AUTOMATION AND CONTROL EQUIPMENT

The term *automation* refers to an engineering philosophy that concerns the automatic nature of a collection of machines, or entire processes or systems having many components configured to achieve a goal. An automatic system can be characterized as being self-actuating, self-regulating, and self-reliant by carrying out preset commands combined with automatic feedback. Automation is widely practiced as a substitution for human effort and intelligence, thus finding applications in industrial and nonindustrial human endeavors. The application areas include communication, defense, transportation, education, recreation, health care, retail industry, banking, manufacturing, research and development, business and commerce, chemical, and other process industries. However, because of economic, social, environmental, and other restraints, systems may not be fully automated, but they can be semiautomated. Because automation and process control find a wide range of applications, many companies, as listed in Table 1, offer an extensive range of related equipment.

Automation involves numerous scientific and engineering disciplines, such as electronics, electrical, control, mechanical, chemical, metallurgical, and industrial engineering. There are four basic building blocks of automation: (1) a source or power to perform action, (2) feedback control and data from the process, (3) machine programming, and (4) decision making. All these require extensive knowledge of measurement and control technologies, computers, and information and communication sciences supported by extensive knowledge in mathematics and physics. Nowadays, these fundamental elements are enhanced to the extent that most modern automated systems can operate without human intervention.

Recently, progress made in control systems, the derivation of mathematical theories, information and communication systems, sensors and measurement systems, computers and digital systems, and man–machine interactions enhanced the automation systems and made them cost effective for widespread application. Automation has become the cutting edge of technology leading to higher productivity; hence it has become the major factor for deciding the competitiveness or the survival of many businesses or even countries.

Today, many advanced automation systems, such as mobile or fixed robots, are readily available. In many cases, automation is custom-designed to meet specific application requirements. From the business point of view, the decision of whether to go automated or not is shaped by the cost, profitability, and long-term objectives of the organization. In general, automation leads to improved productivity and better product quality. But, by the same token, it has a high initial cost and may lead to loss of flexibility in production. Nevertheless, since the mid-1980s, many large firms have invested heavily in the procurement of automation hardware and software that created extensive demand and accelerated Research and Development related to automation. Also, there are publicly funded programs such as the Automated Manufacturing Research Facility (AMRF). The collaboration between organizations and governments for the development of automation also is quite noticeable. As a result, these efforts have shifted automation from the general conceptual stage to widely practiced implementation.

The advances and widespread use of computers played a major role in the development and implementation of automation. Computers find applications in large systems as the direct digital control (DDC), supervisory control, distributed control systems (DCS), hybrid control systems, supervisory control and data acquisition (SCADA) as well as simple systems such as single loop controllers. SCADA, for example, allows reliable communication between devices located in remote sites by using various communication techniques such as microwave signal transmission. Further developments in automation are supported by many secondary concepts, such as computer aided design (CAD) and computer aided engineering (CAE). Automation is integrated with management concepts in the form of computer aided manufacturing (CAM), computer integrated manufacturing (CIM), just-in-time (JIT) inventory management, and flexible manufacturing system (FMS).

CAD and CAE involve design and geometric modeling of drawings, engineering analysis, and computer kinetics to observe the animated movement of parts. CAM is developed in a number of areas, such as machine automation, interconnection of machines, computer numerical control, robotics, process planning, and factory management. In many applications, CAD and CAM are used together to increase efficiency of operations. The JIT approach eliminates the need to keep large stocks by allowing the acquisition of goods and services as required. CIM enables the logical integration of engineering, production, cost accounting, physical distribution, inventory control, planning, purchasing, marketing, and other support functions into a single system. FMS enables manufacturers to run different batches at the same time or to change production lines easily from one to different products.

The modern industrial automation systems largely use distributed control systems. A DCS is made from three main components: the data highway, the operator stations, and the microprocessor-based controllers. The data highway handles information flow between components and ensures effective communications. The microprocessor controllers are responsible for effective control of the process and are configured to accommodate multiloop or single-loop controllers. The operator stations allow the control command to be given, the system database to be maintained, and the process information to be displayed. For instance, the displays can be arranged to be group displays, detail displays, trend displays, or alarm annunciation displays. Operator consoles can handle a large number of loops, up to 10,000. Nevertheless, there are limitations in DCS such as user orientation, communications, capacity, speed, reliability, and sequencing. Some of these problems are eased by faster and improved communication highways, powerful microprocessors, effective database man-

Table 1. List of Manufacturers

Automated System Engineering 11821 Parklawn Drive Rockville, MD 20852 Tel.: 800-221-0286
Automating Tooling Systems 2222 Shasta Way Simi Valley, CA 93065 Tel.: (805) 583-8961 Fax: (805) 583-0442
Automation Application, Inc. 680 Flinn Avenue, Unit 36 Moorpark, CA 93021 Tel.: (805) 529-4374 Fax: (805) 529-8630
Automation Displays, Inc. 3533 N. White Avenue Eau Claire, WI 54703 Tel.: (715) 834-9595 Fax: (715) 834-9596
Automation Innovators, Inc. 5364 Mainsail Drive Roscoe, IL 61073 Tel.: (815) 637-6963 Fax: (815) 637-6855
Burns Machinary, Inc. 2580 South Brannon Strand Road Dothan, AL 36301 Tel.: (334) 793-7086 Fax: (334) 671-0310
Bristol Babcock 1100 Buckingham Street Watertown, CT 06795 Tel.: (203) 575-3000 Fax: (203) 575-3170
Capitol Technologies, Inc. 3613 Voorde Drive South Bend, IN 46628 Tel.: (219) 232-3311 Fax: (219) 233-7082
Custom Engineering, Inc. 16250 E. 33rd Place Aurora, CO 80011 Tel.: (303) 375-0050 Fax: (303) 375-1112
Dynaologic Engineering, Inc. 3285 Martin Road, Suite 106 Walled Lake, MI 48390 Tel.: (810) 669-3275 Fax: (810) 669-1150
Dynamic Automation, Inc. 320 North Michigan Avenue, Suite 405 Chicago, IL 60610 Tel.: (312) 782-8555 Fax: (312) 782-8808
FeedeR Corporation of America 4429-T James Place. Melrose Park, IL 60160 Tel.: (800) 225-5322 Fax: (708) 343-0057
FTI International, Inc. 10914 North Second Street Rockford, IL 61115-1400 Tel.: (815) 877-4080 Fax: (815) 877-0073
Hierath Automated System 4950 Iris Street Wheat Ridge, CO 80033 Tel.: (303) 423-641 Fax: (303) 423-7405
Industrial Computer Source 9950 Barnes Canyon Road San Diego, CA 92121-2720 Tel.: 800-619-2666
Inox-Tech, Inc. 405-C Queen Street, Box #302 Southington, CT 06489 Tel.: (514) 638-5441 Fax: (514) 638-2865
Jade Corporation 3063 Philmont Avenue Huntington Valley, PA 19006-4299 Tel.: (800) 787-1798 Fax: (800) 400-6575
Jewet Automation, Inc. 2901 Maury Street Richmond, VA 23224 Tel.: (804) 233-9861 Fax: (804) 233-6732
Kolbus Controls, Inc. 8408 Rainbow Hwy., Building #1 West Salem, OH 44287 Tel.: (800) 833-5194 Fax: (419) 853-4834
Kuntz Manufacturing Company, Inc. 402 Goetz Street, Dept. 7 Santa Ana, CA 92707 Tel.: (714) 540-7370 Fax: (714) 540-6287
McNeill International 7041 Hodgson Road Mentor, OH 44060 Tel.: (216) 953-0005 Fax: (216) 953-1933
Mekanize Engineering, Inc. 975 Elkton Drive, Dept. T Colorado Springs, CO 80907 Tel.: (719) 598-3555
MSK Automation Company 158 Viking Avenue Brea, CA 92621 Tel.: (714) 255-0960
Orbitron Systems, Inc. 8400 Magnolia Avenue, Suite G Santee, CA 92071 Tel.: (619) 448-5676 Fax: (619) 448-6916
Precision Automation Company, Inc. Box 2848-T Macon, GA 31203 Tel.: (912) 741-0918 Fax: (912) 741-4402
Process Controls 475 Som Center Road Mayfield Village, OH 44143 Tel: (216) 979-7378 Fax: (216) 442-1811
Sims Machine and Control, Inc. 15338-B Aviation Loop Drive Brooksville, FL 34609 Tel.: (904) 799-2405 Fax: (904) 796-5842
Southern Engineering and Automation, Inc. 1166 Kapp Drive Clearwater, FL 34625 Tel.: (813) 446-1922 Fax: (813) 443-4178
State Engineering 4419 Ardmore Avenue Ft. Wayne, IN 46809 Tel.: 800-777-6195 Fax: (219) 747-4990
Swanson-Anaheim Company Dept. E, 4955 London Drive Anaheim, CA 92807 Tel.: (800) 554-3142 Fax: (714) 970-8709
Westech Automation Systems 720 Dartmouth Lane Buffalo Grove, IL 60089-6999 Tel.: (708) 541-5070 Fax: (708) 541-0096
Westfield Controls, Inc. 152-2 Remington Boulevard Ronkonkoma, NY 11779-6912 Tel.: (516) 467-2397 Fax: (516) 467-2398

agement, improvements in programming languages, and enhanced data storage capacity.

The understanding and study of the control of systems is an important part of modern automation. In order to implement automation, the process is monitored continuously, and the data are acquired from the sensors and actuators that are operating on the floor. After the data are collected, automation and process control can be implemented. Therefore, the automation and control equipment is largely based on the measurement and control of process variables, the transmission of information, signal conditioning, and decision making. Today, highly advanced measuring devices exist for monitoring process variables, and variously sized computers, microprocessors, and microcontrollers are used for information gathering, decision making, and decision implementation.

Control is not limited to the software in a computer, but it resides in the whole loop that includes instruments and elements. A fundamental and essential part of automation are the instruments that include sensors, transducers, and other measuring systems. The instrumentation is a part of the process involving the choice of measurement and the use of the output information. Advances in sensor technology provide a vast array of measuring devices that can be used as components of automation systems. These devices include highly sensitive electromechanical sensors, optical scanners, and machine vision. In all applications, the reliable and effective way of measuring the process variables is essential, so that further decisions may be made concerning the overall automation of the system. The monitoring instruments are designed to maintain prescribed relationships between the parameters being measured and physical variables under investigation. The physical parameter being measured is known as the measurand. The sensors and transducers are the primary sensing elements in the measuring system that senses the physical parameters to produce an output. When the sensors generate the signals, the type of signal processing depends on the information required from it. In many automation applications, the outputs of the sensors are converted to digital form to integrate the information with the overall system.

There is a diverse range of sensors and transducers available to meet the measurement requirements of a physical system. For instance, many different methods are available for position or motion sensing. These methods include capacitive sensors, inductive sensors, and optical sensors, and they may be used for static or dynamic measurements. The static measurements are relatively simple because the physical quantity does not change in time (e.g., fixed dimensions and weights). If the physical quantity is changing with time, which is often the case, the measurement is said to be dynamic. In this case, steady state and transient behavior of the physical variable must be analyzed and matched with the dynamic behavior of the instrument. In choosing the equipment for measurement, the first priority is deciding the type of measurement to be done and why. The sensors and transducers, instruments and measurements are a vast area, which can not be dealt with here in detail. Interested readers can refer to the references in the bibliography [e.g., Connel (1996)]. It is sufficient to say that sensors and transducers are important parts of automation, and in this article, some detailed treatment of specific types will be given in the following sections.

DIGITAL AUTOMATION AND CONTROL EQUIPMENT

Nowadays, digital systems, computers, microprocessors, and other integrated circuits (ICs) are essential parts of automation and control. They are widely accepted because they offer many advantages, such as improved sensitivity, system flexibility, ease of information transmission, and so on. Most of the equipment associated with digital systems can be divided into a number of major sections, such as sensing and controlling instrumentation of the process, interface devices, input and output facilities, communication devices, main information processing equipment, and man–machine interfaces. A typical digital control arrangement is illustrated in Fig. 1.

Digital control systems enable the implementation of advanced control methods such as predictive control, inferential and internal model control, adaptive control, statistical control, fuzzy control, and neural network and other artificial intelligent control methods such as expert systems and a combination of advanced techniques. Some of these control methods will be detailed in the following sections.

Digital automation systems are organized by taking the following factors into consideration: (1) user requirement or specifications, (2) functional design specifications, (3) complete system design and structure, (4) test specification, (e.g., codes and integrated testing), (5) warranty and other support such as training, and (6) health and safety issues.

Digital devices perform several functions: (1) computing on-line mathematics, which enables the monitoring and control of process variables that cannot be measured directly but can be computed from other measurable variables; (2) determining set points, setting limits for variables and signals that represent variables; (3) selecting variables and performing programmed operations for control and decision-making purposes; (4) determining logic and conditional moves.

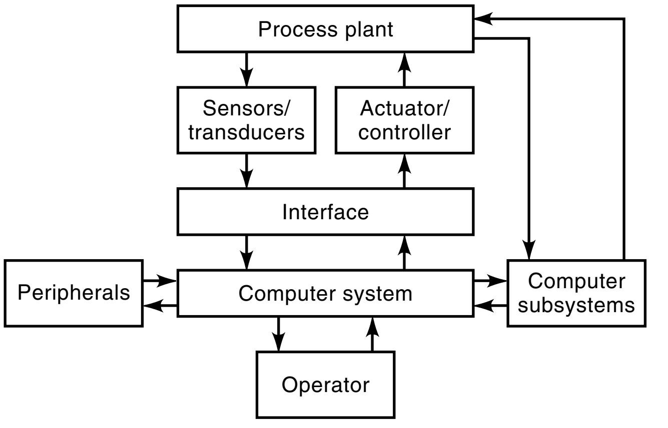

Figure 1. A computer control system. Digital systems and computers are used extensively in automation and control applications. The digital systems interface with the process by means of analog and digital interface units. Man–machine interface and the information flow between digital equipment are easy to handle compared to analog counterparts.

In many automation and control systems, the computers are arranged in a centralized, distributed, or hierarchical manner, and networked together by using one of the techniques illustrated in Fig. 2. In a centralized computer control system, all the information is gathered, and the decision is made and implemented by a central computer. Typical examples of centralized computer control systems are MDC 85 and PCS 8000. These computers are not general computers with control software, but are specifically designed and manufactured for process control applications. The control functions are programmed in such a way that the user can select from a library as required. The dependence of the entire automated system on a single computer and hence a single computer manufacturer is the major drawback.

There are many distributed digital control systems on the market, such as the Honeywell TDC series and the Toshiba TOSDIC series. The multitask function of a centralized computer system is divided into independent, dedicated functional units. The spatial distribution of the modules is made possible by using data highways. All distributed systems have a control layer, a communication layer, and a process interface layer as illustrated in Fig. 3.

A hierarchical control system is a combination of centralized and distributed control systems. It has two layers of computers; one of the layers is dedicated to in situ process control, whereas the other layer contains a central computer responsible for the management of the total plant. In this system, all the computers work together via a communication network, such as a local area network (LAN) or a wide area network (WAN).

Regardless of the computer system selected, digital data communication must obey software protocols to ensure effec-

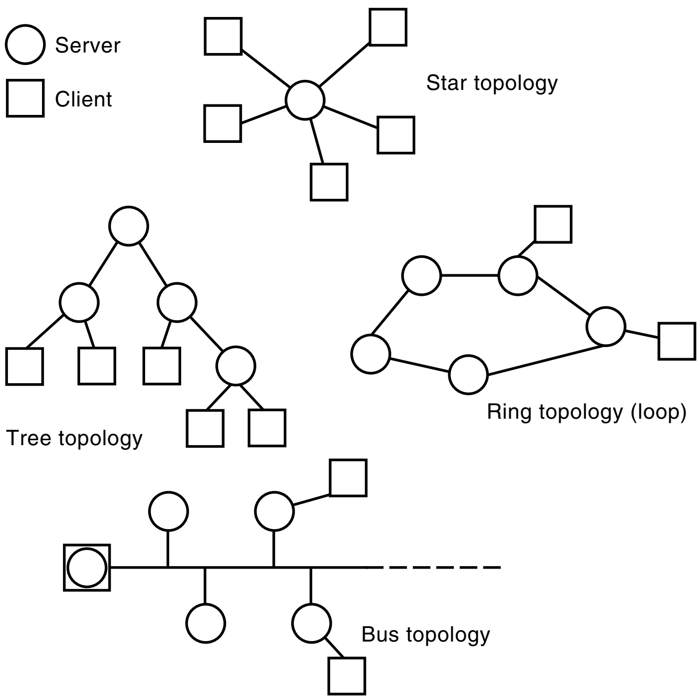

Figure 2. Networking of computers. The digital systems are networked to enable information flow among the members. The network topology selected depends on the process, hardware, and software available. In automation systems, the bus structure appears to be popular. The contention and collision problems generated by the use of the bus by many devices need to be addressed carefully.

tive and efficient data flow. The protocols are managed by international organizations such as the Institute of Electrical and Electronic Engineering (IEEE) and International Standards Organisation (ISO). The communication protocols have a number of layers as illustrated in Table 2.

In automation, the characteristics of the signal conversion and transmission can affect the overall accuracy of the system in terms of possible losses and interference of useful signals. The losses can be caused by electrical or mechanical interference, noise, cabling arrangements, power supplies, and so on.

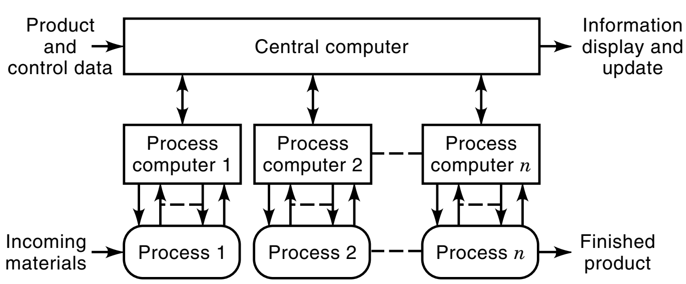

Figure 3. A hierarchical arrangement of computers. The central computer interfaces with all the other computers located in different parts of a complex automated system. Apart from process control, many other tasks such as system optimization, product design, scheduling, and inventory control can be implemented by the central computer.

Therefore, careful selection of communication techniques and equipment is critical.

PROCESS MODELING

The processes are modeled to capture the process dynamics with sufficient accuracy to ensure good control performance. The model of a process gives a good understanding of the inherent nature and characteristics of the system, an indication concerning future changes of the system, and the system response to external stimuli. The two main approaches concern system identification via process input/output data and mathematical modeling from physical laws.

A number of different types of process models can be configured; these are the analog models, pilot plant models, simulation models, and mathematical models. Analog models are the electrical representation of the system, which can be constructed in the form of circuits. In pilot plant models, a smaller version of the system is implemented to gain experience about the process. Simulation models purport to approximate the real system by using computers. Mathematical models represent the system by sets of differential and difference equations derived from fundamental physical laws, as exemplified in Table 3.

Even though all types of models have advantages and disadvantages, mathematical models enable the application of theoretical concepts. In mathematical modeling, the dynamic behavior of the system is described by differential equations, and the relations between the inputs and outputs are obtained in the form of transfer functions.

Transfer functions represent the interconnected components in the form of block diagrams or signal flow graphs. If the system is represented in a linear form, other mathematical tools, such as the Laplace transform, can be applied. A typical single-input single-output closed-loop control system model is shown in Fig. 4. In this figure, the relation between the input and output of the open-loop system is obtained from ordinary differential equations as

$$a_n\frac{d^n c(t)}{dt^n} + a_{n-1}\frac{d^{n-1}c(t)}{dt^{n-1}} + \cdots + a_0 c(t) = b_m\frac{d^m r(t)}{dt_m} + \cdots + b_0 r(t) \quad (1)$$

where $c(t)$ is the output, $r(t)$ is the input, and a_n, a_{n-1}, . . ., a_0, b_m, . . ., b_0 are the coefficients of the differential equation.

If all the initial conditions are zero, this equation can be expressed in Laplace as

$$M(s) = \frac{C(s)}{R(s)} = \frac{b^m s^m + b^{m-1}s^{m-1} + \cdots + b^0}{a^n s^n + a^{n-1}s^{n-1} + \cdots + a^0} \quad (2)$$

For example, neglecting friction, the linear motion of a mass under a tractive effort of an engine can be expressed by

$$f(t) = \frac{Md^2x(t)}{dt^2} + B\frac{dx(t)}{dt} \quad (3)$$

Table 2. OSI Reference Model

No	Layer	Application	Protocols
1	Physical	Electrical, mechanical, and packaging specifications. Functional control of data circuits.	ISO/IEEE 802.4, Broadband 10Mbs data rate, phase Coherent Carrier Band, etc.
2	Link	Transmission of data in local network. Establish, maintain and release data links, error, and flow.	IEEE 802.4 Token Bus. IEEE 802.2 Type 1 Connection services.
3	Network	Routing, switching, segmenting, blocking, error recovery, flow control. Wide area addressing and relaying.	ISO DIS 8473, Network services, ISO DAD 8073 (IS).
4	Transport	Transparent data transfer, mapping, multiplexing, end-to-end control, movement of data among network elements.	ISO Transport, Class 4. ISO8073 (IS).
5	Session	Communication and transaction management, synchronization, administration of control sessions between two or more entities.	ISO Session Kernel. ISO 8237 (IS).
6	Presentation	Transformation of information such as file transfer. Data interpretation, format, and code transformation.	Null/MAP transfer. ISO 8823 (DP).
7	Application	Common application service elements (CASE); manufacturing message services (MMS); file transfer and management (FTAM); network management.	ISO 8650/2 (DP), RS-511, ISO 8571 (DP), IEEE802.1.

In Laplace transform, for zero initial conditions,

$$F(s) = (Ms^2 + Bs)X(s) \tag{4}$$

$$M(s) = \frac{X(s)}{F(s)} = \frac{1}{Ms^2 + Bs} \tag{5}$$

The mathematical model of the system in Fig. 4 can be written in the form of the closed-loop transfer function as

$$M(s) = \frac{C(s)}{R(s)} = \frac{G(s)}{1 + G(s)H(s)} \tag{6}$$

An alternative modeling is offered by the state-space approach in the form of a first-order differential equation

$$\frac{d\boldsymbol{x}(t)}{dt} = \boldsymbol{A}\boldsymbol{x}(t) + \boldsymbol{B}\boldsymbol{r}(t) + \boldsymbol{F}\boldsymbol{w}(t) \tag{7}$$

where $\boldsymbol{A}$ is the state vector, $\boldsymbol{B}$ is the input vector, and $\boldsymbol{F}$ is the disturbance vector. Then the output may be expressed as

$$\boldsymbol{C}(t) = \boldsymbol{D}\boldsymbol{x}(t) + \boldsymbol{E}\boldsymbol{r}(t) + \boldsymbol{H}\boldsymbol{w}(t) \tag{8}$$

Matrices $\boldsymbol{A}$, $\boldsymbol{B}$, $\boldsymbol{C}$, $\boldsymbol{D}$, $\boldsymbol{E}$, $\boldsymbol{F}$, and $\boldsymbol{H}$ can be manipulated for solutions.

The automatic control theory and equipment are essential parts of automation. The most common type of automatic control is based on the closed-loop control systems. Nevertheless, the application of control includes traditional negative feedback control, optimal control, adaptive control, and artificial intelligence techniques that require different types of mathematical models.

The optimal control and adaptive control theories are concerned with defining an appropriate index performance for the process and then operating the process to optimize its performance under continuously changing and unpredictable environment. In artificial intelligent models, computers are programmed to exhibit characteristics that are commonly associated with human intelligence. These characteristics include understanding, capacity to learn, reasoning ability, problem solving ability, and rendering a diagnosis concerning a condition or situation.

Many other types of models such as stochastic models, discrete time system models, adaptive system models, and optimal system models are also available. For instance, the process modeling for an optimal control may be explained as follows.

Optimal control maximizes (or minimizes) the value of a function chosen as the *performance index* or *cost function* from an operational control system subject to system constraints. Modern optimal control theory is developed within a state-space framework, and performance indexes can be complex. Suppose that the control command of a system is expressed in vectorial form as $\boldsymbol{u}$ and the state of the system is described by $\boldsymbol{x}$. Further, suppose that the rate of chance of state $\dot{\boldsymbol{X}}$ is a function of state $\boldsymbol{x}$, control command $\boldsymbol{u}$, and time t

$$\dot{\boldsymbol{X}} = f(\boldsymbol{x}, \boldsymbol{u}, t) \qquad \boldsymbol{x}(0) = \boldsymbol{x}_0 \text{ known} \tag{9}$$

Then a control law $\boldsymbol{u}(\boldsymbol{x}, t)$ or a control history $\boldsymbol{u}(t)$ is determined such that a performance index or a scalar functional

$$\boldsymbol{J}(u) = \int_0^T g(\boldsymbol{x}(\tau), \boldsymbol{u}, \tau)\, d\tau \tag{10}$$

takes a minimum value out of all other possibilities, and a boundary relationship $\boldsymbol{x}(T) = \boldsymbol{x}_f$ must also be met as a constraint.

A most common form of $\boldsymbol{J}(u)$ is the minimum time control in which

$$\boldsymbol{J}(u) = \int_0^T d\tau = T \tag{11}$$

Many different criteria can also be used. These include minimum fuel, minimum energy, and other quadratic forms as

$$\boldsymbol{J}(u) = \int_0^T |\boldsymbol{u}(\tau)|\, d\tau \tag{12}$$

or

$$\boldsymbol{J}(u) = \int_0^T \boldsymbol{u}^2(\tau)\, d\tau \tag{13}$$

Table 3. Fundamental Physical Laws for Modeling

Transfer functions for electrical networks			
Capacitance	$v(t) = \frac{1}{C}\int_0^t i(t)\,dt$	$v(t) = \frac{1}{C}q(t)$	$\frac{v(s)}{i(s)} = \frac{1}{Cs}$
Resistance	$v(t) = Ri(t)$	$v(t) = R\frac{dq(t)}{dt}$	$\frac{v(s)}{i(s)} = R$
Inductance	$v(t) = L\frac{di(t)}{dt}$	$v(t) = L\frac{d^2q(t)}{dt^2}$	$\frac{v(s)}{i(s)} = Ls$
Transfer functions of mechanical systems			
Spring ($x(t)$, $f(t)$)	$f(t) = K\int_0^t v(t)\,dt$	$f(t) = Kx(t)$	$\frac{F(s)}{X(s)} = K$
Friction ($x(t)$)	$f(t) = fK_v v(t)$	$f(t) = K_v\frac{dx(t)}{dt}$	$\frac{F(s)}{X(s)} = K_v$
Mass (M, $x(t)$, $f(t)$)	$f(t) = M\frac{dv(t)}{dt}$	$f(t) = M\frac{d^2x(t)}{dt}$	$\frac{F(s)}{X(s)} = M$
Transfer functions of rotational mechanical systems			
($T(t)$, $\theta(t)$)	$T(t) = K\int_0^t \omega(t)\,dt$	$T(t) = K\theta(t)$	$\frac{T(s)}{\theta(s)} = K$
($T(t)$, $\theta(t)$)	$T(t) = B\omega(t)$	$T(t) = B\frac{d\theta(t)}{dt}$	$\frac{T(s)}{\theta(s)} = Bs$
($T(t)$, $\theta(t)$)	$T(t) = J\frac{d\omega(t)}{dt}$	$T(t) = J\frac{d^2\theta(t)}{dt^2}$	$\frac{T(s)}{\theta(s)} = Js^2$

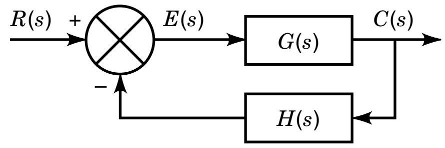

Figure 4. A closed-loop control system. The system has a forward path transfer function $G(s)$ and a feedback path transfer function $H(s)$. The relation between the input and output which is used in analysis and design of systems can be expressed in terms of these two terms.

or

$$\boldsymbol{J}(u) = \int_0^T (q\boldsymbol{x}^2(\tau) + r\boldsymbol{u}^2(\tau))\,d\tau \tag{14}$$

A general term for the continuous time performance index leading to optimal control is expressed as

$$\boldsymbol{J}(\boldsymbol{u}(t)) = \int_0^T g(\boldsymbol{x}(\tau), \boldsymbol{u}(\tau))\,d\tau \tag{15}$$

This performance index is minimized for the constraints

$$\dot{\boldsymbol{X}}(t) = f(\boldsymbol{x}(t), \boldsymbol{u}(t), t) \qquad \text{for } t \in (t_0, t_f) \text{ and}$$
$$\boldsymbol{x}(t) \text{ is an admissible state}, \boldsymbol{x}(t) \in \boldsymbol{X}(t), \forall t \in (t_0, t_f) \text{ is satisfied}$$

Slight variations of these equations lead to mathematics of the discrete time or digital versions of optimal control.

In a process, there may be many variables. The task of the designers is to identify those variables that affect the process. The variables also need to be controllable such that the process can be controlled by the manipulation of these variables. These carefully identified variables of the process are sensed by the use of many appropriate sensors ranging from simple thermocouples to sophisticated microsensors. The signals from the sensors are processed to achieve a good control system and effective automation.

PROCESS CONTROLLERS

Feedback control systems constitute an important part of modern automated systems. A feedback control consists of five basic components: (1) the input, (2) the process under control, (3) the output, (4) the sensing elements, and (5) the controllers and actuators, as illustrated in Fig. 5.

The input to the system is the set point or the reference value for the system output, which represents the desired value. The input is given as a reference signal by setting an appropriate mechanical device or electrical signal in analog or digital form. If the nature of the input signal of the process is not known, test signals in the form of step input, ramp input, or parabolic inputs are used as the test signals.

The output and other important system parameters are sensed by the sensing elements. The value of the output of the system is then compared with the desired input to correct any deviations. The sensing elements are selected and designed appropriately depending on the requirements of the process, and they can include a wide variety of sensors and instrumentation systems. For example, in the manufacturing industry, for position, motion, and speed sensing, the choice may be made between servo systems, encoders, potentiometers, limit switches, optical sensors, ultrasonic techniques, photoelectric devices, and so on. Some sensing elements appropriate for particular automation systems will be detailed below.

Process Controllers

Process controllers can be divided into four main levels. (1) Individual controllers control single machine or simple processes, where few controlled parameters are involved. They

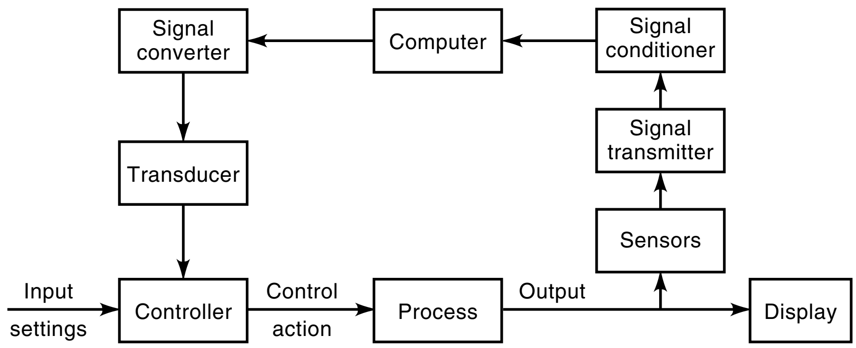

Figure 5. The components of a closed-loop control system. The sensing elements are used to monitor the system variables and the output. Information gathered from the sensors is processed to control the actuators and other system controllers so that the desired response from the system can be achieved.

can be programmed as single purpose as well as multipurpose. (2) Group controllers are two or more devices working together to complete a task. A master controller coordinates the operation of group controllers. (3) Total process controllers are a number of work cells coordinated further to achieve total plant control. (4) Enterprise controllers include control decisions that take into account many other issues such as forecasting future production levels and cost reduction scheduling.

The range of individual controllers embraces a wide variety of devices. In simple cases, the controller can be an amplifier, mechanical linkages, filters, or other control elements depending on the nature of the system. In more sophisticated cases, the controller can be a computer or a system of computers and microprocessors. The controllers, acting as the actuating devices, in a single-loop feedback system, take corrective action to reduce the difference between the input and the output. They are the mechanisms that change the process to accomplish the desired output. These mechanisms are usually designed in accordance with the system specifications. They consist of a variety of electrical, chemical, and mechanical devices such as motors, valves, solenoid switches, piston cylinders, pulley systems, gears, chain drives, hydraulic or pneumatic apparatus, or a combination of these devices.

Controllers acting as actuators can be very simple or very complex. For example, a switch connected to a temperature sensor is the controller and actuating device for a heating system. When the temperature is below the set point, the switch turns on the heating element to increase the temperature. If the temperature is higher than the set point, the switch turns off the heating element. On the other hand, a complex vision system may be the controller and actuator of a robotic assembly plant.

Controllers may be divided into such subgroups as direct acting controllers, logic control systems, valves, and actuators.

Direct acting or self-actuating controllers do not require an external power supply, such as a spring mechanism or a safety valve. They are also called regulators. They tend to be inexpensive and very robust. Other typical examples of these regulators would be the manometric temperature regulators and self-actuating pressure controllers, among others.

Logic controllers may be extremely simple or very complex. A simple logic controller is an on–off control switch. More sophisticated ones are programmable controllers, logic arrays, and pneumatic or hydraulic logic control systems.

Control valves are an important category of controllers. There are several different types, such as globe valves (e.g., single seat, double seat, V port, cage), ball valves (e.g., plug, eccentric disc, camflex), and gate valves (e.g., diaphragm, butterfly, pinch valve, slide valve). The proper selection and sizing of control valves is crucial for the stable, safe, and economical operation of control systems.

In general, controllers, which are sometimes called actuators, are driven by electric, pneumatic, and hydraulic power. They can be grouped to be continuous or two-position actuators. Continuous actuators can be electric, pneumatic or hydraulic two-position actuators that are obtained magnetically by solenoids, some of which may be pneumatic as in the case of diaphragm and piston-type actuators. Electric motors are used in valve-type actuators that link to the system via gears. Pneumatic actuators usually have a diaphragm–spring arrangement. Hydraulic actuators are composed of pistons and hydraulic motors, and they are used in systems where large forces and stiffness are required.

In most automation applications, one of the following controllers is used: a simple on–off controller, a phase lead and phase lag controller, or a proportional, integral, and/or derivative (PID) controllers. These controllers can be located at various points in the feedback system, as illustrated in Fig. 6. The most popular arrangement is the forward path control arrangement. On–off controllers produce two discrete control positions, which are either wide open or completely shut. The frequency of operation of the on–off controllers determines the variations in the system output.

Phase lead and phase lag controllers are often used, and they can easily be obtained by passive network elements as

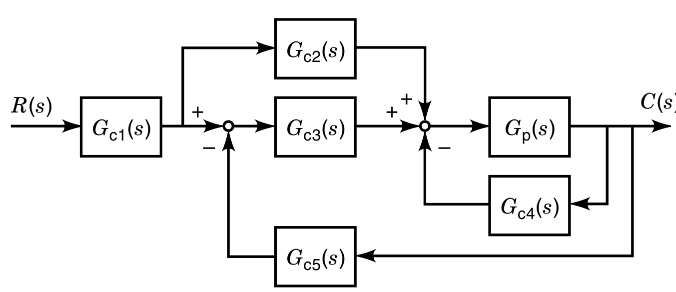

Figure 6. Controllers in a feedback system. The controllers can be located at various positions on the closed-loop control system. $G_{c1}(s)$ is the precompensator, $G_{c2}(s)$ is the feedforward compensator, $G_{c3}(s)$ is the series compensator (cascade), $G_{c4}(s)$ is the minor feedback compensator, and $G_{c5}(s)$ is the state feedback compensator. These compensators may be introduced in combination to allow more degrees of freedom. The cascade compensator is the most commonly used type.

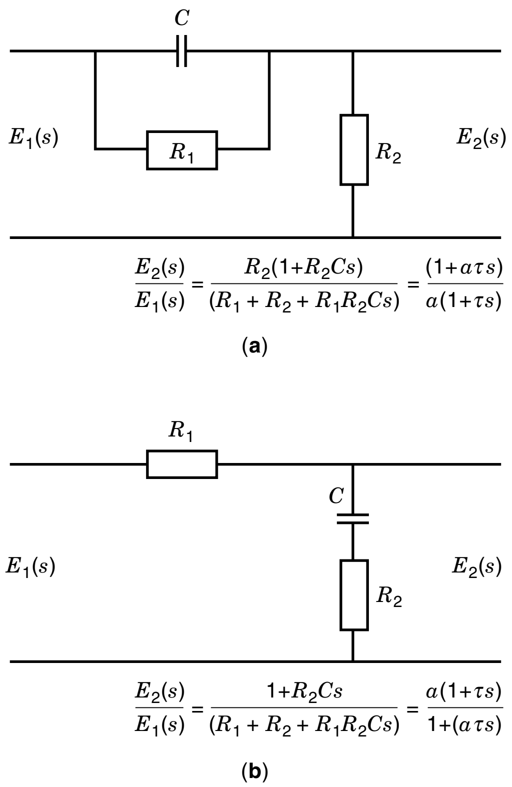

Figure 7. Phase lead (a) and phase lag (b) controllers. These controllers can easily be obtained by simple passive electrical components. They can also be obtained by using operational amplifiers.

shown in Fig. 7. Their Laplace transfer function can be expressed as

$$G_c(s) = \frac{s+z}{s+p} \tag{16}$$

The ratio of z/p determines if it is a phase lead or a phase lag controller.

The proportional controller generates a signal that is directly proportional to the error between the output and the input. In the integral controller, the time and size of the error signal is considered by taking the integral of the signal. As long as the error exists, integral action takes place to drive the output to reduce the error. In the case of derivative controllers, the rate of change of error is taken into account. If the error is constant, the derivative controllers will have no effect on the operation of the system. However, if the rate of change of error is high, the controller will act to reduce the rate of change. The transfer function of a PID controller can be expressed as

$$G_c(s) = K_P + K_D s + \frac{K_I}{s} \tag{17}$$

where K_P, K_D, and K_I are real constants.

The design problem involves the determination of these three constants so that the performance of the system meets the requirements. For a process system to operate satisfactorily, each constant associated with the PID controller is adjusted to match the process characteristics. The adjustment of the controllers is known as *tuning the controllers.* Successfully tuning the controllers depends on many factors such as process conditions, nonlinearities, and the operator's skill and experience. Some modern automation systems perform the tuning of the PID automatically by using many different methods, including artificial intelligence. PID controllers were implemented originally by pneumatic devices, but nowadays most consist of electronic devices, computers, actuators, and control valves.

In simple systems, PID or cascaded PID are readily available as ratio or cascaded ratio controllers in electrical, mechanical, or pneumatic form. In large systems, more complex controllers are available as noninteracting controllers, multivariable controllers, and delay controllers.

Although the most common type of control systems is the set point feedback control system, in some applications it is necessary to control one process variable at a value that depends on the value of the second process variable, known as the ratio control. In these cases, the set point of the first variable is automatically adjusted in relation to the value of the second variable by so-called ratio controllers. In computer-based systems, the ratio function is generated in the software.

In other applications, the output of an automatic controller can be a set point of another controller as in the case of cascade control systems. These controllers are called primary and secondary controllers, inner and outer controllers, or master and slave controllers. In some cases, selective controllers, which select one of the controllers, may be used. In this case, the function of each controller is different, but each controller is selected by logic or programming depending on the status and requirements of the process.

In most industrial applications, plants have many single and interactive control loops. For such situations, the general, practical, and theoretical approach is multivariable control. The theoretical approach involves the modeling of the plant in matrix form by identifying the loops and interactions between the loops. In practical applications, depending on the severity and significance of the interactions and control objectives, the controllers can be detuned by lowering their settings, or the system may be decoupled by disconnecting one or more of the loops.

Process control can be regulated by using closed-loop feedback systems or sequential operation involving many interrelated devices. Process monitoring uses alarms, graphical displays, and simple reporting of data. The entire process can be managed by interrelating the overall functions by means of product tracking, historical information, production switching, process accounting, laboratory data collection, reliability and safety analysis, scheduling, advisory control, modeling and optimization, and so on.

Application of Controllers

Modern process controllers find a wide range of applications in high-volume and highly automated production facilities, for instance, in chemical industries, petroleum refining, and food processing. In a typical modern process plant, the facilities may be divided into a number of processing units, as illustrated in Fig. 8. Each of these units may have its own computers to perform scanning, control, and alarm functions. The computers of each unit are connected to a central computer in a hierarchical configuration. The individual computers may

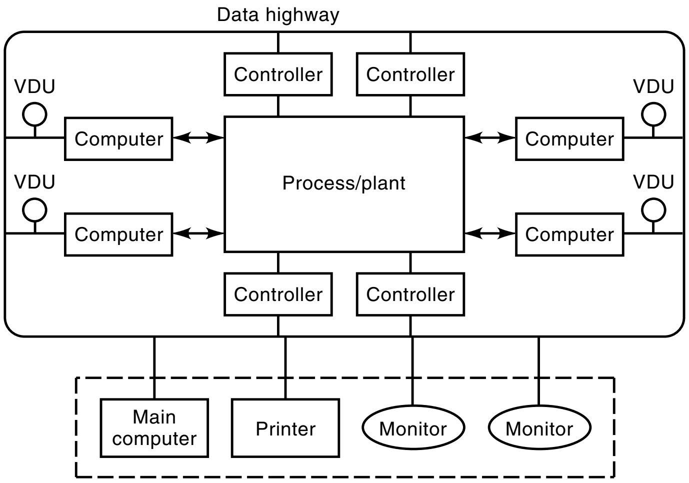

Figure 8. A process plant. In a plant, computers are responsible for controlling dedicated areas of the process. Computers are connected to form a network for effective and efficient operation of the plant.

deal with hundreds of control loops and thousands of parameters involving many control loops (maybe over 2000) such as temperature, pressure, flow rate, chemical concentration, and many other variables that are essential to the process. The central computer receives data from the process computers and ensures optimum operation of the entire plant.

Many metallurgical industries use automation to handle a large variety of products. Control programs are developed to schedule the sequence and rate of processes. One example of such a process is rolling hot metal ingots for different orders and to different specifications in the steel and aluminium industries.

Automation is applied extensively in the assembly industry. A typical assembly line consists of several stations, which perform adding and fastening of components. A typical workhead includes automatic equipment such as screwdrivers, riveting machines, welding facilities, and other joining devices. Modern assembly lines consist of programmable and adaptable assembly systems connected to a central computer. The master computer schedules and coordinates the production and informs the workstation computers of their designated tasks.

In the electronic industry, automated systems are used to design, analyze, produce, and test electronic components, IC, and the like. Examples of automation in the electronic industry are part insertion machines and wire rap machines. Some of these machines include complex equipment, such as vision systems. Automation is also used in the communication industry to monitor thousands of telephone lines, provide tones, make connections, monitor calls, and perform many other customer and management services.

In many applications, computer aided design is used in conjunction with computer aided manufacturing. The technology is applied in many industries including machine components, electronic products, and chemical processes. Suitable computers are used to process, store, and display large amounts of data representing product specifications.

Automation is used in many other industries, such as (1) transportation (e.g., airline reservation, automatic pilots in aircraft, rapid surface transit systems, and cars), (2) military applications (e.g., land, air, and naval operations), (3) service industries (e.g., healthcare, banking, financial services, government service, and retail trade), and (4) consumer products (e.g., microwave ovens, washing machines, alarm systems, and cars).

POWER CONVERTERS

There are many sources of energy and power converters available, but the most commonly used form of energy is electric power. Electric power can be generated in many ways, such as burning fossil fuels, capturing hydroelectric energy, solar or wind energy, or nuclear energy. The choice of power generation depends on the type of application at hand. For example, a natural choice for powering satellites would be solar power. Electric power can also be converted to other types of power that may be necessary in automation systems, such as mechanical, hydraulic, and pneumatic power.

The power in automation and control systems is used to perform at least two tasks: (1) processing and (2) transfer and positioning of materials. Depending on the application, the process may involve many activities such as shaping metals, molding plastic, switching signals in telecommunications, data processing in a computerized information system, and operating robots in an assembly plan. All these actions transform energy from one state to another.

Often, controlling a process or an operation is done with electronic equipment by adjusting the amount of power supplied to the system via high- and low-level controllers. Usually, the power requirements of controllers such as motor-driven solenoids, valves, fans, and pumps, are beyond the output capabilities of simple electronic devices, such as operational amplifiers, logic gates, and computer or microprocessor input/output (I/O) boards. Therefore, for system control, additional power converters that are capable of handling high powers are necessary.

In some applications, a control system requires the power to be switched either on or off. The equipment that accomplishes this task is the dc or ac power switch. Dc power switches are often referred to as dc output modules, and ac power switches are called solid state relays. They can be constructed as discrete components as well as integrated modules.

Dc output modules are capable of providing high currents and voltages to the equipment as well as providing low voltages and currents as control signals. The input circuitry of dc output modules is sensitive enough to be driven directly from the output of a programmable controller, a logic gate, an op amp, or a computer I/O port. Generally, it uses optically isolated transistor switches to prevent high-voltage faults to be electrically coupled to low-voltage control devices. Some modules have input protection against the reversal of polarity. There are many types of commercially available dc output modules; generally those used in control systems have an input voltage range of 3 V to 32 V. The typical output current rating is 3 A to 5 A, and the output voltage rating is 60 V.

Solid state relays are similar to output modules in function, construction, and appearance. They are specifically designed for ac applications with typical ratings of 120 V to 240 V ac. Their current ratings are much higher than those of their dc counterparts, being typically 10 A to 50 A. There are

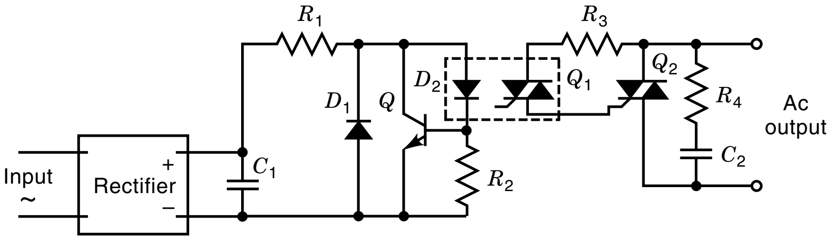

Figure 9. A typical circuit for a solid state relay. As soon as sufficient current flows through R_1 and D_2, Q_2 provides a path for the gate current to the triac Q_3. The bridge rectifier in the front allows the relay to be triggered by ac voltages. Solid state relays are used primarily to switch ac power.

two distinct types of solid-state relays—random-trigger and zero-trigger relays. A random-trigger relay supplies power the instant the input trigger current requirement is met. A zero-trigger relay turns the voltage on when the load supply voltage is less than a specified value, typically 20 V. A typical example of zero-switching solid relays is given in Fig. 9.

However, in many applications, simply switching the load power on and off is not acceptable, and a continuous control of power is necessary. There are a number of ways of achieving continuously varying power supply, especially by using transistors and diodes.

1. Linear analog dc amplifiers—Power transistors, such as Darlington, and power field effect transistors (FET) are used together with operational amplifiers. The operational amplifiers supply the control voltages to the gates or bases of the transistors.
2. Linear digital dc amplifiers—Power transistors are used to supply high voltage and high currents similar to the linear analog dc amplifiers. Using these amplifiers with microprocessors or microcontrollers that generate digital signals for control purposes is particularly effective.
3. Pulse-width modulation—An efficient alternative to linear amplification is pulse-width modulation (PWM). In this case, the output transistors operate in two distinct modes, either fully saturated or fully cut off. By controlling the duration of the width of the pulses and filtering these pulses, the average amount of power supplied can be controlled. A pulse width modulator has four main components: a triangular wave oscillator, a comparator, a power switch, and an output switch. A typical PWM circuit is shown in Fig. 10. With the use of PWM voltage controllers, the output power can be automatically controlled, based on decisions made by a software program.

Today, many ac and dc power converters are made from power semiconductors, such as diodes, thyristors, and triacs. Any power semiconductor system employed for rectifying, inverting, or modulating the output of an ac–dc energy source is called a converter system, or sometimes the power conditioning system. They can be classified as ac voltage controllers, rectifiers, dc-to-dc converters (choppers), inverters, and a cycloconverters.

1. Ac voltage controllers are used to vary the root mean square (rms) value of an alternating current supply by using switched power semiconductors, such as thyristors. They are employed as on–off or phase controllers. In a phase-controller, the thyristors supply a specific portion of each cycle of the single-phase or three-phase voltage source. They are configured to be full-wave or half-wave voltage controllers. A typical full-wave, Wye connected, three-phase controller is illustrated in Fig. 11.
2. Rectifiers can be classified as controlled uncontrolled, with the majority being controlled. They vary the average value of the direct voltage applied to the load. They are suitable for use in rectification of a single-phase or

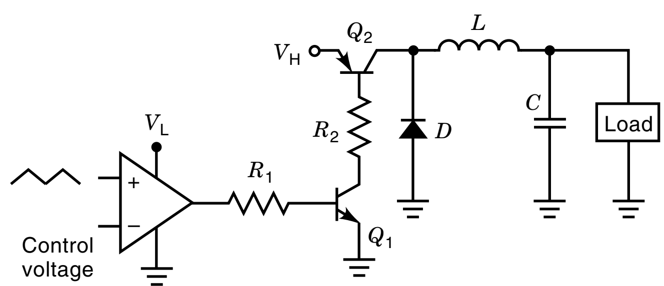

Figure 10. A typical pulse width modulator. They consist of an oscillator, a comparator, a power switch, and an output filter. The frequency of oscillator is usually about 20 kHz, and the control voltage varies slowly with respect to this frequency. The output of the comparator switch Q_1 and Q_2 alternately from saturation to cutoff at a rate equal to the frequency of oscillator. The level of the control voltage determines the duration of each pulse.

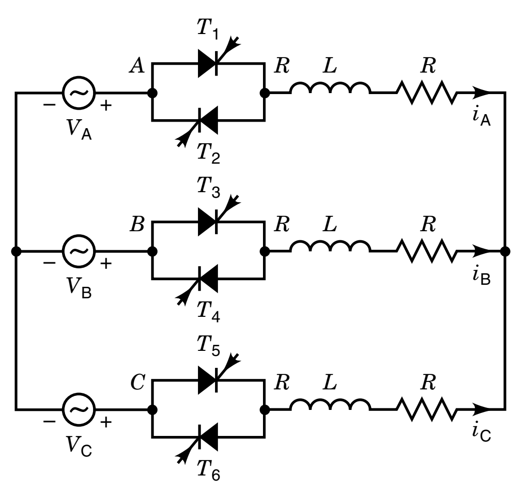

Figure 11. A typical full-wave voltage controller. There are various thyristor voltage control configurations. The selection depends on the type of connection (e.g., delta or wye), load characteristics, and range of control. In all circuits, the firing of the thyristors control the current flow through the circuit. At least two lines must be conducting for the load current to flow.

three-phase constant ac supply. A typical three-phase, full-wave thyristor bridge rectifier is shown in Fig. 12.

3. Dc-to-dc converters (choppers) vary the average value of the direct voltage applied to a load circuit by introducing one or more thyristors between the load and a constant dc source. There are two types of choppers, type A and type B. In a type A chopper, the dc currents and voltages can only be positive as illustrated in Fig. 13, whereas in a type B chopper, the currents and voltages can be positive or negative.
4. Inverters convert dc power to ac power at some desired output voltage and frequency. They are manufactured as half-wave or full-wave inverters that can supply single-phase or three-phase ac power. The output voltage of an inverter is not sinusoidal, containing many harmonics. In many applications, these harmonics are reduced by suitable filtering techniques. An advanced version of an inverter is the frequency converter, which is a combination of a rectifier and an inverter. Ac power is first converted to dc and then inverted back to ac, having variable amplitude and frequency.
5. Cycloconverters convert an m-phase ac source to an n-phase ac source at a desired frequency. They can be designed as single-phase to single-phase or three-phase to single-phase cycloconverters, line-commutated frequency multipliers, and cycloinverters.

Nowadays, microprocessors and microcontrollers are extensively used in all kinds of power converters. With the aid of software, they simplify the hardware, implementation, and trouble shooting of control electronics by acting as timers and logic circuits and by performing arithmetic. The software can be modified and changed easily and can be integrated with artificial intelligence and other control algorithms. They can control many devices when equipped with appropriate I/O and interface facilities.

Artificial neural networks, fuzzy logic controllers and artificial intelligence are used for the control of power converters. Artificial intelligence techniques are often applied in order to meet more stringent distortion and power factor requirements in ac and dc power converters. Generally, the characteristics

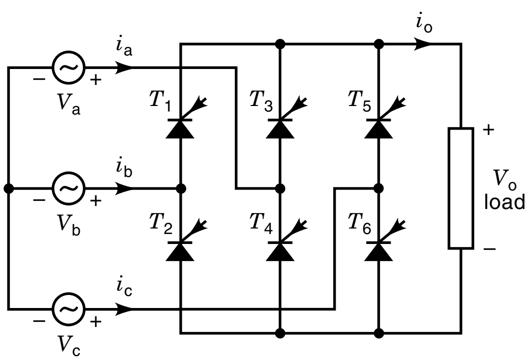

Figure 12. A typical thyristor bridge rectifier. The thyristors are triggered in pairs in sequential manner to supply current to a single load. The current from all phases flows in one direction on the load thus giving a dc. Because of the way that thyristors operate, considerable harmonics are introduced in the output therefore suitable filters must be used to obtain clean dc.

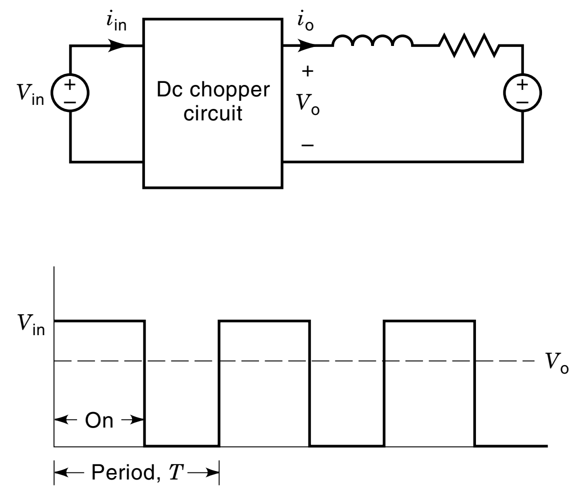

Figure 13. Block diagram of a dc chopper. The chopper applies a series of unidirectional pulses to the load circuit. Although the magnitudes of the pulses are the same as the input voltage, variations of the time between pulses determine the average value of the dc output. After thyristors are turned on, they will conduct unless the current flow is forced to zero. This is called commutation.

of power converters are nonlinear; therefore the conventional fixed structure PID-type regulators cannot be optimized easily for all operating conditions. Neural network-based controllers can handle such nonlinearities. For example, in one application, the neural network identifies the converter dynamics in cases of uncertainties in the load parameter. Conventional closed-loop control techniques are applied for the regulation of the converter in a closed-loop manner by means of neurocontrollers. Fuzzy logic controllers equipped with appropriate algorithms are also used and implemented by means of microprocessors in power converters.

In general, the electric power supply for electronic instruments and process computers should be reliable. This reliability will be achieved not only by maintaining the required voltage on the power lines but also by supplying clean power at all times. Some of the power reliability issues may be addressed by having standby battery or generator systems. The choice depends on the nature and amount of power consumed by the devices to be maintained and the cost of such installations.

MOTION CONTROLLERS

Motion is the movement of an object from an initial point through an infinite series of points to a destination along a path or trajectory. Such movement may be linear or curvilinear, taking place in two dimensions or three dimensions.

Speed relates the motion to the time required to move from one position to another. Speed is a scalar quantity describing the magnitude of velocity. Velocity is a vector quantity denoting both the direction and the speed of linear motion, or the direction and rotation of an angular motion. Industrial linear speeds are generally obtained from rotational motion generated by machines. Acceleration is the rate of change of velocity with respect to time, an important parameter to be measured in many automation and control systems.

In automation and control, the excursion of motion can be a point-to-point system, a path or a trajectory system, a superimposed motion system, and a fixed motion path system.

In a point-to-point motion system only the end points are described, and the coordinates of tool position do not refer to the movement between these points. This type of system is usually encountered in fixed automation systems, such as warehousing and retrieval systems. In path or trajectory systems, the tool movement takes place in a tightly controlled path. A typical example of a trajectory motion system is the automatic welding in which a definite path must be followed. In a superimposed motion system, additional motion is imposed on top of a normal trajectory. An example of this would be automatic painting where wobbling is superimposed on the beginning and end of the motion trajectory. Fixed motion paths are used in fixed automation equipment, such as transfer lines, conveyor belts, and packaging and printing equipment.

Modern motion control is the product of control theory, applications of rapidly progressing technology, and the availability of suitable semiconductors. Development and application of alternative, less expensive motor technologies has become a major factor in minimizing the cost of electronic drive systems. Advances in digital motion controllers have also gained much attention. Motion technology has reached a level that permits the cost-effective conversion of mechanical to electronic motion control solutions. It appears that this development will persist, and drives and controllers will continue to become more powerful, more versatile, and more cost-effective.

There is a diverse range of equipment available for motion control technology in industrial automation applications. A designer may face a confusing array of equipment choices, ranging from powerful microchips to multilevel distributed control systems. There are five groups of motion control equipment

1. Chip level controllers that consist of a few integrated circuits combined to produce signals that drive positioning equipment.
2. Board level controllers that are made from one or more circuit boards containing computer functions as well as input and output; they include general-purpose motion controllers and personal computer add-ons. These devices often handle control, sensing, and the power drive for positioning equipment.
3. Fixed capability controllers or box-level devices that are in menu-driven programming format form; they generally combine displays, keyboards and computing.
4. Modular, configurable controls with flexible programming languages.
5. Dedicated controllers that include programmable logic controllers and pneumatic sequencers. These are designed to handle specific chores common to factory-floor control.

In automation and control systems, the equipment for motion control is generally electrical, mechanical, or electrohydraulic. In addition, purely hydraulic or purely pneumatic motion control systems also find applications. The choice of drive depends on factors such as load, mass, required response, installation environment, and cost. For example, the combination of electronic motion controllers with hydraulic actuation gives advantages by providing high power-to-size ratio and high-speed linear motion. Recently, a great deal of progress has been recorded in the development of digital control for hydraulics. This fact, coupled with the increased sophistication of electronics and software, results in control systems that are easier to use in industrial machinery.

In automation and control, a variety of electrical motion control systems in the ac and the dc ranges are used. In addition to conventional ac and dc motors, servomotors and servosystems, permanent magnet dc motors, brushless motors, stepper motors, and linear and planar motors find a wide range of applications. In general, servo systems and ac and dc motors are selected for continuous motion control, whereas stepper motors are preferred for incremental motion control. Although electrical drives are an essential part of automation and control, the subject is vast and because of the lack of space it will not be treated in detail. Interested readers should refer to the bibliography.

In order to control the motion of systems, the drives themselves need to be controlled. Drives are generally controlled by silicon control rectifiers (SCR), other solid state electronics, analog controllers, and power amplifiers. Some of the controllers will be discussed in greater detail in the speed control section of this article.

Many modern motion control systems are integrated with microprocessors and computers. An example of this is the programmable motion controller (PMC), which is designed to operate as an intelligent velocity and position controller in response to high-level ASCII commands. PMCs can be interfaced with servo drives, tachometers, encoders, and the like, to form a closed-loop digital motion control system. Microprocessors allow the use of high-level user-oriented motion control commands. In addition, dedicated motion processors offer an alternative to packaged motion controllers. They are designed indirectly into the printed circuit board of the machine. This capability enables engineers to package motion control capabilities into the required precise space configuration. In recent years, such processors have gained extensive industrial applications. Currently, several motion processors are available, including stepper motors, servomotors, and dc brushless servomotors.

SPEED CONTROL

Variable speed drives can be classified as hydraulic, mechanical, or electrical. In automation and control applications, the question of cost and capabilities of the variable speed controllers is important. The range of the speed and how quickly it can change in response to the process requirements is significant. Coupling is necessary to change from one speed to another and from one motion to another. Therefore, correct selection of speed control systems, suitable for a particular application, is important.

Variable-speed hydraulic motors are driven by fluid pressure. In some systems, the controller's fluid couplings consist of two halves, one driven by a constant speed electric motor and the other connected to the controlled device. The speed is regulated by the manipulation of the fluid flow between the two halves. In others, the hydraulic speed controller is based on the control of the fluid flow rate in a pipe by means of pumps and control valve settings. The fluid pumped through the system is usually driven by a motor (usually an electric motor). A servomotor-driven valve controls the oil flow to the hydraulic motor. A closed-loop control can be achieved by sensing the fluid flow rate.

Mechanical speed control systems are based on the control of the generated torque and rotational velocity of petrol- or steam-driven engines equipped with suitable throttles controlling the energy input to the engine and a suitable gear arrangement.

In many modern automation and control applications, the speed control is realized electrically. A diverse range of electrical equipment is designed for speed control, such as electromechanical and solid state relays, control transformers, common or specialized electric motors, potentiometers, and solid state power control devices. The electric speed drives include

1. dc drives, which can further be subdivided as
   - single-phase, full-wave SCR
   - three-phase, full-wave SCR
   - three-phase, full-wave SCR power bridge
   - PWM
   - brushless dc or ac servo
2. ac drives, which include
   - variable frequency control (VFC)
   - variable voltage input
   - current source inverter (CSI)
   - pulse width variation (PWV)

The main considerations in selecting a suitable electric drive to control the speed of a system are the torque-speed characteristics, the type of power supply available, the precision needed, and the cost. The selection can be made from (1) dc motors such as series, shunt, compound, permanent magnet, and electronic control motors; (2) three-phase ac motor such as induction, synchronous, wound rotor; (3) single-phase ac motors such as capacitor, split-phase, two capacitor, repulsion, shaded pole, universal; and (4) special motors such as servos, synchros, resolvers, stepper motors, Hall-effect motors, hysteresis, linear, inside-out, and other special control motors. Dc motors are used when full torque is needed at widely varying speeds, but they tend to be relatively large in size and expensive. Ac motors are essentially constant speed devices, but they can be made to operate as speed devices by suitable electronics.

Electric motors have control systems for convenient starting, dynamic torque-speed characteristics, time delays between speeds, and current voltage surges during operations. A simple control for all kinds of motors is the on–off control. This is accomplished by the use of relays, limit switches, timers, and the like, as in the case of most programmable logic controllers (PLC).

The speed of an ac motor is directly proportional to the frequency of the ac supply. Therefore, a common method of controlling ac motor speed is achieved by variable frequency drives. The variable frequencies are obtained by using circuits based on solid state electronics, power transistors, SCRs such as triacs, thyristors, and gate turn off thyristors. A typical example of a frequency converter is illustrated in Fig. 14 in block diagram form. These electronic speed controllers are carefully designed by considering issues such as overvoltage protection, current limits, starting requirements, and phase-loss trip.

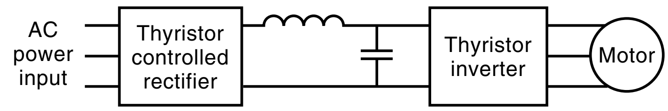

Figure 14. A frequency converter. There are many different types of frequency converters. A popular method employs the conversion of ac voltages to dc voltages by means of thyristor circuits and then inverting back to ac giving the desired frequencies. The output of the inverters contains considerable harmonics; therefore, the use of filters may be necessary for sensitive loads.

The speed of the dc motor is mainly controlled by adjusting currents and voltages supplied to the armature and field windings. These adjustments are achieved by using electronic circuits and devices, as in the case of ac motors.

Electrical motor speed control systems have existed for many years, but usually involve complex and expensive mechanical and electrical solutions. Low-cost, microprocessor-based speed control regulators can provide a flexible building block approach to the problems of accurate closed-loop motor speed control. Several manufacturers provide families of closed-loop digital speed controllers and total control system design. By using equipment from the same family, the equipment cost and the time taken for the system design can generally be reduced.

Modern techniques find many applications in the speed control of electrical drives. For example, in the speed control system of an induction motor, a full fuzzy controller may be used to sense the speed and generate the appropriate command current corresponding to any speed discrepancy. A deadbeat fuzzy scheme in the current feedback loop forces the actual current to track the command current.

In another speed control system, the process takes place in two stages. The first stage yields the number of fuzzy rules and the rules themselves for the fuzzy neural controller. Initial estimates for centers and widths for membership functions associated with the controller input and output variables can also be obtained. From this information, a fuzzy neural-controller is configured. The resulting controller is further tuned by using a backpropagation type algorithm. The fuzzy controller can be applied to dc and ac drives, replacing the conventional PID controllers.

Artificial neural network (ANN)-based speed control schemes are often used. Control is achieved by adjusting the controller parameters. The controller coefficients are tuned by using signals from an ANN that observes the speed patterns exhibited in the motor speed history. These schemes have the ability to adapt to any variations in the motor parameters.

In general, speed control strategies based on artificial intelligence (AI) involve on-line tunable controllers. Motor-drive system parameter uncertainties and the unknown nonlinear mechanical load characteristics motivate the use of these two AI-based speed controllers over the extended range of operating conditions. Because the values of the motor-drive system parameters are not required, the controlled motor-drive system becomes robust and insensitive to the variations in system parameters, operating conditions, and load excursions.

ADAPTIVE CONTROLLERS

Many processes have time-dependent dynamics and are nonlinear and subject to frequent variations in the operating conditions. Therefore, they are subject to parameter changes, thus resulting in deviations from the required performance of the closed-loop control systems. In these systems, self-tuning controllers or self-adaptive controllers, which have the ability to learn about the closed-loop process, can be employed. This is based on the assumption that the present control strategy can be based on past closed-loop observations.

There are many schemes for implementing adaptive controllers, such as dead-time compensation, gain scheduling, model reference optimal control, and feedforward adjustments, which are based on the measurable quantities. These schemes are suitable in control systems for which the characteristics of their components are fully known or can easily be modeled. However, in many processes, the behavioral change of the system is either unknown or unobservable and difficult to model. There are two different commercially available self-tuning control implementations—expert systems and process model approach.

The expert system is a branch of artificial intelligence. Often, it is in the form of software, which attempts to perform like a human expert in a constrained and deep field of knowledge by using heuristics or rules of thumb. It tries to achieve a desired control-loop response by incorporating tuning rules experienced by control engineers to manually tune controllers plus additional rules discovered during field tests.

In automation and control, there are two types of expert systems—diagnostic systems and design systems. Diagnostic systems are used to suggest reasons for a failure or malfunction. In design systems, alternatives to human controllers to make decisions are implemented. The tuning changes the process response without any need for mathematical modeling. The control-loop response is expressed in terms of patterns, such as peak heights, periods, slopes, frequency contents, and zero-crossings. The control structure is usually chosen as the PID controller because of its widespread use in industry. The discrete nature of the pattern characteristics is combined with the tuning rules that are expressed in IF-THEN-ELSE format.

The model-based self-tuning approach depends on the process model. It tries to achieve a desired control-loop response by updating coefficients in the model and using the coefficients to calculate the control parameters. The model-based approach is flexible enough to accommodate a wide variety of parameter identification techniques and controller design strategies such as optimal control. For good control, the model must describe the system accurately by taking the nonlinearities, disturbances, dead-zones, and backlashes into consideration. The self-tuning laws (e.g., pole placement and minimum variance control) entail a system identification, such as a Kalman type filter, and then mapping these parameters into the control parameters by the use of appropriate functions. The self-tuning controllers combined with artificial intelligence and optimal control techniques find a wide range of applications in automation and control. A typical implementation of an adaptive controller is illustrated in Fig. 15.

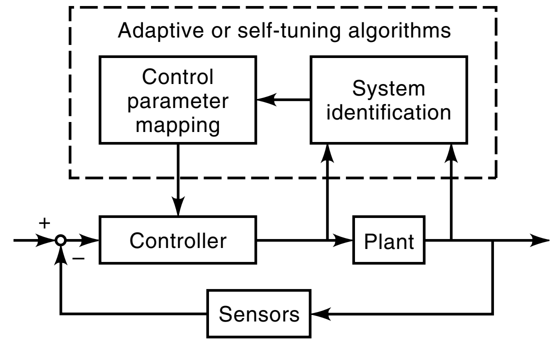

Figure 15. A self-tuning adaptive controller. The tuning of process controller is done by changing the coefficients of the model and setting the control parameters accordingly. For this purpose, parameters must be identified carefully to represent the model. The implementation of an adaptive controller is achieved by using computers and microprocessors.

The implementation of the closed-loop adaptive controller depends on the way that the model is constructed from the process. If the process model is known a priori, the control system is known as the model reference adaptive system (MRAS). If the model is constructed by identification methods, the system is called a model identification adaptive system (MIAS). Most commercial systems are MIAS type, and they are in digital form, although analog forms are also available.

A simple way of getting information on the process behavior is by using pattern recognition. The time response of a process can be analyzed with simple rules, and the new parameters are calculated and set according to the known tuning rules. The result is analyzed again, and optimum tuning is achieved after some iteration. Self-tuning algorithms are used to track overshoots, damping, and process periods to calculate the tuning parameters. The basic control algorithm is usually PID three-term control. Other algorithms, such as deadbeat and minimum variance, are also used extensively.

Electronic industrial adaptive controllers are available to provide accurate process control, adaptation, and autotuning, using digital technology and microcontroller chip sets. The main control loops of the controllers use algorithms that are based on the single-loop control, ratio control, dual-loop cascade control, auto tuning, gain-scheduling, adaptive PIDs, and so on.

Currently, adaptive control techniques are combined with other control technique, such as fuzzy logic controllers. For example, an adaptive fuzzy controller can be constructed from a set of fuzzy IF–THEN rules whose parameters are adjusted on-line according to some adaptation law for the purpose of controlling the plant to track a given trajectory. The adaptive fuzzy controllers may be based on the Lyapunov synthesis approach. It is generally required that the final closed-loop system be globally stable in the sense that all signals involved (states, controls, parameters, etc.) must be uniformly bounded. Adaptive fuzzy controllers can be designed by following these steps. First, construct an initial controller based on linguistic descriptions (in the form of fuzzy IF–THEN rules) about the unknown plant from human experts; then, develop an adaptation law to adjust the parameters of the fuzzy controller on-line. This approach of combining different control techniques has several advantages: (1) all signals in the closed-loop systems are uniformly bounded, (2) the tracking errors converge to zero, (3) no linguistic information is necessary, and (4) after incorporating some linguistic fuzzy rules into the controllers, the adaptation speed becomes faster and the tracking error becomes smaller.

MACHINE TOOLS

Machine tools are an important part of industrial automation. The basic property of machine tools is the ability to position the axes of a machine accurately and to control the cutting feeds and speeds from the information created by the user. There are two basic types—numerical control (NC) machines and computerized numerical control (CNC) machines.

The shaping of metal by means of cutting tools was one of the first manufacturing processes to be automated. An example of machining a high volume of metals at high production rates is the transfer line arrangement. A transfer line is divided into a series of workstations, each performing a designated machining operation. The raw work parts enter from one end of the transfer line, proceed through the workstations, and emerge at the other end as a completed part.

Modern machine tools are precision devices that are controlled by computers. Because of recent advances in technology and the application of computers, the new generation of intelligent machine tools are able to communicate and cooperate with others, conduct the premachining preparation, carry out the machining operation, process the postoperation information, and learn the process performed for the future applications.

Several control techniques are applied to industrial machining processes, such as adaptive and other advanced control methods, and artificial intelligence. As an example, several adaptive control strategies developed particularly for metal-cutting machine tools have self-tuning capability in cutting and milling operations. The control objective is directed mainly to maintain the geometric accuracy of the workpiece. These strategies often involve look-up tables to be able to implement advanced methods such as hierarchical fuzzy controllers. By using these techniques, the index known as the *metal removal rate* is increased, and the in-process time is reduced, thus higher production rates can be obtained.

Another form of machine tools is numerical control (NC), which is a form of programmable automation. In NC, numbers rather than symbols that have been coded in a storage medium control the machine. In modern NC systems, the storage medium usually is the computer or microprocessor rather than punched paper tapes or other storage media, which were used in the past. The coded numbers in the program use sequencing to indicate the various positions of the cutting tool relative to the work part. Usually, position feedback mechanisms are used to verify that the coded instructions have been performed correctly.

One of the most important applications of machine tools is in the manufacturing industry. Three types of automation systems can be associated with machine tools in manufacturing: (1) fixed, (2) programmable, and (3) flexible automation. In fixed (or hard) automation, the equipment configuration is fixed. The preprogrammed commands are contained in the machines in the form of cams, gears, wiring, and other hardware that is not easily changed from one type of product to another. The programmable and flexible automation systems are extensively used in flexible manufacturing systems (FMS). In this case, several machine tools are connected by means of a materials handling system, all controlled by a central computer. Each machine is controlled by a CNC system, and the central processor sends programs to each controller in accordance with a preplanned schedule.

Flexible manufacturing systems are composed of several machining and/or turning centers. To be cost-effective, these manufacturing systems need a particular range of products, a minimum batch size, and/or recurrent products. However, especially in tool shops, these conditions seldom occur because single-part production with total specifications is common. In tool shops, it is important to make the product as soon as possible immediately after the design is ready, in order to meet customers expectations. Therefore, machine tool manufacturers have adapted their machines to the demands of their customers.

Modern machine tools are integrated with computers and microprocessors, which give them advanced capabilities as previously explained. Recent advances in other areas of technology have also contributed to progress in the design and use of machine tools. A typical example is the use of laser technology. In the last few years, lasers have found applications in production engineering as tools for surface treatment, cutting, welding, drilling, and marking. By combining conventional metal-cutting technologies with laser processes in one machine, complete processing of a workpiece with different technologies in one setting is realized. One of the main advantages of the integration of lasers into machine tools is the reduction of material flow between the production machines, which leads to a reduction in processing time and logistics and an enhancement of manufacturing quality.

One point worth mentioning here is that using machine tools in industry is expensive; therefore, their efficient operation is important. Because of the substantial investment in tools and the high cost of tooling in machining centers, the cutting and idle times are generally optimized by considering the tool consumption and the nonmachining time cost components. In most computer-aided processes, plans are made continually to improve system effectiveness by means of tool-operation assignments, machining conditions, appropriate tool magazine organization, and an operations sequence that results in minimum production cost.

FUZZY LOGIC CONTROLLERS

Even though conventional controllers have served their purpose in most automation and control applications, they are based on the assumption of precise mathematical characteristics of the system and the controller. However, accurate mathematical models of a complex real-life system are difficult, if not impossible, to determine. This is mainly caused by the nonlinearity of the plant, the uncertainty of the operation situations, and the involvement of a large number of variables and constraints. Other factors that contribute to further difficulties are noise, limitations on the measurement instruments, and a wide range of temperature variations. This has

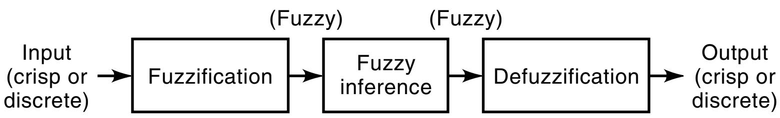

Figure 16. Basic structure of fuzzy controllers. These controllers find a wide range of applications in automation and control. Fuzzification, fuzzy inference, and defuzzification are the three basic steps in the implementation of fuzzy controllers.

led to the study and development of alternative control strategies to overcome such problems. An example of such efforts is the development of the fuzzy logic controller (FLC). The FLC study originated in the early 1970s when the first linguistic rule-based controller for a laboratory-scale steam engine was developed. Since then, FLC has gained acceptance and has been recognized as a viable solution to a broad range of control applications. This includes domestic appliances, industrial process plants, and the automotive industries. The following sections provide a description of the basic structure of an FLC and a discussion on the implementation of fuzzy logic controllers.

The basic structure of an FLC is shown in Fig. 16. A control action is derived based on three basic steps: fuzzification, fuzzy inference based on a set of fuzzy rules, and defuzzification. Prior to the description of these procedures, an introduction to fuzzy set theory and its operations must be introduced.

The theory of FLC is fundamentally based on fuzzy set theory proposed by Professor L. A. Zadeh in the mid 1960s. In classical set theory, operations are limited to and based on a binary system. An element x is considered to be either a member of a set or not a member of a set as shown in the following expression

$$\text{Membership of a set } A, \mu_{\text{A}}(x) = \begin{cases} 1, & \text{if } x \text{ is a member of } A \\ 0, & \text{if } x \text{ is not a member of } A \end{cases} \tag{18}$$

A threshold value is normally used to determine such membership, that is,

$$\begin{aligned} \mu_{\text{A}}(x) &= 1, \quad \text{if } x \geq \text{ threshold value} \\ \mu_{\text{A}}(x) &= 1, \quad \text{if } x < \text{ threshold value } T \end{aligned} \tag{19}$$

However, such threshold value is arbitrary in real life, especially in situations where human decisions are involved. For example, one may consider a height of 1.9 m as the threshold value of “tall.” But surely, one cannot conclude another person with a height of 1.89 m as “not tall.” On the other hand, someone of 1.4 m has little chance to be considered as a tall person. Hence, the term “tall” is fuzzy in the sense that it has no discrete or “crisp” threshold value. So, when one tries to relate the height of a person to some form of linguistic descriptions, a mapping as shown in Fig. 17 is more appropriate. Such mapping is termed a fuzzy set of the term “tall” and it can be expressed as

$$\mu_{\text{A}}\text{:} \quad X \to [0, 1] \tag{20}$$

where μ is the membership value between 0 and 1, X is the physical height and A is the fuzzy term.

A number of mathematical functions have been used by fuzzy logic practitioners to implement the mapping between the value X and fuzzy membership. Examples are Gaussian, quadratic, cubic, triangular, and trapezoidal. By far, triangular or trapezoidal functions are the most popular because of the simplicity of implementation and calculation. The number of fuzzy terms can also be extended to any number n. In the case of height, other fuzzy terms such as extremely tall, very tall, and medium tall can also be incorporated if so desired.

Basic operations on the fuzzy sets are similar to those used in classical logic operations. They are complement (NOT), intersection (AND), and union (OR). Similar to the many mathematical expressions proposed to implement the fuzzy functions, there have been numerous methods suggested to calculate the results of the fuzzy operations. Again, the most popular and simple method is described here, and readers interested in other forms are encouraged to consult the reading list. The basic operations are

$$\begin{aligned} &\text{Complement (NOT):} && \mu_{-A}(x) = 1 - \mu_A(x) \\ &\text{Intersection (AND):} && \mu_A(x) \bigcap \mu_B(y) = \min[\mu_A(x), \mu_B(x)] \\ &\text{Union (OR):} && \mu_A(x) \bigcup \mu_B(x) = \max[\mu_A(x), \mu_B(x)] \end{aligned} \tag{21}$$

Two sets A and B are defined by two different variables, x and y. The set A is the input variable, and B is the output command. Now the fuzzy relationship can be established in the form of IF A THEN B. The relationship function denoted by R can be defined as $R = A \times B$ in which the values are calculated from

$$\mu_R(x, y) = \mu_{A \times B}(x, y) = \min[\mu_A(x), \mu_B(y)] \tag{22}$$

In the context of control, a sample relationship or rule can be established as

IF the error is large, THEN the control action is large.

A set of rules is then required to represent the knowledge on how to determine the output based on the fuzzy inputs. This

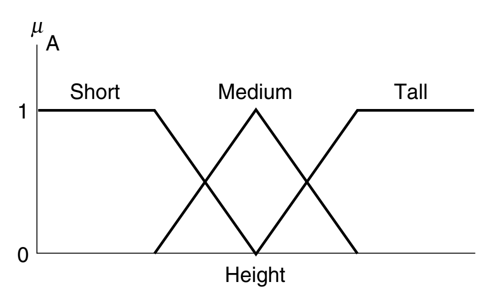

Figure 17. Mapping in fuzzy controllers. The basic operation of a fuzzy controller is similar to classical logical operations. Mapping is an important step in determining the membership. The mapping may be Gaussian, trapezoidal, cubic, etc.

forms the fuzzy rule base of the system. In order to infer the output, the composition rule of inference can be used:

$$\mu_{B'}(y) = \max_x \min[\mu_{A'}(x){:}\, \mu_R(x, y)] \quad (23)$$

This means that given the fuzzy relationship of R between A and B, and the input of A is y', the membership of the fuzzy output variable, B is y'. For multiple inputs and outputs, the fuzzy relationship can be extended as follows:

R_1: IF *Error is large* AND *Change of Error is small* THEN *Action is medium.*
R_2: IF *Error is small* AND *Change of Error is small* THEN *Action is small.*

Because these basic operations are simple and the hardware/software is easy to implement, fuzzy controllers offer attractive solutions when compared to the alternative highly complex mathematical techniques.

Fuzzification, Fuzzy Inference, and Defuzzification

Fuzzification is the process of converting the discrete or crisp input variables to fuzzy variables. It is essentially a mapping between the range of input to the membership values of each fuzzy variable. This is where the definitions of fuzzy sets determine the membership values.

Based on the composition rule of inference, the fuzzified input is then applied to each rule in the rule base to determine the membership value of the output from each rule. The output at this stage is in fuzzy format expressed in membership values for each variable.

This process translates the fuzzy outputs from the inference process into a discrete or crisp output value. There are again many suggestions for the calculation of the output values based on fuzzy membership values.

Implementation of Fuzzy Logic Controllers

Implementation of a fuzzy logic controller has traditionally been realized with a software program running on a general-purpose computer platform. Many commercial software packages or tools are now available to aid the development of the fuzzy rule base, fuzzification, defuzzification, and inference processes. These software tools include Fuzzy Logic Toolbox from MatLab, FIDE from Aptronix, RT/Fuzzy in MATRIX, CubiCalc from HyperLogic, and the fuzzy logic code generator, just to name a few examples. The main features of such tools are the improvement of productivity in the design process, the incorporation of a simple or user friendly interface, and the ability to integrate fuzzy logic without knowing how to implement it from ground level. These packages normally vary in terms of prices, computing platforms, programming approaches and interface, services, technical support, and future development of the product. Also, software tools are designed to generate code specifically for dedicated microcontrollers and digital signal processing (DSP) devices such as the 8051, 80C196, TMS-320, HC05, HC11 and HC12. This allows the development of a dedicated microcontoller-based system instead of a general-purpose computer.

On the other hand, hardware implementation of a fuzzy logic controller is now possible with new devices and off-the-shelf control systems. The main advantage of hardware implementation is the increase in the cost–performance ratio. However, this puts limitations on the number of variables and the number of rules that can be handled. Examples of such dedicated processors are the AL220 from Adaptive Logic and the VY86C570 fuzzy coprocessor from Togai InfraLogic. Another approach to hardware implementation is the integration of fuzzy logic into conventional control devices such as the PID and PLC controllers. An example of this approach is the Omron E5AF temperature controller, which integrates an advanced PID control unit and a fuzzy logic unit.

NEURAL NETWORK BASED CONTROLLERS

Control law is essentially a mapping from measurement history to commands. To this extent, it is possible that the history can be learned by machines using some appropriate self-learning or that self-taught techniques and decisions can be made automatically. The generic term for machine learning is artificial intelligence. Among many others, the artificial neural network (ANN) is one of the branches of AI.

Artificial neural networks are based on the idea of merging the mechanism of the biological operation of the human brain with computing theories. The ANN is composed of numerous single computational elements, known as *neurons,* operating in parallel as shown in Fig. 18. A computational element sums the weighted inputs and passes the result through a nonlinear function. A sigmoid function is used as the nonlinear element. A typical sigmoid function is

$$f(y) = \frac{1}{1+e^{-y}} \quad (24)$$

For a single neuron, if the result of the sigmoid function is above a built-in threshold level, the element is activated and set to a trained value. There are many different variations of ANN; for example, in this article the discussion will center on back-propagation and feedforward error back-propagation techniques, which are the most basic ones.

The feedforward error back-propagation network (EBP) is composed of a number of layers of neurons, as illustrated in Fig. 18. The neurons are characterized by activation functions and threshold levels. Although there are some variations, in

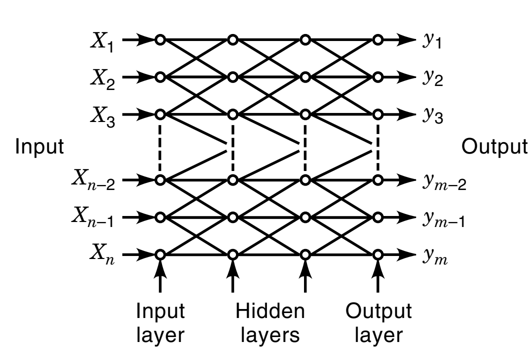

Figure 18. Layers of an artificial neural network. An ANN is composed of computational elements called neurons. The weights of these neurons are adjusted depending on relations of the inputs and outputs to the neuron. There are a number of layers such as input layer, output layer, and hidden layers.

general, the following sigmoid activation function is often used:

$$v_j = \frac{1}{1 + e^{(-\beta\phi j)}} \tag{25}$$

where v is the activation at neuron j with the value of potential ϕ, and β controls the steepness of the activation function.

The network is comprised of synapses connecting the layer of neurons and the input potential. ϕ for a neuron is defined as

$$\phi_j = \sum_i W_{ij} v_i + \tau_j \tag{26}$$

where W is the weight of the synapse between neurons i and j, v is the activation state of neuron i, and τ is the threshold of neuron j.

The training technique back-propagation error is based on the comparison between the output pattern produced by the forward pass and the target values resulting from a specific given input pattern. The absolute differences are collected in a summation function, and an error E is calculated. By beginning each weight at the output nodes and working back to the weight at the input layer, a gradient is determined. This process is described as the back propagation of an error. The gradients are then summed for each weight over the combination of all the input and output patterns. As a function of the resulting gradient, the weights are then updated.

$$\Delta W_{ij}^n = \eta \sum_P \frac{\partial E}{\partial W_{ij}} \tag{27}$$

In this weight update rule, the index n refers to the nth iteration in the process, and η describes the learning rate, being a discrete step size. This procedure is iterated until error E for all outputs is within the predetermined tolerance or until the predefined number of iterations is reached. The process is essentially an improved gradient descent optimization technique performed on the energy surface. The dimension of this surface is equal to the number of weights in the network.

Common to all steep descent methods is the problem of the choice of the step size. A large value for η will induce rapid learning, but it will also lead to oscillations and instability, in which circumstances the network may fail to converge. On the other hand, a small step size will result in a slow convergence, and it may be trapped in local minima. Some of these problems may be addressed by adding a momentum term, which changes the weight update rule as follows:

$$\Delta W_{ij}^n = -\eta \sum_P \frac{\partial E_P}{\partial W_{ij}} + a \Delta W_{ij}^{n-1} \tag{28}$$

where α is the momentum term in the range from zero to one.

The effect of this is the learning rate for flat regions of weight space or across local minima; whereas in steep regions, movement is focused downward by damping the oscillations caused by the alternating signs of the gradient.

Neural networks are capable of tackling linear and nonlinear continuous and discrete control tasks. They are applied in the form of software supported by the appropriate hardware. Common mathematical packages, such as MATLAB, support ANN design tools. The hardware implementation can be done by electronics such as Intel's ETANN 80170 chip. Generally, the programmed commands determine the action to be accomplished by the automated system. These commands specify what should be achieved by the system and how the various components of the system must function to accomplish the desired result. The contents of the program is developed depending on the system, and it can vary from one automated system to another even if they are performing similar tasks. In some simple cases, the programs may specify a limited number of well-defined actions that are performed repeatedly in sequential or cyclic manner. In the case of complex systems, the level and number of commands can be very high and detailed. It is also possible to change programs and commands to perform different tasks.

The commands are related to feedback systems by establishing appropriate inputs for each loop or various loops that make up the entire system. In automation systems, not all the programmed commands are electrical, but they can be mechanical in the form of mechanical cams or linkages. However, it is common today for automated equipment to use computers or microprocessors to generate, store, and execute commands for controlled action.

Artificial neural networks are applied to all aspects of automation and control systems. A typical example is machine learning used in the decision-making process in manufacturing. The machine-learning techniques are applied to represent the machine-specific performance behavior of machine tools for a "knowledge base" in intelligent machining. Accessing this knowledge base allows the selection of process parameters for a given machining operation on a specific machine tool based on the desired evaluation criteria. Determining the process parameters in this manner replaces less accurate methods such as reading process parameters from machining tables. The learning algorithms use an artificial neural network structure to map the process parameters to the evaluation criteria. Learning is achieved by exposing the algorithm to training data.

Another example of applying ANN to intelligent control in modern process automation is fault detection. The ability to detect faults is essential to improved reliability and security of a complex control system. Parameter estimation methods, state observation schemes, statistical likelihood ratio tests, rule-based expert system reasoning, pattern recognition techniques, and artificial neural network approaches are the most common methodologies employed. The artificial neural network, through a back-propagation learning algorithm combined with fuzzy approximate reasoning for fault diagnosis, yields superior results compared to the other methods. Analytical fault symptoms are usually obtained by system dynamics measurements and classification through a multilayer feedforward network. The control actions are based mainly on fuzzy reasoning.

Robots are an important part of automation systems, particularly in the manufacturing industry. Artificial neural networks, with such characteristics as learning, graceful degradation, and speed inherent to parallel distributed architectures, provide a flexible solution to the real-time control of robotic systems. Artificial neural networks are generally used to learn about the process and to coordinate transformation mapping of robots. In many cases, hybrid controllers that include some form of multilayered neural networks are used. In this way, the dynamics of the environment that is contacted can be identified and optimized to determine the parameters of controllers such as PID controllers. After being trained, the robots respond to the training patterns with flexibility and adaptability to the differences between the patterns.

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AUTOMATION, HOME. See Home automation.
AUTOMATION OF BANKS. See Branch automation.
AUTOMATION, OFFICE. See Office automation.
AUTOMATION OF POSTAL SERVICES. See Postal services.