occur at the personal level, in the way we do things using these systems. Certainly we will gain new power—radically increased speed and flexibility in manipulating the substance of our working lives. But, more important, we will have found a new medium for interacting with others. Because of this, these systems will have the power to draw us closer together and change the ways we work and live.

References and Notes

1. P. Strassmann, *Technol. Rev.* **82** (No. 3), 54 (1980).
2. For some of the early signs of this activity, see W. Newman and R. Sproull [*Proc. IEEE* **62**, 4 (1974)] and Metcalfe and Boggs (*3*).
3. R. Metcalfe and D. Boggs, *Commun. ACM* **19**, 7 (1976).
4. See, for example, *Proc. IEEE* **60**, 11 (1972).
5. M. Marshall and L. Waller, *Electronics* **53**, 17 (1980).
6. A. Hoagland, *Computer* **12**, 5 (1979).
7. M. Hammer and M. Sirbu, *What is Office Automation?* (MIT Press, Cambridge, Mass., 1980).
8. M. Zloof, *Computer* **14**, 13 (1981).
9. This tutorial example is closely modeled on the experimental office system created over the last few years at the Xerox Palo Alto Research Center. Other self-consistent configurations exist.
10. C. Ellis and G. Nutt, *Comput. Surv.* **12**, 1 (1980).
11. C. Gaffney, "Selling office automation internally," *AFIPS Office Automation Conf. Digest* (American Federation of Information Processors Societies, Arlington, Va., March 1981), pp. 127–131.

12. I am indebted to my friends at Xerox's Palo Alto Research Center and Systems Development Department. They created much of what I have described here. Their vision, imagination, skill, and hard work made a reality of their early dreams. It has been a pleasure to have learned so much from them.

Advances in Process Control

David L. Morrison, Richard H. Snow, John P. Lamoureux

The important functions for computer process control are measurement, control, actuation, signal processing, and communication. Control and communication are accomplished by electronics, measurement and actuation by special sensors and actuators.

Summary. Advances in electronics and computers have enabled industries to attain better control of their processes with resulting increases in quality, productivity, profitability, and compliance with government regulations. With a hierarchy of computers, distributed data acquisition, and information processing and control, it is possible to achieve overall optimum performance of a plant. While further advances in microprocessors and large-scale integration will be useful to the process engineer, major improvements in process control await advances in sensor technology and software.

Computer control of processes has developed in an unbalanced way because electronics has been extensively developed through government funding. Therefore sophisticated microcomputers and other electronic hardware are comparatively cheap. Sensors and actuators, however, are in a lower state of development. There is a need for industries to devote further effort to developing sensors and actuators that they require. In the meantime, it is prudent to use microcomputers to extract the maximum amount of information from existing sensors and to provide sophisticated control over relatively crude actuators. This means that microcomputers are located in the plant near the sensors. It is also desirable to use electronics to condition signals so that information about process performance can be passed from the microcomputers to a central supervisory computer, where the process goals are set and optimized and where performance can be displayed to operators through graphs on television monitors. A review of recent trends in the paper, petrochemical, and steel industries shows that although many processes are controlled by simpler methods, the distributed method is gaining favor for complex processes.

Since Evans's review of process control in 1977 (*1*), the trend has continued toward more extensive use of microcomputers and large-scale integrated (LSI) electronics. The increased efficiency of process control through electronic advances makes it possible to improve productivity, reduce wastes, improve material utilization, and reduce energy consumption (*2*). Process controllers also maintain safe operating conditions within the plant and ensure compliance with government environmental and occupational health requirements.

Improvements have also been made in software. In addition to improved algorithms or rules for solving complex problems, software has evolved with the user in mind. Controllers now are available that can be programmed in terms of logic functions familiar to process and control engineers, rather than the computer languages that have been the domain of computer/programmer specialists. But the more complex computer systems still require these languages.

Although this article focuses on the process industries, many of the electronic and computer technologies are similar to those described in this issue by Hudson (*3*) for manufacturing industries. For convenience, we follow the simple means Evans (*1*) used to distinguish process industries from manufacturing industries. Manufacturing industries manipulate the geometries of their raw materials so that discrete parts are formed and assembled to produce an integrated, more complex, useful product. In process industries, the composition of materials generally is manipulated by chemical reaction and blending of components to convert raw materials and energy into more valuable products. Process industries also include those involving physical changes such as drying, distillation, and forming through casting and rolling. Chemicals, petroleum, metals, pulp and paper, food, cement, textiles, synthetic fuels, and power production are included among the process industries.

Microprocessors and Distributed Processing

The entire approach to computer control of the industrial system changed with the introduction in 1970 of the first microprocessor, the Intel 4004 (*4*). The subsequent development of LSI electronics leading to low-cost, reliable mi-

David L. Morrison is president, Richard H. Snow is manager of chemical engineering research, and John P. Lamoureux is associate engineer at IIT Research Institute, Chicago, Illinois 60616.

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croprocessors, has had far-reaching effects on process control. It is now practical to control many processes in a manner that was not previously economical and to distribute many controllers near individual process streams (*5*).

The control of an automobile engine is a familiar example of control of a small process. Unlike chemical plants, the engine is mass-produced; nevertheless, it illustrates some important features. A microcomputer-based control computer can be produced for $50, making possible control of combustion in a vehicle costing only thousands of dollars. General-purpose microcomputers are mass-produced too and costs are low when they can be applied, whereas custom designs for special applications are costly.

Current automotive controllers sense several variables and continually optimize the timing of the ignition as operating conditions vary. The main advantages are greater efficiency with lower emissions and reduced maintenance compared with earlier, less sophisticated ignition control systems. Unfortunately, the sensors cost as much as the computer itself. In fact, the computer could further optimize features such as pollutant emission if reliable sensors were available at sufficiently low cost to make it practical to incorporate them into the system. Availability of sensors also limits process control in chemical plants.

Today, the control of a complex industrial plant may be based on the concepts of decentralization, distributed data acquisition, and distributed information processing. This means that local microcomputers acquire data from a sensor, condition the data by amplifying, sampling, and perhaps digitizing them, and transmit them to a central control computer. The local computer may perform control functions as well. The implementation of these concepts calls for a hierarchy of computers, each performing tasks appropriate to its position in the hierarchy. All of the goals and functions from business management to process control are achievable through distributed processing and computer linking (Fig. 1).

There has been an evolution from the totally distributed individual loop instruments and controllers of the 1950's, through the totally centralized computer systems of the 1960's and 1970's, to today's increasingly distributed modular computing units. For example, in the past a central control computer adjusted the set point of a pneumatic analog controller, which in turn controlled the valve. Thousands of tubes and wires transmitted analog pneumatic and electrical signals to the central point, with the hazards of signal degradation or interference. In some plants digital signals are now used to communicate with programmable digital controllers, which are located in the plant near the stream they are to control (*5*).

The advantages of distributed digital techniques are (i) lower controller cost, (ii) greater flexibility and sophistication of control modes, (iii) lower wiring cost, (iv) reduced interference in transmitted signals, (v) lower maintenance cost, (vi) easier interfacing of digital controllers with the central digital computer, (vii) simpler programming since the central computer is relieved of the task of servicing interrupts from the controlled points, and (viii) a more fail-safe system since each individual controller can be programmed to maintain the same set point if the central computer goes down. Also, the central computer can monitor the distributed computers for malfunction, which solves the reliability problem of direct digital control by a central computer.

Of course, a distributed digital system would be at a disadvantage in controlling a simple process. A system without feedback or interactions could more simply be controlled by conventional pneumatic or digital controllers, and if the process has few control points a single control computer suffices.

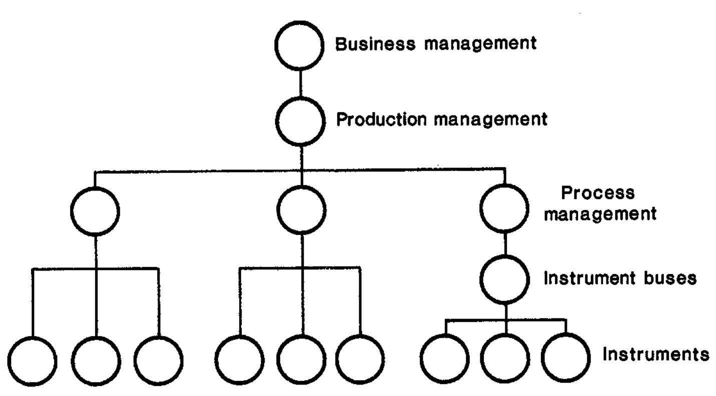
Process Control Functions

The important functions for computer process control are measurement, control, actuation or manipulation, signal processing, and communication. Measurement refers to the sensing of variables such as flow rate, temperature, pressure, level, and chemical composition and transmission of this information to the controller. Control is the decision-making operation. It involves comparing the measured state of the process with the desired state and establishing how the variables are to be manipulated. Actuation is the means by which the operating variables are manipulated: typical actuators are valves, heaters, motors, solenoids, and hydraulic and pneumatic cylinders. Communication includes the presentation of information to the plant operators as well as the transmission of important variables to the plant management. These functions are discussed more fully under the succeeding headings.

Measurement and Control

Most process variables are analog, not digital, yet microprocessors themselves are digital devices (Fig. 2) (*6*). Thus the trend toward employing microprocessors for the measurement and control of analog phenomena gives rise to increased emphasis on the hardware building blocks needed to interface the real world with the microprocessor world. Considerable development effort is being devoted to transducers, sensors, data acquisition products such as analog-to-digital and digital-to-analog converters, isolation and instrumentation amplifiers, analog multiplexers, arithmetic calculation, communication, computer interfaces, and diagnostic and PID (proportional integral derivative) control at a local level (*7–9*).

The traditional approach in the pro-



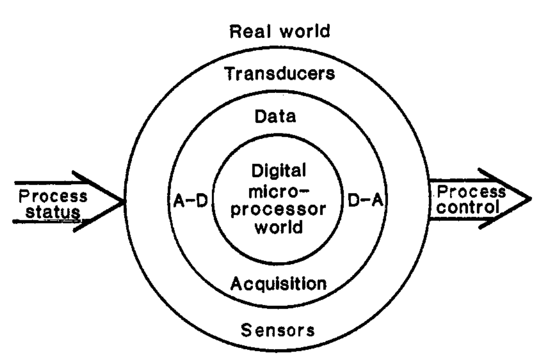


Fig. 1 (left). Elements of a millwide management information system for a pulp and paper mill (*37*). Fig. 2 (right). Structure of process control with a microcomputer (*6*).

cess industry has been to use transducers with a current loop output of 4 to 20 milliamperes (*10*). This analog output current generally is a linear function of the variable being measured. Large-scale integrated circuits have made possible single-chip amplifiers, analog-to-digital converters, and digital data transmitters. Hence a single transducer, with the addition of a few chips, can transmit data digitally. Some of the advantages of this method of data transmission are excellent noise immunity, high accuracy, possibility of error checking (such as parity), and elimination of common mode voltage errors with the use of optical isolators. Furthermore, several transducers can share the same pair of wires, which significantly reduces cabling costs.

Data acquisition and process control are available at the local level in several ways. Dedicated controllers can use a microprocessor and supporting hardware to provide PID control of a single process variable. Single-board measurement and control systems can take several analog and digital inputs and control several process loops simultaneously. A trend toward integration of microcomputers and data acquisition hardware in hybrid or monolithic technology has led to the development of signal processors, such as a complete scanning spectrum analyzer, on a single chip (*11–15*). In the near future such signal processors will probably replace much of what is now realized with analog circuitry.

Controller algorithms can now be assembled to implement specific control policies or strategies. The basic control system configuration is a closed loop in which the controller output is some function of both its input command or set point and information fed back from the process. The function employed depends on the task to be performed and the degree of sophistication that is practical. It can range from simple subtraction or comparison with one fed-back variable to complex combinations of operations (division or ratio, feedforward, linear and nonlinear relations) and time-dependent operations (delay, history, integration, differentiation) with many fed-back variables. When the behavior of a process is adequately predictable, open-loop control (that is, with no information fed back) can be used for simplicity and faster response—especially in processes involving long time delays.

Cascade control occurs when one controller adjusts the set point of a second controller (*16*). For example, assume that a fuel source for a simple fuel heater in a furnace is excess gas produced by the process itself. This is commonly collected in a main supply heater and fed into the fuel heater in the furnace. Being subject to process fluctuations, the fuel gas supply pressure may be quite variable. When the temperature controller adjusts the fuel valve for a new fuel flow, it assumes that there is a constant fuel pressure. If, after the valve has been opened for more fuel, the supply pressure drops, less rather than more fuel will actually flow. Hence the temperature controller needs to be able to call for a flow change and not just a valve position change. This can be achieved by adding a flow control loop to the fuel supply system and having the output of the temperature controller serve as the set point of the new loop.

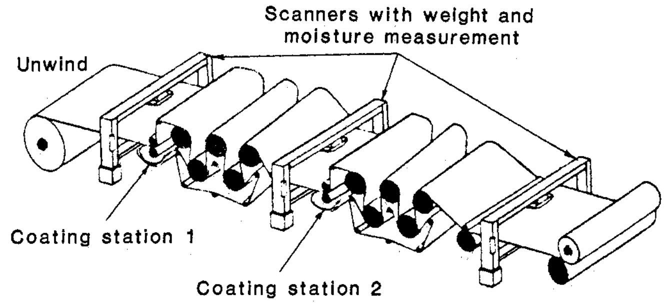


Fig. 3. Schematic illustrating the location of scanners utilized in paper coat weight determination (*24*).

Actuation

In process industries, control valve actuation has generally been accomplished by an actuator and positioner, which feed a pneumatic signal to a diaphragm acting against a spring force. The movement of the diaphragm, in turn, moves a plug in an orifice, which controls the rate of flow through the valve. While this analog method will probably remain the most popular one for many years, digital electronics have begun to present viable alternatives.

A digital control element (DCE), which is part of a process control system, has a signal conditioner, a microprocessor, and a digital positioner all contained in a single enclosure mounted on the valve. The controller can communicate with the valve directly through a serial interface on the DCE, and several valves can be connected to the same pair of signal wires (*17*).

In contrast to analog valves, pure digital valves have several ports of different sizes, each of which is independently fully opened or closed in accordance with an incoming digital signal. The opening and closing of different combinations of ports changes the flow factor of the valve. A valve with six ports can have $2^6 - 1$, or 63, discrete values for the flow factor. The high cost and parts count of such digital valves have slowed their development and usage. However, the advent of low-cost microprocessors may make pure digital valves more practical and increase their popularity in the future, especially in applications in which they perform better than analog valves.

Communication

Process industries recognized early the value of graphic display terminals. The power of these terminals is rapidly increasing as low-cost electronics allow more and more computing power to be packed into a single terminal. It is now quite common for a single terminal to contain one or more microprocessors. The so-called intelligent terminals can even control process variables, machines, other terminals, and floppy disk drives (devices used to record programs or data on a thin, flexible magnetic disk).

From the operator's standpoint, a cathode-ray tube is a "window" to the process. With it, he can inspect process variables such as temperatures, pressures, flows, levels, and compositions. He has the ability to call up process flow diagrams and study the overall process or to focus on one or more individual control loops.

Signal Processing

The LSI electronics that resulted in the microprocessor has also reduced the size and cost of other important components. One of these is the instrumentation amplifier. This is a device, typically employing several operational amplifiers, that can amplify a low-level signal from a sensor such as a thermocouple or strain gauge to a level for analog-to-digital conversion or transmission to the computer, or both. Operational amplifiers are also important for sending and receiving signals by light along glass fibers. Vacuum tube instrumentation amplifiers typically cost \$500; current single-chip and hybrid integrated circuit

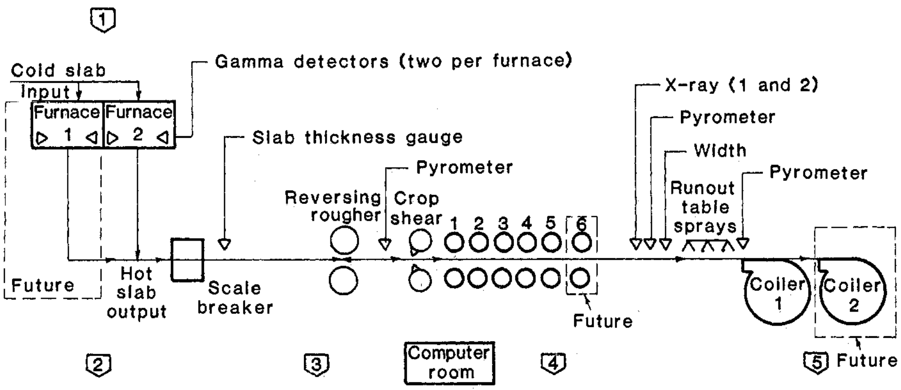


Fig. 4. Layout of Carlam hot strip mill (*32*). Numbers correspond to: 1, furnace charging pulpit; 2, furnace discharging pulpit; 3, roughing mill pulpit; 4, finishing mill pulpit; and 5, downcoiler pulpit.

models cost only a fraction as much, perform better, and are available over a wider range of performance characteristics. Glass optical fibers, which are corrosion-free, heat-resistant, inherently safe, immune to electrical interference, and electrically insulated, have enormous information-carrying capacity. For example, more than 10 million pieces of information per second can be transmitted a distance of 5 kilometers in the visible spectrum with losses of less than 3 decibels per kilometer (*18*). Glass fibers are expected to replace wires for some data transmission within plants and will eliminate major problems of signal interference.

An important application of operational amplifiers is reading of thermocouple signals. Because thermocouple signals often amount to only a few millivolts, sophisticated circuitry is needed to handle them accurately without introducing undue noise. Availability of economic, high-quality instrumentation amplifiers has filled this need. This is a boon for process control, since temperature is usually the most important variable.

Sensors and Actuators

While electronics has been making giant strides, sensors and actuators have been progressing at a more modest pace. The increased sophistication of control computers has led to a realization that progress is needed in developing practical sensors for more process variables.

As an example, consider the difficulties in measuring the performance of a process for extracting copper from its ores (*19*). The copper industry pioneered the application of x-ray fluorescence analysis to measure the copper content of ore processing streams. Although the measurement involves no moving parts, it requires complex instrumentation and is costly. Calibration varies depending on the background composition, so the results are accurate to only 5 to 10 percent. Nevertheless, this sensor has permitted computer control and increased efficiency in copper ore beneficiating plants. These plants also require measurement of the particle size distribution, since fineness of grinding of the ore is the main determinant of efficiency of separating copper from gangue (valueless mineral). Approaches to developing an on-line particle size sensor were reviewed by Davies (*20*). The most practical device seems to be one that sends two sonic signals across the ore slurry in a pipe. By comparing the sound absorption at two frequencies, an average particle size is determined. Clearly, this is a relatively complex sensor too.

Other complex sensors being used in chemical plants include control versions of laboratory instruments such as the gas chromatograph (*21*). Even such a familiar sensor as the *p*H electrode can meet with difficulties when one tries to apply it to process control continuously. These electrodes work well in clean environments, but are permanently damaged in a few hours when exposed to processing streams containing minute droplets of grease. Thus there is still a need for improvement in many types of process sensors.

Although sensors have not developed as rapidly as electronics, advances in electronics have indirectly helped by making certain simple sensors practical. As previously mentioned, improved electronics make the amplification of thermocouple signals accurate and relatively inexpensive. For example, a minicomputer costing $15,000 can now be set up to monitor 100 thermocouples per minute. This is of great importance, since thermocouples are themselves inexpensive and easy to use and temperature is important in all parts of a process.

One reason for the lag in sensor development is that process-type sensors have not received as much R & D funding as electronics. Instrument manufacturers cannot justify major development costs for sensors when they could sell only a few to specialized industries. Improved sensors are of more economic significance to the industries that use them than to those that supply them: the users gain improved productivity from their processes, while the suppliers gain only the profit on the purchase. Therefore, process sensor development will continue to progress slowly unless the user industries support their own basic sensor development, as did the copper industry.

In the following sections we describe several applications of advanced process control in three industries to illustrate the current state of development.

Pulp and Paper

Extensive use of electronics and computers is made by the pulp and paper industries. Applications range from millwide production management to individual process controllers. A self-tuning control loop to reduce reel moisture variations has recently been introduced on a papermaking machine (*22*). In this system a moisture measurement is obtained from a traversing sensor, which scans across the width of the paper once each 30 seconds. The self-tuning regulator consists of a feedback controller in parallel with on-line parameter estimations based on input-output data pairs. The control algorithm adjusts controller parameters to maintain optimum performance levels. Reel moisture variations are reduced by a factor of 2 compared to those observed with a fixed-structure controller in relatively short production runs with a wide range of paper grades.

A microcomputer control system has also been used to automate a process for making paper pulp from wood chips (*23*). Control is provided through calculation of the specific energy of refining, throughput, and chip consistency and measurement of the hydraulic pressure, chip feeder speed, and dilution water flow. Hierarchical control loops act to control the specific energy of the process and the chip/water ratio, by controlling the hydraulic pressure, chip feeder speed, and dilution water flow. Plate clashing (mechanical contact of the plates that grind the chips) is sensed with a detector and is eliminated by controlling the hydraulic pressure that forces the plates together. With this control system the standard deviation of the motor load was reduced by 45 percent, the chip feed regulation was improved by 25 percent, and the calculated specific energy variations were reduced by 50 percent.

Coat weight control (*24*) requires the measurement or calculation of the weight of paper coating after drying even though the coating is applied wet to a sheet of paper. This can be achieved by measuring weight and moisture before and after the coating stations. Process control systems for paper coatings based on distributed processing with microcomputers, as shown in Fig. 3, are being used extensively to improve coat-weight quality and production and to conserve materials. The flexibility provided by the distributed computer network makes it possible to achieve these goals even though a wide variety of product grades must be produced.

In the operation of a batch paper pulp digester, steam constitutes about 15 percent of the total raw material cost. A computer-based control system not only reduces the expenditure of energy but also improves both productivity and pulp quality. It ensures the most economical use of available resources because every part of the mill can run at a more nearly constant rate with fewer disruptive swings (*25*). A three-level control system is appropriate for a batch digester. Process-level controls operate directly to establish the basic function of charge, cook, and blow for each digester in a prescribed manner. Higher level controls prescribe the manner in which these process-level controls perform. An optimizing control establishes the type of performance required of these higher level controls, which depends on the objectives for the mill.

In a typical application (*26*) steam usage has been reduced by approximately 16 percent, and the variance of the permanganate number and the kappa standard deviation (measures of the chemical changes caused by the cooking) have been reduced by 35 percent. The labor expense is substantially less than that for a manual control system.

Microcomputer systems are being used successfully on fine paper, tissue, and board machines (*27, 28*). In these systems, moisture, basis weight (grams of dry fiber per square centimeter of web), and caliper (thickness) are measured and fed back to the microcomputer controllers to effect the needed process corrections. These microcomputer systems can achieve up to an 85 percent reduction in basis weight variations, which results in reduced energy use and increased process speeds.

Iron and Steel

A system of linear-array cameras is being used to provide on-line measurements of the length, height, and width of a steel bloom (a bar of steel with a cross section of approximately 15 by 15 inches and a length of approximately 30 feet) in a rolling mill (*29*). In this application, each linear-array camera contains an integrated set of 1024 infrared-sensitive detectors formed along a straight line on centers of 0.001 inch and a lens system that images an object plan on the array. The camera thus has a very narrow but long field of view. As red-hot steel moves across this field of view, one dimension of the steel is established by the number of detectors "seeing" the hot (infrared-emitting) metal. By using these measurements, shearing can be optimized and the volume of the steel bar controlled despite varying cross sections.

For dynamic control of a basic oxygen furnace (*30*), the initial operating conditions for each heat, which are based on specifications for the finished product, are fed into a computer, and the type and quantity of raw material and amount of oxygen necessary for producing the heat are calculated. About 3 minutes before completion of the heat, a probe is lowered into the bath by the computer to take a sample of the molten metal. A sensor in the probe simultaneously measures the temperature and the carbon content of the melt. From these data the computer determines whether the desired end point can be achieved or whether additional coolant or oxygen is required. Feedback of this information permits process control actions to be taken to ensure that the final temperature and chemical composition are within specifications. With the introduction of dynamic control, the productivity, yield, and lining life of the basic oxygen furnace have been increased.

A multivariate analysis of production factors indicated that the fuel content of blast furnace gas was one of the major sources of fuel costs in a soaking pit where hot metal ingots are held at a fixed temperature until they are needed for rolling into sheets or other forms (*31*). The richness of the blast furnace gas varies from hour to hour, so its fuel content must be enriched with natural gas in the soaking pits. A system is being used that determines the fuel content of the gas from the blast furnace with a calorimeter. A microprocessor compares the value for the incoming gas to the desired value and controls (open loop or feedforward) the injection of natural gas to achieve the latter. A downstream sampling station furnishes final fuel content values to the microprocessor to verify the results of the enrichment. This system permits cost control in spite of variable operating conditions.

A computer-based system provides automatic control throughout the hot-rolling mill represented schematically in Fig. 4 (*32*). The products rolled range from extrasoft and soft carbon steels to austenitic and ferritic steels with finished gauges in widths up to 2400 millimeters. The computer system controls the following functions in the mill: slab data input; furnace charging, mapping, and discharging; product tracking; roughing-mill setup and sequencing; finishing-mill setup with adaptive learning; automatic gauge control; calibration; position regulation; runout-table spray control, which provides coiling temperature control; mill pacing; software director; and data logging.

Construction of a continuous annealing line has begun in a facility for the production of high-strength and ultra-high-strength sheet steels (*33*). Computer-controlled continuous heat-treating and quenching will produce formable cold-rolled sheet products for the automotive market and special sheet products for a variety of other applications.

Petroleum and Chemicals

In the petroleum and chemical industries, computers and electronics are used in distributed and hierarchical computer systems, field multiplexing, and process controllers. Substantial energy savings were achieved at a petrochemical plant after the introduction of a new process control system including an integrated combination of chromatographic analysis, data feedback, and a process control computer that monitors, performs calculations, and transmits signals to control devices (*21*). Fifteen process analyzers, using gas chromatographs, analyze overhead and bottom products in each of eight columns. A second computer feeds analytical data from the chromatographs back to the first computer. The annual energy savings for processes in a typical oil refinery are 86 percent for a BTX (benzene-toluene-xylene) reformer feed splitter, 54 percent for a depentanizer, 28 percent for a benzene column, 23 percent for an orthoxylene column, 17 percent for a toluene column, and 15 percent for a sulfolane feed splitter.

In fuel process development, a multitiered distributed approach is used, with microcomputers, minicomputers, and mainframe computers employed at various levels of the plant to perform functions ranging from process control and data acquisition to data management and interactive scientific computation (*34*). At each level, the computer performs its own function, reports to and receives instructions from the level above it, and receives data from and sends instructions to the level below it. Microcomputers operate at the local level to control process loops and extract and display data. Several microcomputers report to a single minicomputer, which is responsible for decision-making for that segment of the plant. The minicomputer may also be responsible for tracking, analyzing, and reporting results for analytical samples. The number of tiers will depend on the number of tasks to be performed and how the work load is to be distributed. At the highest level, a large computer receives data from the minicomputers and performs scientific and business computing functions. This multitiered approach minimizes the effects of shutdown of any single component, provides stand-alone capabilities for alarm checking, and provides a clear path for modular system expansion.

Modern refining control systems (*35, 36*) tend to replace the traditional control panel and analog displays by operator consoles with cathode-ray tubes. Process units now have standard control packages, including start-up and shutdown procedures.

References

1. L. B. Evans, *Science* **195**, 1146 (1977).
2. R. J. Fowles, paper presented at the Paper Industry Management Association Meeting, Washington, D.C., June 1980.
3. C. Hudson, *Science* **215**, 818 (1982).
4. S. Kahne, I. Lefkowitz, C. Rose, *Sci. Am.* **240**, 78 (June 1979).
5. E. J. Kompass, *Control Eng.* **28**, 4 (August 1981).
6. H. M. J. M. Dortmans, *J. Phys. E* **14**, 777 (July 1981).
7. R. Allan, *Electronics* **53**, 101 (July 1980).
8. S. Ohr, *Electron. Des.* **28**, 59 (September 1980).
9. N. Andreiev, *Control Eng.* **28**, 50 (February 1981).
10. P. Bradshaw, *ibid.* **27**, 57 (February 1980).
11. G. P. Edwards, *Electron. Des.* **28**, 137 (February 1980).
12. M. E. Hoff and M. Townsend, *Elektronik* **28**, 37 (July 1979).
13. L. Lowe, *Electronics* **5**, 171 (May 1980).
14. J. G. Posa, *ibid.* **4**, 100 (April 1980).
15. R. E. Holm and J. S. Rittenhouse, "Implementation of a scanning spectrum analyzer using the 2920 signal processor," *Intel Appl. Note AP-92* (1980).
16. H. M. Morris, *Control Eng.* **28**, 65 (March 1981).
17. S. J. Bailey, *ibid.* **27**, 64 (January 1980).
18. This is a measurement of signal power loss. A value of 3 dB/km indicates a 50 percent loss in the power of the signal in traveling.
19. J. Bolles, A. J. Broderich, H. R. Wampler, Jr., paper presented at the 1977 AIME Annual Meeting, Atlanta, Ga., March 1977; Society of Manufacturing Engineers preprint 77-B-47 (1977).
20. R. Davies, *Am. Lab.* **6**, 73 (December 1973); *ibid.* (January 1974), p. 78; *ibid.* (February 1979), p. 82.
21. *Chem. Market. Rep.* (8 September 1980), p. 66.
22. J. C. Flynn, *Pap. Trade J.* **165**, 27 (July 1981).
23. J. H. Rogers, S. C. Vespa, C. Mills, D. J. Butler, N. D. Legault, *Pulp Pap. Mag. Can.* **81**, T277 (October 1980).
24. R. V. Byrd, *Pulp Pap.* **54**, 100 (May 1980).
25. R. P. Powell, *Tappi* **62**, 21 (December 1979).
26. R. S. MacWilliams and K. Robe, *Chem. Process.* **43**, 40 (April 1980).
27. R. L. Smallwood, *Pulp Pap.* **52**, 98 (February 1978).
28. ———, *ibid.* **54**, 101 (February 1980).
29. E. C. Frost, in *Proceedings of the 1979 Spring Annual Conference* (American Institute of Industrial Engineers, New York, 1979), p. 375.
30. *Iron Steel Eng.* **58**, 69 (June 1981).
31. C. H. Trapp, in *Proceedings of the 1981 Spring Annual Conference and World Productivity Congress* (American Institute of Industrial Engineers, New York, 1981), p. 507.
32. J. A. Jordan and J. Dejnecki, *Iron Steel Eng.* **58**, 33 (April 1981).
33. *Iron Steel Eng.* **58**, 32 (August 1981).
34. J. H. Taylor, J. A. Johnson, W. J. Barton, R. Wang, *Chem. Eng. Prog.* **77**, 41 (August 1981).
35. W. J. Baker, *Chem. Process.* **42**, 16 (mid-April 1979).
36. K. L. Hopkins, in *Proceedings of the 1977 Symposium on Instrumentation and Process Control for Fossil Demonstration Plants* (ANL-78-7, Argonne National Laboratory, Argonne, Ill., 1977), p. 287.
37. AccuRay Corporation, Paper 8, September 1980.

38. We acknowledge the support of many members of the IITRI staff, but in particular we express our appreciation to W. A. Davison, R. DeLaPena, and G. J. Yucuis for their assistance in the preparation of this article.

Computers in Manufacturing

C. A. Hudson

While the United States remains among the most productive nations in the world, other industrialized countries are quickly closing the gap. In Japan manufacturing productivity is currently growing at the rate of 4.1 percent a year. France and Germany have manufacturing productivity growth rates of 4.9 and 5.0 percent a year, respectively. Meanwhile, in the United States the rate of growth in manufacturing productivity has fallen sharply. From 1969 to 1973, output per man-hour increased at a compound rate of 2.9 percent. From 1973 to 1979, the gains dwindled to 1.6 percent a year (*1*).

In the United States the program to significantly reverse this productivity pattern must rely on the continued development of advanced technology and its application. Perhaps the most important element in this reliance on innovation is increased factory automation and a growing use of computers and microprocessor technology in manufacturing. Today, we are on the technological and sociological edge of a dramatic increase in the use of computers in our factories. This will have a profound impact on the nation's productivity growth in the next decade.

Within the next 10 to 15 years, four evolutionary trends will meet on the factory floor: (i) the increasing power and simplification of computers, (ii) a widespread appreciation of the practicality of computerized manufacturing and robotic applications, (iii) a new realization of the impact of computers on people and of people on computers, and (iv) a growing awareness of the urgent need for manufacturing innovation in our society.

Many computerized factory systems exist today as islands of automation. The immediate task of the scientific and technical communities is to use the increased power and simplicity of computers to link these elements into an integrated system. Making use of low-cost computer hardware to perform more and more jobs will make such an integrated factory system economically viable.

Some difficult technical problems remain. We must develop generally accepted, standardized interfaces between computerized design engineering and computerized manufacturing, between individual machines and machining centers, and between computers and the people using them. We must also refine the present state of application technology and reduce the cost of the factory automated system through the increased use of computers. Advances in factory automation are dependent on advances in computer technology.

The author is Manager of Technology, Industry Automation Division, Westinghouse Electric Corporation, Pittsburgh, Pennsylvania 15205.

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