan, a Communications Plan, a Risk Response Plan, and a Procurement Plan.

3. **Executes** – The PM directs and manages project execution, and ensures quality assurance (QA) is being performed. The PM also acquires, develops, and manages the project team; distributes information to the project team and to the stakeholders; and manages stakeholder expectations. The PM is also responsible for ensuring the Procurement Plan is being executed.

4. **Monitors and controls** – The PM monitors and controls project work, and performs integrated change control. The PM verifies and controls scope, schedule, and budget. The PM ensures quality control (QC) activities are being performed per the QA Plan. The PM monitors and controls risks, according to the Risk Response Plan, and procurements according to the Procurement Plan. And, the PM reports status according to the Communications Plan.

5. **Closes** – When the project's objectives and acceptance criteria have been met, as described in the Project Charter, the PM closes the project and any lingering procurement-related aspects.

The amount of responsibility and authority given to the PM varies depending on the type of organization to which he/she is attached, so the PM may or may not be responsible in all the areas described above. However, those responsibilities do reside somewhere, and it is a good idea to determine where these responsibilities lie in your organization. The PMI has grouped organizations into five basic categories:

1. The *Projectized* organization is one in which the PM has almost unlimited authority. Each project has a project team that reports to the PM, who has ultimate authority as to project execution. The PM has budget authority and works full-time on the project.

2. The *Functional* organization is one in which the authority of the PM is the least. Staff report to a functional manager (FM), who is primarily responsible for the staff and for the projects. In this organization, the PM is in a support role, does not have budget authority, and usually works part-time on a project.

3. The *Matrix* organization is one in which a blend of responsibilities exists, shared between the FM(s) and the PM. *A Guide to the Project Management Body of Knowledge* (PMBOK), fourth edition recognizes three variations of matrix organizations:

    a. The *Weak Matrix* is a variation of a functional organization. The PM role in this organization is one of coordination and facilitation. Authority is very limited, and the success of the project ultimately rests with the FM.

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Interpersonal Skills

By David Adler

Introduction

Interpersonal skills are important to automation professionals. When someone has that great job in automation, what determines if they will be a productive employee or an effective leader? Research has found that the key to individual success for professionals is how they manage themselves and their relationships. This is also true for automation professionals. In fact, an emotional intelligence skill set matters more than IQ. In a high-IQ job pool, soft skills like discipline, drive, and empathy mark those who emerge as outstanding [1]. The implications of this research for automation professionals are that they are expected to have great technical skills, but those who have good interpersonal skills experience more career success.

Being part of an automation team is a collaborative effort that requires interpersonal skills. An automation professional does not sit alone at a desk developing an automation design and implementing an automation system. It is a team-based activity that requires many different and complementary skill sets. Successful automation teams have team members who:

1. Know the process, technology, and equipment.
2. Use appropriate business processes and project management skills.
3. Have interpersonal skills.

Team members must plan an automation project, design instruments, write application code, tune process control loops, and start up the automated equipment. They must gather requirements from engineering peers, cooperate on design and development, and train operators.

Interpersonal skills are especially important for automation leaders. Automation leaders need to influence business leaders to invest in new automation technology, upgrade obsolete automation, and support the never-ending optimization of operations that automation enables. Automation leaders select, develop, and motivate team members. Automation professionals need leadership to coordinate the team's many activities when executing an automation project or supporting manufacturing.

Communicating One-on-One

Modern technology has increased the ways automation professionals interact. Email, text messages, instant messaging, and video conferencing are all part of how automation professionals communicate with others today. But, in-person conversations enable automation professionals to socialize and interact in ways that the virtual tools cannot. When give and take is required, there is no form of communication that works better than speaking to another person face-to-face.

Unfortunately, face-to-face contact is not always possible. Increasingly, automation project work requires an international workforce with engineering professionals from different cultures and in different time zones. Automation software development can be done around the clock with separate teams dispersed in Asia, Europe, and North America. Cultural differences or situational circumstances can create barriers to overcome. Communication is via teleconferencing, emails, instant messaging, and desktop sharing rather than face-to-face. This requires flexibility from everyone. Speaking and writing requires clear and crisp communications. Care must be given to what technical content is being discussed, as well as how it is communicated.

Treat even the most casual work conversation as important and take the time to prepare. While automation professionals may prepare extensively for group presentations, when it comes to one-to-one communication, they wing it. Good communicators do not just talk, they also listen. In fact, good communicators spend more time listening than speaking. An automation professional who wants to communicate effectively [2]:

- Eliminates distractions
- Pays attention
- Puts the other individual(s) at ease
- Keeps the message clear and concise
- Asks questions
- Responds appropriately

Eliminate Distractions

Temporarily put current automation problems out of mind. This will enable you to concentrate on the topic to be discussed. If you cannot free yourself from the pressure of other issues, postpone the conversation until you can give this interaction your full attention.

Pay Attention

Focus on the speaker. When automation professionals are conversing, they often aren't listening to each other because they are thinking about what to say next. Avoid the urge to multitask, especially when the conversation is not face-to-face. Avoid reading emails or checking text messages during a virtual conversation.

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