Essentials of Modern Measurements and Final Elements in the Process Industry

A GUIDE TO DESIGN, CONFIGURATION, INSTALLATION, AND MAINTENANCE

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Field Measurement Fundamentals

1-1. Learning Objectives

A. Appreciate the importance of measurements in process monitoring, analysis, control, and risk prevention.

B. Be introduced to the types of measurements and signals.

C. Understand the role of measurements in batch and continuous processes.

D. Learn how process dynamics and disturbances affect measurement requirements.

E. See how industrial instruments can be used in research and development.

F. Find out how the gap between universities and industry can be closed.

G. Learn terminology and issues to intelligently discuss industrial applications.

H. Recognize the advantages of wireless smart measurements.

I. See how measurements are used in safety systems.

J. Know the definition and relative importance of accuracy parameters.

K. Find out how to reduce measurement errors.

L. Distinguish the important aspects of process and measurement dynamics.

M. Gain insight into the relative importance of measurement speed.

N. Be able to set the transmitter damping to meet process requirements.

O. Appreciate the advantage of the electronic device description language in the setup, calibration, and interrogation of measurement devices.

P. Gain an overview of calibration methods and their effectiveness.

Q. Learn the basic types and advantages of process connections.

R. Understand the significance of sensor installation and location.

1-2. Introduction and Overview

Field measurements provide the only window into what is really happening in a process. Any technical job in the process industry depends upon measurements. Jobs in research, process development, process design, process technology, automation, operations, or maintenance depend upon the ability to see, trend, analyze, diagnose, and collect the information from measurements. Ultimately, what you want to know as an engineer or technician is "why." Modern instruments have made great progress in not only answering "why" but also offering a higher level of plant performance.

The performance and integrity of control systems and safety systems depend upon the accuracy, reliability, and speed of the measurements. You cannot control or protect something you can't measure.

The most common measurements in the process industry are flow, pressure, temperature, level, and pH. The measurement of these process variables is important for a plant to run safely and efficiently and provide products that meet customer requirements for quantity, quality, and price.

Advances in Measurements

Modern measurement instruments have made significant advances in addressing an industrial plant's requirements through:

1. Technological advances in sensing element technology
2. Indication and integration of multiple measurements

3. Compensation of application and installation effects
4. Online device alerts and diagnostics
5. Remote configuration and calibration
6. Digital signals with extensive embedded user-selected information
7. Wireless communication

Transmitters with features 1 through 6 are classified as "smart" or "intelligent."

There are 50 or more major types of instruments used to measure the most common process variables. The most prevalent type of instrument to measure flow, level, and pressure is the differential pressure transmitter, simply referred to as the DP. This chapter will use the DP as an example to dig into the details of accuracy, configuration, calibration, and installation. (Note: accuracy is the maximum deviation [error] of the measured value from the true value over a stated range of the measurement). Additional information on the DP and details on the other instruments with the best technology will be covered in the succeeding chapters.

Since the 1980s, the out-of-the-box accuracy of modern industrial instrumentation has improved by an order of magnitude. Consider the differential pressure transmitter. The 0.25% accuracy of an analog electronic DP has improved to 0.025% accuracy for a smart microprocessor based DP. Furthermore, analog DP accuracy often deteriorated to 2% when it was moved from a nice bench-top setting to service outdoors in a nasty process with all its non-ideal effects of installation, process, and ambient conditions [1][16]. A smart DP with its integrated compensation for non-ideal effects will stay close to its inherent 0.025% accuracy. Additionally, a smart DP takes 10 years to drift as much as an analog DP did in one year. (Note: drift is an error that increases with time).

Smart instruments offer the ability to report additional process variables, such as the local ambient and process temperature, and alerts based on a broad spectrum of device diagnostics. These variables and alerts are communicated digitally on the same signal as the primary process variable that is being measured. The visibility of this wealth of additional information has been greatly improved in the modern distributed control system (DCS) and the associated asset management systems (AMS). The use of the Electronic Device Description Language (EDDL) standard technology for the interface to smart instrumentation enables easier and more effective access to and visualization of the information. Instrument suppliers can readily provide an interface that optimizes the look and feel of the data items in their devices [2].

Wireless Opportunities

The wireless transmission of the signals from smart devices eliminates the time and cost of the design, installation, checkout, and troubleshooting of wiring. Devices can be easily replaced and relocated. In plants, this facilitates the movement of measurement instruments for troubleshooting and for finding optimum operating points; for example, the optimum location for temperature control in a fractionation column is the point where the greatest and most symmetrical change in temperature occurs with a change in reflux or steam flow. Also, the temperature profiles in certain sections of the column are more informative than those in others. While some simulation models can provide an idea of the best locations for temperature measurements, the locations could change with load and feed composition. To facilitate the online identification and use of the best locations, additional column connections for temperature sensors have long been provided. However, signal wiring and conduit runs have to be replaced frequently whenever a measurement point is moved [3].

Wireless smart instrument measurements create the opportunity to readily relocate instruments for better analysis and control [3]. Some of the possibilities:

- Wireless temperatures and differential pressures for packed absorber and distillation column hot spot and flow distribution analysis and control
- Wireless temperatures and differential pressures for fluidized bed reactor hot spot and flow distribution analysis and control
- Wireless pressures to debottleneck piping systems, monitor process filter operation, and track down the direction and source of pressure disturbances
- Wireless temperatures and flows to debottleneck coolant systems

- Wireless instrumentation to increase the mobility, flexibility, and maintainability of skids for process equipment service such as cleaning and sterilization
- Wireless instrumentations to increase the mobility, flexibility, and maintainability of skids for lab and pilot plant unit operations. (Note: skids are platforms of pre-assembled equipment, piping, and automation to perform unit operations)

The traditional concerns about using wireless devices in a plant for process control have been addressed in the WirelessHART network [3, 4]. The WirelessHART (Highway Addressable Remote Transducer) network has a sophisticated inherent security mechanism design. Specific keys are required at both ends for a device to join the wireless mesh network. A rolling encryption of messaging protects devices as they communicate. The self-organizing and optimizing capability of the wireless network makes the setup and commissioning of a device fast, easy, and efficient. Simple modifications to the control algorithm in the DCS and exception reporting by the device remove concerns about battery life and control system performance. Wireless smart devices will become the norm for most new plant installations [3].

Smart instruments offer an improvement in installed accuracy, a reduction in drift, an increase in reliability, and the integration of device diagnostics. The latest advances in intelligent features, such as electrode impedance diagnostics for pH, have been put into wireless transmitters. Wireless transmitters eliminate the installation and maintenance cost of wiring and offer the mobility to optimize the measurement location. The significantly lower life-cycle cost and faster speed of installation, checkout, and commissioning offers the opportunity to install more measurements to provide additional process variables. Applications of smart transmitters can be developed in labs, such as inferential measurement of concentrations from conductivity and pH measurements, and readily connected to the control system. When the application has been successfully demonstrated in the lab, the wireless transmitters can be directly moved to the field. These advantages can yield a dramatic improvement in the speed and scope of process information and a reduction in the troubleshooting for real and imagined problems.

Industrial R&D Opportunities

In the past, most process and automation system analysis was done through pattern recognition of trends and calculations performed in custom spreadsheets developed by process engineers. Offline statistical and empirical modeling was done by specialists in these areas. Tools for online advanced data analysis (e.g., multivariate statistical process control), process dynamics identification (e.g., adaptive tuning), and advanced process control (e.g., model predictive control), are now integrated into the modern DCS. These tools take advantage of the increased accuracy, integrity, and scope of smart instrumentation.

The greater accuracy of smart measurements, the greater portability of wireless measurements, and the integrated advanced analysis and control capability of the DCS open up the door for industrial instrumentation and automation systems in the pilot plant and the industrial research lab.

In the past, the measurements used in the lab and plant were quite different. The dramatic improvement in accuracy, self-diagnostics, and wireless communication of smart industrial instrumentation and the advanced capability of the modern DCS make a strong case for better data and control early in the product and process research and development (R&D) phase. The use of industrial systems in R&D offers faster and more effective specification and configuration in the production facility.

The new approach, pioneered by the biopharmaceutical industry, is to use the best smart measurement and a lab optimized industrial DCS [5]. For example, bench-top bioreactors use industrial online measurements of pH, dissolved oxygen, temperature, turbidity (cell density), capacitance (cell viability), and NIR (precursors to cell death) [5, 6]. New at-line analyzers with automated sampling systems provide measurements of the concentration of glucose, amino acids, nutrients, and byproducts. These additional online measurements (analyzers with probes in the process) and at-line measurements (analyzers with automated sample systems connected to the process) are essential for unlocking the secret profiles of these complex batch processes [7]. New basic control systems for glucose and amino acid concentration can set the stage for model predictive control of the batch profiles. Studies have shown a Model Predictive Control (MPC) system that sustains maximum cell growth and product formation rates can provide a more repeatable batch profile, a shorter batch cycle time, and a higher yield [7, 8].

Figure 1-1 shows the integration of wireless smart industrial instrumentation and a lab optimized DCS for a portable single-use bioreactor (SUB). The portable SUB has a disposable liner that eliminates the cost and time required for cleaning and sterilization in place. The sizes of SUBs have increased to the point where they can be used for industrial production of high value-added pharmaceuticals [3][5].

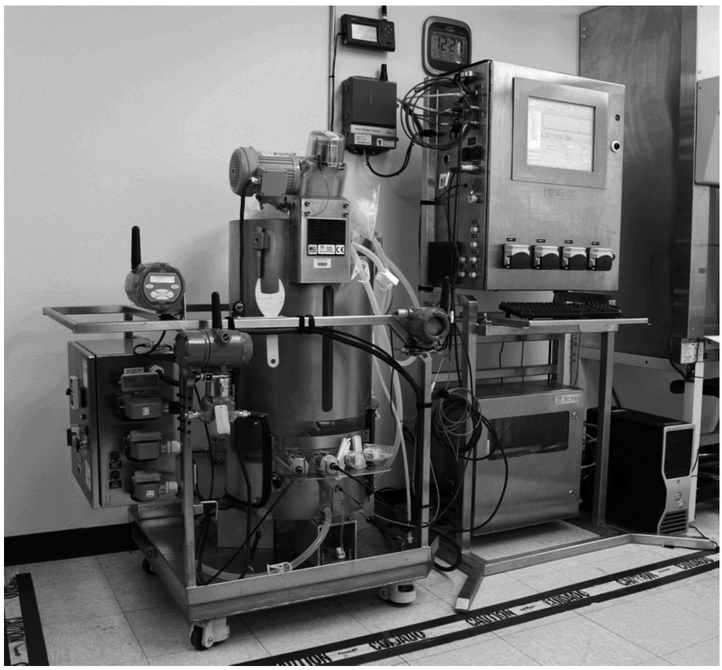


Figure 1-1. Portable Bioreactor with Wireless Industrial Instrumentation and a Lab Optimized DCS (*Courtesy of Broadley-James Corporation*)

Some of the more advanced lab and plant opportunities offered by a modern DCS and wireless smart measurements are as follows:

- Process experimentation
- Process development
- Plant design
- Plant debottlenecking
- Root cause analysis
- Predictive maintenance
- Abnormal situation prevention
- Plant efficiency improvement
- Plant capacity improvement

- Online data analytics
- Adaptive controller tuning
- Process control improvement
- Advanced control

University R&D Opportunities

Universities teach the theoretical basis of process research, development, design, and control. The equations presented and first-principle models developed are essential for developing a conceptual understanding of processes. However, equations and models have parameters that are unknown and relationships that are incomplete. Process measurements are essential for fitting the parameters. There is a great opportunity for universities to work more closely with industry [9].

The DCS is the most prevalent means of implementing batch and continuous control in the process industry. The DCS platform may also be effectively used for the evaluation and demonstration of innovative algorithms developed at a university. The integrated online advanced controls, diagnostics, data analytics, and process modeling capability of a DCS facilitate university research. This working environment also prepares students for careers in industry. Industrial standards adopted by the DCS allow students and researchers to concentrate on the application of new control capabilities. External applications such as Matlab can be used with the DCS to explore control and process modeling.

In this environment, students and researchers may take advantage of preconfigured and automated features of a DCS. Process simulations may be integrated into the DCS to create a virtual plant capability that is capable of running faster than real-time [5][8]. The DCS supports wireless and Internet access to the virtual plant, which increases ease of use in a lab or pilot plant. The DCS enables rapid exploration, discovery, and prototyping of process modeling and control technologies in a university environment and deployment in industry [9].

High technology companies are realizing the synergy between university and industry R&D for new process technology, advanced data analytics, and advanced control. These companies promote the use of the DCS in the labs of the universities that they support. Examples of university labs and pilot plants with modern industrial measurements and a DCS are the following:

- Purdue Engineering Research Center for Structured Organic Particle Systems
- Rose-Holman Institute of Technology Chemical Engineering Lab
- University of Texas Chemical Engineering Unit Operations Lab
- University of Texas Environmental Energy and Resources Pilot Plant
- Washington University in Saint Louis Computer Control Lab

We now move from getting a basic understanding of the capability and opportunities of modern instrumentation to a conceptual view of how measurement signals are created by sensing elements, generated by transmitters, communicated by wiring and networks, and received by control systems. The basic classification and requirements of enclosures for weather protection and safety are briefly summarized. Common measurements are used as examples.

Perspective

This book focuses on modern measurements and final elements with the highest performance, reliability, and maintainability. There are many older technology devices and valves still offered that are not described in this book. The addition of smart features doesn't overcome the inherent limitations of older, more primitive technologies. The life-cycle cost (cost of hardware, design, calibration, installation, commissioning, maintenance, and process variability) of the best technologies is generally less. Some project proposals unfortunately only consider the hardware cost.

The life-cycle cost of even the best technology can be excessive if there is a mistake in selection, specification, sizing, calibration, installation, or diagnosis. A common mistake is to use 1960s and 1970s installation practices [1].

To summarize, the user of smart instrumentation should not be deceived into thinking that smart features in themselves guarantee fool-proof performance. Smart instruments can be handicapped by dumb technologies, dumb applications, and dumb installations. The goal of this book is to provide guidance for getting the most out of the inherent capability of modern measurement instruments.

Sensing Elements

A sensing element converts a process variable into a quantifiable output that can be measured by another sensing element, a safety or control system input card, or a transmitter. The output of the sensing element is the **measurand** [10]. The term "sensing element" is preferred to "primary element" or "primary detecting element" [10]. The term "primary element" should be reserved for elements placed in the process to create a process variable (PV) that can be detected by the sensing element.

Differential Head Flow Measurement Example

The most common example of a measurement with a primary element is a differential head flowmeter with a capacitance type differential pressure transmitter (DP). This flowmeter is widely used because of the low cost of its primary element, which is simply a plate with a hole in it (an orifice plate). The volumetric flow is proportional to the square root of the pressure drop across the orifice. The primary element creates an intermediate PV (differential pressure), the diaphragm sensing element converts the PV to a proportional change in measurand (capacitance), and the transmitter computes the flow from the measurand with square root extraction and communicates it as an analog or digital signal to an automation system. In instruments, such as the DP, where the sensing element is integrated with the transmitter, the instrument is simply referred to as a transmitter with no distinction made to the sensing element component.

The density and hence the mass flow can be computed from the volumetric flow for a known composition by the addition of pressure and temperature measurements. Figures 1-2a and 1-2b show the installation of pressure, temperature, and DP measurements as part of a multivariable transmitter to compute and communicate mass flow instead of volumetric flow.

The DP can be installed at a more accessible location by the use of sensing lines called "impulse lines" as shown in Figure 1-2a. The trade-off for more convenient accessibility of the transmitter is the extra installation and winterization costs, and more importantly, the increased uncertainties and maintenance created by impulse lines. Plants have moved toward the direct coupling of the transmitter to the process connection as shown in Figure 1-2b to eliminate impulse line issues with the realization that a smart DP rarely needs to be removed or calibrated. In the section on installation, some of the many problems with keeping these lines at a known process composition or state will be discussed.

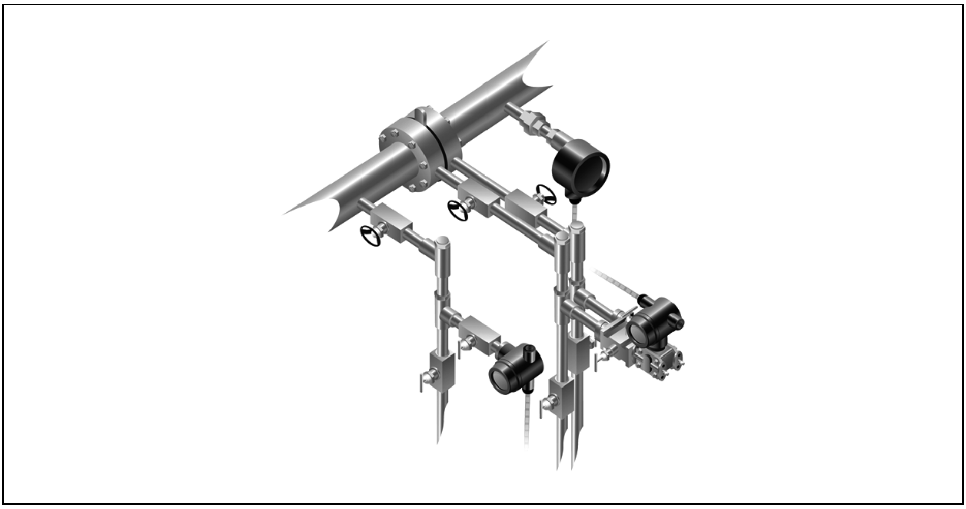


Figure 1-2a. Multivariable Differential Head Flowmeter with Sensing (Impulse) Lines

In Figure 1-2b, the isolation valves are shown as part of a manifold connected to the DP. This manifold would be left in place for removal of the DP. In many plants, piping isolation valves at the orifice taps are used, which provides isolation per the piping spec and enables the manifold to be removed with the DP.

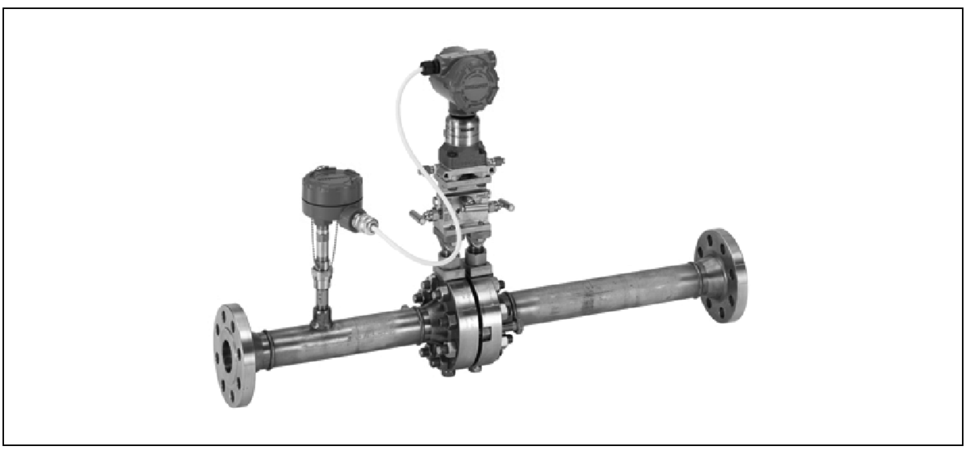


Figure 1-2b. Multivariable Differential Head Flowmeter Mounted on Orifice Taps

The differential pressure (DP) transmitter has an integral sensing element that detects the pressure drop from the resistance to flow imposed by the reduced area of the orifice. The DP transmitter's process connections are piped into the isolation valves at the orifices upstream and downstream pressure taps. The installation in Figures 1-2a and 1-2b also shows an integral valve manifold that allows the user to isolate or equalize DP transmitter's high and low sides. The upstream pressure and downstream pressures that are connected to the high and low side of the isolating diaphragm respectively create a minute displacement of the internal sensing diaphragm. In DP transmitters that use capacitance as a measurement principle, the sensing element diaphragm is inside a chamber enclosed by capacitor plates that is filled with a dielectric. The deflection of the sensing element and consequential change in capacitance is proportional to the difference in pressures on the high and low side of the transmitter. The transmitter extracts the square root of the differential pressure to provide an output signal proportional to flow.

Examples of sensing elements that are often separately mounted from the transmitter are thermocouples, resistance temperature detectors (RTD), remote seals for differential pressure transmitters, pH electrodes, and conductivity sensors. Thermocouples and pH electrodes generate a millivolt measurand that is carried by lead wires from the sensing element to the transmitter, which computes and communicates a temperature and pH signal, respectively. The transmitter is installed nearby or in the case of the thermocouple, can be mounted on the sensing element as shown in Figures 1-2a and 1-2b, which eliminates the need for thermocouple extension lead wires.

While the pH transmitter stays in place, the pH electrode is transient because of its life expectancy and need for periodic removal for calibration and possibly cleaning. The cost for calibration, cleaning, and replacement of electrodes makes the maintenance costs for pH much higher than for other instruments. Modern pH smart electrodes have a micro-chip with their model and serial number and factory calibration. Smart pH electrodes also have a microprocessor and preamplifier to offer the collection and communication of the probe's calibration history in the field. These features significantly improve the effectiveness of the calibration, cleaning, and replacement of electrodes.

Transmitters

Modern systems have progressed from sensing elements, such as thermocouples being directly wired to the input card of a safety system or control system, to using smart field transmitters that can digitally and wirelessly communicate individual diagnostics, scaling, and multivariable compensation for process conditions.

The transmitter converts and scales the sensing element output into a standard signal that becomes the input to a safety system or control system. Since a transmitter converts a measurand into an output signal it is sometimes referred to as a transducer. For the thermocouple and pH electrode example, the millivolt measurand from the sensing element is converted to the process variables of temperature and pH, respectively, and communicated as an analog (milliamps direct current), frequency (cycles per second), or digital signal (bits per second). It is important to realize that implied in these signals is always the engineering units and scale of the process variable to be displayed at the transmitter output's destination.

The transmitter may be integrated with the sensing element (e.g., DP transmitter) or mounted on the sensing element or primary element. For temperature measurements, the transmitter may be mounted on the thermowell that contains the thermocouple or RTD. For flow measurements, the combination of a sensing element and transmitter is often called a "flowmeter" or "meter" with a descriptor in front. Examples are Coriolis mass flowmeters, differential head flowmeters, magnetic flowmeters (magmeters), positive displacement meters, thermal mass flowmeters, turbine meters, and vortex meters.

Early practices that used zero current to represent 0% output were abandoned to use a positive current for 0% to distinguish a failed signal from 0% output and indicate negative measurement errors at 0% output. In the 1960s, the analog output predominantly used a 10- to 50-mA DC signal. In the 1970s, it was changed to a 4- to 20-mA DC signal, which remains the standard today for analog electronic signals. The 4- and 20-mA correspond to 0 and 100%, respectively, of the process variable range specified in the setup of the transmitter. The nonzero or "live zero" low end of the signal range facilitates the detection of sensing element and device failures and the observation of negative errors. The 4-mA signal is also essential for providing power to the microprocessors of smart transmitters to keep the devices awake and alert to problems. Each electronic signal is transmitted from the device by a single pair of wires that is twisted and shielded to reduce electro-magnetic interference (EMI). Single pairs of wire are often terminated in a junction box and/or interface panel to become part of a multi-pair "home run" cable that carries the signals of multiple transmitters to a safety system or control system. For transmitters that require more power than can be provided by the DC voltage on the signal pair of wires, a second separate pair of wires is used to provide power. These transmitters are termed “four-wire.”

HART (Highway Addressable Remote Transducer)

In the 1980s, the HART Communication Foundation (HCF), an independent nonprofit organization, developed a communication protocol for digital devices. HART devices transmit the primary process variable via the customary 4–20 mA analog output but also provide the ability to communicate additional process variables, device identification, commands, status and diagnostic alerts, and calibration information via a digital signal imposed on the analog signal. HART devices can communicate one primary process variable and several additional process variables in a single message. The number of additional process variables for simultaneous communication has increased from three to eight in HART version 7. The user has a choice of up to 256 process variables in a HART device [11]. The availability of additional process variables eliminates the need for installation of additional measurements and wiring. For example, a Coriolis mass flowmeter can simultaneously transmit fluid density, percent solids, and temperature besides mass flow on a single pair of wires.

The HART standard provides for the communication of events (occurrence of abnormal conditions) by the setting of bits. The device manufacturer can choose to communicate a signal bit as an alert or a series of bits to provide detailed diagnostics on the event.

Fieldbus

In the mid 1990s, Fieldbus systems first appeared based on International Society of Automation (ISA) and International Electrotechnical Commission (IEC) standards. The Fieldbus Foundation (FF) was set up as an independent nonprofit organization to support the commercialization of the ISA/IEC Fieldbus standard. Fieldbus devices use the ISA/IEC 1158 physical layer and stack for communication and can embed function blocks per the architectural concepts and terminology of ISA/IEC 61804. The function blocks enable the user to readily configure process computations and process control loops in field devices.

Table 1-1. Example of Data Available for Communication between a HART Device and a Host (“Unleash the Power.” *Control* Supplement, Aug. 2001)

Process Variable Values	Commands from Host	Status and Diagnostic Alerts	Device Identification	Calibration Information for 4-20 madc Transmission of Primary Process Variable
Primary Process Variable (PV) - analog current signal transmitted to host	Set Primary Variable Units	Device Malfunction - Indicates device self-diagnostic has detected a problem in device	Instrument Tag - User defined, up to 8 characters	Date - date of last calibration
Primary Process Variable (PV) - digital value in engineering units	Set Upper Range	Configuration Changed - Indicates device configuration has changed	Descriptor - User defined, up to 16 characters	Upper Range Value - PV value in engineering units for 20 mA set by user
Percent Range - primary process variable in percent of calibration range	Set Lower Range	Cold Start - Indicates device has gone through power cycle	Manufacturer Name (Code) - code established by HCF and set by manufacturer	Lower Range Value - PV value in engineering units for 4 mA set by user
Loop Current - loop current value in milliamps	Set Damping Value	More Status Available - Indicates additional devices status data available	Device Type and Revision - set by manufacturer	Upper Sensor Limit - set by manufacturer
Second Process Variable (SV) - digital value in engineering units	Set Message	Primary Variable Analog Output Fixed - Indicates device in fixed current mode	Device Serial Number - set by manufacturer	Lower Sensor Limit - set by manufacturer
Third Process Variable (TV) - digital value in engineering units	Set Tag	Primary Variable Analog Output Saturated - Indicates 4-20 mA signal is saturated	Sensor Serial Number - set by manufacturer	Sensor Minimum Span - set by manufacturer
Fourth Process Variable (FV) - digital value in engineering units	Set Date	Secondary Variable Out of Limits - Indicates secondary process variable value outside the sensor limits		PV Damping - Primary process variable damping factor set by user
	Set Descriptor	Primary Variable Out of Limits - Indicates secondary process variable value outside the sensor limits		Message - Scratch pad message area (32 characters) set by user
	Perform Loop Test			Loop Current Transfer Function - Relationship between primary value digital value and 4-20 mA signal
	Initiate Self Test			Loop Current Alarm Action - Loop current action on device failure (upscale or downscale)
	Get More Status Available Information			Write Protect Status - Device write-protect indicator

In Fieldbus devices, signal wiring between the device and the control room is replaced by a spur to a Fieldbus segment that is connected to a controller or control system bridge via a home run trunk as shown in Figure 1-3. Up to 32 devices can be connected to an individual segment and 12 of these devices can be powered from the segment. Existing twisted pair wire for 4–20 mA signals can be used for spurs and segments. Fieldbus reduces the wiring and termination cost of new installations by 30–40% [13]. Fieldbus also enables local high-speed control and can communicate more descriptive and quantitative diagnostics.

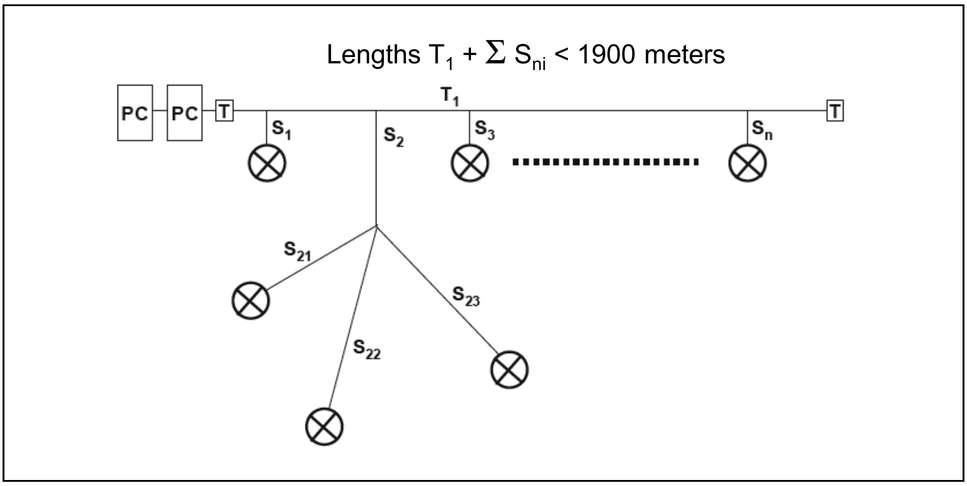


Figure 1-3. Fieldbus System Trunk (T_1), and Spurs (S_{ni})

The life-cycle savings potential for WirelessHART is more than double what is achieved by Fieldbus. WirelessHART eliminates the entire cost of wiring (design, installation, modification, and troubleshooting) and associated EMI noise problems. WirelessHART can meet the speed requirements of all but the fastest loops. Wireless periodic reporting of the primary process variable can be as fast as once per second. To extend battery life, significantly longer update time intervals are used for slow loops.

WirelessHART

The advent of WirelessHART measurements in 2008 eliminated the need for wiring between the transmitter, final elements, and the control system. WirelessHART devices broadcast to a self-organized network (Figure 1-4) that is optimized for security and reliability. WirelessHART transmitters integrally mounted with the sensing element directly to a process connection, such as the DP shown in Figure 1-2b, can save up to 70% of the life-cycle cost of a measurement by the elimination of the design, installation, checkout, and troubleshooting of wiring and sensing (impulse) lines [3].

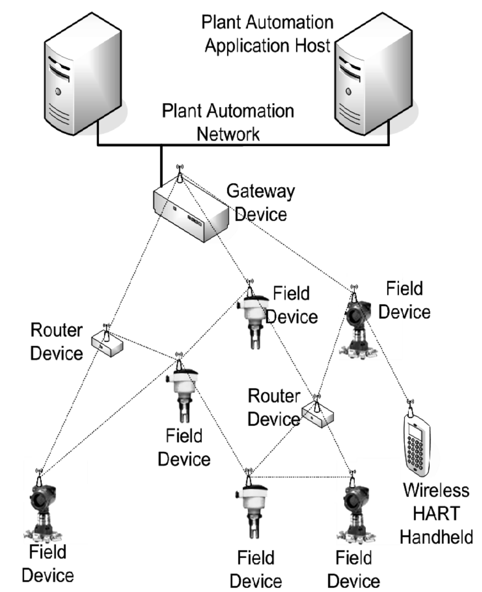


Figure 1-4. Self-Organizing and Optimizing WirelessHART Network

A major disadvantage of wired systems is that the spikes and noise from wiring problems are often intermittent, difficult to track down, and extremely disruptive [12]. The cost in terms of process variability and maintenance is usually underestimated. Whether wiring problems truly exist or not, there is always uncertainty about the integrity of the wiring and grounding system [3].

Enclosures

In the process industry, the enclosure for the transmitter typically has a NEMA 4 (National Electrical Manufacturers Association) high pressure hose proof rating. In solids process areas, the enclosures have a NEMA 5 dust proof rating. In the petrochemical industry, explosion-proof enclosures are frequently specified suitable for Class 1 Div II areas, which means ignitable concentrations of flammable gases, vapors, or liquids can exist but are not present during normal operating conditions. The Class 1 Div I ratings are for ignitable concentrations that are normally present. Plants are designed so that ignitable concentrations are an abnormal event, so this classification is rare. Explosion-proof enclosures have a NEMA 4 or NEMA 5 rating.

The most common field measurement devices are differential pressure (DP) transmitters and thermocouple or resistance temperature detector (RTD) temperature transmitters. Figures 1-2a and 1-2b show a DP flow transmitter with an integral diaphragm sensing element and temperature transmitter with an integral thermocouple sensing element for a Class I Div II electrical area classification.

Types of Measurements

There are more than a thousand different types (model numbers) of transmitters. This book will cover general classes of transmitters that account for 95% of the measurements in modern industrial process plants. Older technologies or devices specific to a particular product that represent less than 5% of instruments purchased for a new facility are omitted to facilitate a focus on the future of automation systems and measurements common to most batch and continuous processes. The most prevalent measurement technologies will be covered in the greatest detail.

A typical production plant has hundreds of process flows. Each piece of process equipment has process flows that enter and exit the equipment, which are then manipulated to control the amount of material, and in many cases the relative concentration of the materials, in the equipment. In addition, to control the temperature within the process equipment, utility flows for heating and cooling go through coils inside the equipment or through a jacket that surrounds the outside of the equipment.

Figure 1-5 shows a process vessel with common field measurements. There are flow measurements of the liquid and gas streams entering and exiting the vessel. There is a level measurement for the amount of liquid in the vessel, a pressure measurement of the overhead vapor space in the vessel, a temperature measurement of the vessel liquid, and a pH probe in the recirculation stream. You can see from this example that there are many more flow measurements than any other type of measurement. A continuous plant with 1000 total online measurements would typically have 600 flow measurements, 200 temperature measurements, 100 pressure measurements, 80 level measurements, and 20 composition or physical property measurements. Batch plants tend to have a higher percentage of flow measurements.

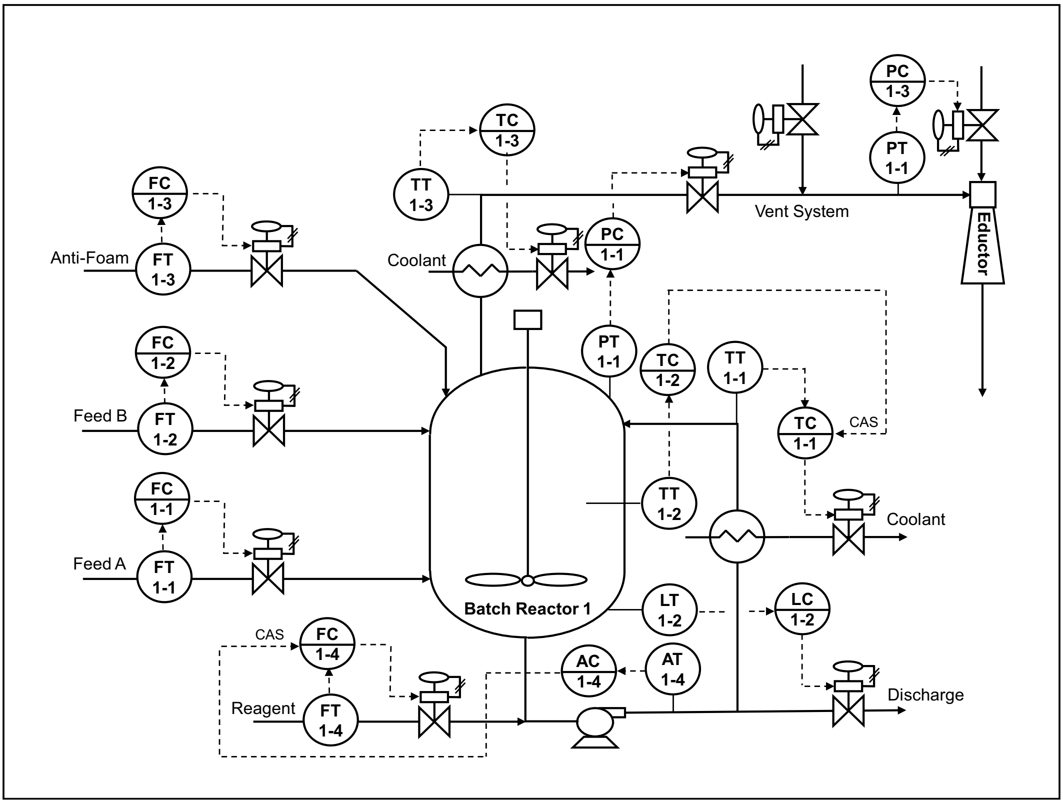


Figure 1-5. Common Field Measurements on a Vessel

Transmitters provide an analog output that is a quantized numerical value of a process variable. The fineness of the quantization is set by the sensing element sensitivity and by micro-processor and I/O resolution.

Distributed Control Systems

Figure 1-6 shows some of the functionality in a manufacturing automation network that results from measurement inputs. The following applications rely on timely and accurate measurement inputs from the field and the laboratory:

- Basic Process Control System (e.g., PID loops)[1]
- Dedicated Unit Operations Control (e.g., Batch Manager)[1]
- Advanced Process Control (e.g., Model Predictive Control)[2]
- Loop Tuning and Performance (e.g., Adaptive Control)[2]
- Data Analytics Systems (e.g., Multivariate Statistical Process Control)[2]

1. These applications are normally in the DCS.
2. These applications are integrated into the more advanced DCS.

- Laboratory Information Management Systems (LIMS)
- Process Information Management Systems (PIMS)
- Supervisory Control Systems (e.g., Real-Time Optimization)
- Manufacturing Logistics (e.g., SAPP)

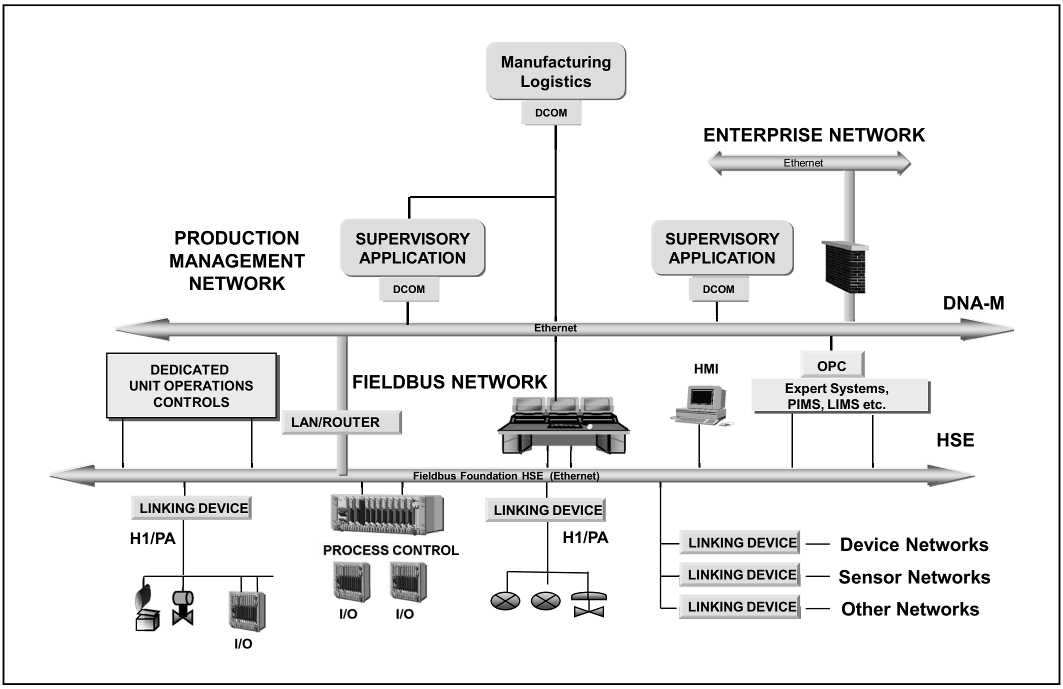


Figure 1-6. Use of Measurements in a Manufacturing System

The DCS has conventional 4–20 mA, HART 4–20 mA, Fieldbus digital, and WirelessHART analog inputs and outputs. An input card and Analog Input (AI) block converts the input signal to a numerical value. Similarly an Analog Output (AO) block and output card converts a numerical value in the DCS to an analog or digital output signal. The analog-to-digital (A/D) input cards and digital-to-analog (D/A) output cards have improved resolution as compared to earlier versions. For example, the 12-bit I/O cards of the 1980s were increased to 16 bit in the 1990s. Numerical values are used within the DCS for monitoring, analysis, prediction, basic process control, and advanced process control. The analog outputs are typically used to manipulate flows for the throttling of control valves or setting the speed of motors for agitators, blowers, conveyors, extruders, fans, pumps, and sheet lines.

The DCS has discrete inputs and outputs with 120 VAC or 24 VDC dry contact or isolated contact closures. Discrete values with a software state of a 1 or 0 (true or false) in the DCS are used in conjunction with measurements in sequential function charts and batch managers for startup, shutdown, grade transitions, and batch process control. The discrete outputs are used to turn motors on and off and to open and close valves. Discrete outputs have a pulse duration option where the width of the pulse in the discrete output for a specified cycle time is proportional to an analog value.

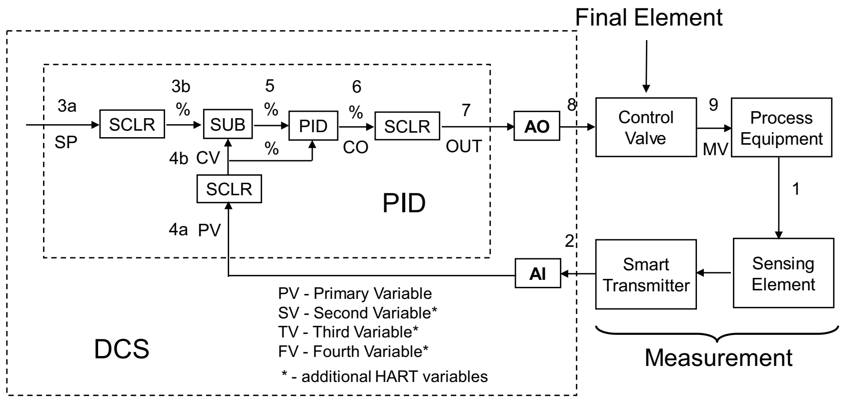
1-3. Process Automation

In order to better understand the role and importance of various measurement features, it is helpful to learn the basics of how processes respond and how measurements are used in automation systems for basic process control and risk prevention.

Control Systems

Important process variables become the controlled variables for feedback control systems. Nearly all these feedback control systems are control loops as shown in the block diagram in Figure 1-7. The control system is called a loop because a signal travels in the loop from point 1, the process output, to point 9, the process input. The process output at point 1 is detected by a sensing element and is transmitted as an input to an analog input (AI) block at point 2 in the DCS as the process variable (PV) in engineering units. The term analog input is used even though the transmitter output may not be an analog signal but may be a digital Fieldbus, an analog signal with a superimposed digital signal (HART), or a frequency-derived value of a WirelessHART signal. The AI block provides scaling, filtering, alarms, and other options. The PV output of the AI block is generally in the same engineering units as the AI block input. At point 4a, the PV is scaled to 0-100% to become a controlled variable (CV) and at point 3a, the set point (SP) is scaled to 0-100% for the Proportional-Integral-Derivative (PID) controller. The CV is subtracted from the SP to create an error in percent at point 5 that is the input to the PID controller. The negative sign applied to the measurement provides "negative feedback," which may be a familiar term from amplifier and servomechanism design that is essential for self-regulation and stability.

When in automatic mode, the controller computes a 0-100% output at point 6 from its input error that is proportional to the error, the integral of the error, and the derivative of the error. (In most loops, the derivative



The scaler block (SCLR) that converts between engineering units of application and % of scale used in PID algorithm is an embedded hidden part of the Proportional-Integral-Derivative block (PID).

Figure 1-7. Block Diagram of Typical Feedback Process Control Loop

mode is not used). At point 6, the sign of the input error is retained for "direct control action" or reversed for "reverse control action." The output is scaled to match the scale of its manipulated variable (MV) and becomes the set point for an analog output (AO) block at point 7. The field output signal at point 8 is used by the control valve to manipulate a flow that goes into the process at point 9.

It is an important but not well-recognized fact that the PID algorithm processes signals in percent and that the conversion from engineering units to percent affects the controller gain calculation. What users see in the operator interface, trend charts, and configuration is the PV, SP, and MV in the specified engineering units.

The AO block offers scaling and a reversal of the signal for reverse acting control valves, also known as "increase-to-close" and "fail-open" valves. The output of the AO block typically becomes the signal to a control valve where it is converted from an analog current or digital Fieldbus signal to a pneumatic actuator pressure via an electronic or digital valve positioner. The valve positioner provides air flow to the actuator until the air pressure in the actuator provides the desired valve position. For older valves without an electronic or digital valve positioner, a current to pneumatic (I/P) converter is used to provide the pressure to a pneumatic valve positioner or directly to the valve actuator. In Chapters 7 and 8, we will see that all valves should have a smart electronic or digital positioner.

The control valve converts the position to a flow at point 9 for a given pipeline pressure upstream and downstream of the valve. While a control valve is considered here, in some cases a variable speed drive is used. Each process has input and output flows called streams. These flows can be liquids, gases, or solids. In 99% of the plant applications in the process industry, control loops ultimately affect the process by manipulation of flows (e.g., liters per minute, gallons per minute, pounds per hour, and kilograms per hour). There may be intermediate loops that control process variables such as stream pressure and temperature, but these loops eventually cascade to a loop that manipulates a final element that changes a stream or mixing (circulation) flow. The flow manipulated is not always measured. In some cases, the control loop output will manipulate the power to an electrical heater or an electrode but these applications predominantly occur in benchtop or pilot plant scale equipment or in specialized equipment such as silicon crystal pullers and electrolytic reactors and furnaces.

Continuous Processes

A process is continuous if the principal discharge flow is non-zero during normal operation. In batch processes, the principal discharge flow is zero until the batch is done. This simple distinction, and its significant implications as to the dynamic response of these processes, is somehow lost in the complexity of automation systems. Most books and courses on process control are based on continuous processes. This section and the following sections are designed to introduce the reader to the significant distinctions and implications of continuous, pure batch, and fed-batch processes.

Most of the older and higher volume processes (e.g., commodity chemicals) are continuous operations, which are characterized by steady state values of the process variables. The dynamic behavior of the process is classified as self-regulating. There can be long periods of quiet operation where the process variables are drawing straight lines (not changing). However, continuous processes may have long lines (trains) of equipment and parallel lines of equipment. The flows of the parallel lines of equipment may diverge from and converge to common points in the process, which are often surge tanks. Consequently, the startup, shutdown, production rate change, and product grade transition of any piece of equipment can spread to other lines and ripple through and upset the whole system.

Recycle streams are process output streams that are returned as process input streams to recover solvent or raw materials that are not completely converted into product. The use of recycle streams makes processes more efficient by a decrease in makeup solvent, an increase in conversion, and a reduction in waste treatment. However, recycle streams can cause the dynamic response of concentrations to be integrating, i.e., if the controller is put into manual, the process variable will ramp up or down at a constant rate provided there are no disturbances or load changes.

In continuous processes that are running, the discharge flows from vessels are open. A level controller manipulates an inlet or outlet flow to keep the level constant except during startup, shutdown, and transitions. In surge tanks, an error squared algorithm or notch gain may be used to reduce the correction for levels well within the tank low and high level alarm limits. This strategy reduces the variability in feed to downstream units. If the level controller is in manual or is not keeping the level constant, the composition and temperature responses move from self-regulating to integrating to a degree dependent upon the mismatch between inlet and outlet flows.

Flow and liquid pressure processes are inherently continuous and self-regulating when in service because the flow out is equal to the flow into the control valve whenever the valve is open. There is no change in mass inventory between the entrance and exit of the system. Gas pressure processes are usually integrating, because there is a change in mass inventory if the loop is in manual. An increase in pressure will not increase the flow out of the volume enough to match the flow going into the volume and vice versa.

When there are several diverging and converging streams from parallel unit operations, the process can be difficult to analyze and control. Complicating factors such as catalyst activity deterioration, coating or fouling of heat transfer surfaces, equipment being pushed well beyond its nameplate capacity, and undersized surge tanks can lead to a system that is in a perpetual state of disruption.

Some people view a continuous process as a long batch process because like a batch, the continuous process has a beginning and an end, and the startup and shutdown sequences are similar to batch sequences. This view is interesting but is misleading because during normal operation, the level of a continuous process is constant and the response is self-regulating. The most important period, which is when the product is being produced, is a continuous process.

Self-Regulating Processes

The dynamic response of a temperature, concentration, or pH measurement as shown in Figure 1-8 is self-regulating for a continuous process. If the controller is put in manual, each process variable will line out at final value provided there are no disturbances or load changes or recycle streams. The observed dead time (θ_o) is the time of no process response after a change in the controller output. The process time constant is the time to reach 63% of the final change after the process breaks out of the noise band with a recognizable response. While the terms "process dead time" and "process time constant" are normally used, more correct terms would be "total loop dead time" (θ_x) and "open loop time constant" (τ_o), respectively. The descriptor "open loop" is an important distinction for tuning methods that use a "closed loop time constant" (τ_c) called Lambda (λ), which is the time to reach 63% of a set point change. Lambda is used to specify the controller's speed of response in the automatic, cascade, or remote cascade mode which is important for the coordination and performance of loops. In contrast, the "open loop time constant" does not depend upon controller tuning but describes the response of the rest of the automation system. When a controller is in manual or remote output modes, there is no feedback control. The loop is open at the controller in the Figure 1-9 block diagram [8][18].

The open loop time constant (τ_0) is the largest time constant in the loop (largest time constant in the Figure 1-9 block diagram). Ideally, the largest time constant is in the process so it slows down process disturbances.

The largest time constant can occur in the measurement with an excessively large sensing element time constant, transmitter damping setting, or DCS filter time setting.

The largest time constant can occur in the final element if a control valve has a large actuator or a positioner with poor sensitivity or a large prime mover has an undersized motor. These scenarios are particularly troublesome for flow and liquid pressure loops because these processes are so fast. Poor temperature sensing elements and fan or vent damper installations can be problematic for furnace and dryer temperature and pressure loops even though their process dynamics are slower. In these situations, the measurement is providing an attenuated and slow view of the actual

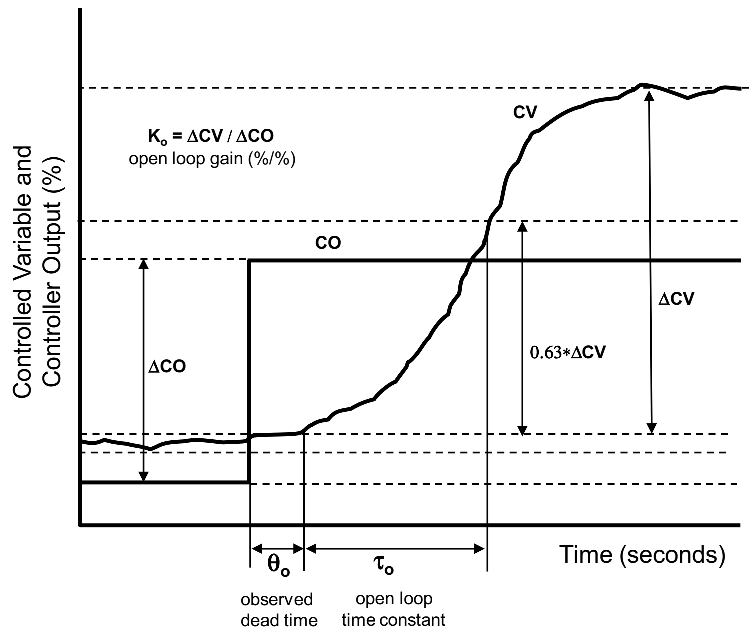
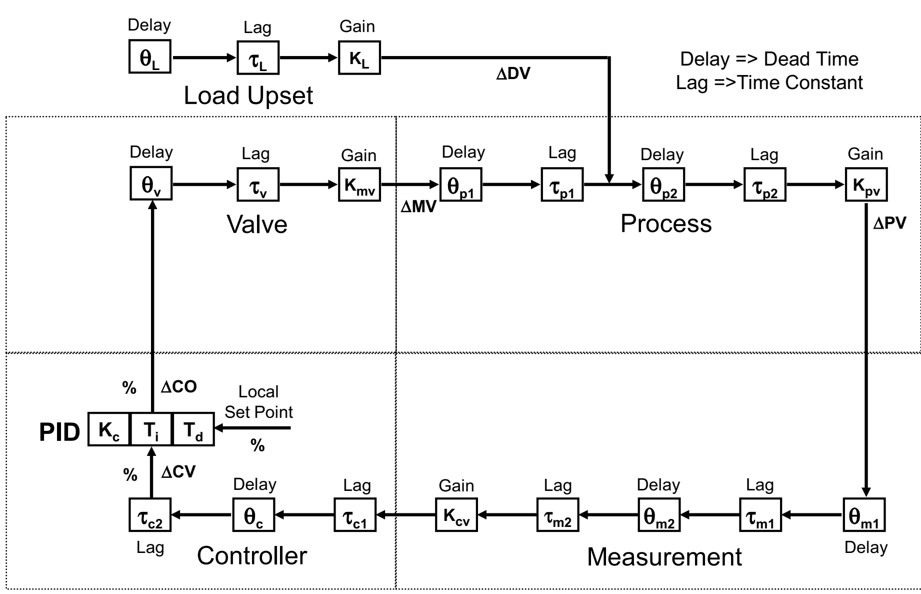


Figure 1-8. Self-Regulating Response of Continuous Process Measurements



Total Observed Dead Time: $\theta_o \cong \theta_v + \theta_{p1} + \theta_{p2} + \theta_{m1} + \theta_{m2} + \theta_c + \tau_v + \tau_{p1} + \tau_{m1} + \tau_{m2} + \tau_{c1} + \tau_{c2}$

Figure 1-9. Final Element, Process, Measurement, and Control System Dynamics

process variable or the final element is providing a slow correction of the process variable [8][18].

The total loop dead time (θ_o) is the sum of the dead times and small lag times in the loop. Dead time is a problem no matter where it occurs because it delays either the observation of or the reaction to a disturbance. The minimum integrated absolute error (IAE) for loops tuned for maximum load rejection (e.g., flow disturbance correction) is proportional to the square of the total loop dead time. The peak error is proportional to the loop dead time — open loop time constant ratio [8][18].

The process gain is the change in the measurement output in percent divided by the change in controller output in percent. The process gain is more properly known as the open loop gain. The open loop gain depends upon the dynamics of the final elements and measurements, as well as the dynamics of the process, as denoted in Equation 1-1a for the typical case where the final element regulates a flow into the process. Equation 1-1b shows the measurement gain is inversely proportional to the measurement span, an important consideration in the effect of measurement setup on controller tuning.

The literature rarely breaks down dynamics in a process control loop into contributing parts of an automation system as shown in Figure 1-9, leading to misunderstandings. In the chapters on final elements, we will see how the response of a control valve depends upon size, installed characteristic, deadband, hysteresis, resolution, and the size and direction of the change. In the chapters on measurements, we will explore how the response of a measurement depends upon the speed of the sensing element and transmitter. The good news is the proper design, setup, and installation of control valves, variable speed drives, and inline measurement devices makes the speed of response of these components negligible for all but the fastest processes.

Some process responses have a time constant so slow that their response in the region of interest around the set point looks like a ramp. These processes are called "near-integrating" or "pseudo-integrating" processes and can be analyzed and tuned as if they had an integrating response (as shown in Figure 1-10) by converting the self-regulating process gain to an integrating process gain per Equation 1-1c. Most integrating processes would eventually reach a steady state if there were no process or measurement range limits. Also, some auto tuning methods do not handle integrating processes very well. For these and other reasons, Equation 1-1c is useful for converting a measured self-regulating process gain to an estimated integrating process gain and vice versa.

$$K_o = K_f * K_p * K_m \tag{1-1a}$$

$$K_m = \frac{100\%}{S_m} \tag{1-1b}$$

$$K_i = \frac{K_o}{\tau_o} \tag{1-1c}$$

Where

K_o = open loop gain for self-regulating processes (CV %/CO%)

K_i = open loop gain for near-integrating processes (CV %/CO%)

K_f = final element gain (Flow e.u./CO %) (e.u.= engineering units)

K_p = process gain (PV e.u./Flow e.u.)

K_m = measurement gain (CV %/PV e.u.)

S_m = span of measurement scale in PID (PV e.u.)

(CV % is percent of controlled variable scale and CO % is percent of controller output)

The span of the measurement scale is the difference between the low and high values of the process variable (PV) scale of the PID controller. The span of the PV scale in the PID is generally but not necessarily the calibration span of the measurement.

Integrating Response

The following process variables and processes tend to have an integrating response:

- Level in vessels with pumps on discharge
- Gas pressure in columns, dryers, and vessels
- Composition in continuous processes with no level control
- Composition in continuous processes with recycle streams

- Composition, pH, and temperature in batch operations

An integrating response has no steady state. When the controller is in manual, the process variable will ramp at a rate dependent upon the unbalance. The easiest integrating process to visualize is level. If the main discharge flow is pumped out, for example, an increase or decrease in level will not appreciably increase or decrease the discharge flow, respectively. The level will ramp up or down whenever the total of the flows coming into the vessel does not exactly match the total of flows going out of the vessel. Any exact match of incoming and outgoing flows is temporary at best. The ramp rate depends on the unbalance in these flows and the size of the vessel. Integrating processes are more difficult to control but fortunately tend to be much slower, giving the controller a chance to catch up with a disturbance provided it is properly tuned to take advantage of the slow ramp rate.

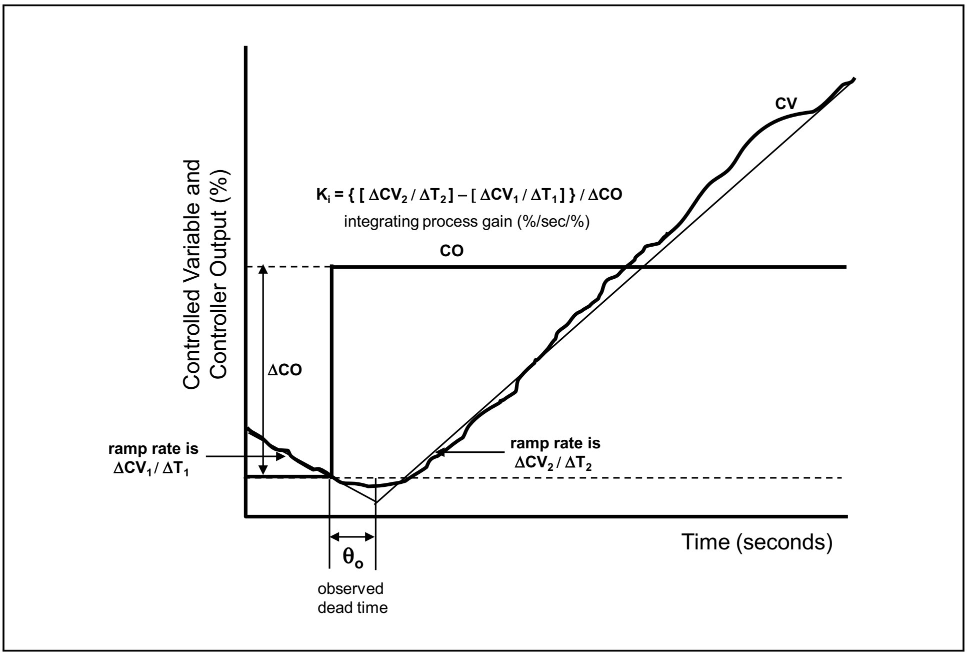


Figure 1-10. Integrating Response of Batch Process Measurements

Batch Processes

Most ingested or injected products (foods, beverages, and pharmaceuticals) use batch processes because the quality is predictable if the recipe is carefully followed and good and consistent quality raw materials are used. There is no retention of old material or buildup of impurities or contaminants as associated with continuous processes since the vessels are completely emptied and can be cleaned and sterilized between batches. New processes for specialty chemicals also use batch operations because a batch system is easier to develop and design since it essentially follows a cookbook approach. However, for a given size of equipment, a batch process will not produce as much as a continuous process. As products mature and production capacity requirements increase, production tends to move from batch to continuous mode.

In batch processes, the liquid or solids discharge flow does not match the total flow coming into a vessel. Consequently, the liquid or solids level is continually rising or falling. In pure batch processes, the discharge flow is shut off until the end of the batch cycle when the vessel is drained. The rise or fall in level from the mismatch of flow going in and out changes the dynamic response of vessel temperature, concentration, and pH from self-regulating to integrating, which has important implications for process control.

To understand the distinctive difference between a batch and continuous operation consider the preparation of a meal. The making of a pot of chili is a pure batch operation as shown in Figure 1-11. There is a definitive sequential recipe where tomato sauce, beans, spices, and secret ingredients are added in precise quantities until the pot is full. The contents of the pot are cooked until the mixture reaches a temperature, simmers, and melds. When the peak flavor is reached, the pot is emptied. The pot is stirred and sampled at a frequency and loss in volume that depend on the taste and hunger of the stirrer and whether your spouse is looking.

A continuous chili process might start out like a pure batch process but once the chili reached peak flavor, a drain valve would be opened and a simultaneous addition of ingredients would be started whose total flow matches the discharge flow of chili as shown in Figure 1-12. Getting to the balance condition would be difficult but when you reached it, the flow and taste should be consistent. For a given size pot, a continuous process can produce more chili because you don't have the addition and drain times and the flow rate can be increased to a point commensurate with the heating capacity. The quality or taste might not be as good as a pure batch process with a correct batch time because a fraction of the ingredients added are going out without enough simmer time or sufficient mixing, particularly as the production rate is increased.

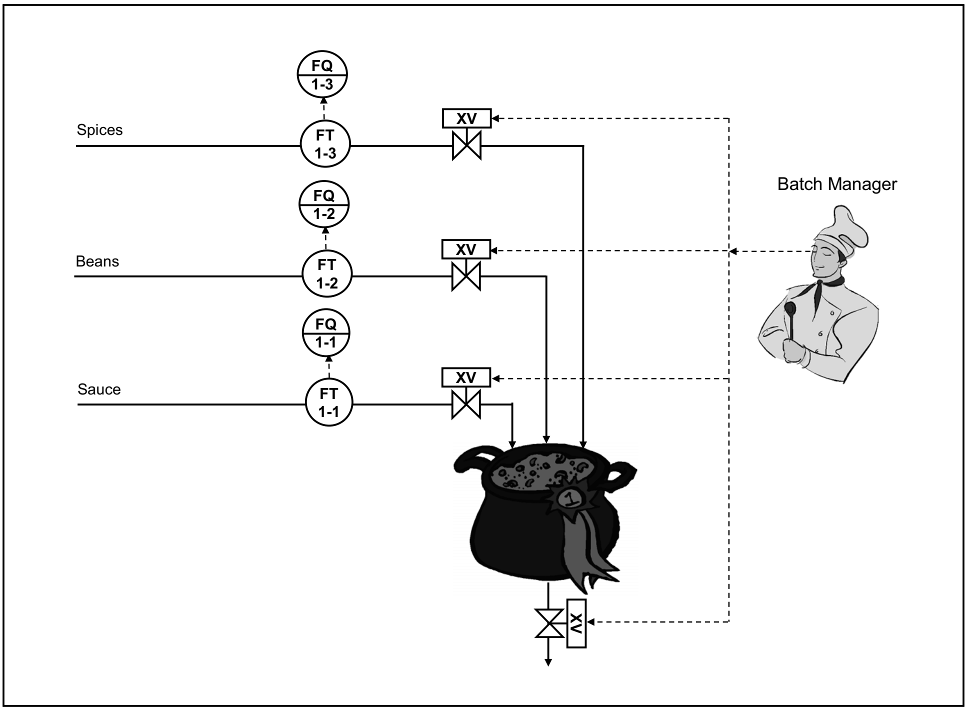


Figure 1-11. Pure Batch Process for Chili

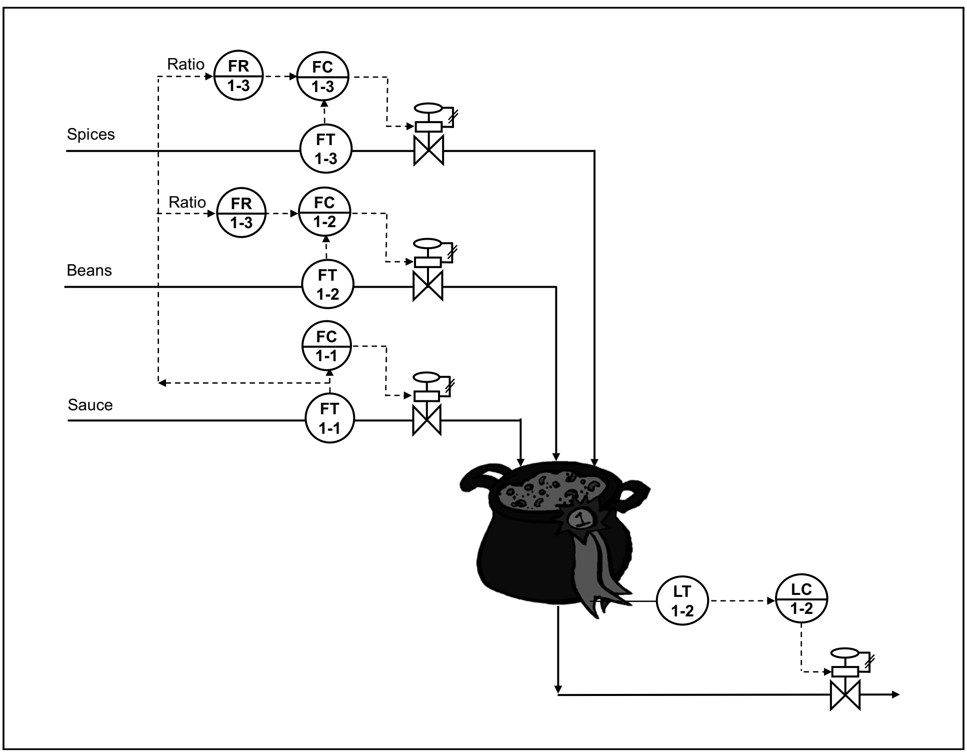


Figure 1-12. Continuous Process for Chili

Fed-batch Processes

Fed-batch operation is also termed semi-continuous operation because ingredients are simultaneously added under a ratio control scheme where the flow of each ingredient is kept in the proper proportion to the others as shown in Figure 1-13. This usually occurs after a pre-charge of some ingredients and heating of the mixture to operating temperature. The simultaneous addition continues until the pot is full, at which time it goes into a simmer mode. In some fed-batch processes, the ingredients do not flow simultaneous but flow sequentially. In either case, the flows are often manipulated by composition, pressure, or temperature control loops. The manipulation of flows may be by the direct adjustment of a flow set point or by the correction of a ratio factor. While this process is termed semi-continuous, it does not have the dynamic characteristics of a continuous process because the level is rising.

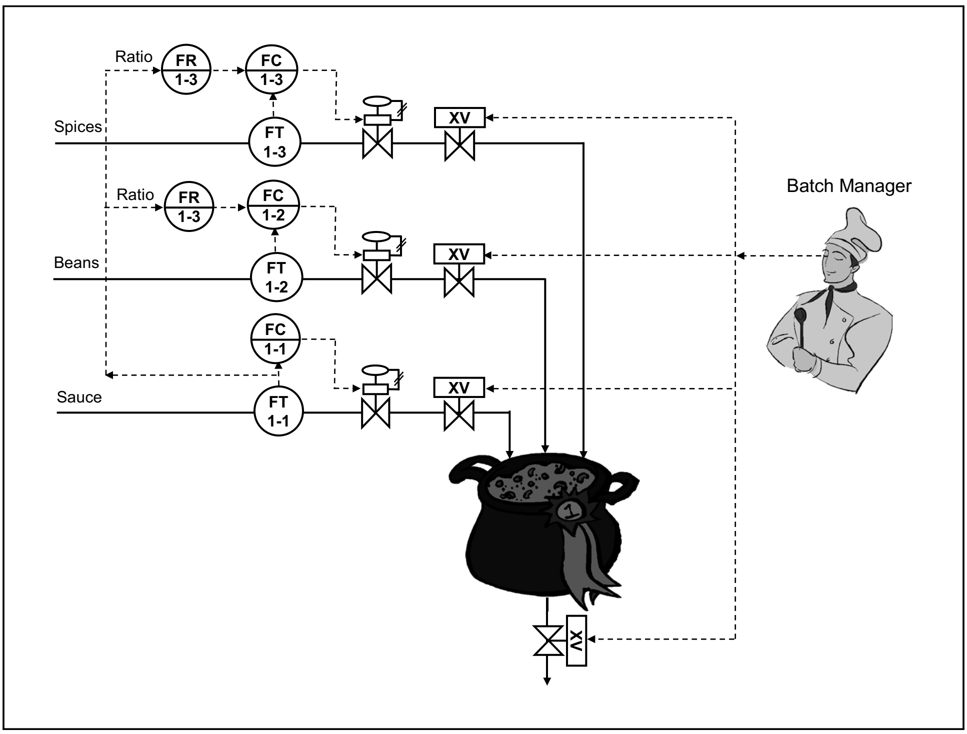


Figure 1-13. Fed-batch Process for Chili

The control systems for pure batch chemical processes tend to not to have as many control loops as do continuous control systems. The feeds are often charged based on a weight or flow total basis without control loops. Online concentration measurement and control is rare in chemical batch processes. The profiles of intermediate and product concentrations are largely secret. Since the product quality depends upon these concentrations, the performance of a batch process is largely unknown until after the batch is done and lab results are available.

Batch processes typically have pressure and temperature loops. The pressure is often controlled by manipulation of a gas or vent flow. Temperature is usually controlled by manipulation of cooling or heating. We should not generalize that batch processes don't have as much process control as continuous processes. While batch chemical processes generally do not have as many field analyzers as continuous chemical processes, there are often more flow control loops in a fed-batch process. Biochemical and biopharmaceutical processes (predominantly batch to date) have more online measurements than chemical processes.

Fed-batch control systems have feed flow loops and pH or concentration control loops to correct the ratio of ingredient flows. In the case of a gas phase reaction, the gas reactant feed flow is often manipulated by a pressure loop that corrects for the consumption of the gas reactant.

Fed-batch cell culture bioreactors have dissolved oxygen, viable cell, biomass concentration, and pH loops besides temperature and pressure loops, and in the near future will have glucose and glutamine concentration control loops as shown in Figure 1-14. This, combined with air, oxygen, inerts (e.g., argon), carbon dioxide, glucose, and glutamine flow loops, add up to a complexity seldom seen in continuous chemical processes.

Many of the batch variables follow a batch profile (curve) that usually starts at a low value and reaches a peak that corresponds to a significant decrease in product formation rate.

Profile Control

The degree of process control determines how many of the measurements of process outputs (batch variables) follow a batch profile (curve). Process control loops make process outputs draw straight lines by transferring variability in process outputs to process inputs.

A simple bioreactor example, where the media (glucose and nutrients) and seed cells have been pre-charged and the batch has reached operating temperature, illustrates the principle of transfer of variability, which has

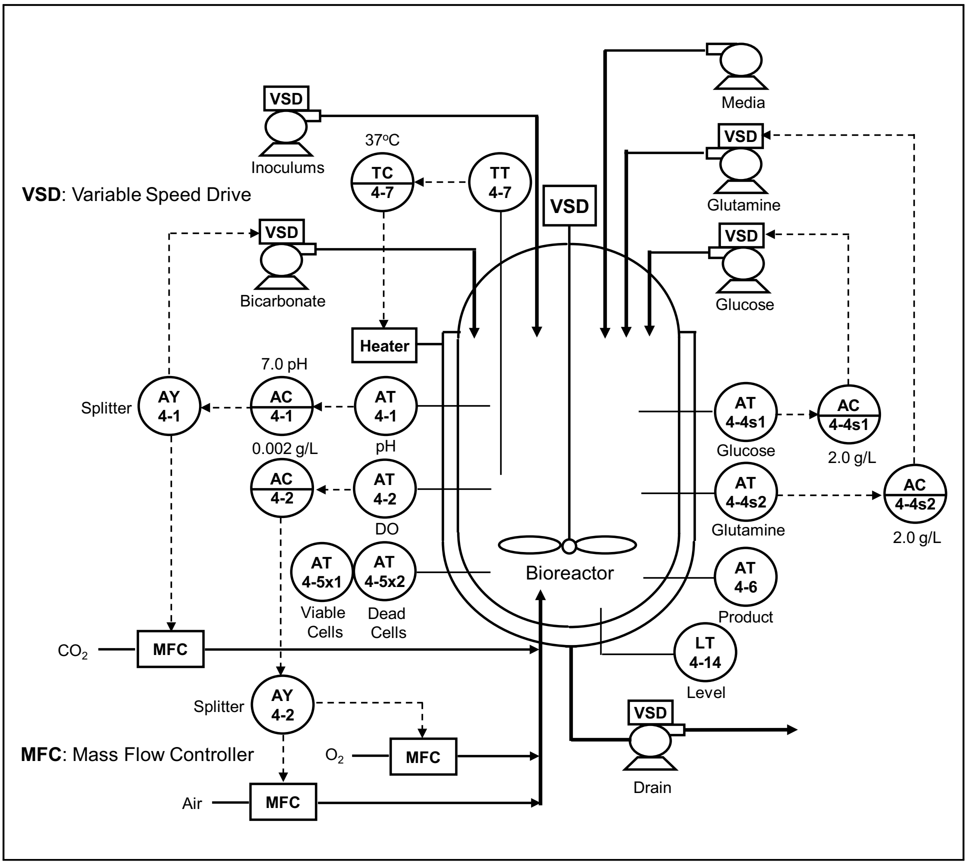


Figure 1-14. Fed-batch Cell Culture Bioreactor Control System

profound implications not commonly recognized in the literature on process analysis, efficiency, and consistency.

The mindset of process research, development, and design in universities and industry is to determine process outputs by fixing process inputs per a script. This mindset, while performance limiting, is difficult to change in practice. The experimentation in research and process development sets the path of fixing the values and timing of additions and heating and cooling. The lack of process control loops in research and process development translates to process definitions that are deficient in basic and advanced process control. If there is variability in the process outputs, there is a more stringent effort to keep most process inputs fixed and to improve the role of a few inputs viewed as key. Process engineers who have achieved particular expertise in orchestrating the process inputs are reluctant to give up personal control of these inputs to a control loop and a process control engineer. The solution is to put a lab-optimized distributed control system with control loops and advanced control tools into the research lab, similar to what has been done for benchtop and pilot plant bioreactors [5].

In Figure 1-15, there are no process control loops on the process outputs. The feeds are sequenced in a batch operation. All the process variables follow a batch profile. The feed rates and timing are experimentally derived for a given set of feed conditions and starting points.

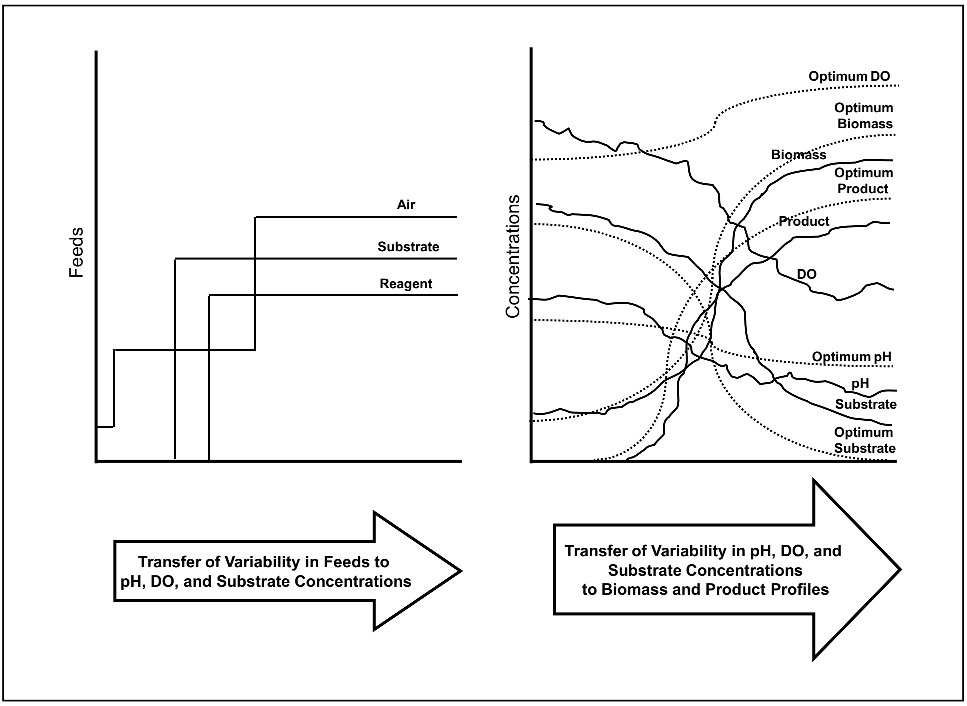


Figure 1-15. Transfer of Variability for Pure Batch Control of a Bioreactor

In Figure 1-16, dissolved oxygen, pH, and glucose are drawing relatively straight lines by the use of process control loops that have transferred variability in these process outputs to the feed rates. These loops automatically take care of disturbances and unknowns in the media charge and seed cells and mutations and alterations in the metabolic pathways of the growing cells.

In Figure 1-17, the biomass and product concentration profiles achieve a more proficient curve shape and end point by the use of model predictive control (MPC) to automatically optimize the dissolved oxygen, pH, and glucose set points. MPC transfers variability from the bottom line process outputs (e.g., product concentration) to the less important process outputs (pH and dissolved oxygen), which in turn via control loops, transfer the

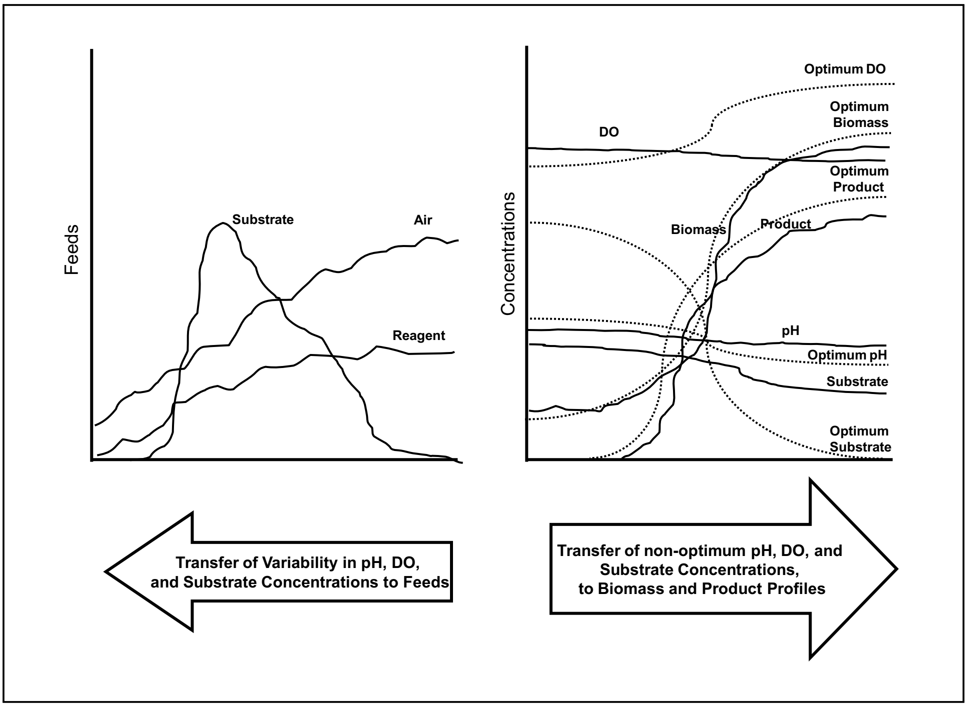


Figure 1-16. Transfer of Variability for Fed-batch Control of a Bioreactor

deviations from the optimum set point to the process inputs (e.g., reagent and air flows).

Real Processes

Regardless of whether a process is batch or continuous the feeds are subject to disturbances in terms of pressure, temperature, concentration, physical properties such as heat capacity, density, and viscosity, and quality parameters such as color. The variation in bulk material shipments, recycle streams, and intermediate products from other processes in the plant and the degree of smoothing in storage tanks is usually not tracked or modeled.

Most university chemical and petrochemical engineering programs exclusively study continuous processes during normal operation and use steady-state simulation software to generate process flow diagrams (PFD). The flows, temperatures, pressures, concentrations, and physical properties do not change with time but are constant for a given set of feed conditions.

Nearly all control theory classes and textbooks on process control focus on continuous processes. Students are not prepared for the dynamics and

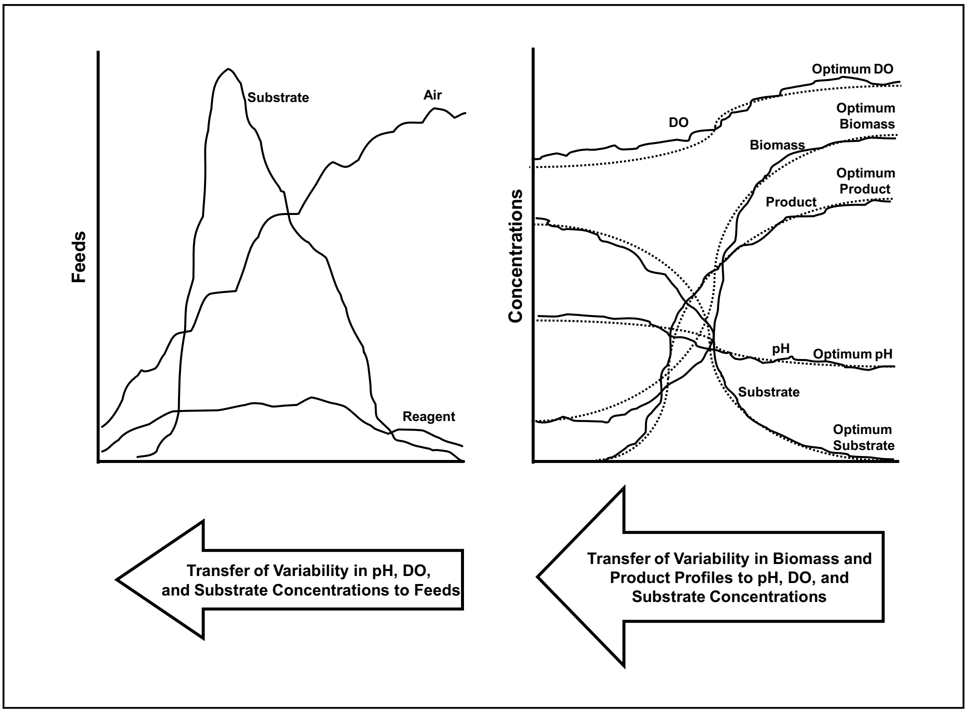


Figure 1-17. Transfer of Variability for Model Predictive Control of a Bioreactor

measurement and control considerations of batch processes or the startup, shutdown, and transitions of continuous processes. Students may even think the streams in a plant are at the conditions depicted in a PFD.

Continuous processes may operate for long times at one steady state and can appear to be quite boring, but assuming the concentrations not measured online are at PFD values is wishful thinking. The real thrill of process control is moving the process to reach a more efficient or productive operating point. In a batch operation, reaching an operating point that creates saleable product is a natural course of action, because the batch manager and process control system are pushing the batch to reach its end point. Continuous processes are more dependent on the operator or an advanced control system to move the process operating point. On the other hand, there is generally more opportunity to increase batch production capacity by reducing batch cycle times by adding process control loops or model predictive control. Increases of 25% capacity from additional process control are common for batch process, whereas increases of 5% capacity in continuous processes is considered exceptional. For both batch and continuous processes improved process efficiency, in terms of providing higher yields, lower utility use, or producing higher grade product are process control opportunities.

Many plants have a combination of batch and continuous processes. A common configuration consists of batch reaction and crystallization processes followed by continuous separation (e.g., distillation and evaporation) and purification processes.

Measurements and process control systems also have the important function of property and personnel protection. These often go hand in hand because damaged or malfunctioning process equipment usually poses a safety risk to personnel.

Safety Systems

Most plants have safety instrumented systems (SIS) as automated protective layers to reduce the risk in process operations, as shown in Figure 1-18. A safety integrity level (SIL) rates the severity of the potential hazard. A higher SIL number indicates a higher severity and greater safety system requirements. The American National Standards Institute (ANSI) and the International Society of Automation (ISA) have developed standards for the Functional Safety: Safety Instrumented Systems for the Process Industry Sector (ANSI/ISA-84.00.01-2004 Parts 1, 2, and 3). These standards provide the framework, requirements, and guidelines for the application of SIS and guidance for the determination of SIL.

Many processes include flammable, explosive, harmful, or even lethal chemicals. A safety hazard can be the result of contact with the chemicals or from the effects of damaged or malfunctioning process equipment. The SIS will initiate actions to prevent or mitigate a hazardous event if process variables get too high or low for safe operation. The discrete status of a process variable being out of safe range is set by field process switches, transmitter signal switches, or software value switches as shown in Figures 1-19a through 1-19c.

Field process switches have a process connection that puts the process fluid in contact with the trigger mechanism or sensing element. Older mechanical examples are bellows or bourdon tube pressure switches, bimetallic or filled capillary temperature switches, paddle type flow switches, and float or displacer level switches. Newer electronic examples include capacitance, ultrasonic, and microwave level switches. Field pressure and temperature switches, despite technical improvements, are not recommended by the author. Field process switches don't provide an online measurement of the process variable (e.g., pressure, temperature, flow, or level). Consequently, it is difficult to monitor their sensing ability

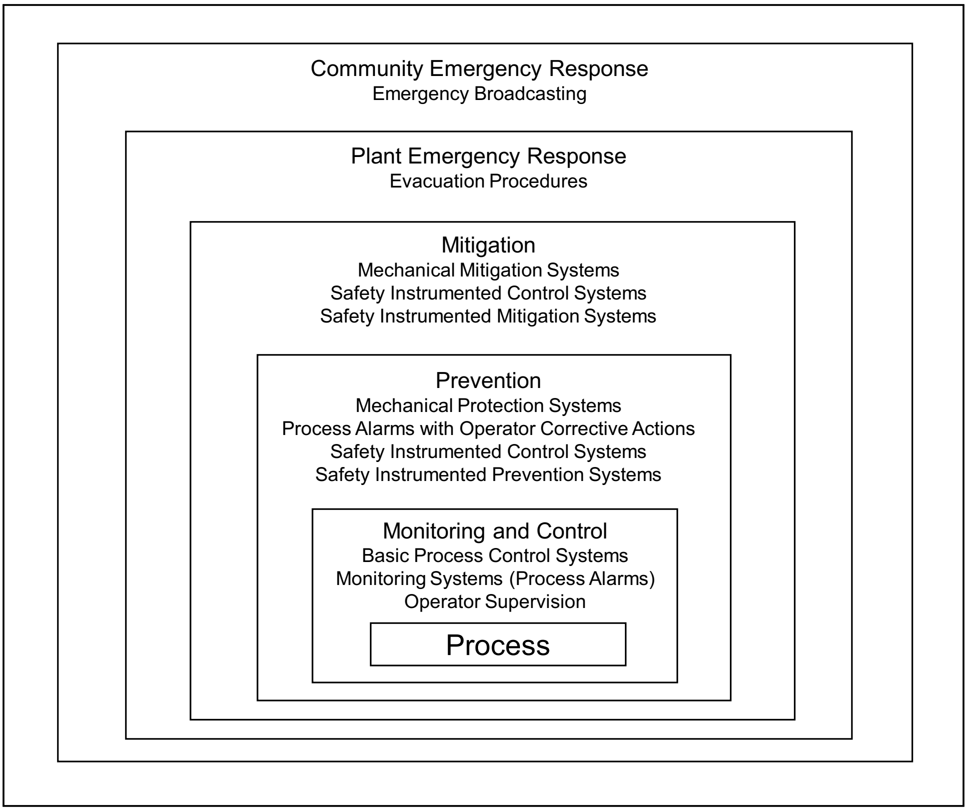


Figure 1-18. Protective Layers for Risk Reduction

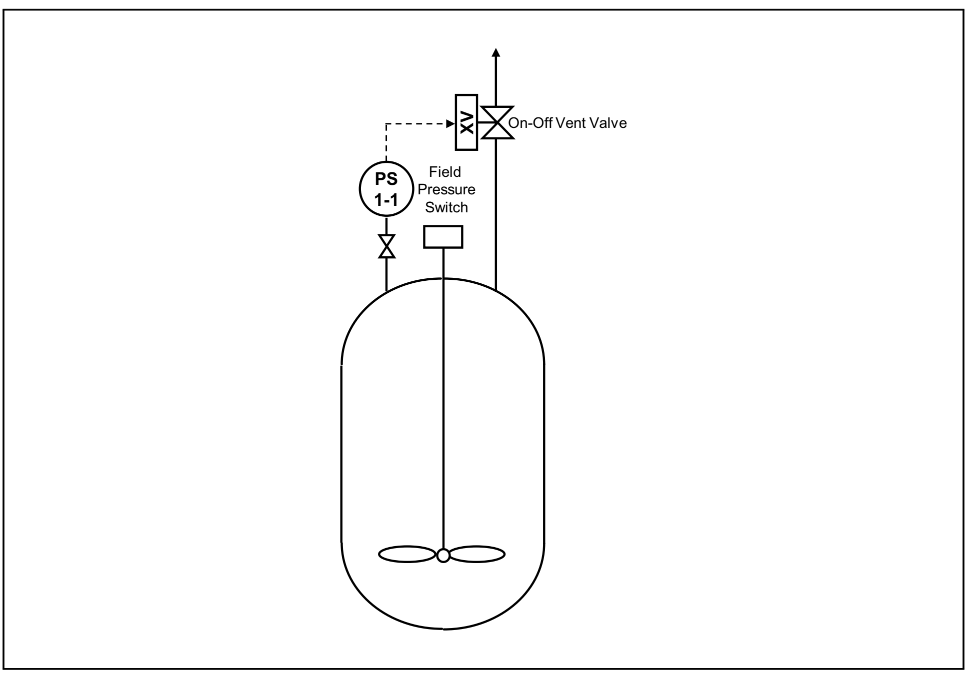


Figure 1-19a. Field Process Switch

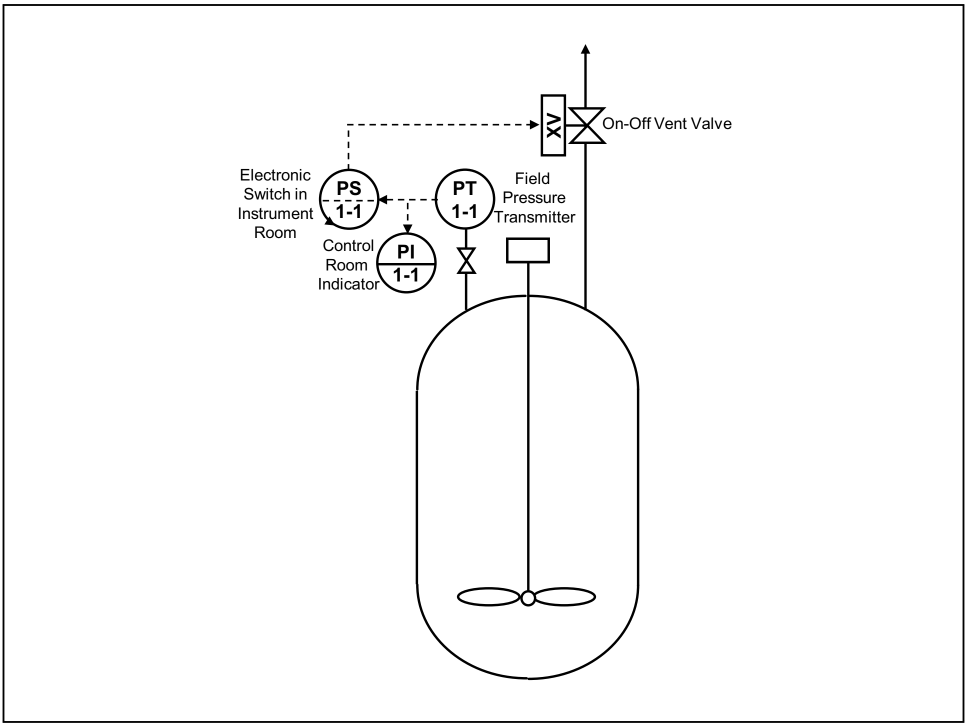


Figure 1-19b. Transmitter Signal Switch

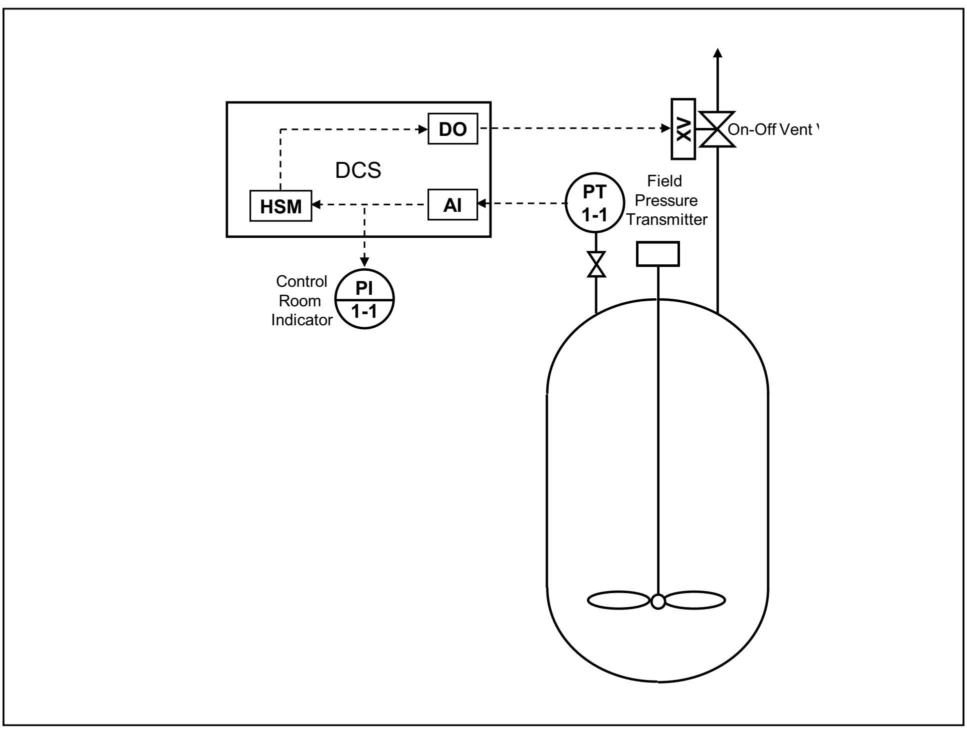


Figure 1-19c. Software Value Switch

or integrity online. Older mechanical switches are particularly problematic because of problems that include hysteresis and repeatability and wear and tear from process exposure and age. These field process switches were predominantly used in packaged equipment and utility systems to reduce the cost of the instrumentation.

Experienced users realized that the reliability and life-cycle cost of safety systems is improved by the use of continuous measurements and switches on the transmitter output signal. In the early days of process control (e.g., 1960s), the pneumatic transmitter output (3-15 psig) went to rack mounted pneumatic pressure switches. With the advent of electronic instrumentation (in the 1970s), the electronic transmitter output (e.g., 4–20 mA or 1-5 VDC) went to rack-mounted current or voltage switches.

The discrete outputs of field process switches and transmitter signal switches were typically contact closures that would de-energize relays, motor control, or solenoid valves for the prevention or mitigation of unsafe conditions. De-energization is normally used as the discrete output state to ensure an electrical failure puts the process in a safe state. The solenoid valve (SV) is a 3-way valve, whose operating and trip positions are set by the energization and de-energization, respectively, of an electrical solenoid. Solenoid valves take less than a second to switch position. The wetted materials for the body and switching element are not extensive and the flow path is not smooth enough for installing an SV on a process line. Some SVs are used on air, water, and other utility streams, particularly on packaged equipment. In most process applications, the SV is in the air line of a control valve, to exhaust air upon de-energization and allow a spring return actuator to open or close the control valve. The spring puts the valve in the fail-safe position. For double acting piston actuators, dual SVs are used to fill and exhaust the appropriate sides of the piston to open or close the valves. Local air tanks are used to ensure a fail-safe position.

Safety instrumented systems are often activated by high temperature or pressure measurements but many types of online measurements are used. These measurements need to be fast and reliable.

A high SIL requires instrumentation and logic solver redundancy for reliability. NooM (N out of M) input voting architectures are commonly used with redundant measurements to trigger a trip, where N indicates the number of votes required to trip and M is the total number of devices used. The typical architectures employed are 1oo1, 1oo2, and 2oo3. A 1oo1 architecture can be used for simple applications, but undetected device failures can cause loss of protection since only one input device is used. A 1oo2 voting system is a common method of improving the reliability of a safety system. If one measurement reaches the safety setting, a trip is initiated. However, this makes the plant more susceptible to false trips due to sensing element or transmitter problems. False trips are quite costly for large continuous processes. The startup after a trip can be difficult, require significant time, and necessitate a transition through process conditions that are more hazardous than during normal operation. Thus, minimization of trips is both an economic and a safety issue.

Consequently, a 2oo3 voting system is sometimes used, where two measurements have to indicate an unsafe process condition to initiate a trip. This voting system eliminates a false trip or disabling of the SIS due to a single measurement problem. A 3oo5 voting system requires three measurements out of five measurements to vote for a trip. These systems are used in nuclear reactors and aerospace to protect against two measurement problems causing either a false trip or the inability to trip on a true unsafe condition.

Large continuous chemical and petrochemical plants with a high production loss from downtime use a "middle signal" system particularly when the startup requires significant operator expertise and time to clean out the equipment and piping and/or get the process back to operating conditions. The selection of the middle signal not only provides protection against a single measurement failure similar to a 2oo3 voting system for safety systems, but also protects an associated control loop against a single measurement failure. The continued operation of the loop may prevent the process from reaching the trip point. Middle signals are used in polymerization lines that might solidify on shutdown and catalyst bed reactors that require careful fluidization and reintroduction of explosive feeds. Here, three transmitters are installed, and the middle signal is selected for both safety systems and process control. This middle signal selection protects against a false trip and prevents a true trip as the result of an unsafe condition created by a disabled process control system from a single measurement failure.

The process control system and its measurements and final elements should be designed so that the safety instrumented system is never activated. The process control system is the primary automatic protective layer. The process control system should be able to handle disturbances and keep the measurements that are inputs to the SIS well within the settings that trigger SIS actions.

These safety systems may set coolant valves or vent valves wide open or close feed valves. The shutdown and startup of a process are usually the most dangerous times because the process is going though large and rapid transients, particularly during a trip. Most shutdowns are completely automated and generally very fast for safety. Solenoid valves described in the chapters on Final Element Fundamentals and Control Valves are electrically de-energized to rapidly move air in or out of the control valve actuator to put the valve in the trip position as fast as possible.

1-4. Dynamics

Measurement devices do not instantly respond to changes in process variables. All sensing elements have a time delay (period of no response) and time lag (time duration after the delay to reach 63% of the complete response). What the control system sees is old information. However, in most cases, the response speed of the sensing element is fast enough to enable the control system to correct for the change. Flow, pressure, and level sensors have a time delay and time lag that are much less than one second. Temperature sensors have multiple time lags due to the time it takes for enough heat to transfer to make the internal sensor temperature equal to the process temperature. These time lags are usually a few seconds but can be much longer when the sensor is in a thermowell. If the thermowell has a large metal mass, the tip of the sensor is not touching the bottom of the well, or the fit is not tight, creating an air gap, the time lag can increase from seconds to minutes (see Chapter 2).

The transmitter can also introduce a time lag through a damping adjustment. The purpose of the adjustment is to smooth out measurement noise, which is any fluctuation in the sensor output that is not representative of changes in the process variable. Some manufacturers have non-zero default damping settings that could be too slow for some processes.

Measurement Response to a Step Change

Figure 1-20 is a trend plot of actual (dotted line) and theoretical (solid line) dynamic response of the transmitter output to a step change in the process variable.

As mentioned, the measurement gain is the change in percent transmitter output divided by the percent change in process input in engineering units. This gain is mostly just a reflection of the measurement scale. The time delay, also known as the dead time, is the period of time before there is any distinguishable change in the output of the transmitter after a change in a controller output. Once the transmitter output gets out of the noise band, it goes through an S-shaped response. While a better fit to the curve would be to use several time constants plus the time delay, a single time constant plus a time delay (dead time) called a first order plus dead time (FODT) approximation is commonly used in industry. The additional complexity of a higher order fit is generally a wasted effort because the improvement in fit is less than the uncertainty in these parameters.

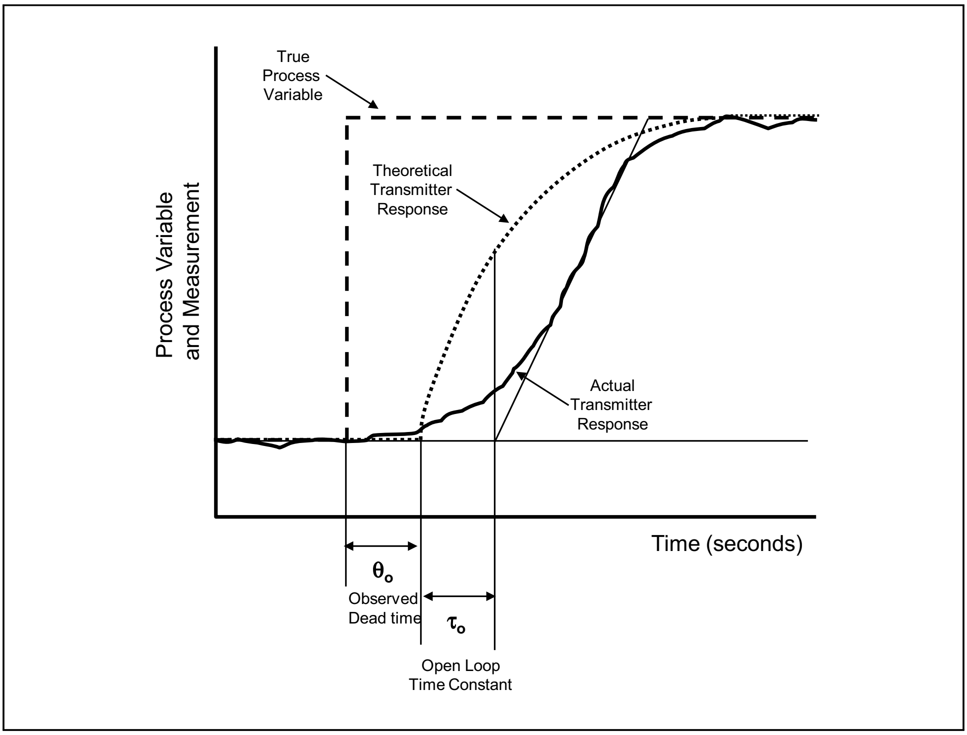


Figure 1-20. Actual and Theoretical Dynamic Response of a Transmitter Output to a Step

Time delays and time constants are not constant but depend upon the size and direction of the change as well as process conditions. This is dramatically the case for pH electrodes and temperature sensing elements. The FODT time constant is the time from the start of recognizable response to the time the output reaches 63% of its final value. The term *lag time* (as opposed to "time lag") is sometimes used in practice to denote a time constant but lag time is defined in *ISA's Automation, Systems, and Instrumentation Dictionary, 4th Edition*, as the transportation delay through an analyzer sample system. The terms *lag* and *lag time* are also used to define how late a changing (ramping) measurement is compared to a changing (ramping) actual value, which could be the sum of the time delay and time constant as noted in Figure 1-21. In this book, "time constant" will be used interchangeably with "time lag" and "dead time" with "time delay," which is the common practice in process control.

The use of the terms "time response" and "response time" is inconsistent in the discussion and specification of the dynamic response of measurements. The consequences can be drastically different assessments of measurement speed. "Time response" may or may not include the time delay and may be used to simply mean "time constant." The "response time" should always have a specified amount of the final response in its subscript for a change in the process variable as seen in the measurand.

A response time is the total time from the step change in the process variable to the time the transmitter output reaches a specified percent of its final change in output. For example, the response time to 95% of the change in output (T_{95}) would take 4 time constants plus the time delay in a FODT approximation. This book will use the 95% response time (T_{95}) for measurements and 86% response time (T_{86}) for valves instead of the 98% response time (T_{98}), because the last part of the response time is often lost in the noise and disturbances and can yield drastically different results for nonlinear systems.

Often there is more than one time constant, which gives the response its curvature as it moves out of the noise band. The small time constants can be summed with the pure time delays from digital device execution and scan times and sample transportation delays as an approximation of the total dead time.

Disturbances from safety systems, switches (e.g., on-off level control), and batch sequences are fast enough to be steps unless smoothed by an intervening volume. Steps are the most disruptive because of the abruptness of the change in the process input. Disturbances that originate from changes in set points, loads, and ambient conditions tend to be ramps. Disturbances from process and sensor noise, sticking control valves, aggressive controller tuning, and interacting (fighting) loops tend to be oscillations. Oscillatory disturbances are particularly problematic if the frequency is near the natural frequency of the affected loops causing amplification of the amplitude (resonance).

Measurement Response to Ramping Disturbance

Whether a measurement response is fast enough depends upon the size and speed of the change in the process variable. Fortunately, process variables tend to ramp rather than make step changes. Figure 1-21 is a trend plot of a transmitter's response to a ramp change in the process variable. The ramp in the transmitter output is behind the process variable ramp by a time that is approximately the measurement time delay plus time lag. Figure 1-21 also shows how much the actual process variable is above the corresponding transmitted value. If the ramp rate is very slow compared to the sensing element time lag, the transmitter digital delay, and the damping setting time lag, the difference between process variable and transmitter output will be negligible.

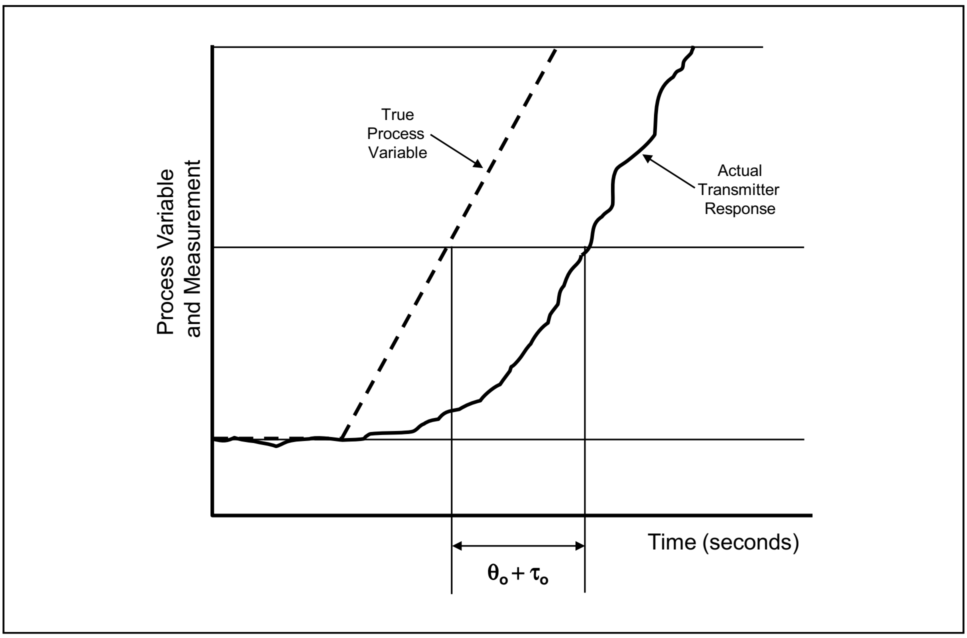


Figure 1-21. Dynamic Response of a Transmitter Output to a Ramp Change

The dynamic response of a transmitter output to a sinusoidal input is an attenuated and delayed sinusoidal output. This section will describe how the attenuation of the oscillation can be estimated if the measurement time lag is much larger than the oscillation period, which is the general case for measurement noise. Oscillatory process disturbances originating from control loops tend have a period much longer than the measurement time constant. For these disturbances, there is no attenuation of the oscillation and the measured oscillation is delayed (shifted) by the sum of the measurement time delay plus the time lag.

Analyzers

In this book, we are only covering "online" measurements which use sensors mounted directly in a process vessel or pipeline. There are also "at-line" measurements, which are typically analyzers that receive a sample that is automatically withdrawn and transported via a sample line to a sample conditioning system and the analyzer in the field. The transportation delays through the sample line, sample system, and analyzer plus the analyzer cycle time usually adds up to a time delay that is orders of magnitude larger than exhibited by other measurements. While the effect of time delay on loop performance is beyond the scope of this book, it is important to know that the maximum error from a disturbance is proportional to the total time delay. The integrated error (area between the set point and measurement on a trend chart) is proportional to the total time delay squared for a well-tuned controller.

"Off-line" measurements are typically done on manually withdrawn samples by analyzers in a laboratory. The time between when the sample is withdrawn and the lab analysis is made is often large and variable. The lab results should be time stamped with the time the sample was withdrawn. Some laboratory information systems automatically communicate the lab results to the process control system. In many plants, the lab results are entered manually. Regardless of whether there is manual or automatic entry of the lab results, the data historian should have the ability to show the results for the point in time that the sample was taken. This historization of the lab sample at the correct process time is essential for visually correlating results and for process analysis and data analytics. The time stamping of when the sample was taken helps deal with issues with the sample results of the raw material or end point being available after the batch has gone downstream. Time stamping is also essential for the correlation of the samples taken from tanks used for raw materials, intermediates, and products with the online measurements from batch and continuous operations in series and parallel.

Disturbances

Process variables are not constants. Any flow, temperature, pressure, or composition value that matches what is shown on a process flow diagram

(PFD) is a momentary coincidence. A production facility is a dynamic environment in a state of flux.

The biggest transients occur during the shutdown, startup, and batch operation of equipment. Some shutdowns are planned for maintenance or product changeovers, but many shutdowns resulting from trips are due to equipment or instrument failures, malfunctioning safety systems, equipment degradation (e.g., fouling or frosting), or operator errors. Even when equipment is operating continuously, there are changes in the composition of feeds from raw material shipments, intermediate chemicals produced elsewhere in the plant, and recycle streams where a portion of a process output flow is returned as a process input feed. Recycle streams can cause disturbances to perpetuate and even grow in magnitude because the upsets are returned as feed disturbances.

The temperature of process streams and the performance of equipment change with ambient temperature and utility stream temperatures. Often, cooling towers and refrigerant units have not kept up with increases in production unit capacity from process control improvement and debottlenecking projects. During hot weather and peak demand, high cooling water and refrigerant temperatures cause process upsets. Similarly, undersized steam headers and boilers cause dips in steam pressure during the coldest months and periods of peak demand. Heat recovery operations, where process output streams are passed through heat exchangers to preheat feeds, cause changes in the feed temperature based on process performance and production rate.

Process control loops can be the source of oscillations in process variables even if there are no process disturbances. The output of a controller in automatic is always moving because an exact match of the process variable to the set point is rare. Too much gain will cause controllers to oscillate whenever there is a load or set point change. Even if the controller is tuned properly and there are no changes, stick-slip in control valves creates limit cycles (sustained oscillations with constant amplitude) and interactions can cause loops to fight each other.

The most frequently encountered source of oscillations in a production unit is a level loop on a surge tank that is tuned with too much reset action (too small of a reset time). For a waste treatment system the use of level switches to pump out sumps is the most disruptive upset. On-off control of any type creates fast and large disturbances.

The constant state of change from disturbances and sequential or manual operations, non-ideal behavior, and imperfect knowledge of the process mean that timely and accurate measurements are needed to meet quality and production rate requirements. Measurements provide the only window into what is actually happening in the process. While each application has specific requirements, there are some concepts about what is most important in measurement performance in terms of measurement accuracy and speed.

Process automation systems rely on PID controllers to use measurements to improve production rate, quality, and efficiency. The performance of a PID depends on whether the PID has measurements of non-desirable process behavior that are sensitive and fast enough. During the time a PID doesn't see a change in a process variable, the process can move to an increasingly poor operating point. Sensing element time lags and transmitter damping adjustments for most slow processes (e.g., level, vessel pressure, temperature, and vessel pH) are effective sources of time delay that increase the total loop dead time. For well-tuned controllers, the total of the measurement time lags should be less than 1/5 the process dead time. In reality most controllers have a controller gain that is less than ½ the gain for maximum disturbance rejection. A loop detuned by a factor of 2 gives about the same performance as an aggressively tuned loop with twice the dead time. Measurement time lags totaling less than the process dead time have a negligible effect on the performance of these loops if these measurement lags are small compared to the process time constant.

1-5. Accuracy

Part of the difficulty in comparing the quality and speed of measurements is the number of parameters used to specify quality and speed and their misunderstanding and misuse. The functional definition and value of a multitude of terms are offered in this section to help practitioners intelligently discuss and understand the effects of device selection, configuration, calibration, installation, and operating conditions for an application.

Accuracy is often used as a simple qualitative term to describe how well a measurement represents the true value of the process variable. The quantitative accuracy of a measurement is the maximum deviation (error) of the measured value from the true value over a stated range of the measurement (e.g., 1000 to 4000 lb/hr flow [453 to 906 kg/hr] for differential head meters), measurand (e.g., 5 to 100 inches [12.7 to 254 cm] orifice differential pressure for differential head flowmeters), or process condition (e.g., 0.1 to 10 fps [3.05 to 305 cm/sec] fluid velocity for magmeters and vortex meters). The maximum error is the worst case of the combined systematic and random errors in the measurement. Systematic errors are errors that can be predicted from scientific principles. The most common systematic error is a bias as shown in Figures 1-22a through 1-22d, and discussed in more detail below. The bias error can be due to an offset (intercept) error or a span (slope) error (see Section 1.6 on setup and calibration). A bias can also originate from a fixed nonlinearity error that is a function of the true value.

Measurement *span* is the difference between the lowest and highest values of a measurement range. For example, a temperature transmitter calibrated for a temperature range of 50 to 150°C (122 to 302°F) has a span of 100°C (180°F). For an offset error, the bias is constant. For a span error, the bias increases with measurement.

An instrument's accuracy specification is often expressed in terms of a *tolerance*, which is the allowable deviation (error) from a true value (more on this later in the chapter). Sensing element error can result from randomness in its manufacturing process, with the result that a given sensor will often display a bias error, which is a systematic error, in the measurement. Systematic errors can be largely eliminated by linearization and calibration, and by set point changes done manually or automatically by higher level primary cascade or supervisory loops.

Random (as opposed to systematic) measurement errors show up as false variability in the process and cannot be eliminated by calibration or changes in the set point of the measurement loop. However, the effect of random errors on important process variables downstream can be attenuated by a "back mixed" volume. A higher level loop on a downstream volume can control the average of the fluctuations so the key variables are closer to the desired value. For example, the effect on vessel pH of random errors in a reagent flow measurement can be minimized by the cascade of the output of a primary pH loop that automatically adjusts the secondary reagent flow set point. In the section on repeatability, the ability of back mixed volumes to attenuate random errors is discussed.

The *precision* of a measurement is the standard deviation of the total random error. The principal sources of random errors are repeatability errors and noise that have a statistical distribution as shown in Figures 1-22a through 1-22d. Sensitivity and resolution limits and hysteresis and deadband create errors that appear to be random due to changes in the start and stop points and direction of the change in the true value of a measurement. For the modern measurement instruments detailed in this book, the random errors from resolution, sensitivity, hysteresis, and deadband are generally negligible.

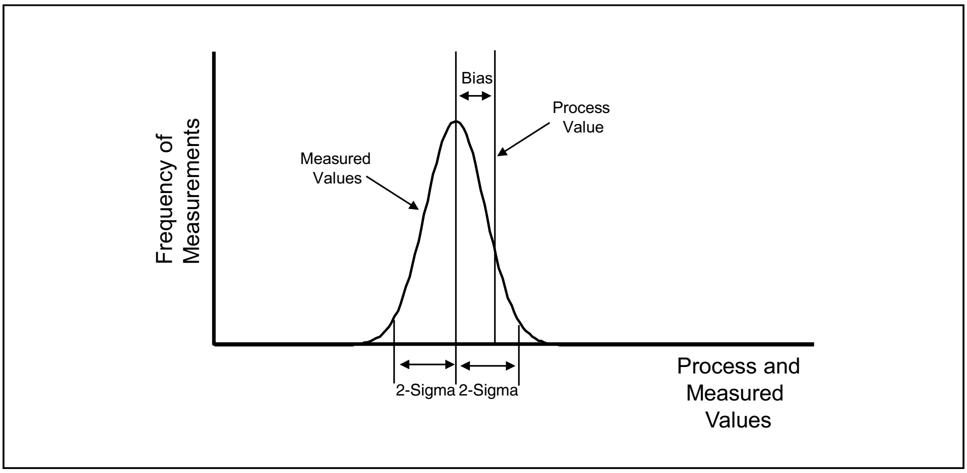


Figure 1-22a. Measurement with Good Accuracy and Good Precision

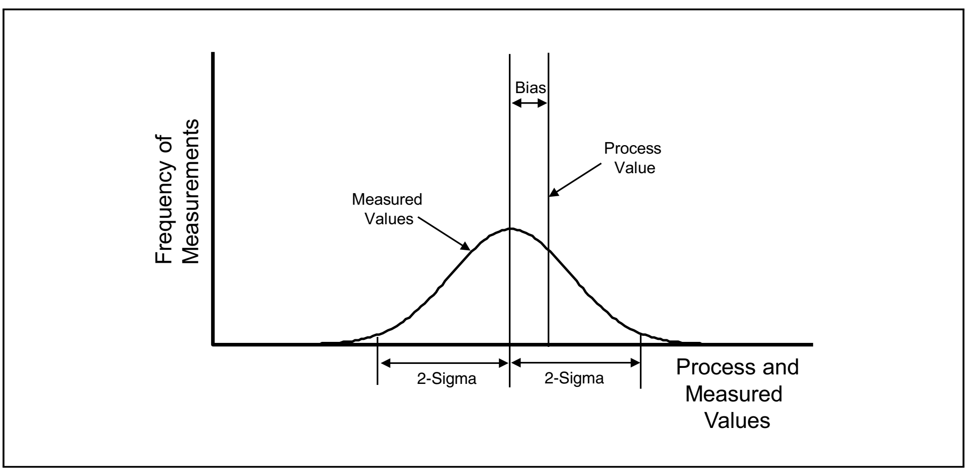


Figure 1-22b. Measurement with Good Accuracy and Poor Precision

Turndown (Rangeability) and Span

Also known as rangeability, turndown is the ratio of the maximum to the minimum measured value of the process variable for which the device's performance is within the specified limits for the device or final element. The maximum value is the high end of the selected device's range rather

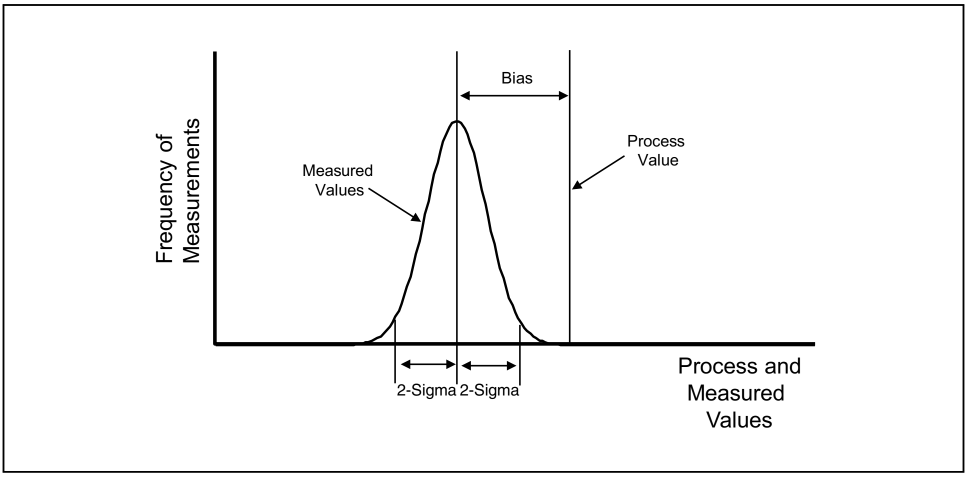


Figure 1-22c. Measurement with Poor Accuracy and Good Precision

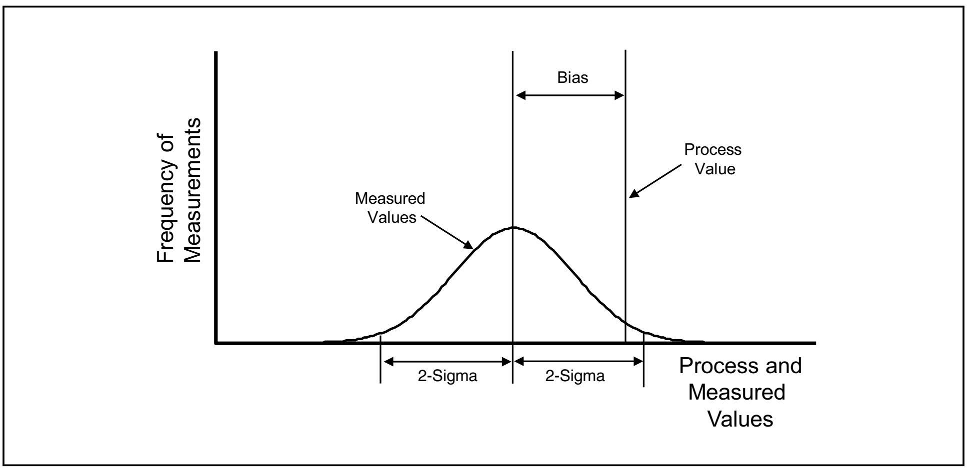


Figure 1-22d. Measurement with Poor Accuracy and Poor Precision

than the high scale value of the calibration. To maximize turndown, the device must be selected to provide as close a match of the device's maximum to the application maximum. For flowmeters, this corresponds to choosing a meter size whose maximum flow is as close as possible to the maximum flow in the process.

Errors are normally expressed in terms of a percent of span (see Section 1.6 on Calibration) but in some cases it is a percent of the reading of the measurand and the transmitter output. The difference in performance can be dramatic, particularly in terms of turndown (rangeability). For example, a 0.1% of span accuracy transmitter for a linear process relationship would have a maximum error of 0.5% at 20% output (5 times larger than a 0.1% of reading accuracy at 20% output).

For a differential pressure flowmeter, the deterioration in accuracy with turndown is much more drastic because the flow is proportional to the square root of the differential pressure measurement. A 0.1% of span accuracy transmitter would have a maximum error of 25% at 20% output (25 times larger than the error at 100% output).

Dramatic Improvements in Modern Measurement Instruments

The quality of measurement instruments has improved dramatically since the advent of smart transmitters. These transmitters have exceptional stability (resistance to drift) and correct for extraneous effects whether sensing element nonlinearity, ambient temperature, or process conditions. Many of these instruments no longer require periodic process calibration. For example, coplanar pressure and differential pressure transmitters have an accuracy of 0.025% of span and 10 year stability. Furthermore, the installed accuracy remains essentially the specification accuracy, because of the compensation for ambient and process effects. In the 1970s, a typical electronic pressure transmitter had a benchtop accuracy of 0.25%, an installed accuracy of 1 to 2%, and a stability specification of 1 to 2 years. Smart microprocessor based measurements such as Coriolis mass flowmeters, coplanar pressure and differential pressure transmitters, and radar level meters have an installed accuracy that is 50 times better than what existed in the 1970s. The accuracy of these devices approaches the uncertainty in process calibration standards and methods. Furthermore, the drift is so small and the stability is so good the average instrument engineer will have changed jobs or retired before the device needs a calibration check. Additionally, dynamic errors are negligible. Their response is so fast that the measurement time constant is too small to be measured in a DCS.

Estimation of Total Error

Since errors can be in opposite directions, where a portion of the errors cancel out, the total measurement error can be approximated per Equation 1-2 as the square root of the sum of the individual errors squared. Equation 1-2 includes the error in the reference value used for calibration (E_c), which is small for properly used and maintained calibration standards. While it is not customary to consider noise in accuracy calculations, noise is a term in Equation 1-2 because noise is often the largest source of measurement uncertainty. However, it is critical to note that noise can be attenuated by a proper setting of the transmitter damping or signal filter in the control system. The most important terms for control loop performance and process variability are the repeatability error (E_r) and measurement noise (E_n). For accuracy statements, the largest source of error is typically a bias error (E_b). For thermocouples and RTDs, the sensing element manufacturing tolerance (E_t) is a key term for temperature measurement accuracy. Equation 1-2 is the magnitude of a vector and does not include any dynamic errors from a measurement lagging behind a true change in the process variable.

$$E_m = \sqrt{E_b^2 + E_l^2 + E_q^2 + E_s^2 + E_r^2 + E_h^2 + E_d^2 + E_n^2 + E_t^2 + E_c^2} \quad (1\text{-}2)$$

Where:

E_m = total measurement error (%)

E_b = bias error (%)

E_l = linearity error (%)

E_q = resolution (quantization) error (%)

E_s = sensitivity error (%)

E_r = repeatability error (%)

E_h = hysteresis error (%)

E_d = deadband error (%)

E_n = measurement noise (%)

E_t = sensing element tolerance (%)

E_c = calibration error (%)

Uncertainty

Uncertainty is the interval within which the true value of a measured quantity is expected to lie with a stated probability [10]. Thus, uncertainty statements imply a quantifiable probability in confidence interval. Uncertainties with a 95% and 99% probability are often used. For a normal distribution, the probabilities that the measurements lie within one, two, and three standard deviations are 68.26%, 95.46%, and 99.73%, respectively. There is also an uncertainty in the true value of the measurement. The term “uncertainty” plays an important role in the analysis of metrological determinations of the ability of calibration standards to provide true values. The term has limited general practical utility for describing the accuracy of measurements in industrial applications but is used for some types of measurements, particularly when there are some unknowns in the measurand. For example, in discussions of the accuracy of differential head flow measurements an uncertainty of the discharge coefficient of the orifice plate, venturi tube, or flow nozzle is stated. In some cases accuracy is viewed as the total uncertainty with a probability that 99%+ of the measurements lie within the stated accuracy range.

Tolerance

Tolerance is the allowable deviation from a specified or true value [10]. It is generally used to quantify the allowable variation in accuracy of a sensing element during the manufacturing process and is usually given in engineering units. A common use is in specification of the manufacturing tolerances of thermocouple (TC) and resistance temperature detector (RTD) elements. Most of the tolerance is a systematic error that can be eliminated by calibration.

The tolerance of a sensing element is indicative of the interchangeability of the element, with a narrower tolerance enhancing interchangeability. Consider the case where in the middle of the night a thermocouple fails. The loop needs to be put back in service immediately so calibration of the transmitter by testing the new thermocouple at a known temperature is not done. If there is a redundant temperature measurement, a one point calibration of the transmitters can be done online. If calibration is not possible, an error is introduced into the measurement that is some fraction of the thermocouple tolerance. A conservative estimation approach would be to take the full tolerance of the sensing element for the term in Equation 1-2.

There are many other uses of the term tolerance. Voltage tolerance is specified as the permissible percentage deviation of the actual voltage (DC or root mean square for AC) from the nominal voltage. Dimensional tolerances are used in manufacturing to specify the permissible variation in size [10].

Resolution

Resolution error (E_r) is the minimum change in measurement output that is most commonly a quantization error determined by digital processor and I/O bits. A large resolution limit is clearly identifiable as a staircase response where the step size is the resolution limit or a multiple of the resolution limit as depicted in Figure 1-23. A resolution limit will cause a limit cycle in a standard PID loop with integral (reset) action. The limit cycle period is much longer than the period of oscillations from steps triggered by sensor noise, which is slower than the oscillations of pure noise with no resolution limits. Consequently, the oscillations from resolution limits are not as readily attenuated as pure noise by signal filters in the control system. The attenuation by a signal filter of resolution error or noise can be approximated by Equation 1-3.

The resolution error in most modern sensors is less than 0.001% because there are no mechanical movements and there are 18 bits or more in the transmitter's processor and digital to analog convertor (D/A). The resolution error from a digital device can be estimated by Equation 1-4 where one bit is a sign bit. In older devices and control systems, the processor of the digital-to-analog convertor and analog-to-digital convertor was 12 bits, which provided a resolution of 0.05%. For large span thermocouple input cards of 500°C (900°F) span or more, resolution error was thus 0.25°C (0.45°F) for older systems which precluded the use of derivative and high gain action in temperature controllers even though these tuning settings were beneficial in terms of load rejection and set point response.

In most temperature processes the true change in the temperature is slower than 0.025°C (0.045°F) per minute. The result is a poor signal to noise ratio. In these temperature loops the use of signal filters with relatively large filter times (e.g., 30 seconds) helps attenuate the resolution error triggered by thermal noise to the point where higher controller gains can be used, but this adds an undesirable time lag that could be detrimental to the ability of the loop to recognize and correct fast disturbances.

$$A_f = A_o * \frac{T_o}{2\pi * \tau_f} \tag{1-3}$$

$$E_r = \frac{100\%}{2^{n-1}} \tag{1-4}$$

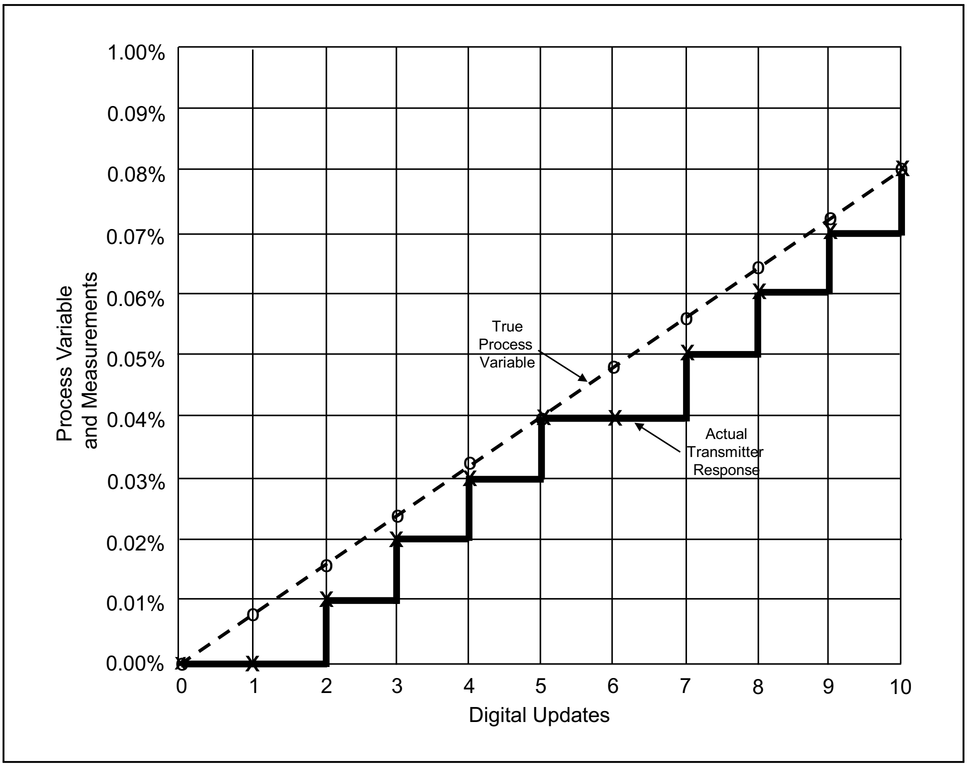


Figure 1-23. Resolution

Where:

A_f = amplitude of the filtered oscillations (e.u.)

A_o = amplitude of the original oscillations (e.u.)

T_o = period of the original oscillations (sec)

τ_f = measurement time lag, damping setting, or signal filter time constant (sec)

Resolution is the top consideration in terms of a loop being able to see a change in the process because there are no intermediate values between the steps. Instead of steps, trend charts may show a slope to the change in the measurement due to smoothing by the historian algorithm and attenuation by signal filters DCS. The presence of the steps, whether seen or hidden, means it would be extremely rare for the process variable to come to rest exactly at the set point. As a result of the continual control error, reset action in the controller will continually ramp the controller output up and down. The result is a sustained oscillation with a period that depends on the tuning of the controller. Detuning (decreasing the controller gain and increasing the reset time) makes the period longer. The amplitude of the oscillations remains constant for a given damping or filter time setting. The oscillations are difficult to filter out since the period is relatively large in Equation 1-3. Fortunately, the resolution of most modern transmitters is extremely fine. However, for wireless control we will see that a resolution (deadband) setting is used to transmit signals on an exception basis to extend battery life. The resolution setting is chosen to be more than the noise after damping, less than the allowable control band (maximum peak to peak amplitude of fluctuations about set point), and less than the resolution (stick-slip) of the control valve quantified as a step in flow multiplied by the process gain. Fortunately a wireless PID algorithm has been developed that eliminates the limit cycle from the resolution setting. Equation 1-3 can also be used to predict the smoothing by continuous back mixed volumes on the loop oscillations from resolution limits. In this case, the time lag in Equation 1-3 is the volume's residence time (volume divided by total throughput flow).

Sensitivity

Sensitivity is the smallest detectable change in the process variable (see Figure 1-24). If the step in the process variable is larger than the sensitivity, then the measurement shows a step size that matches the step in the process variable. Thus a sensitivity error will show step sizes that are in between multiples of the sensitivity limit. Normally sensitivity is determined by the measurement principle and type of sensing element. For example, a resistance temperature detector (RTD) has a sensitivity (0.001°C; 0.0018°F) that is 50 times greater than thermocouple sensitivity (0.05°C; 0.09°F). It is important to realize that sensitivity is a term commonly used in electronics for amplifier gain and automation systems for process gain, where sensitivity is the change in output divided by the change in input to the component or process.

Repeatability

The repeatability error (E_r) is the difference between indications for traverses upscale and downscale as depicted in Figure 1-25a. There is also a practical definition of repeatability which is the maximum difference between changes in the indicated value for the same magnitude changes in the true value as shown in Figure 1-25b. The deviations around the average could be due to random error, more commonly experienced as sensor noise.

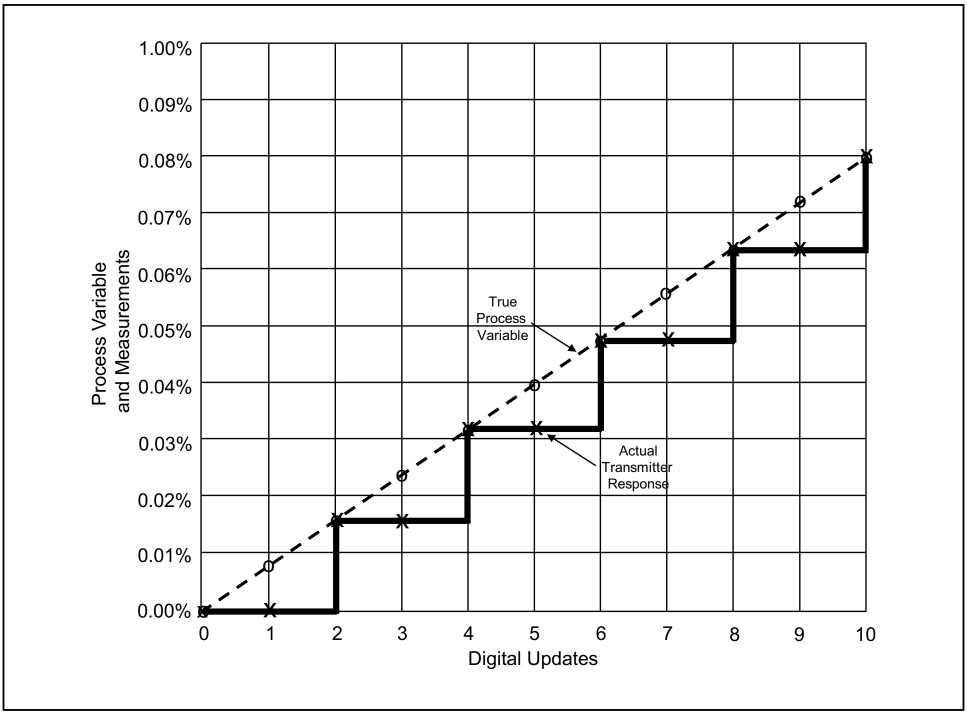


Figure 1-24. Sensitivity

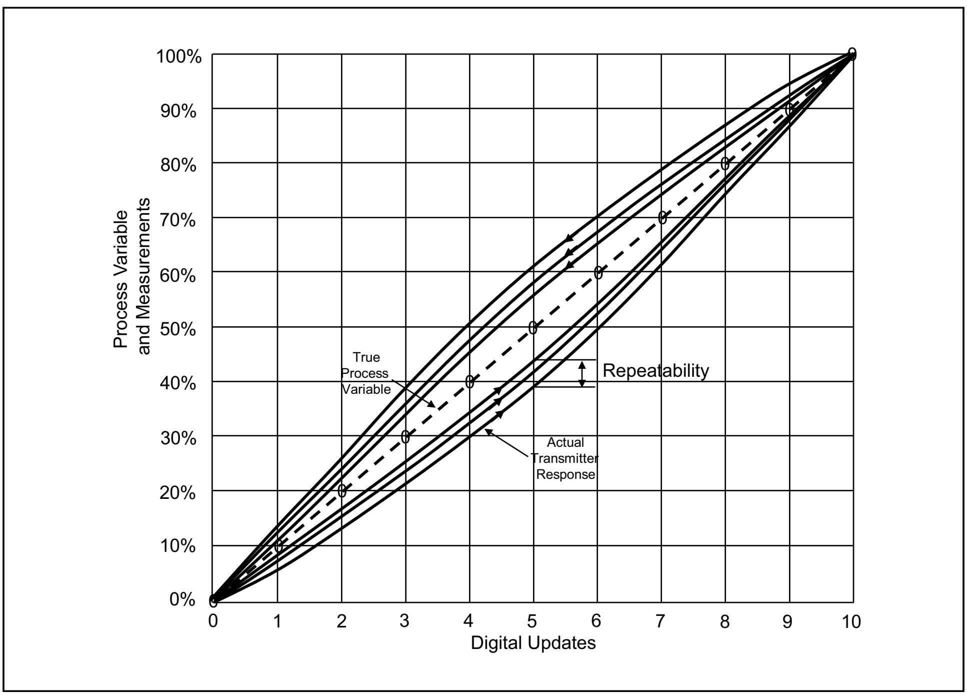


Figure 1-25a. Technical Definition of Repeatability

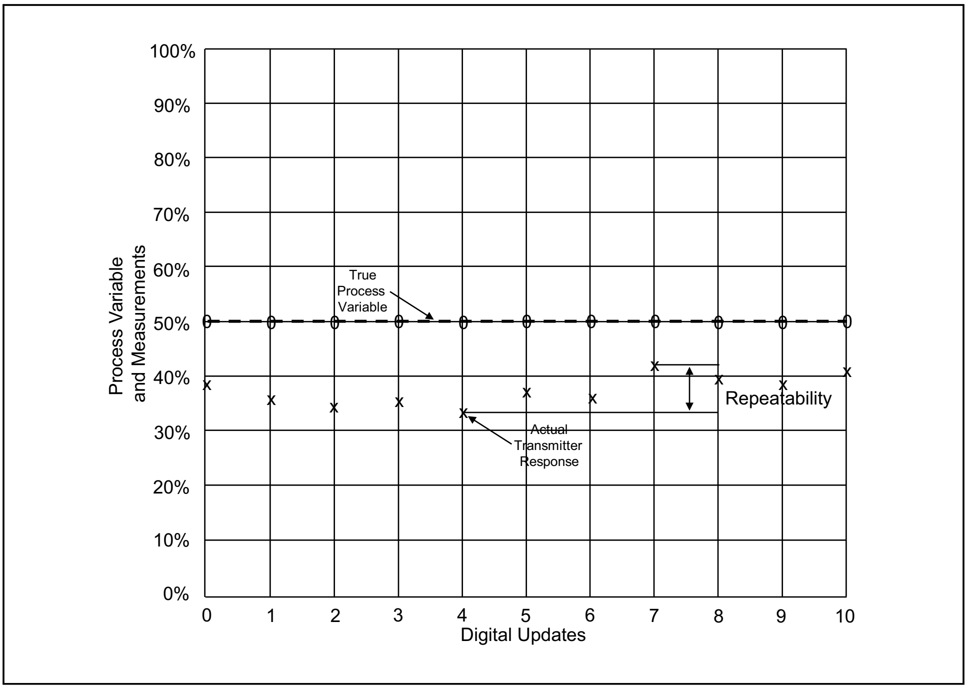


Figure 1-25b. Practical Definition of Repeatability (maximum difference between repeated measurements of same value)

Hierarchy

There is a hierarchical relationship between some of the terms in Equation 1-2 in determining accuracy in that the error level of one term depends upon the error level of the previous one. However, a low error level in one term does not guarantee a low error level in the other term. For example, the repeatability error cannot be less than the sensitivity error but a very sensitive measurement may not be repeatable. Additionally, the sensitivity error cannot be less than the resolution error but a high degree of measurement resolution does not imply a sensitive instrument [14]. In this example, the resolution (quantization) error (E_q) must be less than or equal to the sensitivity error (E_s) which in turn must be less than or equal to the repeatability error (E_r)

$$E_q \leq E_s \leq E_r \qquad (1\text{-}5)$$

Noise

Sensor noise (E_n) is the deviation between the indicated value and a constant true value as shown in Figure 1-26. The indicated value can take on intermediate values. If the period between fluctuations in the measurement is much shorter than the period of the control loop, the random error is termed noise and can be filtered out by a damping adjustment in the transmitter or a signal filter in the analog input or PID block of the control system.

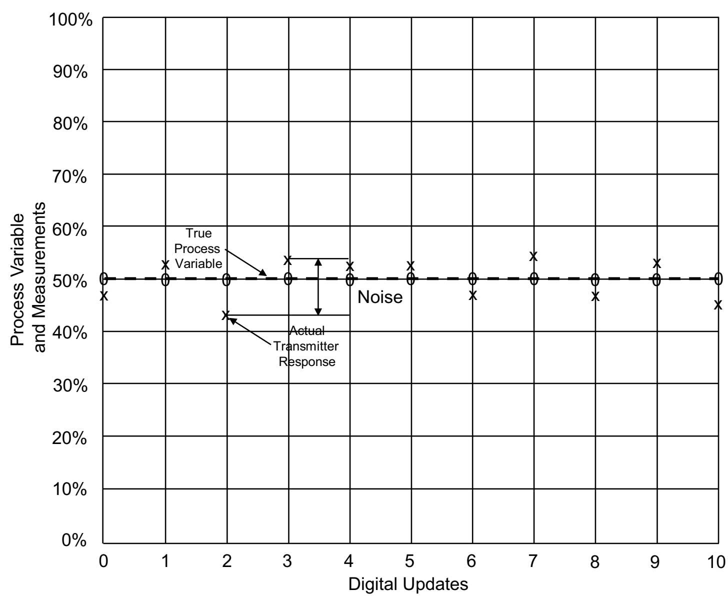


Figure 1-26. Noise (peak to peak)

Hysteresis and Deadband

The maximum difference between the upscale and the downscale traverses is hysteresis error (E_h) if there is an immediate reversal of output for a change in direction of the input. The trend chart shows a football shaped response to full scale traverses as illustrated in Figure 1-27. The amount an input has to change direction before the output changes is deadband error (E_d). Hysteresis error is frequently accompanied by a deadband error. A plot of the measured value versus the true value of the process variable shows a slanted and bowed box shaped response to full scale traverses similar to what is depicted in Figure 7-40b for a control valve. Technically, these parameters are defined for a full traverse of the span but in reality both errors occur with any reversal in the direction of the process variable.

Hysteresis and deadband are usually associated with the movement of mechanical elements. In this book we will concentrate on the more modern measurement devices that primarily involve a fluid or electromagnetic sensing element response so that hysteresis and deadband errors are negligible. However, we will see for control valves, these errors can be considerable, resulting from actuator response and shaft backlash, particularly for rotary valves that originated as on-off or isolation valves.

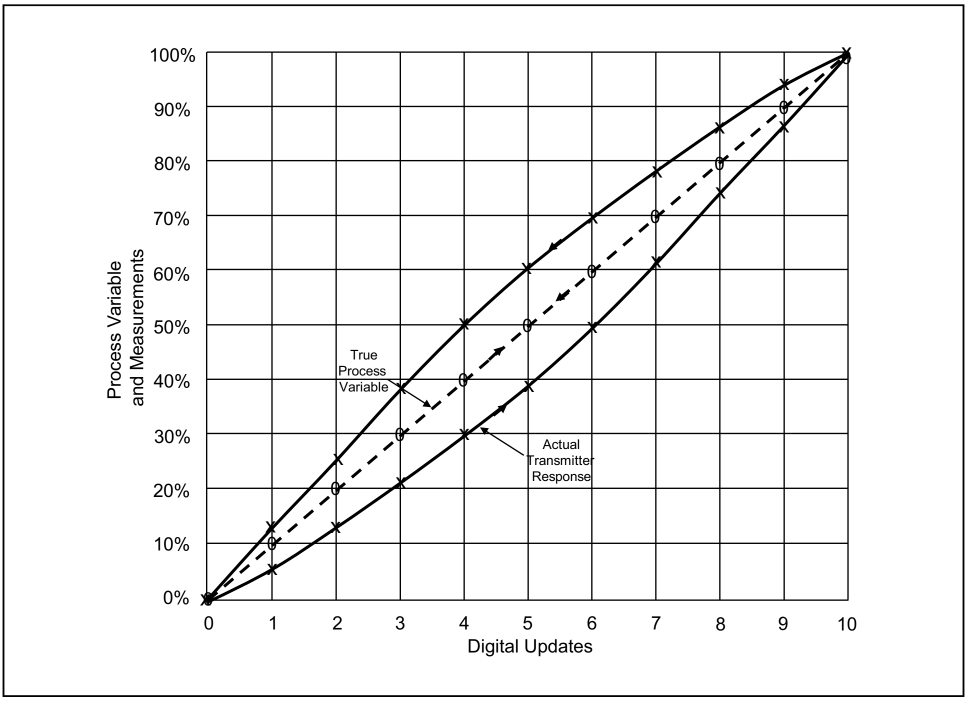


Figure 1-27. Hysteresis

Nonlinearity

Nonlinearity error as shown in Figure 1-28 is the largest deviation of the indicated value's curve from the true value's straight line across the entire measurement range. Well known nonlinearities are usually compensated in the transmitter. Thermocouple (TC) and resistance temperature detector (RTD) sensing elements are important examples of a known nonlinearity that can be corrected by equations in the transmitter.

Bias

Bias error is the offset of the indicated value's average value from the true value's straight line as depicted as the difference in the peak of random values from the true value in Figures 1-22a through 1-22d. A constant bias for all true values can originate from an offset (intercept) error as shown in Figure 1-29. A bias that increases with true value can be due to nonlinear-

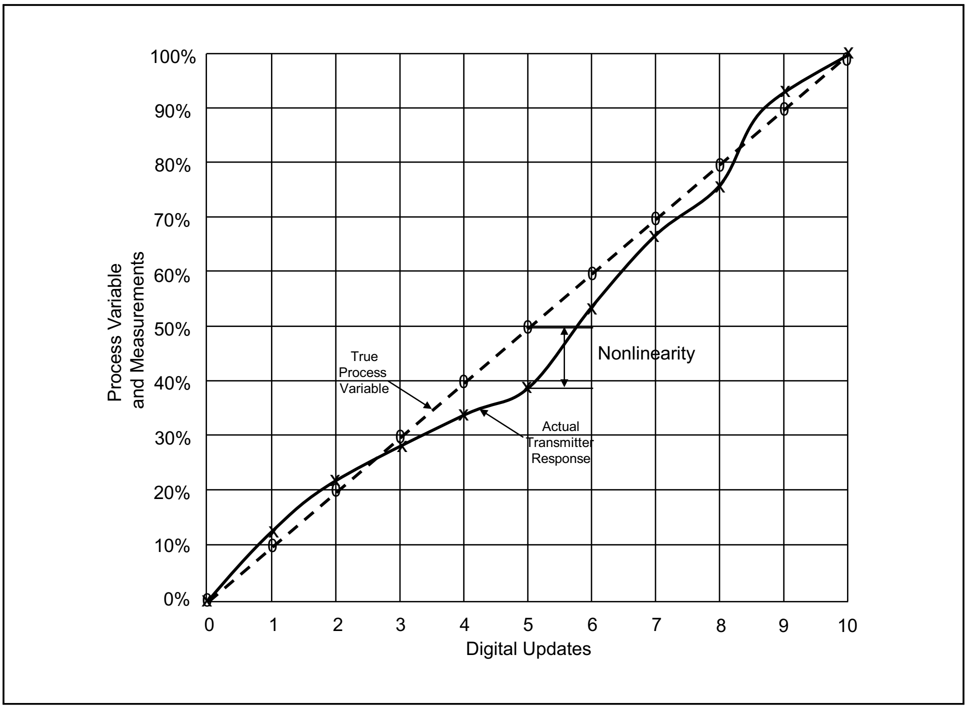


Figure 1-28. Nonlinearity

ity or a span (slope) error. Bias errors are readily corrected by calibration and by manual and automatic adjustment of the control loop's set point. The manual adjustment of process set points is very common but not usually recognized as being due to a measurement bias error until process performance changes when a measurement device is replaced. The best temperature found for running a column, crystallizer, dryer, or reactor (or example) is not exactly at the true value of the optimum but at a value that corrects for the offset in the measurement from the true value. For example, if a column temperature measurement is reading 1°C (1.8°F) higher than the true value, the best column temperature set point is 1°C (1.8°F) lower than the true optimum. Many columns use thermocouples, which have a significant bias error.

Stability

Stability is the period of time during which the accuracy of the measurement stays within some specified bound. Stability is often defined in terms of **drift** which can be visualized as an offset that increases with time. The drift is expressed as % per month for pH and % per year for most other measurement devices. In a trend that covers months of the measurement output where the true value is constant as shown in Figure 1-30 the drift is

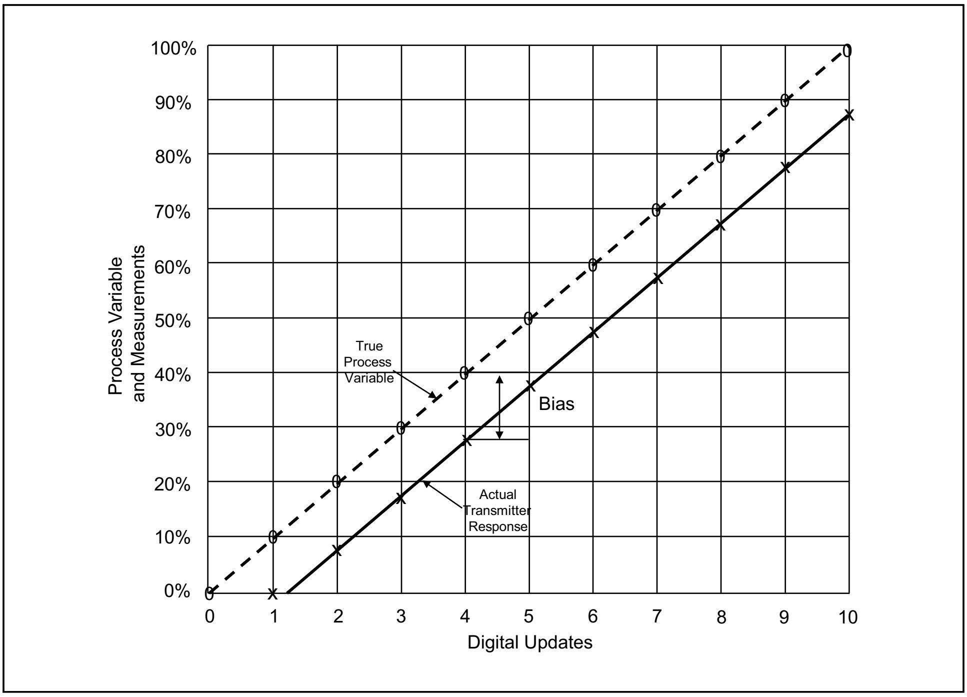


Figure 1-29. Bias

the slope of the line. In practice, drift is difficult to ascertain because the true value is not constant for the months and the measurement may be the process variable of a control loop. For a PID controller with a constant set point and load, drift is seen in the slope of the controller output since the control loop is working to keep the measurement at set point.

Reproducibility

ASTM International, formerly the American Society of Testing and Materials (ASTM), uses the term reproducibility to quantify the variation in calibration results for different testers who use the same test method and test equipment. For temperature measurements, it is used to specify the possible variation in temperature measurements for different sensing elements for the same temperature with the same transmitter [17]. The International Society of Automation (ISA) defines reproducibility as the closeness of agreement among repeated measurements of the output for the same value of input made under the same operating conditions over a period of time, approaching from both directions. Reproducibility includes the effect of hysteresis, deadband, drift, and repeatability. Reproducibility is usually measured as non-reproducibility but is termed reproducibility and quantified as a percent of measurement span over a specified time

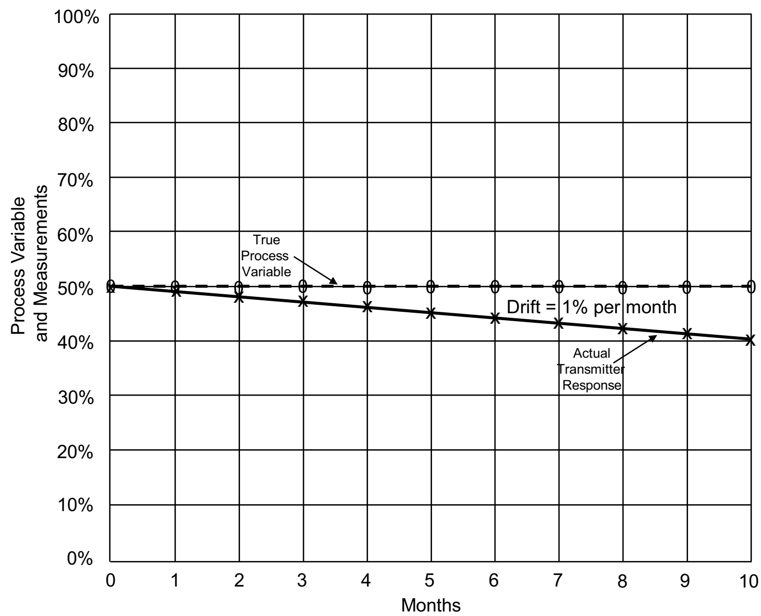


Figure 1-30. Drift

period. If drift is omitted, reproducibility can be evaluated over a much shorter period (hours instead of months).

1-6. Setup (Configuration) and Calibration

Range and Span

Measurement devices have a range and span. The range is the low and high values of the process variable that correspond to 0% and 100%, respectively of the transmitter output. The low end of the range in engineering units is usually (but not always) zero, particularly for flow measurements. The span is the difference between the low and high ends of the range. For measurement devices that have a separate sensing element such as differential pressure flow and level measurements, TC and RTD temperature measurements, and pH measurements, there is a measurand range that corresponds to the process variable range. Some typical examples of PV measurement ranges with the type of sensing measurand and measurand range (in parentheses) are:

- Differential Pressure Flow: 0 to 1000 liters per minute [0 to 264 gal/min] (DP: 0 to 25 kPa [0 to 3.6 psi])

- Differential Pressure Level: 0 to 100% (DP: 10 to 110 kPa [14.5 to 16.0 psi])
- Absolute Pressure: 50 to 250 kPa (7.2 to 36.2 psi)
- Temperature: 50 to 150°C (122 to 302°F) (RTD: 119.4 to 157.3 ohms)
- pH: 2 to 12 pH (glass electrode: 295 to -295 millivolts)

As mentioned, the low end of the measurand range is not necessarily zero. A positive low end of the DP measurand range occurs for a high side connection of a DP transmitter that is below the desired 0% level measurement, as will be illustrated in the section on installation. The negative low end of the pH measurand range for a glass electrode occurs for a high concentration (> 1 normality) of a strong acid.

The transmitter signal is converted at the AI block in a DCS to the engineering units with the same range used by the transmitter so that the measurements seen in the data historian have the same engineering units used in the setup and calibration of the transmitter. The scale of a PID controller usually matches the range in engineering units but most DCS offer the option of a different process variable scale for the PID. This is important because this scale determines the conversion back to percent in the PID block and thus affects the process gain per Equation 1-1.

Setup (configuration) determines the device functionality and specifies the measurement range and span in engineering units. Calibration involves tests and adjustments to match the transmitter output in engineering units to the process variable or the measurand.

Since most device accuracies are given as a percent of span, a practice developed decades ago was to minimize the measurement span to reduce the measurement error. Advances in sensing element technology, the compensation of nonlinearities and non-ideal effects, and the high resolution of the computations and I/O make this practice not as important. Some smart instrumentation specifications will calculate the accuracy in percent of span based on the actual upper and low range limits, eliminating most of the supposed improvement in accuracy from narrowing the span.

Historical View

Before the advent of microprocessor based measurement instruments, instrument setup and calibration was rudimentary. Setup was largely done structurally and preset at the factory, based on options specified in the model number. Calibration was mostly done by screwdriver adjustments of potentiometers. There was usually a zero, span, and damping adjustment. Basically, the output of the transmitter was set to match the measurand range and it was often up to the user to figure out the relationship between the measurand and the process variable. There were few if any alerts to measurement problems. Troubleshooting relied upon sorting through lists of symptoms and possible causes and making circuit measurements, or the comparison of related or redundant measurements.

You would think that not many of these old instruments still exist until you realize that most refineries, chemical plants, and steam plants in the United States were built in the 1960s and 1970s. Some of these plants have the original instrumentation and possibly a DCS that does not support smart instrumentation. The original measurement devices in these plants have installed errors and drift an order of magnitude larger than modern instrumentation. The poor performance of these original devices is due to older sensing element technology, missing compensation for non ideal and non-benchtop conditions, no multivariable calculations, and poor visibility of measurement integrity.

Smart Instrumentation Capability

Microprocessors opened the door to smart measurements that offered:

- Compensation of effects of ambient conditions on sensing elements
- Compensation of effects of process conditions on sensing elements
- Compensation of nonlinearities of sensing elements
- Measurement of secondary variables such as ambient and process temperature
- Multivariable measurement outputs such as density and mass flow

- Computation of abnormal process conditions such as pressure over range
- Detection of sensing element problems such as fixed output or abnormal value
- Detection of device malfunction and possible cause
- Identification of device such as model and serial numbers
- Calibration history
- Installation configuration for sophisticated devices such as radar level

The question then became, how does the supplier develop and the customer use an interface to provide access to this wealth of capability and data? A medium-size chemical plant may have a hundred or more different model numbers of measurement devices. Each smart device may provide a hundred or more data items. The plant could have ten thousand or more different pieces of useful information on the performance and integrity of the measurement system and the process. Obviously a huge need materialized for the standardization of the communication and interface to make it easier for the supplier to develop and the customer to use programs and displays for a wide spectrum of devices, functions, and data items.

Smart Instrumentation Interface

Fortunately, the International Electrotechnical Commission (IEC) developed the IEC 61804 standard that defined the Electronic Device Description Language (EDDL). The ISA104 committee adopted the standard and continues to promote and improve the use of EDDL. The standard was cooperatively designed by industrial authorities to ensure EDDL meets the needs of the end user. The standard specifies a generic language to describe the properties of automation system components. The specific language is capable of describing:

- Device parameters and their dependencies
- Device identification and history
- Device functions
- Historian functions
- Graphical representations, such as charts, plots, and diagrams
- Displays with conditional images

- Interactions with control devices

EDDL is a text-based language that enables an interface to smart instrumentation, such as measurement devices with microprocessor based transmitters and final elements with microprocessor based positioners or digital valve controllers. EDDL is used to provide the user friendly and complete access to smart instrumentation for the following:

- Setup (configuration)
- Calibration
- Testing
- Commissioning
- Tuning
- Identification (model and serial numbers)
- History
- Investigation
- Simulation
- Monitoring
- Analysis

EDDL has several unique characteristics not found in other device integration technologies. EDDL provides a well-defined structure for supporting the most simple to the very complex field device with a common look and feel across applications, which reduces the learning curve and supports multiple host applications. Also, this enables field device additions to be incorporated without affecting the runtime stability of the control system. Taken together, these technology advantages of EDDL provide significant benefits over other approaches in terms of the longevity and stability of the instrumentation and control system over the plant life cycle [2].

One of the greatest benefits that EDDL provides the process industry is interoperability across multiple hosts, devices, and technologies. This flexibility allows the end user to choose the best combination of price and performance for devices and software. EDDL allows instrument suppliers to define their products in a single, open, and consistent format. This format is readable by handheld communicators, control systems, and other process interface devices that are EDDL-enabled. This interoperability simplifies the control system integration process, because all a systems integrator or end user has to specify in the bid process is that all instrumentation and control equipment must conform to the International Standard, EDDL. Competitive bids are easier to evaluate, because the end user does not have to worry if specific software packages are available to support various devices; with EDDL, all comparable EDDL devices can be supported by all control systems. Finally, interoperability means that operators and maintenance personnel can easily find the calibration and diagnostic information needed for a particular device, and all EDDL-compatible devices will provide the necessary information in the "look and feel" of the host system [2].

EDDL is a declarative technology, not a software program. Because it is a text-based description of the field device and its properties, EDDL offers significant advantages over technologies that rely on any code from the device manufacturer to enable data to be displayed or printed. EDDL is independent of operating systems and control platforms. Operating system and platform independency, along with backward compatibility, are some of the biggest advantages of the technology. Through the use of EDDL, it is possible to avoid problems caused by operating system upgrades, control system revisions, and new versions of the device software from multiple suppliers different than that of the host system [2].

The EDDL files can reside in any device that can see and access the parameters, functions, and data in smart devices. EDDL files are used in host devices that have either direct plug-in access or HART or Fieldbus communication access to the smart instrumentation. The smart instrumentation determines what will be displayed while the host determines the "look and feel" via EDDL. Examples of hosts with direct plug-in access are hand-held communicators and laptops. The primary example of a host with HART or Fieldbus access is the DCS and multi-user device management software, such as asset management systems (AMS). These management systems get their information through the DCS if the DCS has "pass through" capability where information can be passed to and from the smart instrumentation through the DCS. If there is no "pass through" capability, the HART and Fieldbus signals of the smart instrumentation have to be connected to the I/O of the asset management system.

DCS and asset management systems provide better visualization with graphics and faster navigation by tabs. The secondary screens may have a subset of tabs so not all screens are directly accessible from the main screen. However, navigation is much easier and intuitive, particularly going back and forth between widely separated screens. This better visualization and navigation is particularly important for the setup of more sophisticated devices, such a radar level measurement, and the monitoring of sensing elements more susceptible to deterioration from process exposure, such as pH electrodes. Figure 1-31a shows a radar level setup screen with basic and more advanced probe settings. Figure 1-31b shows the radar level diagnostic screen details for an invalid measurement due to missing volume configuration. Figure 1-32a shows a pH setup screen for the range, impedance, standard electrode temperature compensation, and custom solution temperature compensation. Figure 1-32b shows the dashboard for a diagnostics screen with dials for the measurand, process temperature, electrode impedances, and RTD resistance.

Handheld communicators rely on a tree menu and navigation via branches from screen to screen. Because of the small display window, graphics and plots are not generally used and only a portion of the information and its interdependency can be seen at the same time. Figure 1-31c shows a partial menu of communicator screens for a radar device. Figure 1-32c shows a communicator menu of screens for the configuration of a pH measurement device.

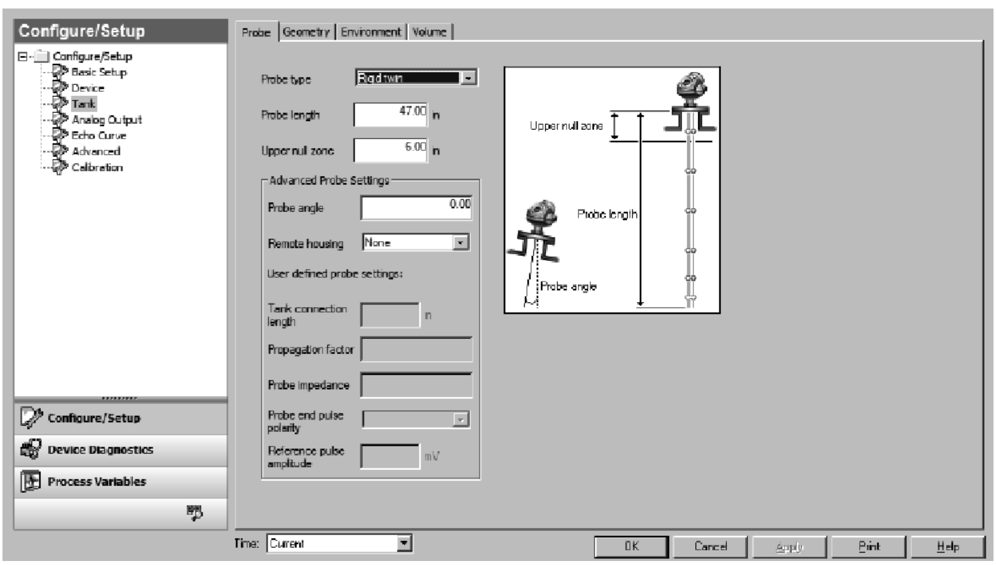


Figure 1-31a. Radar Level AMS Screen for Basic and Advanced Probe Settings

Calibration Adjustments

Calibration basically consists of setting a zero (offset) and span (slope) adjustment to provide a better match between the transmitter output and the true value of the process variable. Zero and span adjustments require

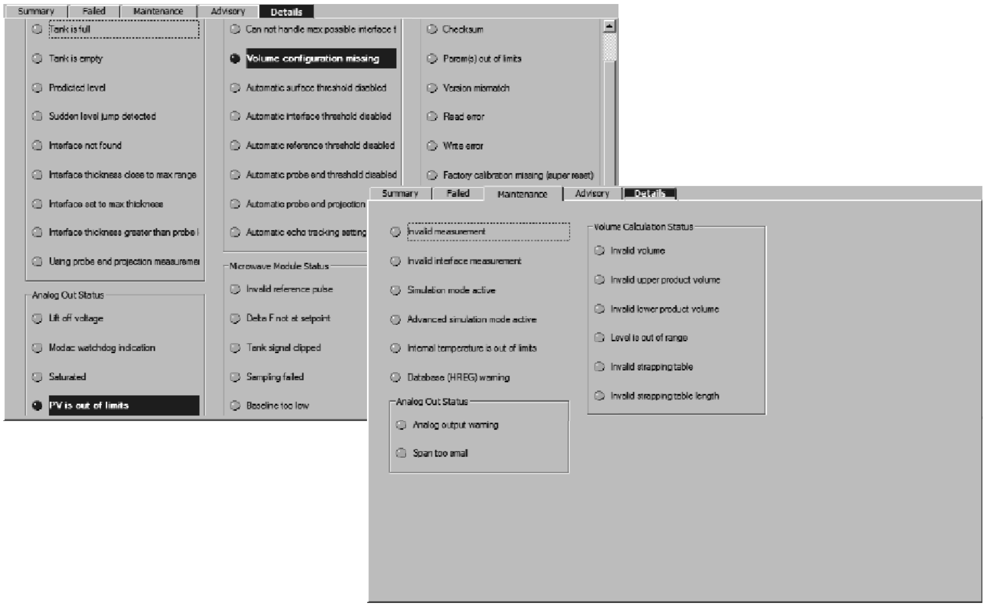


Figure 1-31b. Radar Level AMS Diagnostic Screen

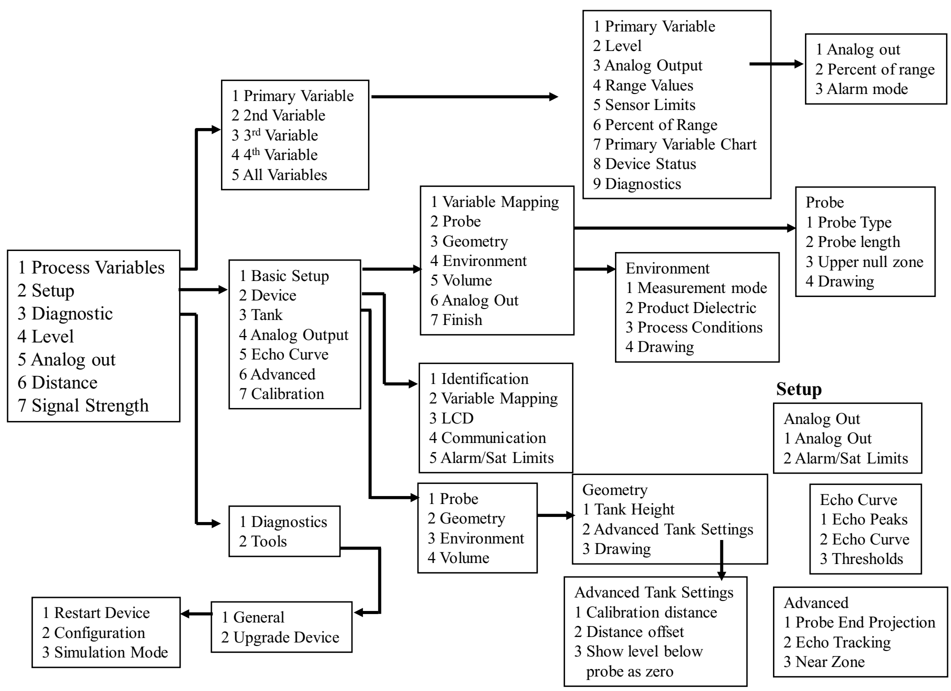


Figure 1-31c. Radar Level Handheld Communicator Menu

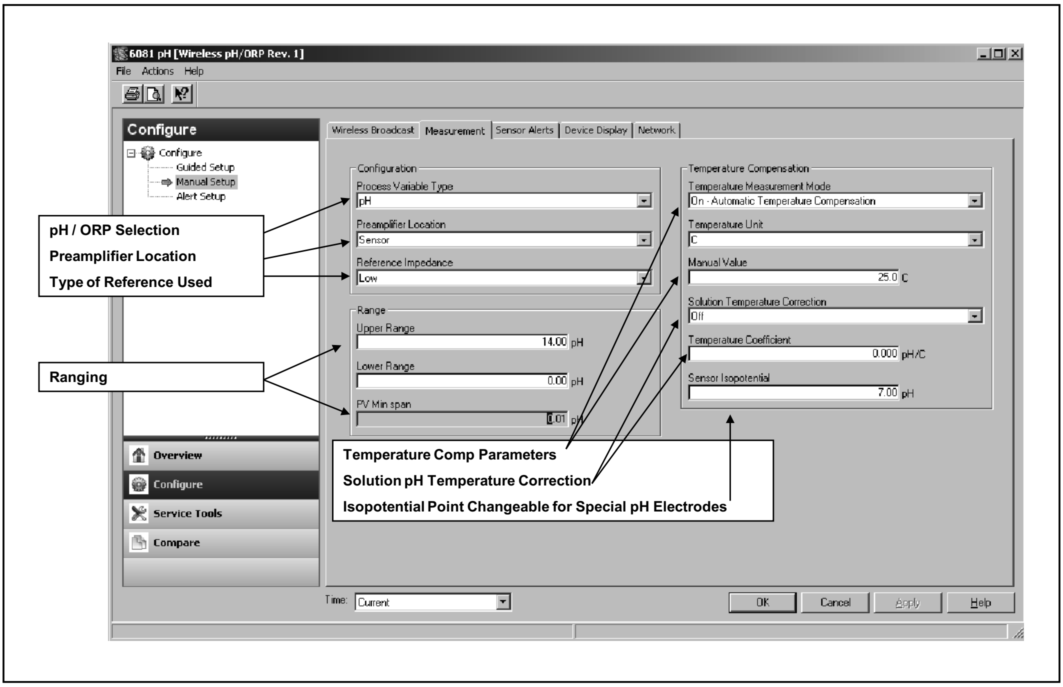


Figure 1-32a. pH AMS Screen for Configuration

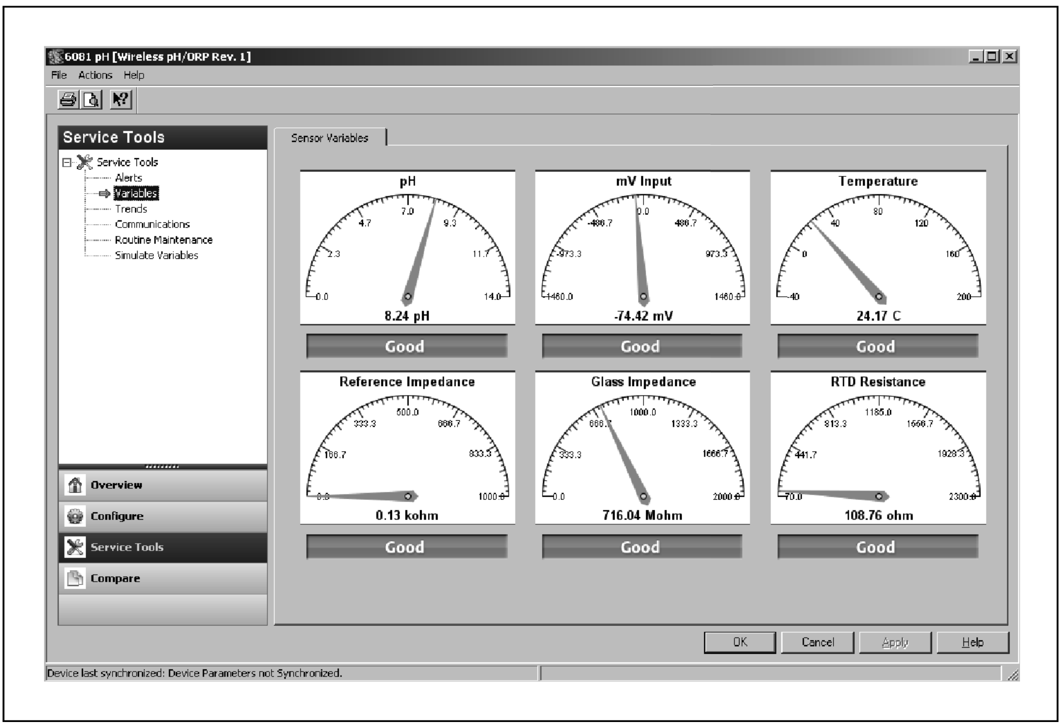


Figure 1-32b. pH AMS Dashboard for Diagnostics

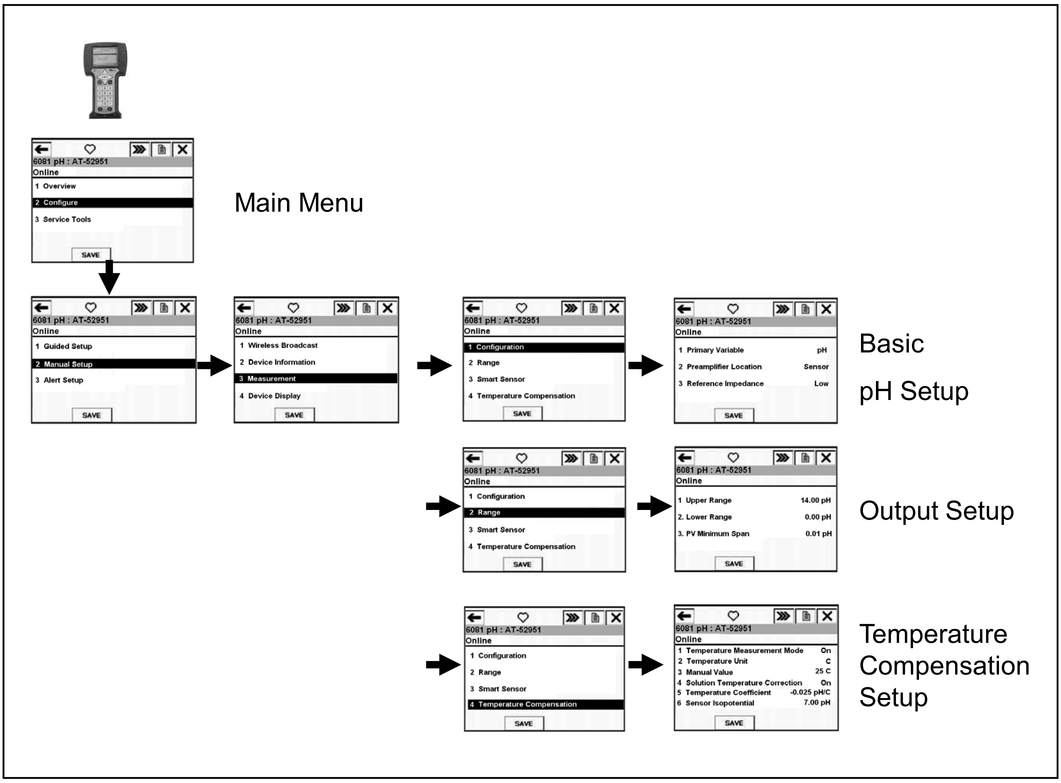


Figure 1-32c. pH Handheld Communicator for Configuration

one and two known values, respectively, of the measurand or process value. These calibration adjustments are compensating for errors or uncertainties in the sensing element and transmitter. If the calibration is done online it also compensates for uncertainties in the process and installation.

The zero adjustment provides a parallel shift to compensate for an offset of the measured value from the true value as shown in Figure 1-33. This zero adjustment is done by comparing the transmitter output with the true value of the measurand or process variable at one point. This adjustment is most typically done at the low range limit (0% transmitter output). For pH electrodes, the zero adjustment is termed an offset adjustment. For initial benchtop pH transmitter calibrations the offset adjustment is often done by inserting the probe into a 7 pH buffer solution, which corresponds to a zero millivolt output and the iso-potential point (point of zero temperature effect) for the glass electrode.

The span adjustment rotates the calibration line to compensate for a mismatch in the slope between the measured and the true value at two points

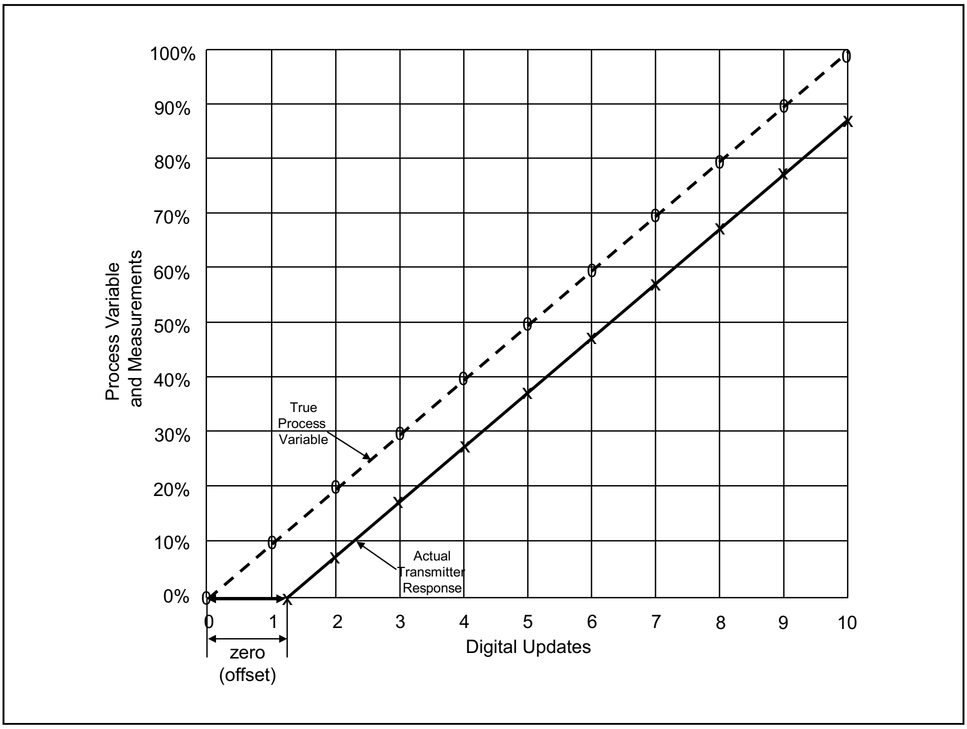


Figure 1-33. Zero (offset) Adjustment

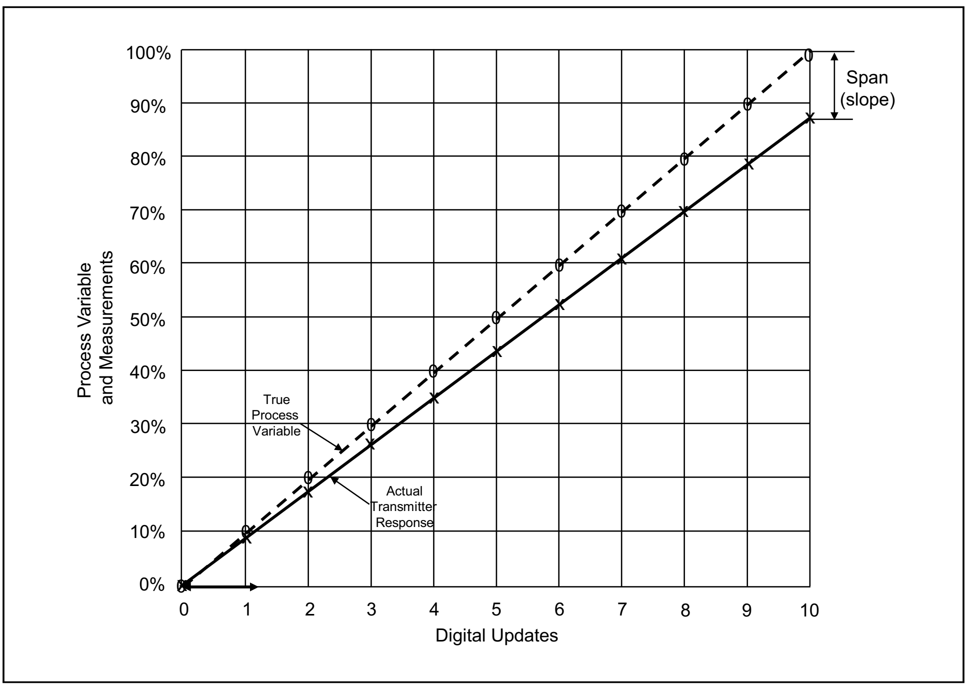


Figure 1-34. Span (slope) Adjustment

as shown in Figure 1-34. It is best to make the zero adjustment first to pin the calibration line at the zero percent output.

In some smart instrumentation, the zero and span adjustments are done automatically when two known values of a process variable or measurand are provided.

Calibration Methods

There are six basic calibration methods. Calibration methods 4 and 5 generally yield the best results because they take into account non-ideal installation and process effects. Calibration methods 1 and 2 are generally done at the supplier and are redone or at least checked in the plant before commissioning. The calibration methods used by the supplier may be proprietary. Suppliers will also perform calibration method 3 for level and flowmeters to establish the accuracy specifications of each model number. For method 3, the supplier installs the flow or level measurement device in a pipe and tank system at ambient temperature with a circulation of water and/or air. For flow, the installation is commonly called a "Meter Prover." Suppliers rarely offer calibrations at process conditions primarily due to the practical difficulties and safety issues with the transporting, handling, venting, and disposal of process chemicals.

1. Offline calibration using a simulator for the measurand
2. Offline calibration using a calibration standard for the process variable
3. Online calibration using redundant measurement(s) at standard conditions
4. Online calibration for zero value of process variable at process conditions
5. Online calibration using redundant measurement(s) at process conditions
6. Online calibration using a grab sample at process conditions

Offline calibration is either done on a benchtop or at the installation point by effectively removing or disconnecting the sensing element from the process. Offline calibration can be done with a simulator for the measurand (e.g., millivolts for thermocouples and pH electrodes) or a calibration standard (pressure, temperature, or pH). Simulators and calibration standards are both commonly referred to as "calibrators."

Consider the calibration of a typical differential pressure flow measurement. A sizing program for the primary element provides the differential pressure for the upper end of the flow measurement range at the process conditions and pipe size. The program also provides the primary element size, such as the orifice beta (ratio of orifice diameter to inside pipe diameter). With both sides of the DP open to atmosphere on the benchtop, a zero adjustment is made to provide 0% transmitter output. An adjustable pressure standard (calibrator) is connected to the high side and the pressure is set to match the upper range value from the orifice sizing program. A span (slope) adjustment is then made to provide 100% output.

If a controller is automatic, when an instrument is removed from service or an online calibration is done, the final element could be driven quickly to its output limit, upsetting the process and possibly shutting down the process unit. It is extremely critical that all plant procedures be followed before any maintenance or calibration is done on an instrument in service. Plant procedures require written details such as the duration of the calibration, approval by an operations supervisor, approval of the control room operator, placement of the affected controllers in manual, and verification of the proper commissioning of the instrument when the calibration is complete.

Online calibration for zero value of the process variable at process conditions is typically done for pressure, DP, flow, and level transmitters. After the instrument is installed and the line or vessel is at operating conditions, a zero adjustment is made when the pressure, differential pressure, flow, or level are known to be zero. For an inline flowmeter, particularly a magnetic or Coriolis flowmeter, the meter should be completely full of process fluid for the zero flow adjustment.

For a differential pressure transmitter (DP) it is recommended that a zero adjustment be done with the process pressure loaded to both sides of the DP. Figure 1-35 shows a DP with a manifold bolted to the high and low side connections. The manifold has an integral set of valves. The valves H1 and L1 enable the high and low side of the DP to be connected or isolated from the high and low process pressure connections, respectively. To provide a zero adjustment at process pressure, the low side valve L1 is closed, the high side valve H1 is opened, and the equalization valve E1 is then opened to load process fluid and pressure on both sides of the DP making the differential pressure zero.

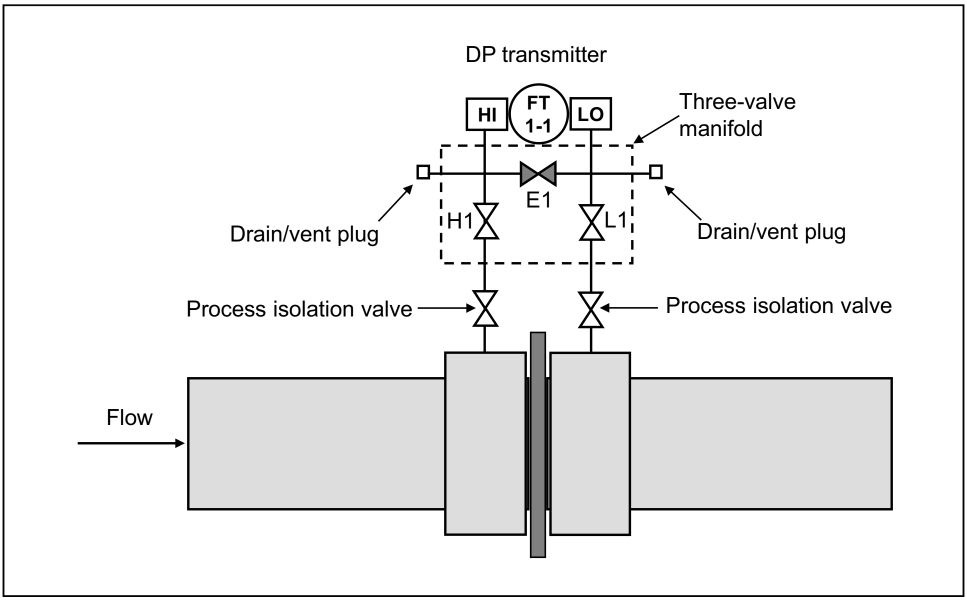


Figure 1-35. Differential Pressure Transmitter (DP) with Integral Valve Manifold

Online calibration using redundant online measurements is done by matching the subject transmitter's output to a more accurate online measurement or to the middle or median value of multiple online measurements of similar accuracy. This online calibration with redundant measurements can be done at standard conditions or at process conditions. See Chapter 6 on pH for a discussion of what middle signal selection offers for online calibration, noise reduction, inherent universal failure protection, and diagnostics.

A process sample is taken (grabbed) and used to make an online zero adjustment to correct for an offset of composition measurement such as conductivity and pH. For pH measurements this online grab sample calibration method is commonly termed a "standardization" adjustment. The sample is usually measured by inserting a fast and accurate lab sensor into the process sample bottle or beaker at the installation site or in the lab. The sample should be stirred and at process temperature.

The calibration methods used in the plants vary considerably in degree of sophistication based on practical considerations such as application requirements, lab and shop resources, and technician staff. The practices for nuclear power plants and pharmaceutical plants are generally the strictest. Metrological labs would probably consider most industrial plant practices as being not up to lab standards. In industry, non-ideal installation and process effects can easily obliterate the benefits from more exact lab calibrations, making the discussion of metrological standards academic.

Online Calibration Examples

The following descriptions are meant to be examples for major types of measurements and do not necessarily represent best practices. The best calibration method for an application depends upon the features and capability of the device, the installation, the process conditions, and the accuracy requirements.

It is assumed for each example that the zero and span adjustments for these devices have already been done on a benchtop in the instrument shop.

Online Level Calibration

An online calibration adjustment of a level device for a zero level can often be done for batch processes and before the startup and filling of vessels in continuous processes. An online adjustment for a specific level requires another level indication. Sight level gauge glasses that provide an outside visual indication of level are not used much any more, particularly in chemical plants, because of safety issues with the glass. During water batching, the water level can be varied, the water level manually measured, and online calibration adjustments made. For level devices that are affected by the physical properties of the fluid (e.g., density and dielectric constant), the calibration adjustment must take the difference between water and the process fluid into account.

A differential pressure transmitter is commonly used for level measurement. The high and low sides of the DP are connected to the bottom and top of the vessel, respectively. The high side measures the pressure from the height of the liquid level plus the pressure in the vapor space in the top of the vessel. If the vessel is open to atmosphere, the pressure in the top of the vessel is atmospheric and the low side connection of the DP can be simply vented. However, for environmental and safety reasons, the top of most process vessels is closed. During the filling and emptying of the vessel, the vessel pressure will rise and drop from the compression and decompression of the gases and vapors in the top of the tank. The vessel pressure set point may also be changed by a control loop. For closed vessels, the low side of the DP is connected to the top of the vessel. The net differential pressure between the high and low side of the DP is then proportional to liquid head (level). The DP zero adjustment for zero level should be made with the vessel pressurized to make sure the low side sensing line is properly installed and functioning. Figures 1-39a through 1-39d show the installation of major types of DP level measurements

Relative Accuracy of Inventory Measurements

Sometimes online level calibration is done by computing the level from a total of feed flow(s) measured by Coriolis mass flowmeter(s) or the change in feed tank weight measured by load cells. The accuracy of the total mass added to the vessel provided by these measurements is better than the accuracy of most level measurements except for radar.

In the author's assessment, the accuracies of properly set up and calibrated inventory measurements for changing process fluid compositions are listed below where 1 is the highest and 10 is the lowest accuracy. For the level devices, random errors are most important because we are looking for a change in level that would cancel out fixed (offset) errors. Note that even the lowest accuracy device might be perfectly adequate for many applications where knowing the exact level or change in level is not necessary, such as surge tank level. For applications where residence time and material balance control are important, such as continuous reactor and column overhead receiver level, measurement noise and sensitivity are more important than overall accuracy.

1. Radar level measurements (provided dielectric constant effects are negligible)
2. Coriolis flowmeter total (provided pipeline inventory effects are negligible)
3. Load cells (provided structural support and wind effects are negligible)
4. Ultrasonic level (provided vessel vapor effects are negligible)
5. Multivariable DP level (provided DP sensing line effects are negligible)