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Impact of the Electronics Revolution on Industrial Process Control

Acceptance of advanced digital communication and control systems in the industrial plant will accelerate.

Lawrence B. Evans

The first computer control system went on-line in an industrial plant in 1959. Since then, there have been remarkable advances in our ability to acquire, process, and transmit information electronically. Developments in the technology of digital computer hardware, software, basic sensors, and all forms of communication offer the potential for industrial process control systems that are highly automated and provide improved operating performance.

The Role of Process Control in Industrial Plants

The focus in this article is on the "process industries" as opposed to the manufacturing industries. Products of the process industries include chemicals, petroleum, metals, electric power, pulp and paper, food, cement, and textiles. Their plants manipulate the composition of materials by chemical reaction, purification, and blending of components to convert raw materials and energy into more valuable products. A modern chemical plant is shown in Fig. 1. The earliest applications of computer control were in the process industries, where instruments were available to monitor the continuous flow of a product and to send the data to the computer, which could then direct changes in the process by adjusting valves and switches.

Automation in the manufacturing industries—automobiles, appliances, electronics—is beyond the scope of this article. These industries manipulate the geometries of their raw materials so that discrete parts are assembled to form products. Computers are being used on the factory floor to run machine tools, track the contents of a warehouse, test products, and so forth, but the methods of measurement and control are basically different from those used in the process industries, and the problems of automation are greater (*1*).

Industrial processes are designed to operate in either a continuous or a batch mode. In the first, materials flow continuously through the plant from one processing unit to the next. At each stage, different operations are performed, such as heating, cooling, mixing, chemical reaction, distillation, drying, and pressurization. For most operations, there are optimum conditions of temperature, pressure, and residence time at each stage.

In the batch mode, the material being processed stays in one place (such as in a reaction vessel), and the process steps are carried out over time during the batch cycle. There is an optimum schedule of such factors as temperature and pressure. For large-scale production, engineers have traditionally tried to develop continuous processes, because they are easier to instrument and control, require less labor, and do not waste time in emptying, cleaning, and refilling vessels between batch cycles (*2*).

Flow rate is by far the most common variable manipulated, whether by adjusting a valve, turning a pump on or off, or by other means. The measured variables in addition to flow rate are normally temperature, pressure, chemical composition, and liquid level. A typical plant, such as one for manufacture of ethylene or ammonia, will have several hundred control valves and more than a thousand measured variables. Changes are made in the operation of the process on a time scale ranging from a few seconds to a few hours.

The elements of a control system are shown in Fig. 2. The important functions are measurement, control, actuation, and communication. Measurement refers to the sensing of variables such as flow rate, temperature, pressure, level, and chemical composition, and the transmission of the measurement to the controller. Control is the decision-making operation; it compares the measured state of the process with the desired conditions and decides how the variables should be manipulated. Actuation is the means by which the operating variables are manipulated; typical actuators are valves, rheostats, switches, and relays. Communication includes the display of information to the plant operators as well as the transmission of important variables to the plant management.

The organization of a plant control system in a hierarchical structure is shown in Fig. 3. The lowest level is occupied by the control computer that regulates a single process unit to hold it to the desired operating conditions and move the unit to a safe condition in emergencies. The next step is a computer responsible for coordinating several units, for scheduling operations, and for optimizing the plant's performance. At the top level is the corporate control com-

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puter, which makes available to management current information about its manufacturing operations.

The operations at the lowest level (of regulating the process and watching for system failures) are the simplest, but they must be done frequently. The optimizing and scheduling tasks at the higher levels are much more complex but are done less frequently.

An advanced automation system is concerned not only with the physical control of the process but also with its management (the gathering and application of both process and business information for decision-making).

There are four basic objectives of plant operation that an advanced management and control system can help achieve. (i) To perform the primary mission of the plant. The plant must produce products of the required quantity and quality and be available and operating when needed. If it doesn't perform its primary mission, the plant is a failure even if succeeding objectives are met. (ii) To maintain safe operating conditions. The control system should constrain processing to safe operating conditions, such as allowable temperatures and pressures, and should be able to shut the system down safely in an emergency. (iii) To comply with government requirements. Society imposes restrictions on the operation of most industrial plants in the form of government regulations. These restrictions require the control of environmental emissions to acceptable levels, control over the exposure of workers to toxic materials, the keeping of records required by law, and so forth. (iv) To improve productivity. This can be achieved by increasing the yield of products, reducing requirements for raw materials, energy, and labor, and reducing capital investment. The greatest opportunities for advances in the application of modern control technology are in those situations that provide obvious benefits in meeting one or more of these objectives.

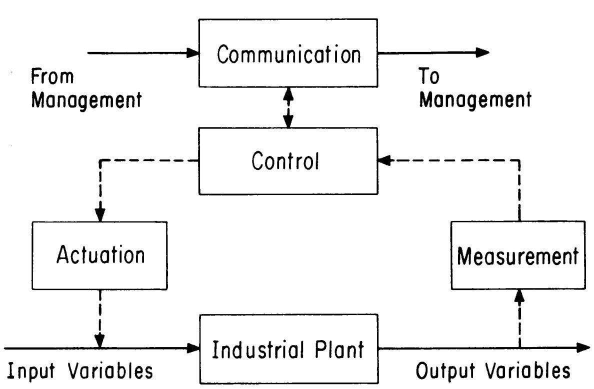
Fig. 1. Modern petrochemical plant. [Courtesy of the Foxboro Company]

Advances in Control Technology

There have been significant advances in control theory, in industrial applications of control, and in hardware and software available for control. Each of these areas will be reviewed.

Almost all of the early control systems, such as the flyball governor developed by James Watt in 1788 for controlling the speed of a steam engine, were developed empirically. Maxwell in 1868 (*3*) wrote the first theoretical paper on control with his analysis of the stability of the flyball governor. Since that time there have been rapid advances in the mathematical theory of control. These have led to improved understanding of the behavior of complex feedback control systems and to the development of mathematical and computational techniques for their design. Major developments in control theory are listed in Table 1. Advances in the application of control technology to industrial processes are summarized in Table 2.

When continuous processes began replacing batch stills in the oil industry in 1910, most processes were controlled manually with use of local temperature and pressure measurements. In the late 1920's the pneumatic controller was developed with proportional and integral (reset) modes that could be tuned in the



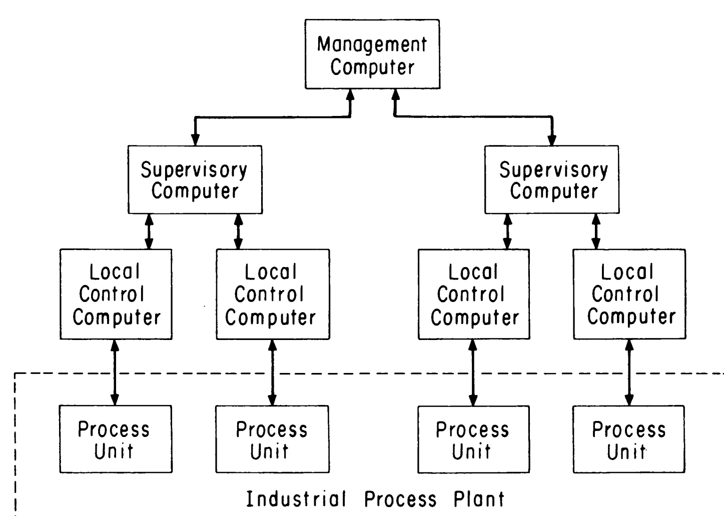


Fig. 2 (left). Schematic diagram of an industrial control system. Fig. 3 (right). Hierarchical organization of an advanced control system.

field. A few years later the derivative mode was added to form the so-called PID (proportional-integral-derivative) three-term controller (*13*). This was a turning point in process instrumentation and led to a tremendous extension of the use of automatic control to processes previously difficult or impossible to control except manually.

Pneumatic transmitters were developed in the mid-1930's and led in the 1940's to centralized control rooms (Fig. 4) with large control panels. Electronic controllers became available in the 1950's. Since installation of the first computer-controlled system in 1959, there has been a steady growth in the number of computers installed in process plants.

An important historic observation is that significant developments took place essentially at plants. The development of the three-term pneumatic controller in essentially its modern configuration was completed in 1942 without the a priori support of any theory.

Among the recent developments in hardware and software for control are decreased cost of electronic hardware, improved communications capabilities, techniques for producing less expensive software of better quality, and the development of specialized sensors.

The cost of complex electronic circuitry continues to decrease exponentially (by a factor of about 1/2 each year) due to large-scale integration (LSI) semiconductor technology. Such technology has led to more powerful microprocessors with greater memory and speed and smaller cost per unit. The real cost of a system is in the hardware for communication between man and that system (displays, keys, typewriters) and this cost is a function of the way the system is packaged. Thus, automation functions and data processing become economic if they can be done blindly, without the need for human communication.

Improvements in cathode-ray tube (CRT) displays are continuing to permit displays of higher quality with greater flexibility at lower costs. Color displays are becoming much less expensive. The problem will be to determine how to present information to the operator so that it will be most useful.

Improved communications are making it possible to use systems in which elements of the control system are dispersed throughout the plant and communicate with each other through networks. New technologies for communication based on the use of coaxial cable, fiber optics, and other carriers are emerging. Communication over these networks is by a digital rather than an analog signal.

The major cost of a computer control system is in the engineering and programming of the system. A new technology for producing computer programs, known as "software engineering" is becoming established. Instead of programmers writing their programs in whatever way they think best, software is designed and produced by engineers who use proven techniques. This approach reduces software costs, errors, and implementation time while improving reliability and maintainability.

Analytical instruments are increasingly used to measure stream composition and condition at the output of a process for on-line control. Sensors are being developed to measure all sorts of specialized compositions, such as flue gas, sulfur in oil, and brightness. Frequently the availability of such a sensor is the key to developing an advanced control system for a particular process.

Table 1. Developments in control theory.

Date	Development
1868	Maxwell (*3*) read his paper, "On Governors," the first analytic study of the flyball governor.
1922	Minorsky (*4*) wrote the differential equations describing automatic ship-steering gear and used it to design a system on the *New Mexico*.
1932	Nyquist (*5*) presented his basic regeneration theory, which established him as the father of feedback control technology.
1934	Hazen (*6*) published the theory of servomechanisms, a term which he coined.
1936	Callender, Porter, and Hartree (*7*) published an early study of the transient performance of a valve-controlled process.
1938	Philbrick (*8*) developed the electronic analog computer at the Foxboro Company.
1953	Mason (*9*) introduced the signal-flow diagram techniques.
1956	Boltyanskii, Gamkrelidze, and Pontryagin (*10*) introduced generalized optimization synthesis techniques for dynamic systems.
1958	Kalman and Bertram (*11*) pointed out the utility of state-space representation of the dynamics of control systems.
1961	Kalman and Bucy (*12*) presented a new approach to filtering and prediction for linear systems.

Fig. 4. Control room for petrochemical plant. [Courtesy of the Foxboro Company]

Trends in Process Plants

The use of advanced control technology has been influenced by developments in industrial processes and in the constraints imposed by society on their operation. The search in industry is for plants that produce more valuable products in greater quantity at lower cost. Plants are consequently becoming larger and more complex and must be operated to closer tolerances. To achieve economies of scale in the production of chemicals that are important commodities, such as ammonia and ethylene, plants of enormous size have been developed in which the processes are designed as a single train. The cost of a malfunction that stops production for any length of time is prohibitive.

The need to reduce pollution and to conserve energy has led to increased recycling and exchange of heat between process streams. Plants are becoming more tightly integrated so that changes in one part of the process have an effect in many other places. The control system must account for the resulting interaction.

Processes are being developed that involve more complex sequences of chemical operations requiring precise conditions of temperature and pressure. The increased use of catalytic processes requires controls to maintain conditions that will preclude catalyst degradation and poisoning.

The production of more sophisticated and valuable products requires closer control of product specifications. To manufacture Polaroid's new color film, nine layers of chemicals no more than a few 10,000ths of an inch thick are deposited on the film as it passes through a large coating machine. As the layers are applied, the sheet of film must be alternately dried, heated, and cooled under extremely precise computer control of temperature and humidity.

All these trends in major industrial processes lead to requirements of more sophisticated control. Social and political considerations affect the way industrial plants are designed and operated. Important long-term forces are the needs for protection of the environment, conservation of energy and resources, safety, and good working conditions.

Because of the need to reduce emissions, it is now economical (in fact essential) to control the contents of waste streams. In the past, plant effluents have been the only streams not placed on automatic control.

The energy crisis has caused many companies to reevaluate their processes. New ground rules for designing plants favor tighter energy integration and the corresponding need for more sophisticated control.

Concern for safety works both for and against automation. Arguments are raised that it is not safe to run a plant without operators present and that an unattended plant would never get past a safety review board of the Office of Safety and Health Administration. However, sophisticated, properly designed systems can get people out of noisy, dirty environments, and this favors automation.

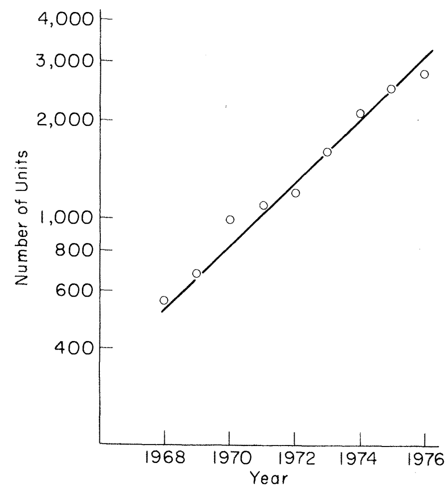


Fig. 5. Total number (cumulative) of computer control applications in the petroleum and petrochemical industry (*14*).

In some parts of the country, there are simply not enough skilled people available to serve as operators. People are less willing to devote their lives to the same employer and geographic region. Thus, industry can no longer depend on having an operator with years of experience available to assume responsibility. This encourages the use of more automated processes that are easier to operate.

Advanced automation affects job enrichment in two ways. On the one hand, it eliminates some drudgery, but, on the other, operators tend to get bored with computer systems. A highly automated system must be carefully designed if it is to enrich the job.

Industrial policies on the proper role of the operator in running plants vary, and there is corresponding variation in practice. There are two extreme approaches: (i) to automate the process as much as possible and use a relatively unskilled operator who could do little more than shut the plant down in case of an emergency; and (ii) to use a better trained, perhaps college educated, operator who would also serve as a manager. The ultimate direction industry will take is not clear at this time.

On balance, the social and political forces for environmental protection, energy conservation, safety, and better working conditions favor greater automation.

Rate of Acceptance

In recent years there have been some striking successes in the application of advanced digital communication and control systems in industrial plants. Computers have become commonplace in refineries, steel mills, chemical plants, and most process industries. They are no longer considered revolutionary or glamorous but have become an accepted part of the process control.

Each year the *Oil and Gas Journal* (*14*) publishes a list of the computer control

Table 2. Major advances in industrial process control.

Era	Measurement	Control	Communication and display
1900 to 1915	Indicating thermometers and pressure gauges	Manual control; off-on controllers; pneumatic valve actuators	Local indicators
1915 to 1930	Orifice plate used for flow measurement	Pneumatic proportional controller; reset mode added	Field-mounted recorders
1930 to 1945	Laboratory analysis of product quality; recording viscometer	Adjustable controller gain; derivative action added	Pneumatic transmission; centralized control rooms beginning to be used
1945 to 1960	On-line analytical measurements; *p*H measurement; gas analyzers	Electronic controllers; first computer control system installed	Miniaturized instruments; graphic panels introduced; electronic transmission used
1960 to present	Specialized sensors; on-line chromatograph	Feedforward control; direct digital control; supervisory control	Cathode-ray tube console for display; computer hierarchies

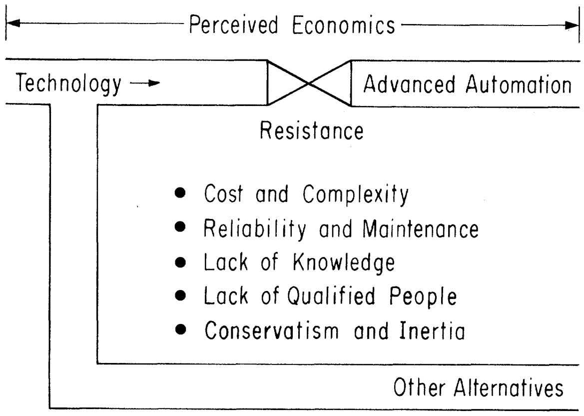


Fig. 6. Model of factors influencing acceptance of advanced automation.

systems in operation, being installed, or contracted to be installed worldwide in refineries, petrochemical plants, pipelines, and producing plants. There has been a steady increase with a growth rate of about 25 percent per year (Fig. 5). These figures include only a portion of the process industries, and many computer control projects are kept secret for proprietary reasons. But they indicate a trend. A recent estimate (*15*) states that today there are well over 200,000 digital computers worldwide in on-line industrial control applications (not just in the process industries) with the number increasing by 67 percent annually.

Despite the successes and the large number of process control computers that have been installed, there is still a great untapped potential for introduction of advanced computer-based automation systems into the industrial plant. Most observers in the industry agree that the acceptance of advanced technology is far less than the state of the art would permit.

In the late 1950's and early 1960's there was a burst of enthusiasm and a feeling that process control was about to enter a new era. Vannah and Slater (*16*) observed that "process control today is at the start of a new era—an era of analysis, introspection, and basic improvement." Yoxall (*17*) remarked that "We stand upon the threshold of a new decade and there is a general feeling that we shall see during these next ten years, significant developments in the specialized field of instrumentation." It was visualized that there would be computers connected to processes, that these processes would be optimized, that there would be improved techniques for measurement.

The new technology has not been accepted at anything approaching the rate forecast. McMillan (*18*) in 1966, writing a review of on-line computer control in the process industry, noted that "It is clear that the explosion never came and probably never will. Real progress has been made, but, as always, it continues to be hard-won."

While the practitioners in the field were lamenting the lack of use of advanced computer hardware, the control theorists were also complaining that modern control theory was not being used to its potential. A number of papers sought to explain the gap between theory and practice [for example (*19, 20*)].

Blocks to Acceptance of New Technology

A major stumbling block to the application of advanced control systems has been our lack of understanding of the processes to be controlled. To apply single-loop controllers, one needed to know only the direction of a change. (If the fuel supply to the boiler is increased, the steam pressure rises.) The application of advanced control, however, requires refined process knowledge and mathematical models.

Another block has been a shortage of trained people who both understand the industrial processes and also have knowledge of and sophistication in computer control.

A third limitation is the inertia and conservatism in the industry. The heavy process industries with large capital investments are hesitant to take technical risks because the penalty for failure is so large. Some companies had bad experiences with systems installed in the early days of computer control that failed to deliver as promised; it may take a generation to overcome this resistance.

Part of the resistance to advanced control systems is technological. It is economically difficult to provide systems that are reliable and maintainable. It may well be technically feasible to achieve the required degree of reliability, but for some applications such systems are so expensive they are no longer practical.

The lack of standardization in control systems and plant designs poses yet another problem. Because each control system is custom designed, it is difficult to automate design. Great engineering talent, for instance, is often wasted making routine decisions on matters such as the size of valves. If some of these routine decisions could be automated, the productivity of a systems engineering team could be increased substantially.

The lack of key sensors can prevent the installation of advanced contol systems. We need better, more reliable, fundamental measurements of the composition and condition of material being processed. We need direct measurements of the quality of final products. For every achievement of an unattended industrial plant, suitable solutions have been available to the problem of directly measuring the quality of the final product.

Another factor that slows acceptance of advanced control systems is the availability of other ways for plants to solve their problems. The company that makes a product is concerned primarily with making enough material that meets the specifications and satisfying its customers; it often has a number of options for solving these problems, only one of which is more automation.

The factors that influence acceptance of advanced automation can be explained by means of a model based on an analogy to the flow of a fluid through two branches in a flow network (Fig. 6). The model mimics the application of resources to solve process problems. These resources may flow along the path toward advanced automation, or they may flow toward other alternatives.

The driving force is the economic perceptions of the industry. The resistance to the application of advanced automation involves such perceived risk factors as the cost and complexity of control, the lack of systems that are reliable and maintainable, the lack of understanding of the process to be controlled, the lack of qualified, experienced technical people, and the conservatism and inertia of the industry. The other alternatives toward which resources may be directed include adopting a different process, using a new raw material, changing the business plan, finding an alternative market for a product, and negotiating a revised labor contract.

Conclusions and Future Directions

The major driving force for acceptance of advanced automation will continue to be the perception of economic benefits by the users. As the cost of control hardware decreases, the economic forces increase. The resistance is steadily being reduced by new technology and by education. Therefore, we can expect a continued evolutionary introduction of advanced control in industry but no revolutionary change.

Research and development should focus on reduction of the resistance. Work should be aimed at systems that have increased reliability and maintainability, reduced cost and complexity, require less expertise to implement, are explainable to users with limited sophistication and knowledge, and can be implemented in an evolutionary fashion. There is need for education of potential users and for increased standardization whenever possible.

These are exciting times for workers in the field of industrial process control. There are great opportunities for improved operation of industrial plants by means of advanced automation. The revolutionary developments in electronics now becoming commercially established are apt to greatly accelerate the evolutionary change in process control in the next 5 to 10 years.

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Electronics and National Defense: A Case Study

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As large-scale integrated circuits become available to take electronics into the homes and the daily lives of a larger public, we may see a diminution in the role that national defense will play in shaping the future growth of this technology. Up to now, however, that role has been crucial; of all the major ingredients of "the continuing revolution in electronics," only the transistor originated without the stimulus of military requirements and the support of military funding (*1*). At the same time, electronic innovation has bolstered our defenses, stimulated new concepts of military tactics and operations, and, when indulged in by others, presented major challenges to our strategic position among the nations of the world.

It is not possible to examine all these complex interactions in a short article, and we have accordingly chosen to concentrate on a particular case—the problem of aircraft surveillance and warning. We have picked this example because it is one that is most familiar to us, and also because it typifies that aspect of defense, command, and control, which is the special province of electronic technology.

Although the scientific principles that underlie modern electronics were reasonably well understood in the 1930's, it was the urgent and uniquely military requirement for early warning of possible air attack that led to the development of radar and with it the large body of associated technology that became generally available in 1947 through publication of the 28-volume Radiation Laboratory Series. The Radiation Laboratory had been established at the Massachusetts Institute of Technology in 1940 to investigate the exploitation of microwave frequencies for radar. This was considered to be a highly speculative venture at the time, but it proved to be remarkably successful in extending the usable frequency spectrum by some three orders of magnitude. Power sources were developed that could deliver several megawatts of peak power at 3000 megahertz, and kilowatts up to 24,000 megahertz. The short pulses required for good radar range resolution necessitated the design of equipment and components with megahertz bandwidths rather than the few kilohertz required for voice radio circuits. Other system needs stimulated developments that ranged from the theory and design of servomechanisms to techniques for precision engineering of large structures. Included were the pulse techniques and the cathode-ray tube and delay line storage devices that supported early electronic computer development, as well as the circuitry and components that made possible the immediate, explosive growth of television after World War II.

Only 3 years after the dissolution of the Radiation Laboratory, the problem that had stimulated the development of radar returned in a new form to force-feed the evolution of the digital computer and the digital technology that would complement the microwave technology developed during World War II. In August 1948, years earlier than expected, the Soviet Union exploded an atomic device, and, for the first time in history, the United States was forced to consider the possibility of a devastating air attack. Not only was there virtually no active air defense in being, but it was clear that early warning and raid tracking at the level of capability developed in World War II was not sufficient to meet a threat

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