Technology Trends in Microcomputer Control of Electrical Machines

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Abstract—Computer automation of factories, homes, and offices is ushering a new era of industrial revolution. Our automated factories, homes, and offices of the future will significantly advance our industrial civilization and profoundly influence the quality of human life on this planet. Microcomputer-based intelligent motion control systems which constitute the workhorses in the automated environment will play a significant role in the forthcoming era.

Electronic motion control technology has moved a long way since the introduction of power semiconductor devices in the mid-1950's. In course of its dynamic evolution during the last three decades, the area of motion control has grown as diverse interdisciplinary technology. The frontier of this technology has taken a new dimension with the advent of today's powerful microcomputers, VLSI circuits, power integrated circuits, and advanced computer-aided design (CAD) techniques.

The paper gives a comprehensive review of state-of-the-art motion control technology in which the salient technical features of electrical machines, power electronic circuits, microcomputer control, VLSI circuits, machine controls and computer-aided design techniques have been discussed, and wherever possible, appropriate trends of the technology have been indicated.

I. INTRODUCTION

Microcomputer-based intelligent motion control systems are playing a vital role in today's industrial automation. In an automated industrial environment, a hierarchical computer system makes decisions about actions based on a preset strategy, and a motion control system, as a workhorse, translates these decisions into mechanical action.

Today's motion control is an area of technology that embraces many diverse disciplines, such as electrical machines, power semiconductor devices, converter circuits, dedicated hardware signal electronics, control theory, and microcomputers (Fig. 1). More recently, the advent of VLSI/ULSI circuits and sophisticated computer-aided design techniques has added new dimensions to the technology. Each of the component disciplines is undergoing an evolutionary process, and is contributing to the total advancement of motion control technology. The motion control engineer today is indeed facing a challenge to keep abreast with this complex and ever-growing multidisciplinary technology.

Motion control is a new term defined by the present generation of engineers. It is an offspring of electrical machine drives technology, which has grown at a rapid pace over the last two decades. The era of electronic motion control essentially started with the advent of power semiconductor devices in the late 1950's, though hydraulic, pneumatic, and other mechanically driven actuation systems were known for a long time. Gradually, the use of integrated signal electronics simplified the electronic control hardware. The introduction of microcomputers in the early 1970's profoundly influenced motion control systems, not only by simplifying the control hardware, but by adding intelligence as well as diagnostic capability to the system.

We have seen an explosive growth in the application of motion control systems during recent years. Mechanical motion control systems found widespread acceptance in industry since the invention of the steam engine started the first industrial revolution in the eighteenth century, when mass industrial manufacturing replaced manual labor. Since then, the evolution of motion control engineering has been influenced by the development of electrical machines, vacuum tube electronics, gas tube electronics, saturable reactor magnetics, solid-state electronics, and control theory. The advent of computer technology and microelectronics during recent years has brought us to the doorstep of a second industrial revolution. Today, a tremendous momentum has developed for computer automation of our factories, homes, and offices. The principal motivation for this automation is improvement of productivity and quality and minimization of less predictable human elements; and these motives in turn are being inspired by international competition. Computer-aided design (CAD) and computer-aided manufacturing (CAM) are playing increasingly important roles in factory automation. The concept of computer-integrated manufacturing (CIM), in which business decisions are translated to designs, which are then translated to manufacturing through a hierarchy of
computers and motion control systems, will become a reality in the near future.

A motion control system, as mentioned before, is the workhorse through which higher level computer decisions are translated into mechanical actions. Motion control applications in industry include robots, numerically controlled machine tools, general-purpose industrial drives, computer peripherals, and instrument type drives. In the home, applications include home appliance drives for washers, dryers, air-conditioners, blenders, mixers, etc. In a typical computer-controlled manufacturing system on a factory floor, as illustrated in Fig. 2, there are three layers of control. The master control (usually a minicomputer) operates the entire network. It includes parts transportation and material handling on machine tools by robots. The direct numerical control (DNC) unit, usually a second minicomputer, collects programs for the microcomputers which directly control the machine tools. The computerized numerical control units (CNC), in addition, contain diagnostic programs that can detect mechanical and electronic malfunctions in a machine tool and report them to central controllers. The data entry units allow communication between the operator and the DNC computer.

In motion control systems, the application of robots is of significant interest today. The robot essentially symbolizes the challenge of synthesizing all state-of-the-art component technologies shown in Fig. 1. The modern industrial robot was introduced by Japan in 1980, and since then, it has evolved from performing simple tasks, such as handling and transferring, to performing sophisticated work including welding, painting, assembling, inspection, and adjustment. In Japan, the world leader in factory automation, almost two hundred thousand robots are in operation today. This is about 60 percent of all industrial robots in the world. One noticeable trend is the growth of robot use in non-manufacturing fields, for example, nuclear power generation, medical service and welfare, agriculture, construction, transport and warehousing, underwater work, and space exploration. More intelligent robots that will mimic the brain and muscles of human beings will be put to work in the future, for factory, home, or office automation.

The application of motion control has growth at a phenomenal rate in the computer peripheral industry. For example, in the U.S. alone, electronic printers, disk drives and tape drives used 24 million motors in 1983. and this figure is expected to rise to a staggering 80 million by the year 1988. It has been estimated that an average American home uses 50 motors in all the household appliances, and this amounts to a staggering 12.5 billion motors in all U.S. homes. Eventually, all these motors will be controlled by microcomputer. In an automated home of the future, all the motors will have a central home computer-based control through an integrated power-and-signal wiring system. Similar integrated motion control concepts will be applied to automobiles, airplanes, and so on.

This report is intended to review the technology trends of motion control that relate to electrical machines, power semiconductor devices, converter circuits, microcomputers, VLSI circuits, control of machines, and computer-aided control design techniques. Particular emphasis will be paid to intelligent motion control based on microcomputers. Again, motion control systems that use small machines will be our main theme of discussion. The literature on motion control has grown enormously, and proliferated so diversely that it is impossible to deal with all the aspects of the technology. Therefore, only the salient features will be highlighted.

II. ELECTRICAL MACHINES

An electrical machine is an electromagnetic energy conversion device that translates its input electrical energy into output mechanical motion. Electrical machines have been available for nearly a century, and during this period the world's leading universities, research laboratories, and industries have made extensive studies of them. The evolution of machine technology, unlike that of electronics and computer science, has been long and slow, and we have not seen any dramatic invention in this area for a long time. The first machines were bulky, expensive, and had poor performance. Better understanding of machine principles coupled with evolution of new and improved materials has contributed to the improvement of machine design. The advent of modern digital computers and more recently the theory of finite element design have helped in further design optimization.

In motion control applications, the prime competitive candidates in electrical machines are dc machines, induction machines, synchronous machines (brushless dc form), step motors, and switched reluctance machines. Recent literature on motion control has extensively discussed the behavior of these machines. To a unified machine analyst, the generic behavior of all the machines is the same. A dc machine is essentially an ac machine internally, where commutators and

1This year the Polytechnic di Torino, Italy, is celebrating the hundredth anniversary of induction machines.
brushes function as elements of a position-sensitive mechanical inverter. Here, the orthogonal disposition of field mmf and armature mmf is the prime reason for enhanced speed of response. This type of machine has been traditionally favored in electronic motion control applications, and by far the majority of industrial drives today use this type of machine. Although its control principle and converter equipment are somewhat simple, a dc machine, in general, is bulky and expensive compared to ac machines. In addition, the principal problem of a dc machine is that its commutators and brushes make it less reliable, and unsuitable to operate in a dusty or explosive environment. A dc machine definitely needs periodic maintenance. High reliability and maintenance-free operation are prime considerations in industrial motion control systems.

For these reasons, we are beginning to see a tremendous surge in the application of ac machines in motion control systems. Historically, ac machines, such as the induction and synchronous types, have been favored for constant-speed applications. In the last two decades, ac motion control technology has grown by leaps and bounds. Traditionally, the induction machine, particularly the cage type, has been the workhorse in industry because of its ruggedness, reliability, efficiency, and low cost. Although ac machines are simple, the cost of conversion and control equipment is generally high, which makes the total drive system expensive. The scenario has been changing recently, however, because of the advent of the integrated converter and microcomputer-based controllers. One reason for the control complexity of an ac machine is its complex dynamic behavior, which must be taken into consideration in feedback control systems. An ac machine is basically a nonlinear multivariable system with coupling between direct and quadrature axes, and its dynamic model is usually specified by a state-space equation in a synchronously rotating reference frame.

An induction motor always operates at a lagging power factor because its rotor field excitation has to be supplied from the stator side. In a permanent magnet synchronous machine, however, the field is established by the magnets. The stator will supply reactive current only (leading or lagging), if mismatch between supply voltage and induced voltage demands it. The concept of a brushless or commutatorless dc motor using a synchronous machine was developed by Ohno et al. [8]. A dc machine is a synchronous machine internally with magnets on the stator and armature on the rotor (commutators and brushes serve as the rotor position commutated inverter, as mentioned before). The same operation mode is possible if magnetics are transferred to the rotor, and the stator which contains the armature winding is supplied with ac power through an electronic inverter. The inverter commutation or gating signals must now be derived from a rotor position encoder to maintain absolute synchronism between magnet fluxes and stator winding induced fluxes. The reward of eliminating mechanical commutators and brushes is offset to some extent by the penalty of an absolute position encoder in the rotor and an expensive electronic inverter with the complex control. Besides in this new configuration, a dc machine-like transient response may not be straightforward.

It is important to mention that PM machines have essentially two different configurations. The conventional surface magnet machine (Fig. 3(a)) is essentially nonsalient (it has a large airgap) and is popularly used in a brushless drive. The large airgap again weakens the armature reaction effect, and therefore the operation is essentially restricted to a constant torque region. Recently, synchronously machines have been introduced with interior or buried magnets (Fig. 3(b)), which, because of their narrow airgap, overcome the above drawback of surface magnet machines. A buried magnet machine is essentially a hybrid machine in which torque is contributed by the reluctance component as well as the field component. The evolution of magnet materials is contributing to the size reduction of PM machines. Fig. 4 shows characteristics of several viable magnet materials. Ferrite material, which is low in cost and has excellent demagnetization linearity, is traditionally used in PM machines, but the machine tends to be bulky because of low remanence. Cobalt-samarium has a higher energy product and excellent temperature insensitivity, but its high cost restricts its use for specialized applications. The neodymium–iron–boron magnet, which has been introduced only recently (June 1983), has maximum remanence and coercive force force, and because of its reasonably low cost, shows great promise for future applications. This material, however, has some temperature sensitivity which must be taken into consideration during machine design.

In incremental motion control applications, the most widely used class of machines is step motors. While the machines discussed so far are characterized by continuous motion, step motors are characterized by discrete steps of motion and respond directly to digital command pulses. Step motors have been available for nearly half a century, but much attention has been focused on them recently because of the surge of

![Fig. 3. Profile of permanent magnet machines. (a) Surface magnet machine. (b) Interior magnet machine.](image-url)
applications in the incremental motion control industry. Basically, step motors have characteristics similar to synchronous machines and are constructed in PM hybrid form or variable reluctance form. An example of a variable reluctance step motor with 1.8° step movement is shown in Fig. 5(a). A step movement of the rotor corresponds to the effective angular rotation of stator poles created by the stator winding mmf’s. The inherently simple and economical construction of this “brushless” machine coupled with its simple open-loop control makes it extremely popular in the motion control industry. However, a number of performance penalties must be paid for these good features. Besides limited angle resolution, the open-loop synchronous machine-like operation gives load-dependent position accuracy, underdamped step response, high loss, and a tendency to lose synchronism as speed is increased. However, these characteristics are not limitations in application such as printer and disk drives and remote indicators, where these machines are most popularly used. As the market for motion control systems grew, the proponents of step motors came out with sophisticated controls using position encoder signals to solve some of the above problems. With these modifications, however, the appeal of inherent simplicity and economy is lost, and the margin of difference between step motor drive and brushless dc drive is narrowed. In summary, the points in favor of the closed-loop controlled step motor in comparison with the brushless dc motor include the following.

1) Below a few hundred watts of power, a PM step motor is cheaper than a PM synchronous motor, mainly because the former needs only one magnet, whereas the latter needs four (four poles).
2) A large holding torque and a high stiffness near the detent position are inherent in a step motor, whereas in the brushless dc motor the feedback mechanism (which may be sluggish) is responsible for establishing the above parameters.
3) A step motor requires a simple incremental position encoder, whereas a brushless motor needs an absolute position encoder.

The switched reluctance machine (SRM), the principle of which has been known for over a century, has seen a revival of interest in recent years for small-machine drives. Basically, the SRM is a variable-reluctance, continuous-movement machine (Fig. 5(b)), which is structurally identical to the single-stack, reluctance-type step motor. In this machine, continuous movement is regulated by current magnitude control and rotor synchronized commutation of stator phases, where commutation signals are derived from an absolute position encoder. The control is analogous to that of a concentrated winding brushless dc machine, and speed can be smoothly increased beyond the constant torque region. One drawback of this machine is its large pulsating torque, which makes it difficult to apply in position servo drives. Pulsating torque compensation has been proposed through such schemes as pole shaping, current command profiling and adaptive feedback control, and these show good promise.

III. POWER CONVERTERS

An electronic power converter translates the control signal at the input to the power actuation signal for the machine. The modern era of electronic motion control technology came into existence because of the advent of power semiconductor devices. These devices have grown in power rating and performance by an evolutionary process in the last two and a half decades. The improvement of device model, computer-aided simulation and design techniques, and semiconductor processing improvement have contributed to performance enhancement. Silicon is the principal material and will remain so in the foreseeable future. Phase-control thyristors were first introduced in the late 1950s; they found ready acceptance in
rectifier controlled dc machine drives and variable-voltage constant-frequency controlled induction machine drives. The devices that are primarily important for small machine control applications are power transistors and power MOSFET's.

Bipolar Darlington transistors have been established as power switching devices for the high end of motion control converters. Second breakdown effects were the prime killers of power transistors for a long time. Today, these phenomena are understood better, and devices and circuits are being designed for better reliability and higher utilization factor.

Power MOSFET devices were introduced in the late 1970's, and these devices have found a tremendous growth of applications in converters up to several hundred watts. This frontier is expanding with the introduction of higher power devices in the market. Unlike the bipolar transistor, the MOSFET is a majority voltage-controlled device. Its second breakdown effect is minimal. One great demerit of the MOSFET is its high conduction drop; this drop increases with voltage rating and operating temperature. The on-resistance of the device has been improved over the last several years, but there seems to be a fundamental limit for silicon. While the conduction loss of the MOS device is high, its switching loss is almost negligible. In sinusoidal-output inverter applications, the PWM frequency can be extended to a high value so that conduction loss is offset by an improvement of the machine harmonic loss.

Very recently, we have seen the emergence of several hybrid power semiconductor devices. An example is the insulated-gate transistor (IGT), which is also known as the GEMFET or COMFET. It is essentially a MOSFET-driven bipolar transistor, and, therefore, combines the advantages of both the devices. It has the high input impedance of the MOSFET but the low conduction drop of the bipolar device. The switching speed is slow because the minority carrier storage and the second breakdown effect of the bipolar device are retained. The device has thyristor-like reverse voltage blocking capability. IGT's have been introduced in the 500-V 50-A range, and soon this range will be extended. Another hybrid device worth mentioning is the MOS-controlled thyristor. The device, as the name indicates, is designed in such a way that a MOSFET can control the turn-on and turn-off operations of a thyristor.

The converter in a motion control system is expensive, primarily because of the high cost of discrete power devices. The bulk of device cost is due to packaging complexity. The trend toward integration in low power signal electronics is being applied to power circuits also. Hybrid integration of half-bridge of full-bridge converters with or without control electronics has been available for some time. A more significant change is in monolithic integration of power circuits with embedded signal electronics. Such a circuit not only reduces cost and size, but eliminates EMI and interface problems. Further, integration of power devices and control electronics is so-called “smart” power devices brings in easily the additional functions, such as temperature control and overvoltage and overcurrent protections. This would not be possible with discrete power devices. The principal technical hurdles in this area are isolation between high-voltage devices and low-voltage circuits, and efficient thermal management. The birth of power integrated circuit (PIC) technology has brought us to the doorstep of what we call the “second electronic revolution.” The first electronic revolution started with the integration of small signal electronics. Power IC's are already appearing in the low end of motion control applications. Eventually, as the technology advances, these will appear in our home appliances, automobiles, robots, and other factory floor drives. Researchers in this area are optimistic that eventually PIC's will incorporate sensing signal processing, and will directly interface speed and position encoders. Hall sensors, temperature sensors, and so on. If sensing, power control, and signal processing can be combined, a standalone, single-chip system that will interface with a central microcomputer can be constructed, and mounted on the drive machine directly.

Computer-aided power circuit design techniques have evolved over a number of years. Compared to trial-and-error design with the help of a breadboard, computer-based design systems are very convenient for design optimization. Because of its switching elements, a converter is essentially a discrete time system. Therefore, it can be simulated on a digital computer as a time-varying network topology, i.e., in each switching state of a converter, a linear state-space equation can be described and solved by Fortran-like programs. Alternatively, the network can be described as a graph by nodes and branches, and programs such as SPICE II (University of California, Berkeley) can be used. CAD techniques for signal electronics (both logic and analog) and control systems have reached a stage of maturity, and therefore the problem of how to integrate various design and simulation tools of an integrated power system remains. Fig. 6 illustrates a CAD of a converter circuit with conversions and links to the various programs [18]. In the beginning, the user defines a circuit schematic from given specifications and requirements by preliminary analysis and design. The P-CAD (Personal CAD Systems Inc.) programs capture the schematic, extract the netlist, and produce the SPICE input file. The SPICE-NIP translator converts the SPICE input file into the NIP (nodal description input program—California Institute of Technology) input file. The function of NIP is to generate (from a nodal description input file) the state-space equations, output equations, and feedback/forward equations associated with linear switched networks that a converter goes through in each switching cycle. The SCAP (switching converter analysis program—California Institute of Technology) program generates a state-space-averaged model of the converter that can be used to study steady-state and frequency-response behaviors. SIMNON (nonlinear simulation program—Lund Institute of Technology, Sweden) accepts the state-space equations from NIP through a translator and permits the simulation of time domain behavior SIMNON will be further discussed in Section VI. After optimizing the converter design with several iterations, the program can be integrated with controller simulation and/or used to generate the layout of a power integrated circuit.
IV. CONTROL OF ELECTRICAL MACHINES

The advent of gas tubes, such as thytrons and ignitrons in the 1930's, and then, magnetic amplifier or saturable devices in the 1940's gave birth to the first generation of motion control systems using dc machines. Advancement of feedback control theory in post World War II years intensified evolution of the technology, but modern motion control technology was truly born with the advent of power semiconductor devices. In a feedback control system, the machine as well as the converter are elements in feedback loops, and therefore their dynamic models should be taken into consideration. A dc machine, particularly a small machine with a permanent magnet field, can be modeled as a linear second-order system between applied armature voltage and speed-neglecting armature reaction, saturation, temperature, and brush nonlinearity. However, a converter-machine system with digital control is a discrete time system because of the sampling effect. It is convenient to analyze, simulate, and design such a system on a computer.

Control of a dc machine is considerably simpler than that of an ac machine. A dc machine can be interfaced with utility ac supply through a phase-controlled converter, and the output (speed, position, or torque) can be regulated by controlling the converter firing angle. A universal motor can be controlled by anti-parallel thyristors or triac devices. A high-performance dc servo, in which dc power is obtained from a rectified ac supply or from a battery and then controlled by a pulsewidth modulated chopper, is shown in Fig. 7. The addition of inner current control (which is indirectly torque control) and speed control loops not only expand the system bandwidth but help in limiting the excursion of the state variables.

Control of an ac machine with a feedback loop is considerably more complex, and this complexity increases as higher performances are demanded. The main reason for this complexity is that ac machine dynamics are more complex; they must be represented by nonlinear multivariable state-space equations. For example, an induction motor model can be represented by a sixth-order state-space equation, where voltage and frequency are inputs to the stator and the outputs may be speed, position, torque, flux stator currents, or a combination of them. The additional reasons for complexity in ac drives are intricate feedback signal processing and the requirement for complex control of the variable-frequency power supply.

Many different control techniques of varying degrees of complexity have appeared in the evolution of ac drives. The acceptance of a particular method depends on the nature of the application. A simple and economical method of control of an induction motor is to vary the stator voltage at utility frequency through a phase-controlled anti-parallel thyristor or a triac converter. Such a scheme, though inefficient, is used in blower and appliance drives. A simple open-loop volts/Hertz control method has been popularly used for a long time. It will continue to be used in the future for low-performance, low-power, and cost-effective industrial drives. Feedback flux control, torque control, slip control, angle control, etc., have been used extensively where better performance is demanded. The penalty in such feedback controls is the difficulty of feedback signals synthesis using distorted ac voltage and current waves. Problems arise in such a "scalar" control method, because of the nonlinearity of the machine model and the inherent coupling effect between the direct (d) and quadrature (q) axes. The poles and zeros of machine transfer functions vary at each operating point. The control can be optimized at a certain operating point, but the performance will deteriorate if the operating point shifts. Besides, the coupling effect causes sluggish transient response.

The field oriented or vector control techniques are now being accepted almost universally for control of ac machines. Such control methods were developed in Germany in the early 1970's. Blaschke [21] introduced the direct or feedback method of vector control and Hasse [22] invented the indirect or feedforward method. But the world ignored these techniques because of the complexity of their implementation. With the advent of the microcomputer era, such control complexity is no longer a problem.

The vector or decoupling control considers the generic analogy between ac and dc machines (Fig. 8). The underlying principle of vector control is to eliminate the coupling problem between the d and q axes; then an ac machine will behave like a separately excited dc machine. The fundamentals of vector control implementation with the machine model in a synchronously rotating reference frame are explained in Fig. 9. The phase and coordinate transformations within the machine are cancelled by two stages of inverse transformation in the control so that $i_{ds}$ and $i_{qs}$ currents correspond to $i_d$ and $i_q$. 

![Fig. 6. CAD of a converter from a schematic entry.](image)

![Fig. 7. Control block diagram of a dc machine.](image)
respectively. The converter dynamics and sampling delays are omitted for simplicity. The unit vectors \( \cos \omega_t f \) and \( \sin \omega_t f \) assume alignment of \( i_{df} \) (field component) with the flux and \( i_{qs} \) (torque component) orthogonal to it, in order to have dc machine-like decoupling. The vector control not only gives the advantage of fast transient response, but also eliminates the conventional stability limit of the induction motor. The torque relation becomes linear with \( i_{qs} \), and the drive can be easily designed for four-quadrant operation. Of course, the price to be paid for all the benefits is complex coordinate transformation, phase conversion, and intricate feedback signal processing.

Blaschke’s direct method for a PWM voltage-fed inverter with current control is illustrated in Fig. 10. The principal control parameters \( i_{df} \) and \( i_{qs} \), which are dc quantities, are converted to a stationary reference frame with the help of unit vectors as shown. These are then converted to phase current commands for the inverter. The unit vectors are generated from \( d \) and \( q \) components of airgap flux with the help of the phase-locked loop so that \( \cos \omega_t f \) and \( \sin \omega_t f \) are cophasal to
In applications such as servo drives, the drive system must operate at truly zero speed with best possible transient response. The accurate stator drop compensation near zero speed is very difficult. Blaschke derived flux estimation equations which use speed and stator current signals. These equations are valid at any speed (including zero speed), and can be given as follows:

\[
\frac{d\psi_r^q}{dt} = \frac{L_m}{T_R} i_{ds} + \omega_r \psi_r^q - \frac{1}{T_R} \psi_r^q \tag{1}
\]

\[
\frac{d\psi_r^d}{dt} = \frac{L_m}{T_R} i_{ds} + \omega_r \psi_r^d - \frac{1}{T_R} \psi_r^d \tag{2}
\]

where \( T_R = L_r/R_r \) is the rotor circuit time constant, and all other parameters are in standard symbols. The estimation block diagram for unit vectors and rotor flux from these equations is shown in Fig. 11. Note that the estimation is machine parameter dependent; the rotor resistance variation due to temperature and skin effect, and the inductance variation due to saturation, are all important.

Hasse’s method generates unit vectors indirectly from rotor position and feedforward slip signal, the control method otherwise remaining the same as before. Fig. 12 explains the indirect vector control principle with the help of a phasor diagram, and Fig. 13 shows a position servo implementation using this method. In order to satisfy the criteria of decoupling control, the following equations can be established from the rotation frame equivalent circuit [1]:

\[
\omega_d = \frac{L_m R_r}{L_q} i_{qs} \tag{3}
\]

\[
L_r \frac{d\psi_r^q}{dt} + \psi_r = L_m i_n. \tag{4}
\]

In Fig. 13, the \( i_{qs}^s \) signal for the desired rotor flux \( \psi_r \) is determined from (4). The \( i_{qs}^s \) signal, which is proportional to torque, is derived from the speed control loop. The set value of slip \( \omega_d \) is related to current \( i_n \) by (3). The slip angle vectors \( \sin \theta_d \) and \( \cos \theta_d \), which determine the desired electrical axis with respect to rotor mechanical axis, are generated from \( i_{qs}^s \) in a feedforward manner. The rotor position vectors are then added with the slip angle vectors to generate the desired unit vectors for coordinate transformation. Since induction motors can locate the field flux at any position, an absolute shaft position encoder is not needed. In fact, the rotor speed can be added directly with the slip signal, and then unit vectors can be synthesized by a VCO, counter, and SIN/COS waveform generator. Both the indirect method and the direct method are dependent on machine parameters. The dominant parameter to be considered is rotor resistance, which has been estimated on-line by various techniques giving improved performance in decoupling control. Fig. 13 can be modified to incorporate control in the field-weakening region as shown in Fig. 14. Below base speed, the machine operates at constant flux, and, therefore, operation is identical to that in Fig. 13. Above base speed, \( |\psi_r| \) is weakened to be inversely proportional to speed so that the drive system remains under the vector control mode. Note that here flux is controlled in an open-loop manner by solving (4).

Control of synchronous machine drives is, in many ways, similar to control induction drives. Synchronous machines may have essentially two different modes of operation. One is the open-loop true synchronous machine mode, where a simple volts per hertz method of control locks the machine speed with
the frequency of an independent oscillator. This method of speed control is popular in multiple reluctance or PM machine drives where close speed tracking is essential in such applications as a fiber-spinning mill. The other is the self-control mode, in which variable-frequency inverter control pulses are derived from an absolute position encoder. A self-controlled machine, as mentioned before, is known as an electronically commutated motor (ECM), brushless dc motor (BLM), or commutatorless brushless motor (CLM).

Fig. 15 shows a control scheme of a brushless dc drive using a trapezoidally wound surface-type PM machine. Since the induced phase voltages of the machine are trapezoidal in shape, it can be shown that a six-step line current wave in phase with the induced voltage wave will maintain constant developed torque. A Hall-effect or optical encoder properly aligned on the shaft with respect to rotor poles generates three-phase, 180° square pulses, which are shaped to six-step waves by a decoder as shown. The speed loop generates the current magnitude command, which is multiplied by the decoder output to generate phase current command waves. The current control loop generates the voltage command, which is pulse-width modulated (PWM) by a fixed frequency triangular carrier wave. The simplicity of the machine, the position sensor, and the control electronics makes this type of brushless drive very popular in industrial motion control systems. However, the drive has a pulsating torque problem because of the mismatch of current switching instants and the machine counter emf wave. Besides, an extra tachometer is needed for a speed control system as shown in the figure.

For a sinusoidally wound PM machine, the inverter can synthesize sine wave line current, and then the pulsating torque problem does not arise. Since in a surface magnet machine the armature reaction effect is very weak, the stator current phasor can be positioned orthogonal to the magnet flux.
(i.e., in phase with counter emf) with the help of an absolute position sensor. Such a decoupling or vector control method, as discussed before, will give true dc machine-like response from a sinusoidal brushless dc motor. Fig. 16 shows a speed control system using such a control scheme. This scheme can be derived from the induction motor vector control method shown in Fig. 13 with the modifications $\omega = 0$, $\theta = \theta$, and $\omega_{m} = 0$. Since the rotor establishes the airgap flux, the stator need not supply any reactive current. Generally, an expensive position resolver is required in such a control scheme. If a resolver/digital converter is used with an analog resolver, then its outputs can be used not only for vector transformation, (i.e., commutation), but for speed and position control loops as well.

A simple open-loop step motor control scheme (Fig. 17) consists of sequence logic, a power converter and the machine. The sequence logic receives a step input pulse train and direction signal from the host controller, and these are then translated into sequential drive signals to the converter such that the machine stator poles advance by a step in response to a step input pulse. With a step input of constant frequency, the machine runs in the specified direction with the corresponding number of steps per second. In such a "time-dependent commutation" (unlike the position-dependent commutation in a brushless dc machine), the step motor behaves as a synchronous motor, and, therefore, oscillatory response and loss of synchronism are possible, as indicated before. There is also a possibility that the machine may miss step pulses. These disadvantages can be eliminated by a closed-loop control using an incremental position encoder (Fig. 17). Adding the complexity of closed-loop control, step motors have been used for more accurate position control, much higher and smoother speed, and greater versatility in many other aspects. A commonly used closed-loop control, where the phase switching angle is rotor-position-synchronized with advance angle excitation as a function of speed, is shown in Fig. 17. Schemes have been proposed in which rotor position is estimated by observer techniques.

It was indicated before that the switched reluctance machine (SRM) is nothing but a variable reluctance step motor with different controls. An SRM is a continuously controlled machine in which holding torque is established by feedback method. An absolute position encoder is essential for an SRM to provide rotor position synchronized excitation to the stator windings. Fig. 18 shows an SRM position servo with an inner speed control loop. An inner high bandwidth torque loop can be provided to compensate pulsating torque at low speed. An absolute position encoder generates commutating signals for converter switches. The machine operates with full performance in all four quadrants. In the forward motoring mode, the stator phases are turned on at an advance angle $\theta_{a}$ with respect to positive inductance slope so that full active stator current can be established. The torque is then controlled by chopping the level of current $I$. Beyond the constant torque region, chopping control is lost, and then turn-off angles can be controlled in the constant power region.

There has been a recent interest in applying modern control theories to motion control systems. The theories have been advanced since the 1960's, but in general, they have not found practical applications. They were initially applied to aerospace systems and general process control applications, but the advent of inexpensive and powerful microcomputers has made it possible to apply them to time-critical motion control systems as well. Although dc drives are receiving most of the attention, ac drives are being considered as well. Applying modern control theory to motion control systems in general is difficult because of large time-critical computation requirements.

Optimal control theory, such as Pontryagin's minimum principle, or the dynamic programming technique, which is based on extensive iterative computation, can be generally applied to a single optimal profile of the drive system. The optimal precomputed profile can be generated, for example, on the basis of minimum time of transit or minimum energy consumption subjected to a number of control constraints. Such optimal control principles are extremely difficult to apply in general motion control systems.
The applications of adaptive control theories, still just beginning, are growing at a rapid pace. They are extremely useful in systems such as robots and machine tool drives, where the system must be robust, insensitive to parameter variations. A conventional PI (proportional-integral) or PID (proportional-integral-derivative) controller with fixed parameters cannot generate optimal response in a plant parameter-varying system. In self-tuning adaptive control, the controller parameters are tuned to adapt to plant parameter variations. Such a general control scheme is indicated in Fig. 19. The plant parameter estimation algorithm solves the plant model in real-time and updates the plant parameters on the basis of recursive least square identification techniques. A tuning algorithm then adjusts the regulator parameters based on plant parameters. The tuned system may have pole-assignment control, but dead-beat, state-space, or design of time-series control can also be used. The regulator parameters may be updated at a slower rate than the main control loop sampling rate if the plant parameters vary slowly (which may not be necessarily true). For successful operation of the global system, stability is essential.

In a model referencing adaptive control (Fig. 20), the plant response is forced to track the response of a reference model irrespective of plant parameter variation. The reference model with fixed parameters is stored in microcomputer memory, and therefore the response of the plant becomes insensitive to parameter variation. The speed command \( \omega^* \) generated by the position control loop in Fig. 20 is applied in parallel to the reference model and plant controller. The reference model output \( \omega_{\text{ref}} \) is compared with the measured plant speed \( \omega_p \), and the resulting error signal \( e \) actuates the adaptation algorithm. The feedforward and feedback gains \( K_f \) and \( K_g \), respectively, of the plant controller are iterated by the adaptation algorithm so as to dynamically reduce the error \( e \) to zero. The plant can track the reference model without saturation, provided the parameters in the reference model are defined on a worst-case basis. Therefore, the desired robustness of the control system is obtained at the sacrifice of optimum response speed. In general, the structure of the reference model and the plant should be the same, and the parameters should be compatible for satisfactory adaptation. The global stability of the system can be analyzed by Popov's hyperstability theorem.

A model referencing adaptive control system with a PI controller that is based on an on-line search strategy is shown in Fig. 21. For example, the plant under consideration may be a vector-controlled induction motor, where rotor resistance variation causes a coupling effect and torque sensitivity with \( \Phi^* \) changes. The parameters of PI torque controller can be adapted to compensate the plant parameter variation, so that the system tracks the reference model. The controller parameters \( K_1 \) and \( K_2 \) are varied by trial-and-error so that the error between actual and desired responses remains bounded within a hysteresis band. Again, the reference model is to be determined on the basis of worst-case parameters of the plant so that the torque loop can physically track the reference model.

A sliding-mode or variable-structure control technique has been applied successfully to both dc and ac drive systems. Basically, it is an adaptive model-referencing control (MRAC), but is easier to implement by microcomputer than the conventional MRAC system. The sliding mode control is ideally suitable for position servo, such as robot and machine tool drives, where problems related to mechanical inertia variation and load disturbance effect can be eliminated. The control can be extended to multiple drives where close speed or position tracking is desired. In sliding mode control, the "reference model" or a predefined trajectory in the phase is stored in a microcomputer, and the drive system is forced to follow or "slide" along the trajectory by a switching control algorithm, irrespective of plant parameter variation and load disturbance. The microcomputer detects the deviation of the actual trajectory from the reference trajectory and corresponding changes the switching topology to restore tracking. Fig. 22 shows sliding mode control applied to a vector-controlled induction motor drive system, and Fig. 23 shows the sliding trajectory for both forward and reverse motions in phase plane. The sliding trajectory of the reference contour defines acceleration \( (b_1) \), constant speed \( (b_2) \), and deceleration \( (b_3) \) segments which are beyond the drift band, so that the system always remains controllable. The actual sliding curve that follows the defined trajectory is given by a zigzag line in the direction of the arrow. The phase plane trajectory
can easily be translated into a corresponding time domain response. In a sliding mode controller, the position loop error \((X_1)\), its derivative \((X_2)\), and a constant \(A\) are transmitted through single-pole double-throw (SPDT) switches and the respective gains to constitute the effective control input \(U\). The position of SPDT switches is determined by the operating point with respect to the defined trajectory. The jitter in the response can be regulated by good resolution of signals, small sampling time of computation, and high switching frequency of the inverter.

V. MICROCOMPUTER CONTROL

The advent of microcomputers has brought a new dimension in motion control technology. The impact of this evolution is as significant as the advent of power semiconductor devices in the 1950s. It is interesting to see that both ends of the spectrum
are digital: power semiconductors provide the muscle, whereas microcomputers provide the brain. Microcomputers have now found universal acceptance in motion control systems.

The advantages of microcomputers, seem obvious. They provide significant cost reduction in control electronics, improve reliability, and eliminate drift and electromagnetic interference (EMI) problems. They also permit design of universal hardware and flexible software control. Software can be updated or altered as the system performance demands change. "Micro" has the powerful capability of complex computation and decision-making. With the present trend toward computer-automated factories, microcontrol provides a compatible communication link in the computer hierarchy.

Microcontrol has the disadvantage of signal quantization and sampling delay. It is sluggish compared to dedicated hardware. In motion control, micro has time-critical functions which are unheard of in general process control applications. Of course, computation speed can be enhanced by parallel processing, use of more dedicated hardware, and assembly language programs.

Since the introduction of microcomputers in 1971 by Intel Corporation, the technology has gone through an intense evolution in the last two and a half decades. Intel microcomputers have dominated in motion control systems; other key competitors in the market are Motorola, Zilog, Texas Instruments, and National Semiconductor. Fig. 24 shows an overview of Intel microcomputer evolution. Here, the performance can be considered as a weighted average of bit size, components, improvement of hardware and software features, and so on. The 8080 is, in fact, the first generation microcomputer, which was once the industry's most commonly used micro. The evolution indicates two general directions: the multi-chip and single-chip families. Both 8- and 16-bit microcomputers are widely used, but as the price is coming down and system functions are increasing, the 16-bitters are finding more acceptance. A very dominant member of the Intel family is the 16-bit, single-chip 8096 microcontroller, which is designed for real-time control applications. The key features of the 8096 are summarized in Table I; Fig. 25 shows its architecture. It has a built-in A/D converter that can accept unipolar signals and a PWM output that can be used for
D/A conversion. With a 12-MHz clock frequency, the 8096 can do 16-bit addition in 1.0 µs and a 16 × 16 multiply or 32/16 divide in 6.5 µs. The other interesting features are high-speed trigger inputs (HSI’s) and high-speed outputs (HSO’s). The HSI’s look for transition of input lines and record the times at which external events occur. The HSO’s trigger external events at preset times and therefore can be used to generate interrupts at preset times. This microcomputer is expected to find wide applications in motion control.

Digital signal processors are high-speed microcomputers that generally act as peripheral components to a central processor and help in processing I/O signals. A very dominant member in this family is the TMS32010, which was introduced by Texas Instruments several years ago. The key features of this chip are given in Table II. The 16-bit microcomputer has 160 ns instruction cycle time (32010-25), which includes 16 × 16-bit multiply instruction. More recently, a CMOS version (320C25) has been announced in which the speed has been enhanced to 100 ns. Faster program execution has been possible in the TMS320 family by using what is called modified Harvard architecture, which permits overlap of instruction fetch and execution of consecutive instructions. In addition, the chip uses a dedicated hardware multiplier and barrel shifter. The TMS32020, which represents a considerable enhancement of its predecessor, the TMS32010, contains 544-word on-chip RAM, 128 K-words of ROM, sixteen input and output channels, three external interrupts, and one hardware timer.

We are beginning to see the emerging growth of 32-bit microcomputers in the market. Though National Semiconductor originally introduced 32-bit architecture four years ago, the age of the 32-bit machine truly started with the introduction of Motorola’s 68020. At present, the other prominent members

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**Table I**

<table>
<thead>
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<th>Feature</th>
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<tbody>
<tr>
<td>8K-byte on-chip ROM</td>
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<tr>
<td>232-byte register space (RAM)</td>
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<tr>
<td>10-bit, eight-channel A/D converter</td>
</tr>
<tr>
<td>Five 8-bit I/O ports</td>
</tr>
<tr>
<td>Full-duplex serial port</td>
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<tr>
<td>High-speed pulse I/O</td>
</tr>
<tr>
<td>Pulse-width-modulated output</td>
</tr>
<tr>
<td>Eight interrupt sources</td>
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<tr>
<td>Four 16-bit software timers and two 16-bit hardware timers</td>
</tr>
<tr>
<td>Watchdog timer</td>
</tr>
<tr>
<td>Hardware (microcoded) signed and unsigned multiply/divide</td>
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</tbody>
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**Table II**

<table>
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<th>Feature</th>
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<tr>
<td>160-ns instruction cycle</td>
</tr>
<tr>
<td>144-word on-chip data RAM</td>
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<tr>
<td>1.5 K-word on-chip program ROM-TMS320M10</td>
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<tr>
<td>External memory expansion to a total of 4 K words at full speed</td>
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<tr>
<td>16-bit instruction/data word</td>
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<tr>
<td>32-bit ALU/accumulator</td>
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<tr>
<td>16 × 16-bit multiply in 160 ns</td>
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<tr>
<td>0 to 15-bit barrel shifter</td>
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<td>Eight input and eight output channels</td>
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<tr>
<td>16-bit bidirectional data bus with 50 megabits/s transfer rate</td>
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<tr>
<td>Interrupt with full context save</td>
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<tr>
<td>Signed two’s complement fixed-point arithmetic</td>
</tr>
<tr>
<td>NMOS technology</td>
</tr>
<tr>
<td>Single 5-V supply</td>
</tr>
<tr>
<td>Two versions available</td>
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<tr>
<td>TMS32010-20—20.5 MHz clock</td>
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<tr>
<td>TMS32010-25—25.0 MHz clock</td>
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**Fig. 25** Architecture of Intel 8096 microcomputer.
of the 32-bit family are Intel's 80386, Zilog's Z8000, AT&T's WE32100, and National's NS32C532. In terms of data processing capability, microcomputers can now successfully complete with mainframes and minicomputers. An interesting architecture of 32-bit machine is RISC (reduced instruction set computer) architecture which, because of its simplicity and single-cycle per-instruction operation, can considerably enhance the capabilities of microcomputers. The Inmos "Transporter" family are the first commercially available RISC machines. An example is the 32-bit T414 (1.5 micron, 200,000 transistors), which runs at 10 MIPS (million instructions/s) with memory transfer rate up to 25 MHz. The 32-bit machines will initially make inroads for data processing applications, but as prices come down, they will be considered for real-time control. Besides high-resolution signal processing, they will be useful in high-performance control systems using modern control theories.

As semiconductor processing technology improves, it will be possible to integrate more devices in a chip, and therefore to achieve more functional integration in a microcomputer. At present, the speed of microcomputers is limited because they operate in an inherently sequential manner. Using VLSI techniques, systems can be built in which many elements work in parallel on the same problem, thus allowing an enormous increase in processing speeds. In such a parallel computing system, a large number of processors are arranged in a rectangular grid, with each processor able to communicate with its nearest neighbors on the grid, and, using a global communication system with any other processor in the machine. The machine operates in a single-instruction, multi-data mode, which means that all component processors execute the same instruction at the same time. Super microcomputers based on parallel machines will be very expensive initially for real-time control applications.

What role can the microcomputer play in digital motion control systems? Practically all the control functions discussed so far can be implemented by microcomputer. The application areas may include gate-firing control of phase-controlled converters, closed-loop control, nonlinearity compensation, digital filtering, programmable delay, sequencing of control modes, programmable set point commands, system signal monitoring and warning, and data acquisition. Microcomputers have been used for optimal PWM wave generation of an inverter. Powerful micros are permitting vector control and optimal and adaptive control in motion control systems with intricate signal processing. The cost of a drive system can be reduced by using cheap sensors and by reconstructing precise signals with the micro's intelligence. In many cases, sensors can be completely eliminated, or redundant sensor information can be provided by observer computation. System reliability can be enhanced by micro-assisted fault-tolerant control. As the micro's speed and functional integration improve, it will be used in real time or quasi-real time for simulation of motion control systems. Artificial intelligence, another area where the microcomputer will find applications will be discussed later.

The micro will play an increasingly important role in system tests and diagnostics. The data from a system under test can be captured and processed to determine efficiency, power factor, etc. A personal computer is an important tool in such an application. Automated tests can be performed on a system, and structure and parameters can be identified. System diagnostics can be designed on either an on-line or an off-line basis. On-line diagnostics indicate the healthiness (or sickness) of system operation and give warnings if problems arise. Off-line diagnostics help in troubleshooting a system and minimize plant outage time. Diagnostic programs can be very user-friendly, and can be exercised by unskilled technicians.

Programmable controllers (PC's) are finding increasing applications in today's factory floor environments. A PC is basically a general-purpose microcomputer controller that can be programmed for any application. Originally, it was intended to be an electronic replacement of industrial relay panels. Interestingly, the development of this application led to the invention of the microcomputer. From their initial applications in on-off sequencing of motors, solenoids, actuators, etc., PC's have evolved into intelligent workhorses with such advanced capabilities as data acquisition and storage, report generation, execution of complex mathematical algorithms, servo motor control, stepping control, axis control, self-diagnosis, system troubleshooting, and talking to other PC's and mainframe computers. The reasons for the proliferation of PC's on the factory floor are low off-the-shelf hardware cost, ease of programming and reprogramming by an ordinary electrician, system reliability, and ease of maintenance.

The supremacy of the microcomputer has been challenged recently by semi-custom or custom-VLSI circuits. Typically, a chip containing 100,000 or more devices is defined as a VLSI chip. All the peripheral chips of a micro can be integrated into a single chip, or both micro and peripheral chips can have a large single VLSI chip replacement. The advantages of VLSI design are low cost at high volume application, improvement of speed, reliability, and lower power consumption. The semi-custom design in VLSI is shown increasing popularity. The dominant member in this group is the gate array system, which is based on logic system synthesis using identical NAND or NOR gates. The chip may have analog devices to give more functional capability. The design and fabrication of gate array systems are highly computer-aided. Reasonably simple logic functions can be directly translated to gate-array design through what is known as a "silicon compiler." A programmable gate array permits flexible logic system design which can be erased and reprogrammed like an EPROM. In a standard cell VLSI design, individual cell or device parameters may be specified to gain tighter performance control of the circuit. The standard cell approach of semi-custom design normally permits large system design using logic analog, ROM, RAM, and even complete microcomputer function.

VI. COMPUTER-AIDED CONTROL SYSTEM DESIGN

CAD tools are playing an increasingly important role in motion control system design. It is convenient to design and simulate a newly developed control system on a computer before building a breadboard. The traditional paper-and-pencil
design of a control system and then trial-and-error experiment in the laboratory may be very time-consuming, expensive, and frustrating, especially if the control system is complex and a lot of uncertainty is involved in performance. Both analog and digital computers have been used in the past for system design and simulation. In a hybrid computer, the control system can be appropriately partitioned for analog, logic, and digital simulation. Digital computers have found preference in recent years, and more and more powerful and user-friendly CAD programs are appearing in the market. By way of illustration, two general groups of CAD programs will be briefly reviewed. 

The VAX-based federated CAD system [39] essentially consists of several independently developed subsystems tied together (Fig. 26) by a system supervisor and unified data base. The objective is to provide the user with a unified system that spans the entire control design problem: modeling, design, and simulation. In a federated system, the subsystems are loosely coupled, and each subsystem can be used as a standalone program. The additional advantages are that component programs can be added, deleted, or altered without affecting the main system. The first package, called IDPAC, is used for data analysis and identification of linear system. It can manipulate and plot data, and make correlation analysis, special analysis, and model identification. The next package, CLADP, permits frequency domain design methods. These include Bode, Nyquist, and root-locus design. The SSDP is a state-space design package that provides time domain design techniques. The MATLAB, which stands for "matrix laboratory," is used to solve matrix-related problems. The SIMNON is a Fortran-based simulation program for nonlinear dynamic systems. Both continuous and discrete time systems can be simulated on a VAX using SIMNON. The simulation of a discrete time system with prescribed sampling time is of particular importance to a microcomputer-based control system. SIMNON accepts descriptions of a dynamic system in state-space form; i.e., a continuous system is described by differential equations and a discrete time system by difference equations. For simulation, a large system is normally resolved into small interconnected subsystems. A connecting system routine links the subsystems by I/O signals. SIMNON can interface specially formatted FORTRAN to expand its capabilities. 

CTRL-C, developed by Systems Control Technology, is an interactive computer language for the analysis and design of multivariable linear control systems and signal processing. Systems may be described in state-space, transfer function, or continuous or discrete-time forms. Transformations between representations are simple and straightforward. A powerful matrix environment provides a workbench for system simulation, signal generation, matrix analysis and graphics. The ACSL is a continuous system simulation language that can be used for simulation of nonlinear dynamic systems, both in continuous and discrete time form. It can be integrated with CTRL-C (Fig. 27) to form a complete CAD design and simulation package. Both the programs are Fortran based, and the completed package is available for VAX and other computers.

The tools for design of control systems can be divided into two categories: computer-aided control system design (CACSD), which is based on a mathematical model of a system, has been discussed above; the other is hardware/software architecture simulation for microcomputer-based control systems. An example in the latter category is HCSE (Hierarchical Control System Emulation), which was originally developed by Bolt, Beranek and Newmans, Inc. [42] for the National Bureau of Standards to support the development of their Automated Manufacturing Research Facility. The VAX-based HCSE simulation tool set permits emulation of a multiprocessor/multitasking system in the form of finite state machine (FSM) [47]. As mentioned before, only the hardware/software architecture is considered in the emulation without regard to actual implementation in hardware and software. The controller emulation in HCSE can be linked with plant simulation in SIMNON to evaluate design tradeoffs. When performance criteria are established, prototype hardware and software can be designed.

Computer-aided system design tools are in the process evolution and will undergo many changes in the future. The personal computer is expected to play an increasingly important role in this area. As microcomputer speed improves and memory becomes cheaper, more time-critical controls will be implemented in high-level languages. Eventually, the simulation software will be down-loaded directly to prototype microcomputer memory and used as real-time control software.

VII. ARTIFICIAL INTELLIGENCE IN CONTROL

A significant advance has been made recently in control and CAD techniques by the introduction of artificial intelligence, or expert systems. Artificial intelligence involves programming a computer so that it can mimic human thinking. An
expert system essentially tends to mechanize the expertise of a human being. A human expert has knowledge, an experience base, and the power of reasoning, judgment, and intuition. In a sense, conventional computer programs have some degree of artificial intelligence: they make decisions on questions which have clear-cut “yes” or “no” answers. But human thinking is often qualitative, involving ideas such as “large,” “small,” or “medium.” Fuzzy logic and fuzzy set theories have been developed for computers to quantify and objectively evaluate the subjective ambiguity of human thinking.

There is now a tremendous surge of activity in expert systems applications. These include robotics, industrial process control, computer-aided design and diagnosis, medical diagnosis and prescription, medical knowledge automation, chemical and biological synthesis, mineral and oil exploration, space defense, air-traffic control, VLSI design, speech understanding, and knowledge-based management. An expert system can help in designing control structures and parameters for a desired performance goal. For example, a pole-placement design of a multivariable control system can be obtained automatically if a plant model and the desired set of poles are furnished to the computer. Expert-system-based diagnostics can locate faults in a complex control system with extensive man-machine dialogues. Such troubleshooting methods have already been used for diesel electric locomotives and jet engines. Expert systems are also being used for real-time control applications. In such a system, a controller can tune itself as it monitors the process and learns the dynamics of the operation, much as an experiences human operator would do. An example of such an auto-tuning regulator is the Foxboro Model 760, which can control a system that is not well understood and difficult to model. It is essentially a microcomputer-based PID controller with some 200 production rules.

The self-tuning method is a pattern recognition approach that allows the user to specify desired temporal response to disturbances in the controlled parameter or in the controlled set point. The controller than observes the actual shape of these disturbances and adjusts its PID values to restore the desirable response.

A typical architecture of real-time expert control system is shown in Fig. 28. The plant under consideration may be unknown or difficult to model. A set of sensors measures the important variables that characterize the state of the process, and the pattern recognizers extract the features to detect important events. The rule base contains the knowledge of expert operators or designers and of the overall control strategy for all the regimes. The “meta control” can select the control strategy and define the control parameters. The speed of computation, system stability and robustness are serious issues in expert system control, and generally it requires extensive computer simulation study before actual implementation.

Fuzzy logic is a kind of logic using graded or qualified statements rather than ones that are strictly true or false. The results of fuzzy reasoning are not as definite as those derived by strict logic.

Fuzzy sets that do not have a crisply defined membership, but rather allow objects to have grades of membership from 0 to 1.

VIII. CONCLUSION

This report has presented a comprehensive review of technology trends in microcomputer control of electrical machines. Although microcomputer control and computer-aided design techniques are our main themes of discussion, motion control as multidisciplinary technology has been reviewed in the broad perspective of electrical machines, power semiconductor devices, converter technology, microcomputers, and VLSI circuits. The concepts discussed in this report are valid not only for small machines, but for large machines as well.

Before concluding, I think that it is relevant to give some thought to the consequences of the “new” industrial revolution. Will it create more affluence for a privileged segment of society—thus furthering the gap between haves and have nots? Will it create a massive unemployment problem? Will the material prosperity deprive us of peace and tranquility and fill us with hypertension and restlessness, and consequently, aggravate the problems of our society? Will technological accomplishments bring more power rivalry in the world and bring us closer to war, and eventually destroy us with the results of our “accomplishments?” I think that we—the engineers, the creators of this technological society—should involve ourselves in answering these questions and help in shaping the future of our society. We, the human beings of this planet, are collectively responsible for our destiny. If accomplishments in technology have adverse influence on the society, that is not a justification for halting the march of technology.

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