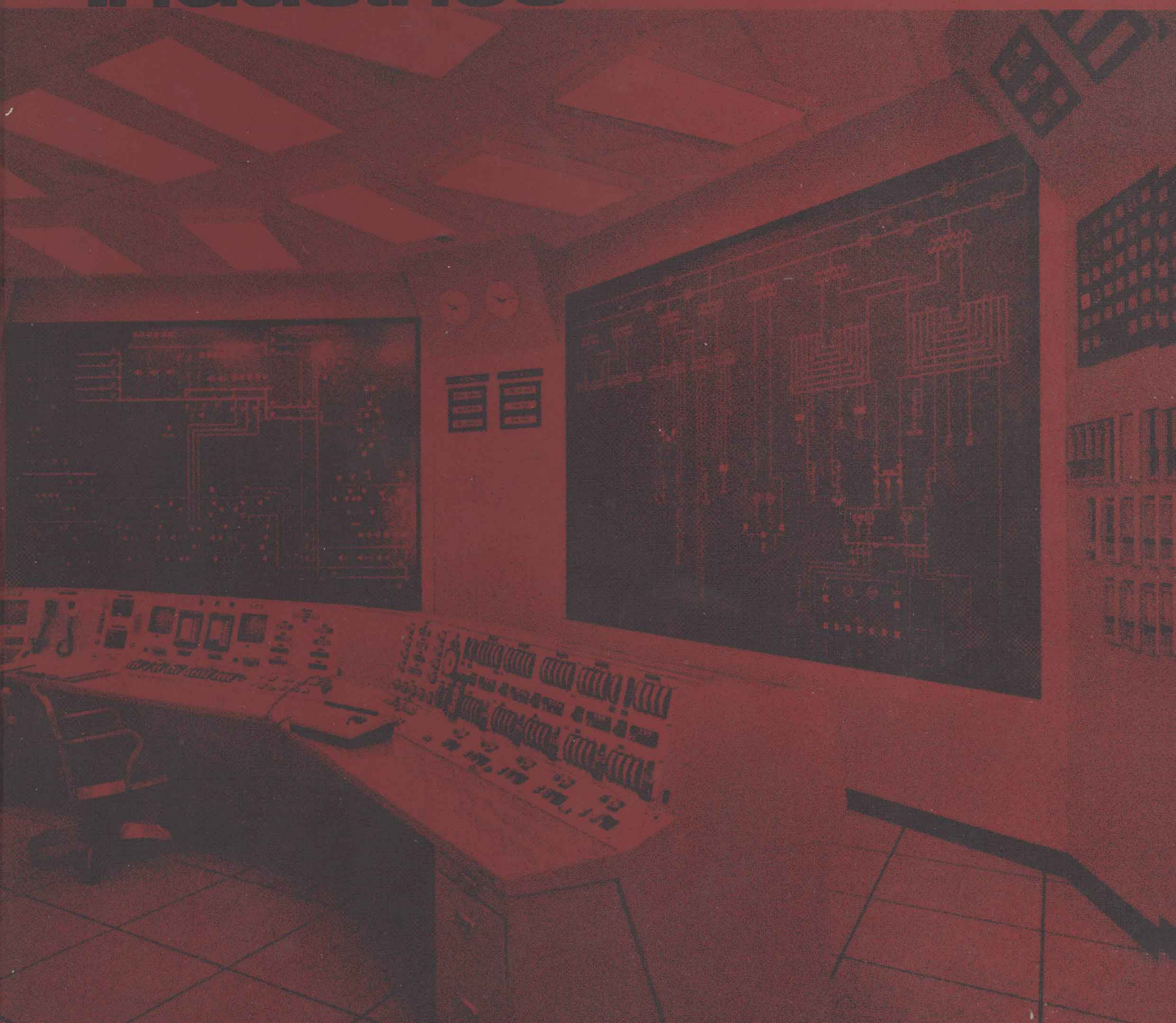
Applied Instrumentation in the Process Industries

Volume 1
A Survey



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A Survey

W.G. Andrew

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Applied Instrumentation in the Process Industries
Volume I: A Survey

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Preface

The word *automation* has become a familiar sound to the average American. In the process industries, the somewhat synonomous term *instrumentation* is no less familiar. It is ironic that in a day of automation (or instrumentation) there still exists a partial void in efforts to train people engaged in a field that involves both art and science. The scientific aspect has often lagged the state of the art. Formal education for the field has been nil; practitioners have come from other disciplines, primarily electrical, chemical, and mechanical. The training afforded those entering the profession has come through formal and informal communication within the small but closely knit group. Trainees are often bewildered by the slow rate at which they grasp the entire field and achieve the level of competence and confidence of a professional.

These three volumes present the combined knowledge and experience of many people by providing a survey of instruments used in the chemical, refining, and petrochemical industries; a compilation of practical guidelines widely accepted throughout the industries; and engineering information and resource material that provides shortcuts to the practicing profession, for engineers, designers, and operating people.

The scope of the books and their presentation make them profitable library additions for experienced as well as inexperienced people. Instrument engineer trainees, process engineers, project engineers, and managers who desire easily referenced sources to confirm control concepts and methods will use this source confidently.

Technicians and maintenance men who aim at proficiency, operators who want to know how their processes are controlled, ambitious designers who want to progress in the instrument field will find the coverage to fit their needs.

Instrument manufacturers and sales personnel will find it interesting and profitable to understand more fully the user's view of the industry they serve.

Experienced instrument people will also find it useful as a thought-tickling reference for many applications. The experienced professional, more aware of the need for thorough analysis than are the novices and inexperienced, still seeks authoritative references for the control problems of today's industries. These three cross-referenced volumes serve a very useful tool for the accomplished professional in the field of instrumentation.

Volume 1, "A Survey", provides a comprehensive coverage of measurement and control devices in the processing industries. A high percentage of devices used in industry are described briefly and their operating principles are explained. Many of these are pictured or illustrated so that their use and function are easily understood.

The book provides an excellent introduction to the instrument profession, including a brief historical treatment that sets the stage for an appreciation of the measurement and control concepts and methods prevalent today. An interesting trail of progress is reviewed.

Volume 1 presents the basic fundamental concepts and theories of automatic control. The presentation is a nonmathematical, layman type treatment easily understood by the novice. The clarity and conciseness with which these theories and concepts are given provides an excellent reference for experienced and inexperienced readers.

Volume 2, "Practical Guidelines," is unique in the field of instrumentation literature. For the first time a work is available that formally sets forth information, suggests methods, makes comparisons, issues principles, and provides guidelines for those who want to master instrumen-

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tation quickly and thoroughly. It provides the accumulated knowledge and experience of instrument practitioners who are applications-minded.

Volume 3, "Engineering Data and Resource Material," is yet another unusual addition to the instrument field. It is filled with resource material necessary for people involved in instrument application, engineering, design, and operation.

This volume includes a thorough treatment of fluid flow problems. Physical properties of fluids are discussed, the nature of liquid and compressible fluid flows are treated clearly and concisely. There are charts, tables, nomagraphs, formulas, and symbols that instrument people need in their work. The information is arranged topically and indexed for easy reference. There is an abundance of information on the physical properties of fluids, flow data, conversion data, mathematical functions, piping information, and electrical data that are essential to instrument engineering.

Other features in Volume 3 are a listing of formulas needed for calculations in engineering work, typical installation details for instrument devices and sample calculation problems that are helpful to novices in the field. Sample problems include fluid flow problems, orifice calculations, control valve and relief valve calculations, and other problems involving the use of charts, tables, etc., given in Volume 3.

These three volumes are directed at hastening the development of new instrument trainees, bridging the gap between instrument people and engineers and designers in other engineering disciplines, and aiding experienced instrument engineers in their jobs.

Dedication

To my wife Betty, and children, Karen, Debbie, and Mark, for their patience and understanding

Acknowledgments

Any technical book draws material from a large number of sources. Although many of these are referenced in the text, it is not feasible to include all the contributors to whom the author is indebted. Data and information were furnished by many industrial companies.

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In addition, the author is deeply appreciative to S.I.P., Inc. and its staff in providing the environment and materials for producing this work.

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Contents

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Introduction

William G. Andrew

Necessity has dictated many of the advances of technology. In no other field is this more apparent than the discipline known as *instrumentation*—a word unkown 50 years ago.

In this 50-year development period, instrumentation has evolved from a series of devices, developed to fill specific needs of measurement and control, to a science in itself, where the premises and economics of entire plants and processes are based on suitable control strategies and instrumentation systems.

Initially, instrumentation had no separate status. Primarily, it consisted of mechanisms devised to fill the needs of specific localized control problems. Its development was relatively slow until the 1940s.

The critical demands of wartime production schedules during World War II pulled the instrument industry into the twentieth century. New control techniques were developed and used to keep pace with the accelerated output of America's wartime industrial complex. New control system technologies were developed for weapons control systems and for chemical and petroleum processes developed and/or expanded by wartime demands.

In the postwar period, the wartime technology continued to infuse the industrial community so that when the economic boom period of the 1950s and 1960s occurred, rapid expansions in petroleum, chemical, pulp and paper, automotive, machine tool and space industries provided a terrific impetus to instrumentation, producing great advancements that have brought the discipline to the respected status it commands today. These industries and most other process and assembly-type industries would fail to survive today if they were to be deprived of modern control techniques.

A technology as dynamic as instrumentation requires a constant inflow of new people who need to know not only the latest analytical control techniques from educational institutions but also the more practical aspects of hardware knowledge and application philosophies and guidelines from industry. The latter function is usually obtained through experience—frequently slowly and expensively.

This three-volume series presents a practical source of information and background on instrumentation based on experience in selection, application and maintenance. It is toward this goal that this series is aimed: Volume 1 is a survey of the commonly used instruments; Volume 2 presents practical guidelines for application; and Volume 3 presents engineering data and resource material.

The material in these volumes has been selected for applications-oriented people. People who need a broad understanding of the many factors which enter into instrument selection—process operating demands, maintenance requirements, economics, operator interface, cost of downtime and innumerable other factors which must be weighed and considered—will find them a valuable asset to their library of references.

The remaining portion of this chapter reviews early instrument development, examines the status of instrumentation as it stands today and projects future trends. The industry is dynamic and ever-changing, and its scope is difficult to define because of its changeable nature.

Early Instrument Development

In the 1920s and 1930s industrial instruments were rather crude compared to today's standards. Local control was prominent. Efforts to centralize controls were confined primarily to units or subunits of processes, even for the more sophisticated plants. Indicators and recorders revealing the basic measurements of temperature, pressure, level and flow were used in many cases, with the operator observing measurements and adjusting valves as necessary to achieve desired results.

Prior to 1940, few people were working on control theory as it is now defined. Instead, empirical methods were used in attempts to apply control methods to process problems. It was a period of cut-and-try. Applications were founded primarily on experience and not on a strong theoretical base. This point is emphasized when one considers that it has been estimated that probably more than 90% of all control engineers who ever practiced are still active today.

From the beginning of World War II through the 1950s, control theorists produced a rather complete and general body of knowledge for the analysis, synthesis and design aspects of linear control systems. This has been referred to as the "classical" period in control theory development. Subsequent work is referred to as being in the "modern" period. This does not imply that the work of the 1940s and 1950s is not correct or appropriate; in fact, most control systems used today are based on the concepts of the classical period theorists.

The 1950 period also witnessed the introduction of electronic instruments. Among the earliest were Swarthout Instruments using AC voltage signals and Manning, Maxwell and Moore's Microsen line using DC milliamp signals. The increasing use of electronic transmitters and controllers, no doubt, has hastened the use of computer techniques, and the adoption of the more advanced control methods such as adaptive and optimal control.

This same period saw the beginning of miniaturization in packaging of control components, both pneumatic and electronic. Large case indicators, recorders and controllers that had occupied front-of-panel areas of approximately 180 square inches (12 by 15 inches) soon took no more than 36 square inches (6 by 6 inches). These were subsequently reduced to 18 square inches (3 by 6 inches) and even smaller. Not only have instrument sizes been reduced, but the density of instruments has also increased to provide much more process information in a given area.

While new control theories evolved and new and improved equipment was introduced, improved signal transmission methods also came into use. Multiconductor tubing cables of copper, aluminum and plastic began to replace the single tubing runs installed in the 1940s and 1950s in 50-foot lengths. Single tubing runs required stretching to attain rigidity and stiffness and rather expensive supports to provide for proper installation. Joints were made with connectors (fittings) or by soldering. Installation and testing methods were long, laborious and costly.

These brief highlights of control theory development and hardware use provide an interesting perspective for viewing instrumentation and control system concepts used in today's industrial plants.

Instrumentation Today

Instrumentation is now in a state of flux. There exists today plants with old but operable control systems, just as there exists processes which are old but still profitable. If they were being built today, changes would be made, but a time for change has not been deemed appropriate in these plants.

Today, plants are being built using the latest available electronic hardware, computer controls and advanced control concepts; others are built with appropriate hardware for future conversion to computer control; and still others are built with conventional hardware (pneumatic or electronic) that would require major, expensive modifications to convert to computer control.

In the last two decades, there has been much debating among those involved in instrumentation and control system technology about the relative merits of local versus central control, pneumatic versus electronic instrumentation, computer versus conventional control systems and direct digital control versus supervisory control. A rationale has emerged from these seemingly conflicting approaches which dictates that the application engineer must judiciously select from among these alternatives the system(s) which best fit the criteria under which he is working. Each system has its own merits, yet none has been demonstrated universally superior in *all* applications.

A dominant factor in current instrumentation is the impact of computer applications. Computers are being used to control directly, to perform economic optimization calculations, to make heat and material balance calculations or simply to perform the conventional monitoring, logging and alarm functions so essential in today's industrial processes. Computer applications have penetrated all the major industries as well as specialized applications in many smaller industries.

Large computer systems are being designed and built, having fully redundant computers, with complete, fully automatic transfer of data and controls in the event that the on-line computer fails. These systems include sophisticated display features and require complex interface hardware and software techniques.

Mini-computers are finding increasing usage in control systems as their costs decrease and as reliability and improved packaging of integrated circuits improve. Prices for a small system with standardized programming capability are competitive with systems utilizing conventional control systems. Dedicated computer systems with a mini-computer used exclusively for controlling a single unit or portion of a process are becoming popular for several reasons.

1. Attractive economic benefits can be realized by controlling and optimizing only a few critical loops in a process.
2. Hardware and software costs are reduced.
3. Operating losses from downtime are reduced.
4. Manpower for design, operation and maintenance is small compared to that required for a large computer system.

The increased frequency of computer applications has not stopped the expansion and improvement of conventional control hardware. One major instrument manufacturer has completely redesigned a pneumatic panel instrument control line in the last few years. Another instrument manufacturer has redesigned its transmitter line.

Bumpless transfer when switching from automatic to manual control and vice versa, anti-reset windup and plug-in capability for adding alarm functions, output limiters and feedforward units are features that are offered by various controller manufacturers. Following are other facets and features of today's changing control technology.

Implementation of New Hardware and Control Techniques

Even in conventional control systems, new and improved hardware and useful control features have been added. Electrohydraulic valve operators with extremely fast (compared to pneumatic or electric) operating speeds are available for processes demanding fast response speeds. Electric operators that respond to the low-level electronic signals of modern controllers are offered, but they do not yet meet the speed, power and cost requirements to be competitive with pneumatic or hydraulic operators.

Equipment Packaging

There have been many recent improvements in this area. The size of both pneumatic and electronic panel instruments has been reduced; instrument density in control panel arrangement has increased; and field connections have been simplified (for panel mounted instruments). Electronic instruments increasingly use solid-state components for increased reliability and improved maintainability. One of the most significant improvements introduced is the modular concept of construction. Plug-in assemblies and subassemblies have made replacement and repair much easier. Elimination of vacuum tubes and the use of solid-state devices have given components longer life expectancy and more freedom from vibration, heat and other environmental problems.

Analytical Equipment

Analytical techniques for on-line measurement and control are changing rapidly, particularly in gas chromatography. Reliability and reproducibility have been recognized problems. These are improving with better sampling systems, more reliable programming techniques and the ever-increasing storehouse of applications data. Memory units have been developed allowing the periodically sampled signal levels to be used on a continuous basis. Other significant analytical techniques and devices include:

1. pH measurement and control for product quality improvement, corrosion inhibition and neutralization of waste effluents
2. Oxygen analysis for its essential role in oxidation, combustion and processing applications (the analysis for dissolved oxygen is highly pertinent to the ecological field)
3. The measurement of total hydrocarbon content in waste streams
4. Numerous methods of moisture analysis important to many processes in the refining, chemical and petrochemical industries as well as other processing applications
5. A variety of other physical and composition measurements including conductivity, density, turbidity, refractometry, colorimetry and viscosity

These type measurements are being refined and improved to provide essential characteristics of processes which determine quality and reproducibility. These, of course, are prerequisites to product profitability.

Basic Measurements of Flow, Temperature, Pressure and Level

The accuracy of these basic process measurements have not increased significantly in recent years. Accuracies to within ±½ to ±1% have been attainable for a long time. Many devices accurate to within ±¼% (or better with proper calibration) are available now, but this cannot be claimed as an outstanding achievement. Several new principles and techniques for flow measurement have been introduced and find increasing use. These include electromagnetic meters, turbine meters, the recently introduced swirlmeter and vortex shedding meter and several variations of mass flow gas meters which utilize gas flow to remove heat from constant power (heat) sources. (In this type mass flow meter, the amount of heat removed depends on the thermal properties of the gas which either must be known or else calibration must be made to determine the thermal properties.)

The swirlmeter and the vortex shedding meter use flow disturbance in the line to provide pulse signals detected by resistance elements. These meters are new enough that their use is not yet widespread.

Methods of temperature measurement have not changed appreciably in the past few years. Filled systems and thermocouples are still predominant in use. Radiation and optical pyrometers are suitable for certain applications. Resistance elements are used when high accuracies are needed. There probably have been fewer new techniques introduced in temperature measurement than in any other of the basic process measurements.

Few changes have been made recently in pressure measuring techniques. Bourdon tubes, spiral elements, diaphragms and bellows remain most often used. Probably the greatest change in pressure measurement has been the increased use of strain gauges. They are particularly adaptable for high-pressure measurement where high accuracy and fast response are necessary.

There have been many new techniques introduced for level measurement. As a complement to standard float, differential pressure, gas bubbler and displacement types, there is increasing use of newer capacitance, radiation and ultrasonic type devices. The newer devices are more likely to be used for special applications where the more standard types are not suitable.

Thus, when the question is asked about the status of instrumentation today, the answer depends largely on the experience of the person queried. People who are researching and developing new equipment, studying advanced control theories and techniques and applying them to new process installations have vastly different concepts of "where we are" than the people whose duties relate to 15- or 20-year-old plants that are still functioning economically with control hardware of the same vintage.

"Where we are" is somewhere between the two extremes. There have been significant advances in the application of advanced control methods, in improved equipment designs and in the acceptance of sophisticated data acquisition, monitoring and control systems. However, recognition of these advances and improvements does not warrant scrapping existing operable controls. They will be replaced by better and more sophisticated controls only when replacement can be economically justified.

Looking to the Future

A historical review of instrumentation and an analysis of "where it stands today" lead to the question, "What will instrumentation be like tomorrow?" Some needs, trends and predictions for the future can be enumerated.

One of the greatest needs is for new and improved measuring sensors. While the technology for processing, displaying and using sensor-produced signals has increased tremendously, there has been a notable lack of progress in introducing new sensors or improving accuracies and realibilities of those existing.

In the basic process measurements of flow, temperature, level and pressure, the majority of measurements have accuracies of ±½ to ±2%. Most flow measurements are still made by the restriction orifice method where many errors may exist because of the condition of the element, the installation method, the calibration of the instrument, etc. The other basic measurements have similar problems in application. There needs to be an order-of-magnitude increase in accuracies. Instead of ±½ and ±2%, there should be ±0.05 and ±0.2%, or even ±0.01 and ±0.02%, which would be much closer to matching accuracies available in some of the signal processing devices.

In addition to accuracy improvements, sensors should be unaffected by ambient temperature variations, vibration, power supply fluctuations and corrosive environments. A better understanding is needed to identify applications which are critical and utilize the highest levels of accuracy and dependability for those cases.

Because of the cost of handling and installing field devices, they should be small, compact, simple and easy to install and calibrate.

There is a need now for new insights into processes. Instead of the standard flow-temperature-pressure-level measurements, there are more meaningful physical functions and process conditions that might be used. For example:

1. Heat transfer coefficient is preferable to steam pressure alone.
2. Mass flow is better than orifice ΔP.
3. Knowledge of complete chemical composition is more valuable than proof of the presence or absence of a particular component.
4. Sensors to measure thermal conductivity, sound, speed, shear modulus, color, odor and other physical properties of products are needed.

The increasing use of computers dictates the need for digital transmitters and transducers outputting directly into the computer. Final control elements must be capable of receiving directly the digital outputs from the computer. A digital pressure transducer has recently appeared on the market, as well as a digital valve positioner, but widespread usage of these elements has not been evident.

Computer usage will also permit redundancy not presently possible. With the present emphasis on large, single train processes, instrument failures that cause shutdowns are very expensive. Multiple measurements of critical process variables may be feasible where action may be taken on the best two-out-of-three measurements, with alarms functioning at any time that one of the three measurements deviates from the other two, outside of prescribed limits.

Predicting sizes and configurations of computer systems is difficult. As previously mentioned, large sophisticated systems are being installed, on line, with full backup capability, and it appears certain that these systems will continue.

A new trend seems definitely established in the control industry—the application of the mini-computer to perform many of the logic and control functions normally associated with conventional instrumentation. These computers are frequently limited or dedicated to a single unit or piece of equipment critical to the process to monitor, to perform logical decisions, to control and sometimes to optimize operation of the unit.

This trend will likely increase because:

1. Programming becomes standardized for various process units (i.e., fractionation).
2. Hardware costs decrease as the integrated-circuit impact in mini-computer manufacturing increases.
3. These systems will compete cost-wise with conventional instrument controls as overall costs decrease.
4. Many of the advantages of small computer systems can be obtained with far less capital and operating risk than for a full-blown system.
5. These systems may be linked to an overall hierarchial computer management system when the need arises.

Conversion of existing plants to computer control will continue as they are economically justified, depending on several factors.

1. Careful studies of the process to assure that the conversion will increase profits.

2. The availability of personnel for programming, operating and maintaining a more complex system—long-range planning for acquisition and training of these people can be difficult and expensive.
3. An analysis of the impact of computer downtime on the process and plant. Reliability of computer systems has increased greatly, but the cost of downtime may dictate redundant or backup systems which would push total systems cost out of economic range.

Configurations of computer systems in older plant conversions depend on the type of existing instrumentation, the size of the plant to be converted and whether or not concurrent control room consolidations are occurring. Depending on these circumstances, all-new electronic transmitters may be selected, or pneumatic to electronic transducers may be used.

Graphic display, particularly the interactive cathode-ray tube devices, will find increasing use for operator interfacing—for display of trends, profiles, tabulated data, as well as diagrammatic display with real time process data information. An associated keyboard allows additional data entry or changes.

The use of analytical instrumentation will continue to increase. On-line control of processes has been achieved in many other industries. The food industry, for example, is using gas chromatography to describe or identify compounds which are partly or largely responsible for good and bad odors and flavors in food products. In the beverage line, pH values are used to determine the condition of the finished product.

Pollution control regulations are introducing a complete new era in analytical instrumentation. Because of legal implications, the design of analytic systems must yield not only qualitative and quantitive information but also the time analysis occurred, the duration of the analysis and the source of the various contaminants. Many of the measurements required cannot be continuously measured by existing instruments. Sample systems themselves become a difficult design problem.

Signal transmission techniques are changing. The use of telemetry has made remote control of pipeline compressor stations possible. Greater exploitation of techniques are likely for other industries. Cost reductions are possible through use of time-division multiplexing, analog-frequency channels and audio-tone matrixing. The use of remote multiplexing and analog-to-digital conversion units with serial digital transmission to a central area will be common. Eventually, the use of microwave or radio transmission may eliminate hard-wire transmission altogether. A system has already been demonstrated that can transmit and receive 248 points of control over a single pair of wires.

The increase of electronic instruments has caused some people to predict the phase-out of pneumatic instruments. Others predict the use of pneumatics into the 1980s at least. A significant contributor of the demise of pneumatics could be the use of wireless transmission techniques which would drastically reduce signal transmission costs.

Miniaturization of equipment and the high density arrangement of readout and control devices have been evident for several years. There is little indication that the ultimate has been reached in this respect. As this trend continues, the need for more alert and better trained operators will be evident. The present limitation on this type display is the physical size of the meters, knobs and switches required for adequate observation and operation by the operator.

The next step in development appears to be a limited display/operating function with blind controllers. In such a system, the controllers would function normally within their prescribed limits, but with no display or available controls. On operator demand or on out-of-limits operation, the control loop and its necessary operating functions would be selected through logic circuits to be displayed on the control panel, permitting the operator to view and control the loop as required, thus minimizing the requirements for panel face area.

Preparing for Now

As one contemplates the changes of the recent past and the possibilities of the future with its advancing technology, it is easy to overlook the problems of today. This must not happen. Equipment and plant facilities worth billions of dollars are being built today and planned for tomorrow. It is essential that the best equipment be selected for the job consistent with the control philosophies for each of these facilities.

It seems ironic that a recognized study discipline has not been assigned to the technology of instrumentation. Few schools offer degree courses in the field, yet no discipline covers such a wide area of application and none is more important to today's industrial world.

There is a need for expertise at every level involved in instrumentation—in the design and development of the instruments, in the application and design of control systems and in their maintenance. The people needed are difficult to find and hire; they are difficult to keep. Some can be bought, but in general they must be reared and trained.

The ultimate success of any plant control system rests on the ability of instrument experts to make proper application of components and systems and on the ability of maintenance people to keep them calibrated and working properly. The purpose of this volume and the two volumes to follow is to prepare people for these tasks.

2 Fundamentals of Automatic Control

William G. Andrew

The study of automatic control is a complex subject. Exact solutions to particular control problems require detailed process knowledge, not only of the physical and chemical characteristics of the fluids, but also of the mechanical aspects of the process—equipment (pumps, mixers, reactors, heat exchangers, etc.), piping systems and the control loop itself. Fortunately, good control usually is achieved with limited knowledge of these physical, chemical and mechanical conditions, and control applications are made quickly and economically with a high degree of confidence in their successful operation. The next few paragraphs discuss some fundamental principles underlying all control problems. A review of these principles makes it easy for the engineer and designer to cope with control problems when the occasion arises.

Control Defined

Automatic control may be defined as the technique of measuring the value of a variable and producing a counter response to limit its deviation from a selected reference. Many other equally suitable definitions could be given, but automatic control can be understood better in terms of why it is needed, the advantages it offers and the forms of energy it controls. A really simple approach is taken in the discussion of these facets, for a complete understanding of basic principles is necessary in comprehending and evaluating control problems.

A closed control loop may use several devices to accomplish the control of a process variable. Regardless of the number of elements used, the loop will contain at least four basic elements: (a) detecting, (b) measuring, (c) controlling and (d) final control element. Often, a transmitting element is added to these. More than one element is often designed into the same housing so that a loop does not always contain four separate units.

Purpose

The one basic purpose for using automatic controls is that production is achieved more economically. Some processes would not be possible except through the use of automatic controls. Economy is achieved in several different ways:

1. Lowering labor costs
2. Eliminating or reducing human errors
3. Improving process quality
4. Reducing the size of process equipment and the amount of space it requires
5. Providing greater safety in operation

Material Properties and Energy Forms Controlled

The control of any chemical process reduces to a balance of materials and energy related to that process. It involves operating conditions peculiar to its requirements, such as the ratio of material flows, and the correct temperatures,

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