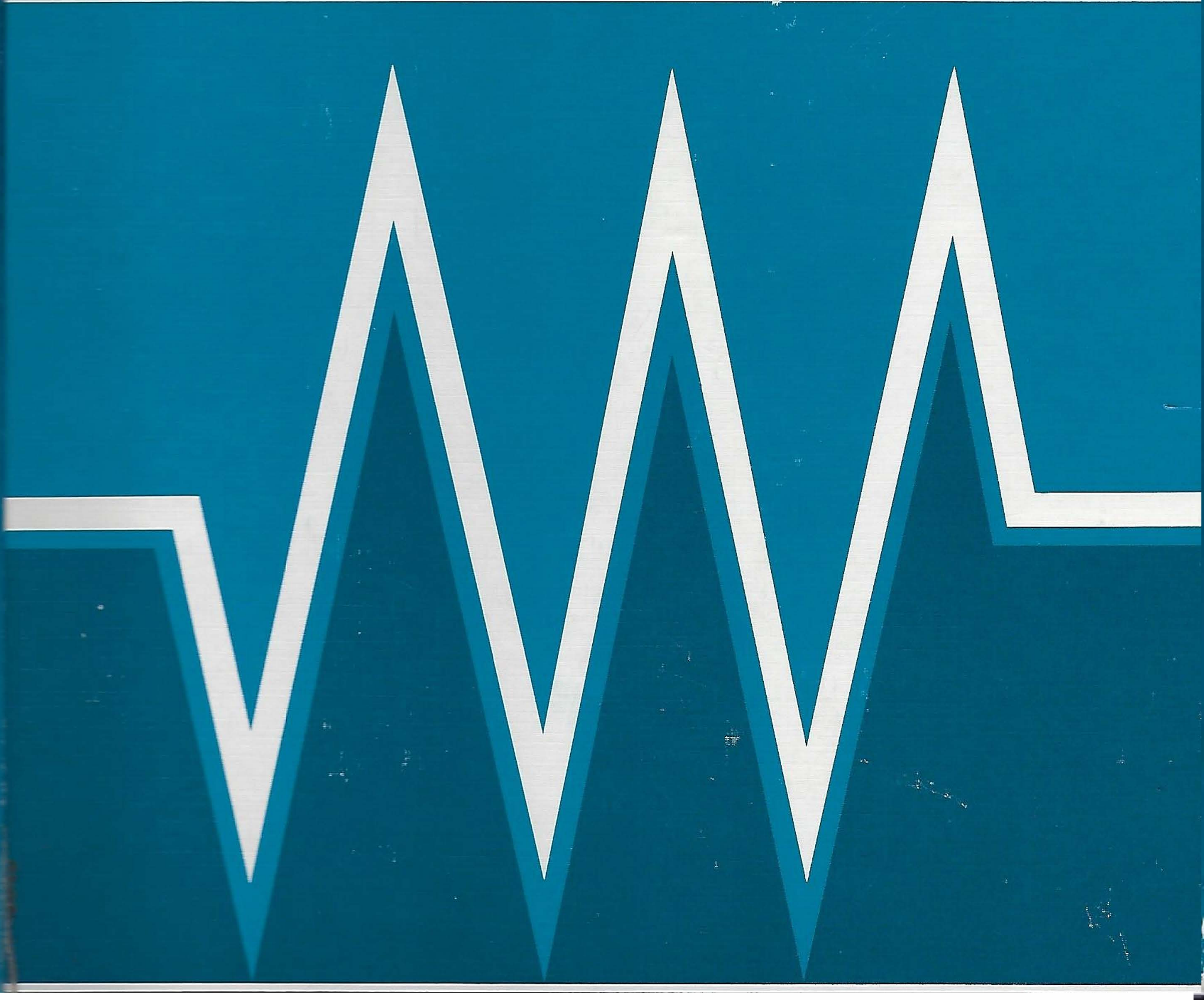
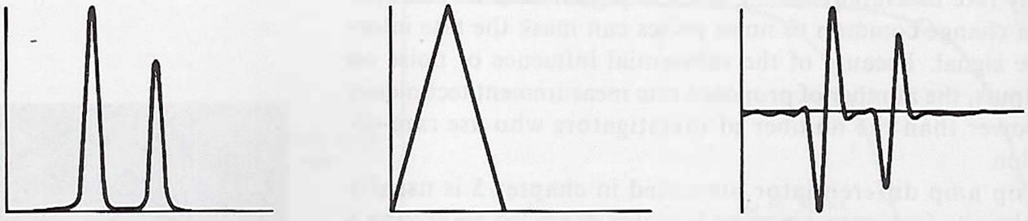
Electronics and Instrumentation for Scientists

MALMSTADT · ENKE · CROUCH





(a) Original spectrum (b) Differentiating filter (c) Differentiated spectrum

Fig. 14-33. Application of a derivative filter. The Fourier transform of the spectrum (a) is multiplied by the differentiating filter function (see text) (b) and the inverse transform taken. The resulting differentiated spectrum is shown in (c). This is analogous to a derivative smoothing operation in the time domain.

14-5 Control

We have seen that the microcomputer is basically a device for perform
programmable sequence of operations. The ability to vary the program
availability of conditional branch and loop sequences, and the speed
execution of the programmed operations make the microcomputer
extremely versatile and powerful general-purpose sequencer. This sequenc-
ing capability can be applied to the control of external devices and process
through interfaces that effectively make such controls part of the CP
instruction set. In this way the computer can alter signal pathways, open
close valves, control power to motors, heaters, and lamps, generate
signals, and perform other tasks at times and in sequences determined by
operating program.

The various control functions can be either open-loop or closed-loop
illustrated in figure 14-34. In **open-loop control**, the setting of the controller
results in the desired change in the process variable. For example, in
control of a cooling fan in a piece of equipment, the control element
switch that is actuated by the controller. The manipulated quantity is
power to the fan, and the process variable is the movement of air through

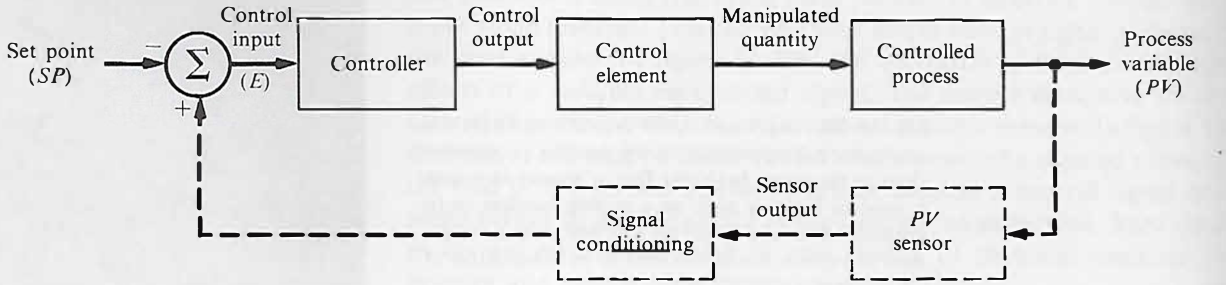


Fig. 14-34. Block diagram of generalized control system. In response to a control setting or input signal, the controller actuates a control element such as a motor, valve, or switch so that the desired action occurs in the controlled process, which might be heating, illumination, rotation, etc. The result of this action can be monitored by sensing the process variable *PV* and producing a signal related to the controlled quantity. In a closed-loop system, this signal is compared with a set point signal (the signal for the desired value of *PV*), and the controller acts to reduce the difference between these signals to zero. Signal conditioning is generally used to make the sensor output linear so that the conditioned signal is proportional to the process variable.

equipment or perhaps the temperature of some part of the equipment. It is assumed that when actuated, the switch closes, the fan is powered, and the air moves at a rate that keeps the equipment at a safe temperature. In **closed-loop control** the process variable *PV* is monitored by a sensor. The value of *PV* is then compared with the desired value *SP* to produce an error signal *E*. The controller responds to the error signal by changing the manipulated quantity to bring *PV* closer to *SP*. A home furnace is a closed-loop system. The thermostat compares the room air temperature with the set value and closes a switch when the temperature is below the set value. The controller responds to the closed switch by activating the burner to perform the process of heating the air. The heating process continues until the set point temperature is reached.

In this section the application of microprocessors in control systems is explored. The discussion includes interfaces for control, control system dynamics and modes, and examples of practical control systems.

Digital Drivers

In order for a microcomputer to function as the controller in an automated system, it must be interfaced to the required control elements. This is generally accomplished with a parallel output port. Since each bit in the latch of an eight-bit parallel port is independently controllable by the word written into it, eight different devices could be turned on and off by that one port. The interface to the device is completed by a **digital driver** circuit that can control power to the device in response to the logic level at its input. One of the simplest digital drivers is the open-collector gate shown in figure 14-35. The gate output is the collector of a transistor driven by the gate logic. The output is thus a logic-controlled switch for positive current to common. The voltage and current in the switched circuit are limited by the characteristics of the output transistor. The limits for some representative TTL devices are given in table 14-1.

Many low-voltage dc devices can be controlled by the open-collector buffer and driver just by connecting them in the load position shown in figure 14-35. Such loads include small incandescent lamps and LEDs (with appropriate current-limiting resistor in series). If the device is inductive, such as a relay coil, solenoid, or motor, the circuit of figure 14-36 should be used. The supply voltage *V* is chosen to match the requirements of the load, with 0.2 to 0.7 V allowed for the drop across the on transistor. Normal relays and solenoids require that the current in the coil remain on as long as the armature is to remain in the ON position. This uses power during the ON time and the device automatically reverts to OFF when the system power is turned off. A **latching relay** or **latching solenoid** remains in its ON position once put there by a momentary current. To return it to the OFF state, a

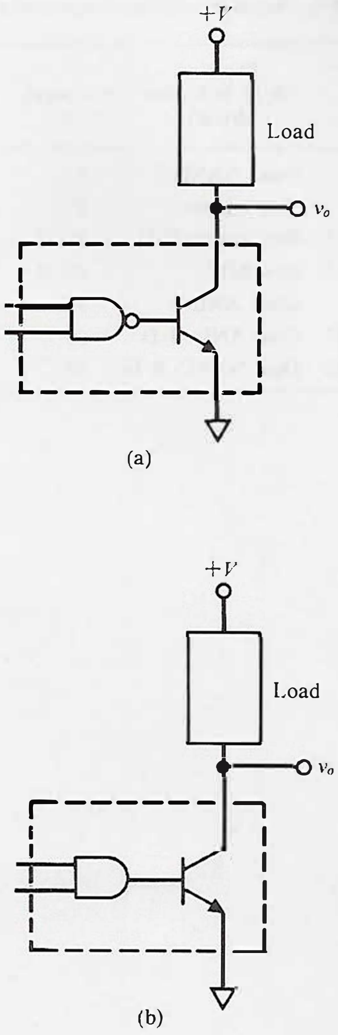


Fig. 14-35. Open-collector gates. An output transistor switch is turned on or off by the output of a logic circuit. When the logic output is HI, the transistor is ON and the connection from $+V$ through the load is complete; i.e., the load device is turned on. If the load is a resistor, v_o is LO when the logic output is HI, and vice versa. Thus circuit (a) is called an AND gate and (b) a NAND gate. If there is only one input to the gate circuit, (a) is a buffer-driver and (b) is an inverting buffer-driver.

Table 14-1. Output capabilities of open-collector gates.

Type	Function (B/D = buffer-driver)	$+V$(max), V	I_L(max), mA
7401, 03	Quad NAND	5.5	16
7405	Hex inverter	5.5	16
7406/7416	Hex inverter B/D	30/15	40
7407/7417	Hex B/D	30/15	40
7409	Quad AND	5.5	16
MC 75461	Dual AND B/D	30	300
MC 75462	Dual NAND B/D	30	300

momentary current is applied to an opposing coil, or current is removed from a holding coil.

The relay shown in figure 14-36 is an example of a control device that provides electrical isolation between the controller and the control element. There need be no direct connection between the digital driver and the circuit controlled by the relay contacts. This can protect the controller from accidental damage due to high voltages or power in the controlled circuits. The maximum controlled circuit power is limited only by the relay contact ratings. A device that provides isolation between two logic-level systems is the **opto-isolator**. An input gate is used to control an LED that is optically coupled to a phototransistor as in figure 6-17c. The phototransistor controls the input state of a separately powered output gate. Opto-isolators are very useful when digital information must be exchanged between two systems where the commons may not be at the same voltage. Circuits using ac line voltage can be controlled by a relay or a logic-activated zero-crossing switch. This device, described in figure 7-25, is often combined with an opto-isolator input to provide complete electrical separation between the logic and power-line circuits.

The above drivers all provide simple two-level, or ON-OFF control. Additional levels of control can be achieved by using more bits of the output port and some means of converting the digital output word into a multi-level control signal. For control in the analog domain, a DAC is generally used. A DAC is not designed to provide significant power at its output.

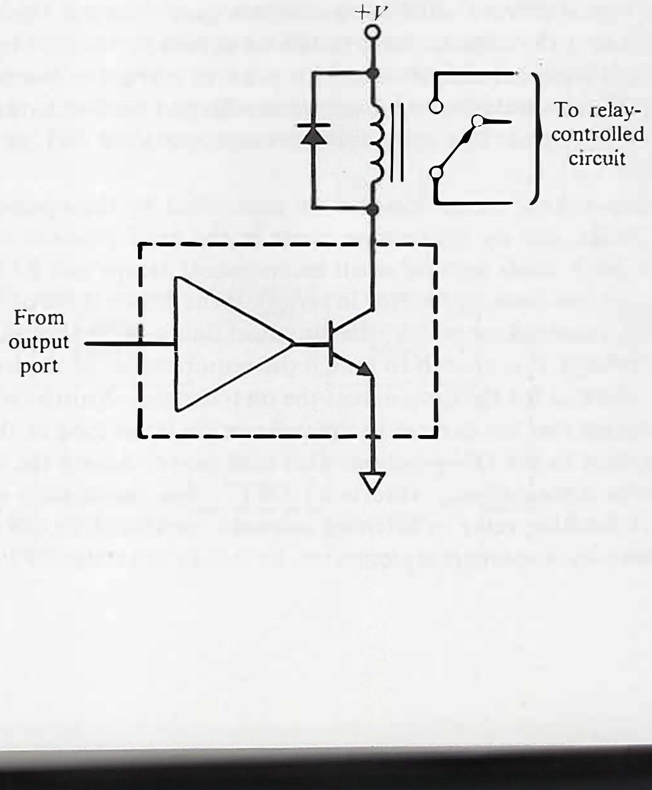


Fig. 14-36. Driving an inductive load with an open-collector output. The diode protects the transistor from the voltage spike produced when the current through the coil is turned off.

Therefore a DAC output that is to control a load such as a dc motor or heater requires a power amplifier. A simple power amplifier can be made from an op amp and booster as shown in figure 14-37. Incorporating the booster amplifier in the follower-with-gain feedback loop as shown maintains precise control over the booster output voltage. The booster amplifiers available from op amp manufacturers can provide many watts of output power to a load. For still greater power the DAC output can be used to control a voltage-programmable power supply (see section 7-8).

Another kind of driver that can provide a variable control output is a pulsed drive output. An ON-OFF driver is used to provide an output drive pulse that adds a single increment to the manipulated quantity. The total for the manipulated quantity or the rate of change of that quantity is equal to the number or rate of incrementing pulses applied. A primary example of pulsed control is the **stepper motor**. The shaft of a stepper motor rotates an exact fraction of a turn for each pulse applied to the motor windings. This is actually accomplished by a multipoled permanent magnet rotor surrounded by fixed electromagnetic poles driven in a four-step sequence. Between steps the rotor is "locked" in place by electromagnetic fields that attract the rotor poles. Upon the application of a step, electromagnetic fields one-fourth of a rotor pole position away are energized, and the rotor is attracted in that direction. On the next step, the rotor moves another quarter of a pole position, and so on. A motor with a 12-pole rotor completes one revolution in exactly 48 steps. The coil energizing sequence in a four-coil (unipolar)

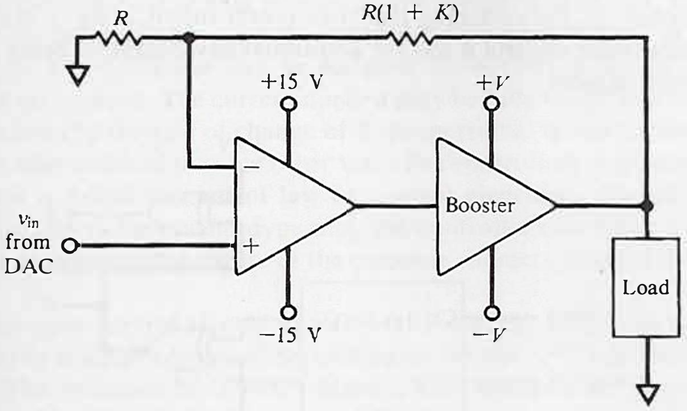


Fig. 14-37. Power amplifier for driving a load from a DAC. The booster amplifier acts as a higher current (and sometimes higher voltage) output stage for the op amp. Because it is included in the gain-controlling feedback loop, the circuit acts as a high output voltage follower with a gain of K.

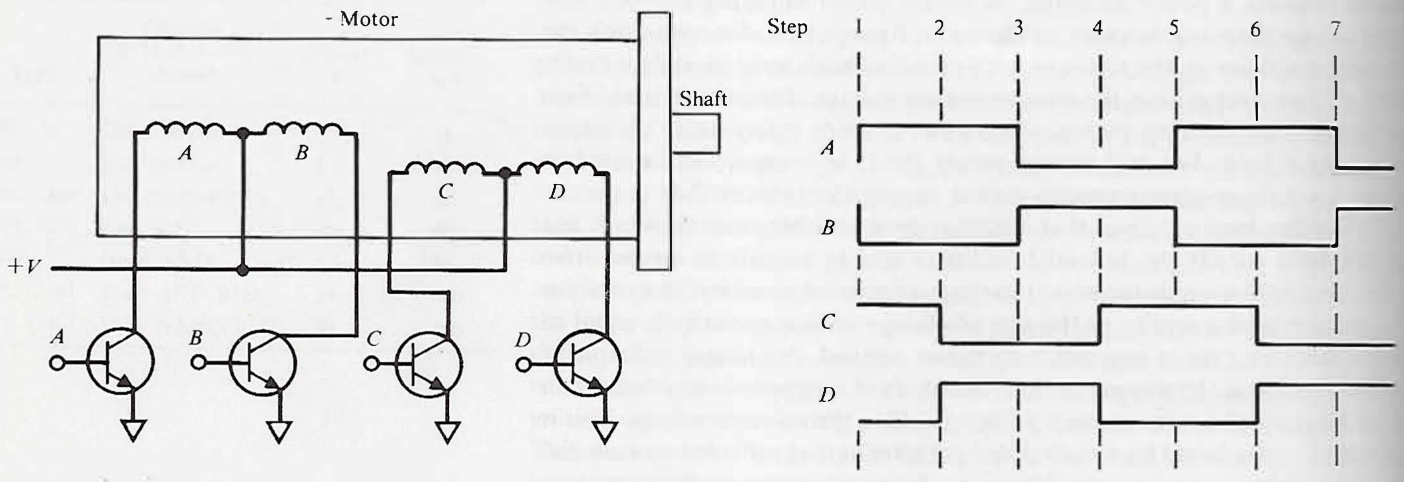


Fig. 14-38. Stepper motor coils and drive sequence. When coils *A* and *C* are energized, they attract a N pole of the permanent magnet rotor. Coils *B* and *D* attract the S poles since their current is in the opposite direction. As the coils are sequentially energized, the rotor turns in steps. If the pulse sequence is reversed, the rotor turns the other direction.

motor is illustrated in figure 14-38. The pulse sequence can be generated software using four bits of an output port or by clocking a counter and log circuit to produce the desired sequence as shown in figure 14-39.

Incremental or pulsed drivers can be used to generate increments charge, heat, light, or many other quantities, and the controller can act adjust the increment rate to obtain the desired value of the process varia (voltage, temperature, illumination, etc.). Pulsed control can be economic and precise (cf. the switching regulator power supply of fig. 3-25), and unde microcomputer control it has the additional advantages of being simple an inherently digital.

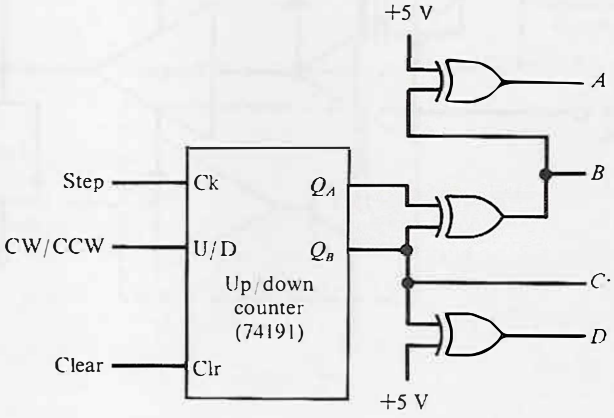


Fig. 14-39. Stepper motor drive sequence generator. The first two stages of a binary up-down counter are used to provide a bidirectional four-step sequence. Exclusive-OR gates decode each of the four states into the appropriate combinations of drive signals as shown in figure 14-38.

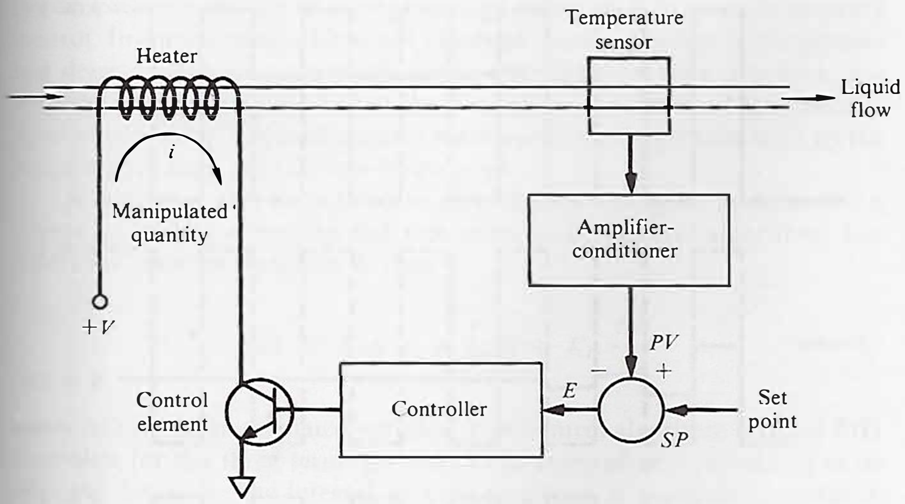


Fig. 14-40. Temperature controller for flow system. The current in the heater is controlled to produce the set point temperature in the flowing liquid. Response delays in the heater and sensor and dead time in the flow system between the heater and sensor contribute to the dynamics of the control system. The ideal controller would compensate for undesirable dynamic characteristics of other components to produce a stable, responsive, and accurate control system.

Control System Dynamics

A typical control system is shown in figure 14-40. Every element in the control loop affects the system response to changes in some variables (flow rate, set point, or input temperature) and thus contributes to the system dynamics. There is **lag** in the heater since the temperature of the heating element and pipe cannot change instantly with changes in heater current. Then there is a delay called **dead time** between the heating of a portion of the liquid and the transport of that portion to the sensor. The sensor, too, has lag, since its temperature cannot instantly follow the changes in liquid temperature. The controller can be designed to respond in any of several ways to an error input. The current applied may be fully on, proportional to *E*, proportional to the rate of change of *E*, proportional to the accumulated error, or it may respond in some other way. The controller's response to the error signal is called its **control law** or **control algorithm**. The choice of control law affects the system dynamics; the controller can either compensate for or exaggerate the effects of the dynamic characteristics of the other elements.

The simplest control algorithm is **ON-OFF control**. In this the manipulated quantity is simply on or off depending on whether *PV* is greater or less than *SP*. The dynamics of ON-OFF control are illustrated in figure 14-41. The lag and dead time in the system result in overshooting the set point from both directions. Cycling and overshoot are characteristic of ON-OFF control. If the controller has fast response and negligible ON-OFF gap, the amplitude and frequency of the *PV* variation are not affected by the controller but by all other lags and delays in the system.

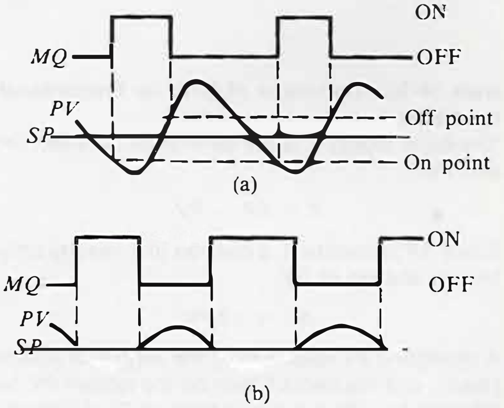


Fig. 14-41. ON-OFF control dynamics. In (a) the turn-on and turn-off values for *PV* are separated. When *PV* drops below the ON point, the controller turns on the manipulated quantity *MQ*. The decrease in *PV* continues, however, due to lags and delays. The manipulated quantity is turned off when *PV* exceeds the OFF point, and overshoot is again produced by the delay. Eliminating the gap between ON and OFF points as in (b) reduces the variation in *PV* and increases the control cycle frequency.

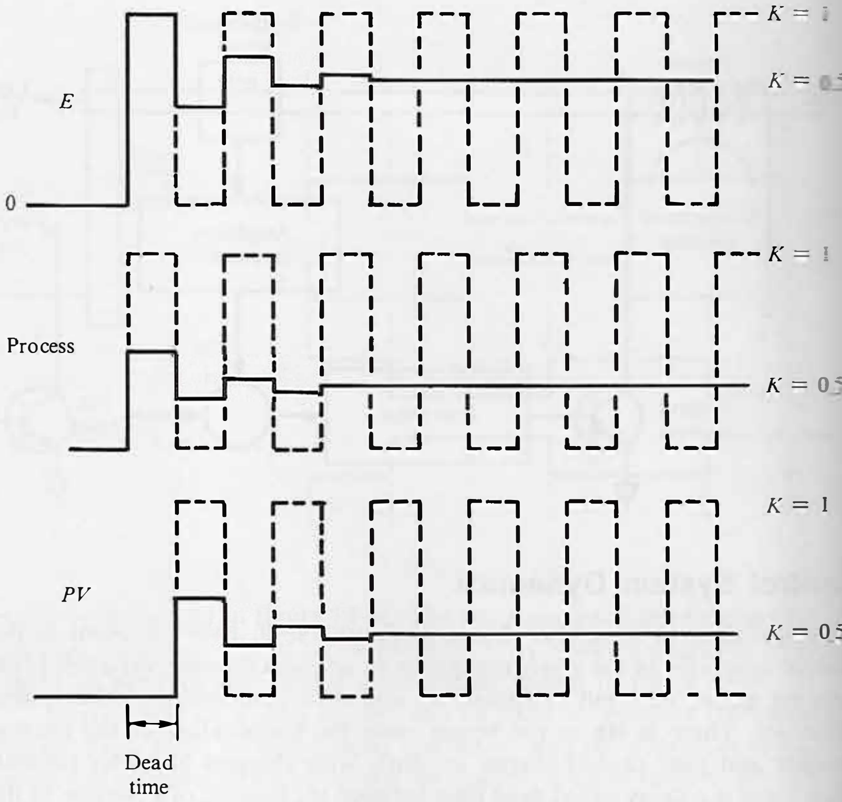


Fig. 14-42. Response of proportional controller to step change in E. Two cases are illustrated; loop gain $K = 0.5$ (solid lines) and $K = 1$ (dashed lines). The system has a finite dead time, which is longer than the lags. The step change in E affects the process immediately according to the gain. This change does not appear at PV until after the dead time. An increase in PV results in a decrease in E and the process. This decreases PV one lag time later and increases E again. For $K < 1$, a steady value is reached with less than half the error corrected. For $K = 1$, a continuous oscillation results, and if $K > 1$, the amplitude of the oscillations increases.

A more sophisticated control algorithm is **proportional control**. In this strategy the manipulated quantity is set at a value proportional to the error magnitude E. Thus as PV approaches SP, E decreases, the drive quantity decreases, and PV changes more slowly. This increasingly gradual approach to SP can eliminate the overshoot and cycling problems of ON-OFF control. The dynamic response of such a control system depends upon the overall gain, dead time, and lag in the control loop. The **loop gain** K is the change in PV that results from a unit change in E when the loop is opened by disconnecting PV from the summing unit. (In fig. 14-40, $K < 1$ if a value of E equivalent to a 10° temperature error results in a temperature change of less than 10°.) The response dynamics of a proportional control system are shown in figure 14-42 for $K \leq 1$. The perturbation in E could have come from a change in SP or from a change in the process conditions. As the dynamics show, a loop gain of less than one results in imperfect compensation while a loop gain of one or more produces oscillations with a period of twice the dead time. The fraction of the perturbation that is uncompensated is $1/(1 + K)$ which is 2/3 for $K = 0.5$, 1/2 for $K = 1$ and approaches zero as K approaches infinity (see note 14-10). It is clear that the dead time in the

Note 14-10. Derivation of Error for Proportional Controller.

The error signal E is the difference between SP and PV:

$$E = SP - PV$$

Since SP is constant, a change in E results only from a change in PV:

$$\Delta E = -\Delta PV$$

A change in PV results from the controller action ($K\Delta E$), and the perturbation on the system PV' in terms of the effect it would have on PV is uncompensated.

$$\Delta PV = K\Delta E + PV'$$

Substituting to eliminate ΔE,

$$\Delta PV = -K\Delta PV + PV'$$

The ratio of the change in PV to the perturbation on PV is then

$$\frac{\Delta PV}{PV'} = \frac{1}{1+K}$$

system prevents the use of a large enough value of K to provide accurate control. In some systems this is not observed because the lags in the process and detector responses are much longer than the dead time. For such systems the loop gain is very low at the frequency at which dead time oscillations would occur. Accurate control is achieved on a longer time scale by the much higher loop gain at low-frequencies.

A controller can be tailored to give close to optimum response for a system by adding averaging and rate terms to the control algorithm. The controller response function is then

$$MV = K_P E + K_I \int E\,dt + K_D \frac{dE}{dt}$$

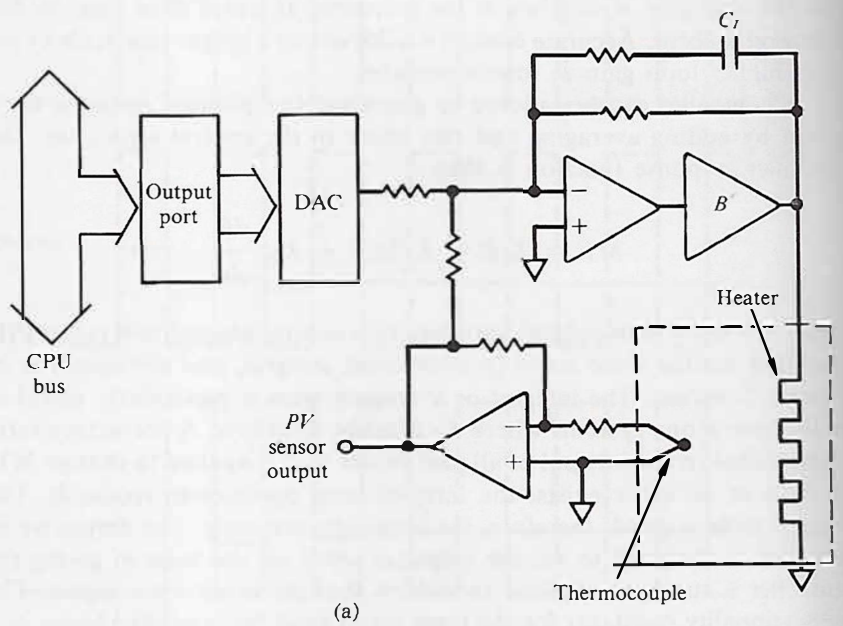
where MV is the manipulated variable. This control algorithm is called **PID controller** for the three terms (*proportional, integral, and derivative*) in its response function. The integral or averaging term is particularly useful in oscillation-prone systems where K_P must be kept low. A correction term proportional to the integral of all past values of E is applied to change MV. As long as an error exists, the integral term operates to reduce it. The integral term is good, therefore, for long-term accuracy. The derivative or rate term is designed to aid the response speed on the basis of giving the controller a stronger response to sudden changes in the error signal. The proportionality constants for the three terms must be carefully chosen in a given system to provide quick and accurate response to perturbations as well as good stability against oscillations.

One advantage of using a microprocessor for the controller is that once it is interfaced to the sensor and control element, any useful algorithm can be implemented or adjusted by simply changing the program. Even more complex algorithms that respond to combinations of sensors are very practical. Another advantange is that, given the time scale of many processes, one microprocessor can often manage several control loops. Subsystem control can be economically implemented so as to optimize sections of a process independently. For example, the mixing ratios of fuel components could be controlled by a loop separate from the one that controls the rate of consumption of mixed fuel. In turn, the fuel consumption might be only one of several controlled aspects of an overall process. Each subsystem can be optimized individually, and overall control is greatly simplified because each of the perturbing variables is separately controlled.

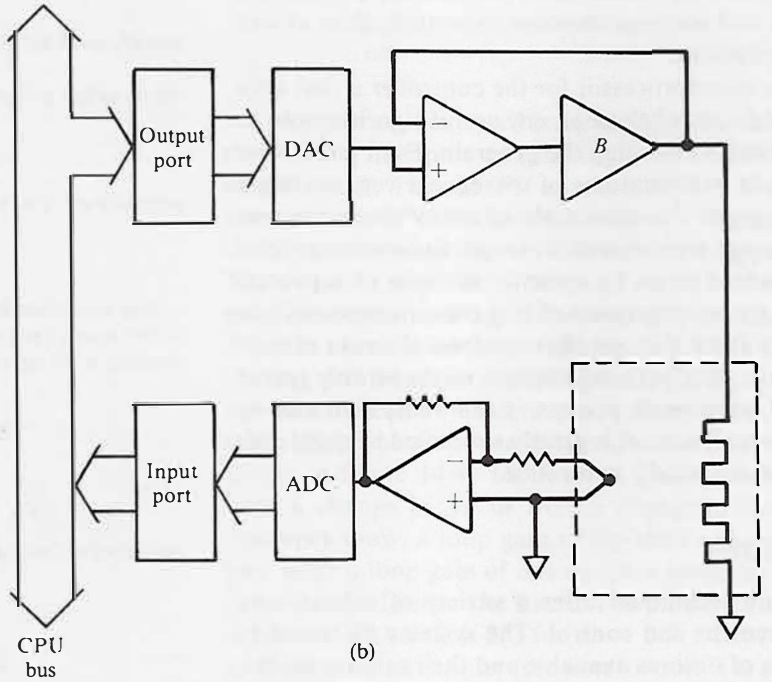
Practical Control Systems

Modern electronic devices and techniques offer a variety of solutions to practical problems in measurement and control. The systems discussed in this section illustrate the kinds of options available and their relative merits.

Temperature controller. Two approaches to a computer-contro temperature regulator are shown in figure 14-43. In the first, the compute not part of the control loop but provides the set point value. This contro



(a)



(b)

Fig. 14-43. Computer-controlled temperature regulators. In (a) the computer determines the set point for an analog temperature control system. The loop gain is adjusted by the control amplifier input and feedback resistors. The capacitor provides an integrating function in the control algorithm. In (b) the computer controls the manipulated quantity directly and reads the value of the process variable through the ADC. The computer is part of the control loop, and the control algorithm is executed through the computer program.

assumes that the *SP* command is correctly executed by the analog controller. The *PV* sensor output could be interfaced through an ADC so the computer could check for reliable operation. Alternatively, a comparator could be used to check the difference between the DAC and *PV* sensor outputs and raise a flag in the I/O port if the difference is excessive. In any case, the computer's attention is only needed to vary *SP* or to respond to control failure. The control system of figure 14-43b depends on the computer to maintain the correct value for the heater voltage. This it does by reading the value for *PV* through the interfaced ADC and calculating the appropriate response. The advantages of including the computer in the control loop are: the control algorithm is readily changed without altering the system hardware, continuous information about the process dynamics is available to the computer, and the computer detection of control error is inherent in the system. The disadvantage is that the computer must execute the control loop subroutine often enough to maintain adequate control.

These two approaches to temperature control illustrate the **hardware-software trade-off** in interface and control system design. Operations performed in the interface hardware increase the hardware complexity, but they relieve the computer of the need to provide frequent or extended attention to the interfaced task.

DC motor controller. A dc motor controller with position sensing is shown in figure 14-44. An encoded wheel is attached to the motor shaft, and its clear and opaque sections are sensed by opto-interrupters as in figure 4-33. In this case two interrupters, separated by half a segment (or 1½, 2½, etc.), provide both speed and direction information. An edge-triggered *D* flip-flop decodes the direction information as shown and an up-down counter keeps track of the net rotations from the reference point when the counter

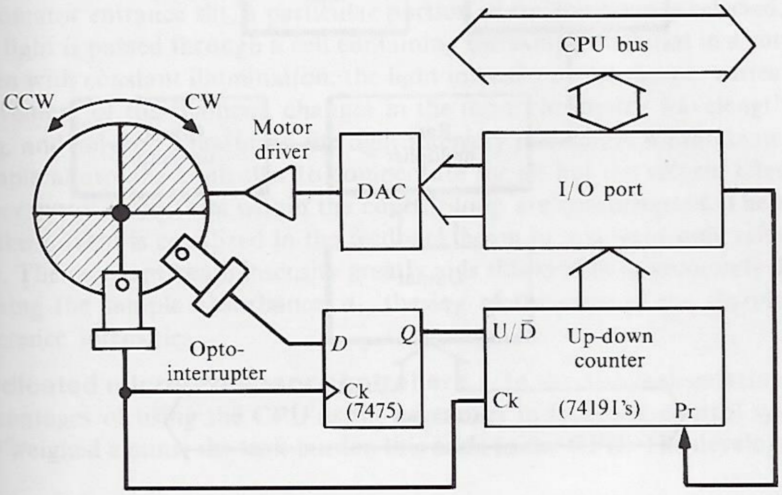


Fig. 14-44. Dc motor controller with position encoder. The motor speed and direction are controlled by the CPU through the DAC. Clockwise (CW) rotations cause the counter to increment, and counter clockwise rotations (CCW) reduce the count. For clockwise rotation, the LO→HI (dark→light) trigger at the *D* FF occurs when *D* is HI, so *Q* is HI (count up). For counterclockwise rotation, *D* is LO (dark) when the LO→HI trigger occurs, so *Q* is low and the counter reverses. The encoding wheel shown produces two counts per rotation. The position of whatever the motor is driving can be read from the counter contents within half a revolution of the motor shaft.

was reset. The resolution of the controller (counts per revolution) can be increased by using a wheel with more sectors. If a binary counter is used, the count is in 2's complement notation. With the interface shown, the CPU can control the motor to turn its load to any desired position as determined by reading the counter. The control algorithm can include slowing the motor as the counter approaches the desired value, approaching the desired value from the same direction to eliminate gear backlash effects, automatic resetting upon encountering an absolute load position index (a separate, single-point detector on the motor-driven load), or other actions. The counting function could be done by software, in which case the input interface would be one bit for the U/$\overline{\text{D}}$ indicator and a flag for the count (Ck) signal. If the motor control interface were an ON-OFF pulse-width or pulse-rate controller, the interface would be extremely simple.

Another example of dc motor control is the motor-speed controller in figure 14-45. The control loop is identical to the phase-locked loop controller of figure 9-24, except that the voltage-controlled oscillator is replaced by a

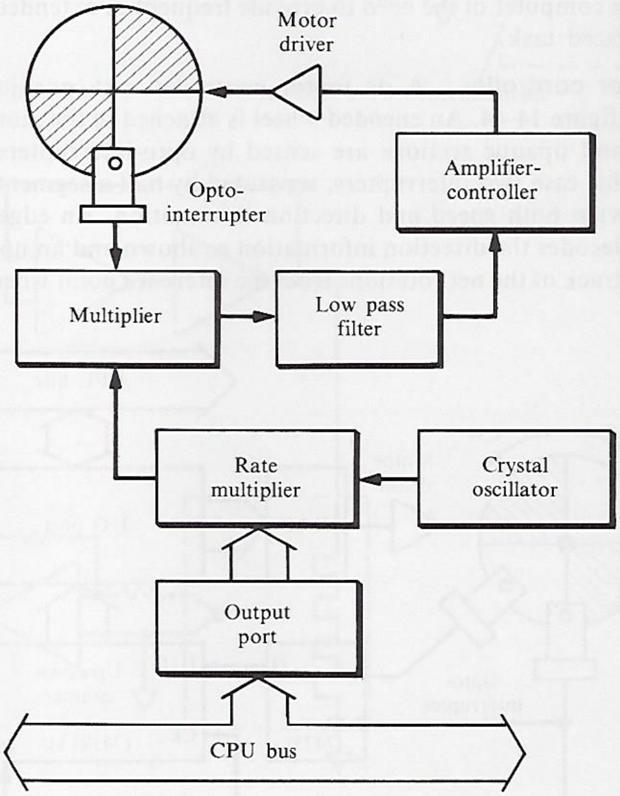


Fig. 14-45. Dc motor-speed controller. The output frequency from the opto-interrupter is compared with a CPU-controlled fraction of the frequency of a crystal oscillator. The result of that comparison determines the control signal to the motor driver. The control loop is of the phase-lock loop type and involves both analog and frequency domain signals.

motor and opto-interrupter. The control loop signal is in the frequency domain at the sensor output and is converted to an analog signal by the multiplier phase comparator. The computer can provide the speed set point as shown, or it could take over the multiplier, filter, and controller functions in the control loop. In a completely computer-controlled system, the computer real-time clock would provide the frequency reference, and the only interface would be the motor drive control and a flag input from the opto-interrupter. The choice between software and hardware control would be based on the need for a simple interface or a sophisticated control algorithm and the load on the CPU from other tasks.

The recognition that motor speed and frequency are both rates and therefore analogous quantities allows the techniques of frequency control to be applied to the control of motor speed. In solving a new design problem, the identification of an already solved analogous problem can provide a direct solution.

Light-intensity controller. The control of light intensity is used in figure 14-46 to illustrate the desirability of deriving the feedback control signal from the quantity that is actually to be controlled. Controlling the voltage across a lamp certainly produces a more constant illumination than operating the lamp from an uncontrolled supply. However, this approach assumes that the power input is constant (the lamp resistance is constant) and the relationship of power input to light output is constant (that is, there are no aging effects in the lamp). Sampling of the light intensity with a photodiode as in figure 14-46b allows a control loop to keep that quantity constant at the set point value. Such a feedback light control is often used in spectrophotometry, and long-term stability is improved. In such systems several of the operations are performed on the light before it impinges on the sample. In the illustrative system of figure 14-46c, the light is focused on a monochromator entrance slit, a particular portion of the spectrum is selected, and the light is passed through a cell containing the sample material in a solvent. Even with constant illumination, the light intensity at the sample varies with movement of the filament, changes in the monochromator wavelength setting, and solvent. Measuring the light intensity just before it illuminates the sample allows the controller to compensate for all but the solvent effect. In other words, all effects within the control loop are compensated. The effect of the solvent is equalized in the feedback beam by a solvent-only reference cell. The constant beam intensity greatly aids this system in accurately determining the sample absorbance A_s, the log of the ratio of the sample and reference intensities.

Dedicated microprocessor controllers. In the above discussion, the advantages of using the CPU as the controller in feedback control systems are weighed against the task burden this adds to the CPU. The development

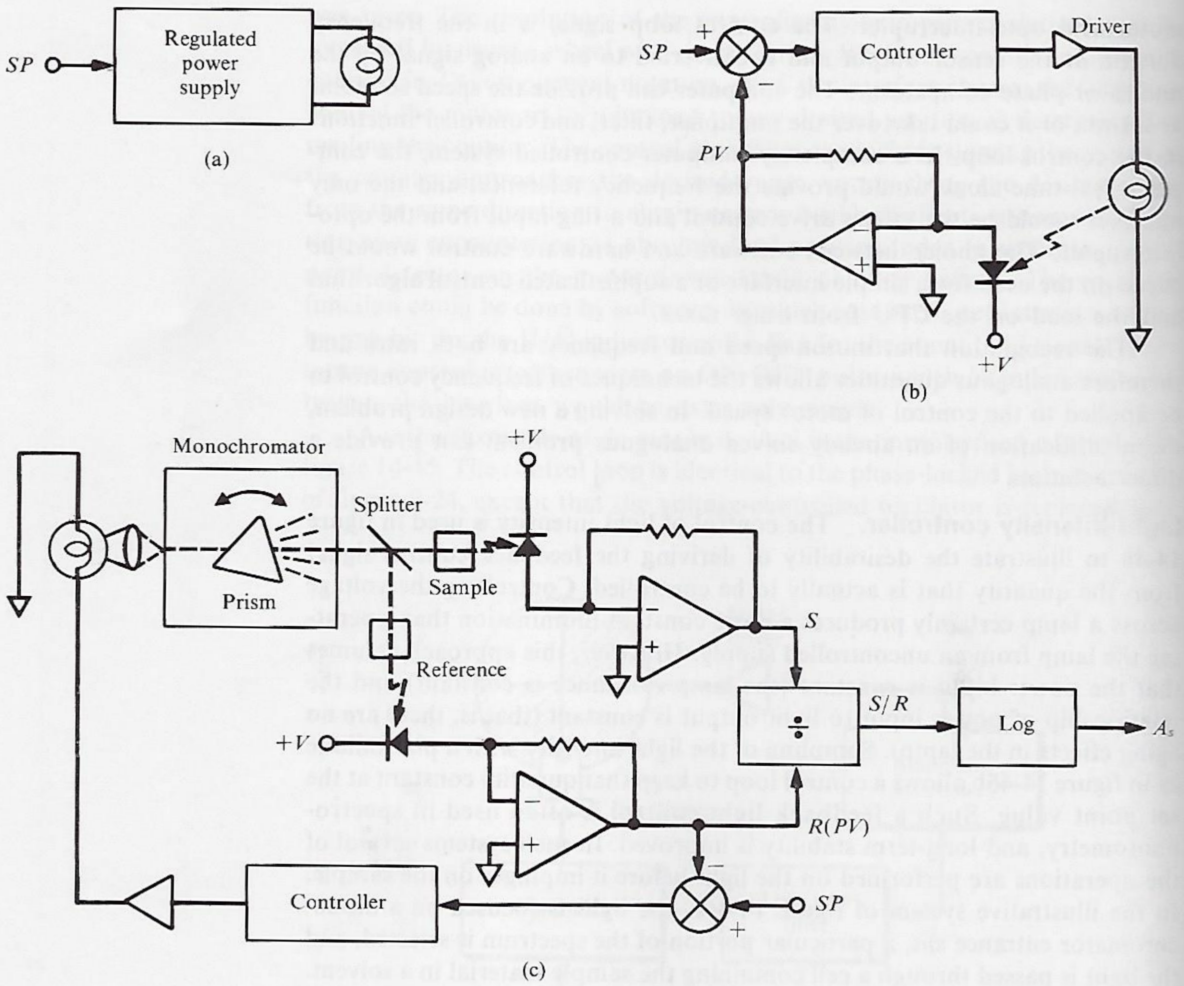


Fig. 14-46. Light intensity control. The regulated power supply (a) controls the voltage (or current) to the lamp. Adding a light detector (b) controls the actual light output rather than the power input to the lamp. In a spectrophotometer (c), many other factors affect that portion of the light used in the measurement. To keep that portion constant, the feedback quantity should be sampled as close to the point of use as possible.

of inexpensive microprocessors and memory has made it economical, in many instances, to design a hardware controller using a dedicated microprocessor. In other words, the main microcomputer is interfaced to a controller that incorporates another microprocessor to achieve the control function. Thus the hardware simplicity and software flexibility are obtained without burdening the main CPU with the control task. Some microprocessors such as the Intel 8048 have been designed for general-purpose peripheral control; others have been tailored to specific tasks for which there is a substantial market.

LSI controllers that include microprocessors are available for control of CRT displays, floppy disc drives, and stepper motors. The control algorithms are often in ROM, which is part of the LSI controller IC. Except for the device handlers, these "smart" control chips are all that is needed to interface the main CPU bus with the controlled device.

The development of microprocessor control systems for applications in home heating, cooling, cooking, and lighting systems to optimize efficiency without loss of effectiveness could affect great savings in our energy resources. The improvements resulting from sophisticated, computer-controlled systems for automobile engines are already widely recognized. Industrial processes could similarly be improved through the adoption of these increasingly inexpensive and effective control techniques. Because of the now widespread awareness of the values of conservation, dramatic advances in control system applications are to be expected in the near future.

14-6 Self-Optimizing Systems

Instruments, machines, and peripheral devices are increasingly referred to as being "smart" or having local intelligence. Usually this means that there is a CPU controlling the device operation, but it can also mean that the instrument is adaptive—that is, it does not continue to follow blindly a routine that is inappropriate for the circumstances. One of the most exciting areas of modern electronic technology is in the development of intelligent systems. Electronic **adaptive control systems** provide a level of automation beyond mere control. Through the speed and precision of modern electronics, adaptive systems can greatly extend the capabilities of virtually any operation or measurement. In this section, examples of four types of "optimizing" control systems are described: an input amplifier that automatically adjusts to the best amplification, some techniques that compensate for imperfect system components, a system that alters its measurement strategy in response to changing signal conditions, and a system that searches for the particular combination of variables that best achieves a given objective.

Autoranging

One relatively simple operation that a smart controller can accomplish is to keep a measuring instrument in range. In a voltage measurement system, for example, a programmable gain amplifier is often used between the signal input and the ADC. When the ADC indicates an overrange, the amplifier gain is reduced. A digital comparator monitors the ADC output. If the conversion falls below the comparison value, the amplifier gain is increased. Note that the resulting gain setting is part of the conversion information. In a digital meter the autoranging circuit keeps the decimal point in the display in the correct place. In a computer system the gain control lines must be interfaced to an input port to complete the information about the signal amplitude. A computer-controlled autoranging system is shown in figure 14-47. The gains of the three integrating amplifiers provide a 64-fold range control, and the control of the integration time can extend that range by orders of magnitude. With a twelve-bit converter, the steps of 2^3 in amplifier gain ensure that nine bits of the ADC are used to give a minimum resolution of one part in 2^9 = 1:512.

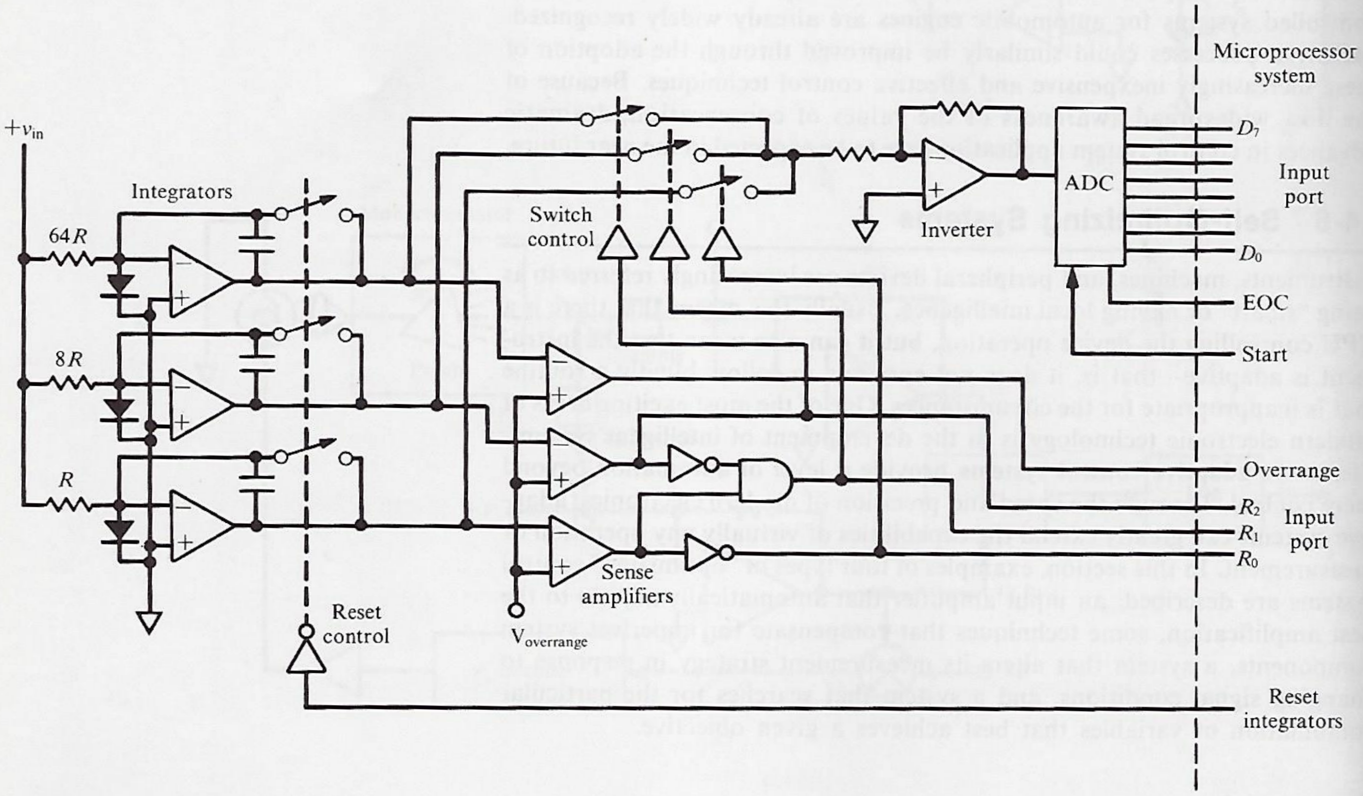


Fig. 14-47. Autoranging integrating amplifier for a microcomputer-based data acquisition system. The sense amplifiers detect integrator overrange and, through the logic, connect the most appropriate integrator to the ADC input. The computer triggers the conversion at the end of the integration time. The three simultaneous integrations with different gain greatly reduce the possibility of a lost data point due to overranging.

Autocalibration

A smart controller can be used to test for and compensate for drift in device characteristics. For example, a principal limitation in high-resolution ADCs and DACs is the problem of keeping the drift in offset and gain to less than the value of the LSB. A controller can be used to test for drift in these parameters and make necessary adjustments. A DAC designed on this principle is shown in figure 14-48. Note that low-resolution control is sufficient to calibrate a high-resolution system because only a few of the least significant bits are affected by the drift.

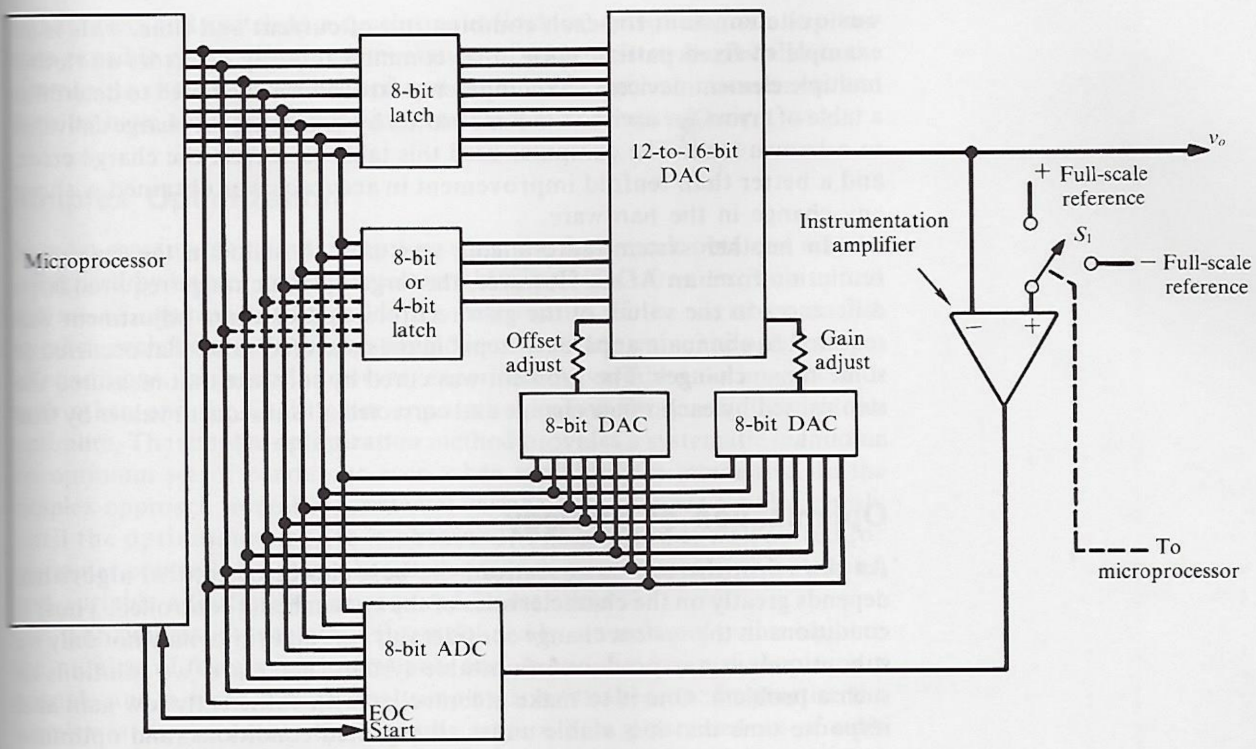


Fig. 14-48. An autocalibrating DAC. The microprocessor periodically compares the DAC output extremes with positive and negative reference values. The error is read from the eight-bit ADC output and used by the computer to determine the needed change in gain or offset. These are applied by altering the values in the low-resolution gain or offset DACs.

Autocompensation

Most traditional measurement systems attempt to minimize the change in any conditions that might cause an error in the measured value. Even so, the dominant source of error in many measurements is the variation in quantities that affect the measurement system characteristics. For example, if temperature is a factor in a strain gauge or a pH measurement, its effects could be compensated by measuring the temperature accurately, experimentally determining the effect of temperature on the measured quantity, and applying an appropriate compensating correction to each measured result. A rough temperature control could be used to limit the degree of compensation needed.

Compensation can also be used for known errors in generated signals. For example, a charge pulse generator can be made by gating a controlled current pulse for a controlled time. The charge, which is the current-time product, can readily be made accurate to within 1% for various combinations of current and time. However, to obtain 0.1% accuracy of charge generation is much more difficult. In one example, the error in the charge was quite constant for each combination of current and time. This is an example of **fixed pattern noise**. It is common in array detectors and other multiple element devices. The computer controller was then used to determine a table of errors for each $i \times t$ combination by measuring the charge delivered to a known load. The computer used this table to correct the charge error, and a better than tenfold improvement in accuracy was obtained without any change in the hardware.

In another system, autoranging was used to maintain the maximum resolution from an ADC. However, the large dynamic range required large differences in the values of the gain resistors, and constant adjustment was required to eliminate apparent "steps" in the measured value that occurred at some range changes. The problem was cured by software that measured the step caused by each range change and corrected all subsequent values by that amount.

Optimization of Strategy

As shown in the previous section, the best choice of control algorithm depends greatly on the characteristics of the system being controlled. Thus, if conditions in the system change considerably, the algorithm may not only be suboptimal; it may produce an unstable system. There are two solutions to such a problem. One is to make a controller with sufficiently low gain and response time that it is stable under all expected conditions (and optimum under none). The other is to analyze the system's response to changes in the driven variable and to adjust the control algorithm as conditions change in the system. This approach is widely used in the flight control systems of commercial airliners.

Adaptive control is a useful concept in measurement as well. The optimum measurement strategy often changes with signal conditions. An example is in instruments that measure the spectrum of the light emitted from a sample or a star. If the light source is weak, photon counting might be used. Waiting at each setting of the grating or prism until a set number of counts have accumulated would give a constant standard deviation for each value. However, if the source does not emit light at some wavelengths in the spectrum, the integration time of the system is longest at the wavelengths of no interest. An adaptive strategy could be used to determine first whether there is enough light to be of interest and then either to wait for the desired number of counts or to move to the next part of the spectrum. If the counting (integration) is to continue for a long time, the count rate may drift during this period because of slow variations in the system (background counts, amplifier gain, and so on). In such cases an adaptive measurement strategy could anticipate the need for long integration times based on low signal levels and switch to a synchronous (lock-in) detection mode to eliminate possible drifts. The implementation of adaptable strategies allows the operator to choose between speed and accuracy in a given measurement and then to have the chosen goal implemented in the most efficient way.

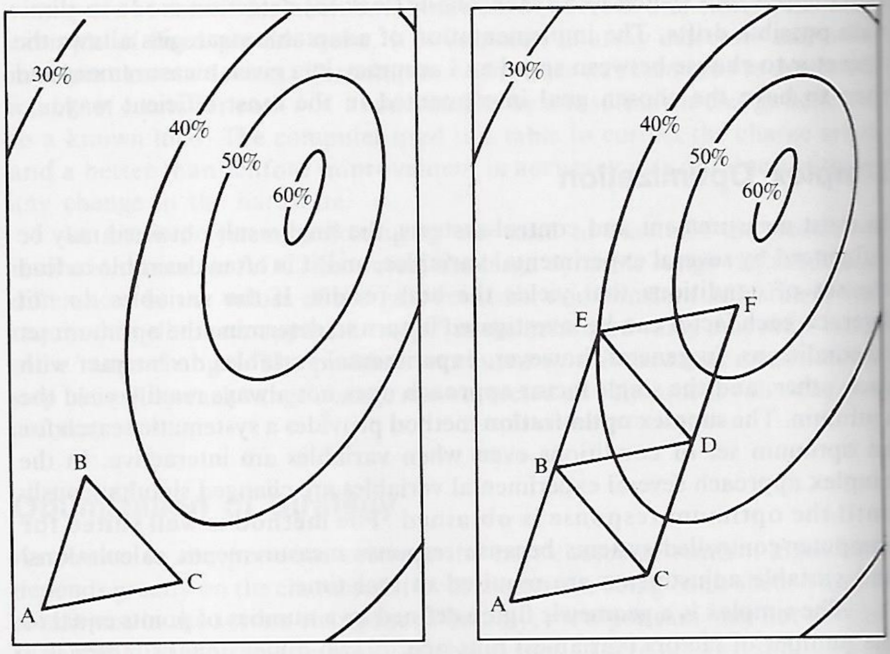
Simplex Optimization

In most measurement and control systems, the final result obtained may be influenced by several experimental variables, and it is often desirable to find the set of conditions that yields the best results. If the variables do not interact, each factor can be investigated in turn to determine the optimum set of conditions. In general, however, experimental variables do interact with each other, and the single factor approach does not always readily yield the optimum. The **simplex optimization** method provides a systematic search for an optimum set of conditions even when variables are interactive. In the simplex approach several experimental variables are changed simultaneously until the optimum response is obtained. The method is well suited for computer-controlled systems because response measurements, calculations, and variable adjustments are required in real time.

The simplex is a geometric figure defined by a number of points equal to the number of factors (variables) plus one. A two-dimensional simplex is a triangle and a three dimensional simplex is a tetrahedron. In practice the simplex is moved across the response surface by a prescribed set of rules until it reaches the optimum response or undergoes failure.

A major problem in any optimization procedure is defining the goal of the optimization and choosing the variables to be optimized. In a spectroscopic experiment, for example, many different optimization goals can be defined. Some worthwhile goals are highest measurement precision (signal-to-noise), highest measurement accuracy, highest signal, best signal-to-background ratio, highest resolution, etc. Among the many variables influencing the measurement are monochromator slit width, photomultiplier voltage, current-to-voltage converter gain and bandwidth, and any variables that influence the light output. Obviously the choice of the optimization goal and the specific variables to be optimized greatly influences the set of conditions obtained.

Let us assume that a chemical reaction is being optimized for best yield. For simplicity, the variables considered are the temperature of the reaction mixture and the pH of the mixture. Let us also assume that a computer can control these variables and monitor the yield after each change in conditions. To illustrate the initial simplex and its moves toward the optimum, consider the contour map of figure 14-49a. Three evaluations of yield vs. temperature and pH define the initial simplex. The simplex moves by discarding the



(a) (b)

Fig. 14-49. Two-dimensional simplex for optimization of product yield. The lines represent equal product yields in a chemical reaction as a function of temperature and pH. Points A, B and C in (a) represent the vertices of the initial simplex. The point of lowest response (point A) is discarded and reflected across the face of the remaining points generating a new simplex, BCD in (b). The lowest response of the BCD simplex (point C) is now discarded and reflected to give point E. This process continues until the optimum response has been found.

vertex with the worst response and replacing it with a response obtained at the mirror image position across the face of the remaining points. Thus, in figure 14-49 point A is discarded and reflected across the BC face to generate a new set of variables for which the response is evaluated. This new vertex is indicated as point D in figure 14-49b. Points B, C and D now form a new simplex. If the new point in the second simplex (point D) had the worst response, it would not be discarded as in the initial simplex for this would only regenerate the ABC simplex. Instead the second worst response would be rejected, and the process continued. Boundaries can be assigned to the independent variables to limit the simplex to an appropriate region. Modifications to the simplex procedure allow expansion and contraction of the simplex which can accelerate movement and cause the simplex to adapt to particular response surfaces.

Simplex optimization is particularly well suited to computer-controlled experiments where several interactive variables are present. It has been applied to such problems as optimizing magnetic field homogeneity in nuclear magnetic response spectroscopy, optimizing signal intensity vs. spatial observation window in flame spectroscopy as well as optimizing yields in synthetic chemical procedures. As more and more instrumental systems become intelligent, simplex procedures are certain to become more commonplace.

14-7 Conclusions

From the many examples presented in this text, it is apparent that scientific and process control instrumentation and measurement techniques can be considerably improved by modern microelectronic concepts and technology. There have been dramatic improvements in the past few years, and we should witness even greater developments during the 1980s. It seems inevitable that nearly all scientific research and development laboratories will become highly automated during this decade, and consumer products will be influenced increasingly by the ubiquitous microprocessor.

Perhaps this will be the decade of super laboratory robots. If so, we would be wise to gain some insight into their potential impact on an already revolutionary scientific era. How "intelligent" and versatile will these robots be? Will they provide an economical work force? Will they work "intelligently" on both research and routine projects? How will they affect scientific and manpower requirements? These questions, of course, were not answered by the information in this text because of their speculative nature. However, we hope that your study of the concepts and techniques presented will spur your interest and enable you to envision the potential future impact of microelectronics on all of our lives. Only with vision will we know how best to proceed.