Ralph L. Moore

The DYNAMIC ANALYSIS of Automatic Process Control

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INSTRUMENT SOCIETY OF AMERICA

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AUTOMATIC PROCESS CONTROL

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PREFACE

Instruments and regulators were designed primarily by innate ingenuity prior to the 1930's. At that time, it was realized that control systems could be described by mathematical equations. Great advances in this concept occurred during World War II, in the design of servomechanisms for ordnance control. Advances included the use of heat, mass, and force-balance equations to describe physical systems; the use of differential operators, e.g., Laplacians, to more easily handle the resulting differential equations; and the use of the theory of complex variables, with all the power of its inherent mathematical concepts, to assess stability. The 1950's saw the publication of a number of basic books that applied analytical techniques to the regulation of fluid processing systems. This book serves as a compilation of those techniques, many of which, through the years, have led to simplified guidelines for good control applications.

Since control systems lend themselves so well to mathematical analysis, an immense amount of mathematical development has been published in the ensuing years. It has included new signal flow diagrams, new transforms, new graphical techniques, and new computer algorithms. That effort has culminated in the modern control theory described in the final section of this book.

The material herein is not new. It has been drawn from personal experience, from the authors in the list of *References,* and from associates within the DuPont Company. Significant contributions were made by the late Joseph F. Coughlin, ISA Fellow and Principal Consultant in the DuPont Engineering Department, who conceived portions of Sections 3, 4, and 7 as a training manual; and the late Professor C. R. Otto, of Cornell University and the DuPont Engineering Department, who wrote much of Appendix C. I appreciate the cooperation of the DuPont Company in authorizing publication of this information.

Ralph L. Moore
New Castle, Delaware
December 15, 1984

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INTRODUCTION TO THE STUDENT

1-1 AUTOMATIC CONTROL

Automatic process control is widely used because it results in economy of operation of industrial processes that more than pays for the cost of the control equipment. Some benefits of automatic control are:

- Increased productivity and the resulting lower product unit cost.
- Higher product uniformity, which results in less wastage.
- Greater safety for operating personnel.
- The freeing of human beings from dull and menial tasks.
- The control of processes too fast and too complex for human beings to follow.
- A lower labor cost, which is reflected in a lower product cost.

The principle of automatic control, the use of the feedback of a measurement to actuate a controlling mechanism, is quite simple. Diagrammatically, the fundamental closed loop of action and reaction representative of most automatic control systems is shown in Figure 1-1.

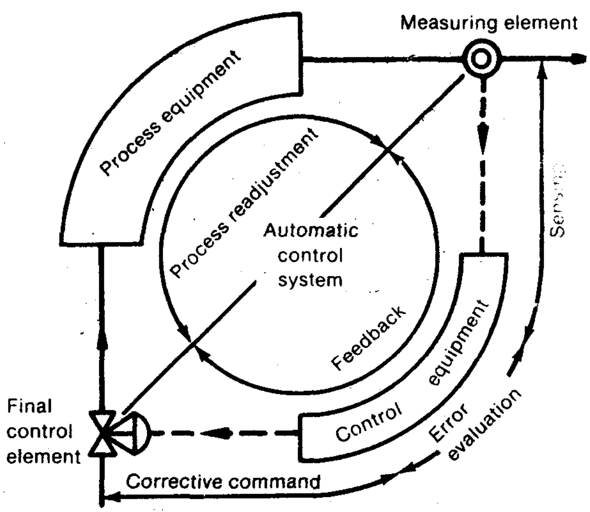

Figure 1-1. Elements of Controlled System

The control system can be seen as a series of elements combined to produce a useful result with little or no human intervention. Many years ago, process equipment was designed using steady-state design concepts. Upon completion of the design of the process equipment, the control equipment was added. Painfully, it became apparent that process equipment design with such limited concepts was in many instances literally uncontrollable. Thus evolved the modern concept that process equipment and control equipment interact intimately to form an automatic control system, as shown in Figure 1-1, and must be designed together as a system for best operation.

1-2 COURSE CONTENT

The design of an as yet unbuilt automatic control system, or the understanding of the difficulties of a poorly operating system, requires an analysis of each element in the system and the assembly of the model of each element into an analogous system. The model includes the *dynamics* of each element. Dynamics is the science of forces and covers cases where no motion results (statics) and where motion does result (kinetics). The concept of analogy is widely used, and much of the analogy is based on the familiar electrical concepts of resistance and capacitance. Some of the systems that can be made analogous to the electrical system are as follows:

Driving Force	Resulting Action
Net force	Acceleration
Voltage difference	Current flow
Temperature difference	Heat flow
Pressure difference	Fluid flow
Magnetic dipole	Magnetic flux
Composition difference	Chemical reaction

Today's automatic control systems are actuated electrically, pneumatically, electronically, and/or digitally. Essentially no mention is made of these various alternatives in this text, because well applied instrument components and a well designed system are independent of actuation. Each type of actuation has advantages and disadvantages: Electrical systems have a very quick response but sometimes are so noisy that large capacitors must be added for stability; pneumatic transmission is slower, but the dynamics of the tubing stabilizes the control system; digital systems are very accurate but are limited by the number of bits that can be carried and by quantization. Generally, the choice of actuation is economic and has little to do with analysis.

The dynamics of processes and instruments can be determined either mathematically or experimentally. Generally, processes will be analyzed mathematically, because experimental testing is costly in lost production and can be dangerous. Instruments, on the other hand, tend to be small and portable and are easily taken to a convenient place for testing. With this in mind, the early sections that follow emphasize the mathematical modeling of processes and process equipment. A later section is devoted to experimental testing and largely emphasizes the testing of process equipment to determine or verify dynamic response. The analysis of temperature sensors is included, and the section on sinusoidal testing describes the frequency response technique for experimentally determining instrument dynamics.

Frequency response techniques are used to analyze the automatic control system as an entity. Frequency response has been largely replaced as a tool for system analysis by computer simulation but still has great value in assessing the interactive relationship of system components to each other and as a fast, simple, pencil-and-paper technique for determining controller tuning parameters. While computer simulation can handle very large and complex automatic control systems and has the great advantage of providing a time domain solution, it does not provide the insight into a single-loop automatic control system as do the frequency response techniques.

The mathematics of automatic control systems are sophisticated and difficult and will not be remembered unless used regularly. However, the mathematical derivations lead to generalizations and guidelines that are readily usable for design and troubleshooting long after the mathematics have drifted away. Sections on mass balance, flow, and temperature control provide guidelines for systems in widespread use.

Finally, sections on higher-level control systems such as feedforward, cascade, and adaptive control are included. Such systems are commonplace because they are so easy to implement (and to revise in the field) with the new microprocessor-based control equipment. State space techniques are included because of their great strength in designing multiple-loop control systems. They provide insight into system design for pairing (deciding which measured variable to use to manipulate each final control element) and for a design to minimize interaction among the control loops.

1-3 PREREQUISITES

Maximum usefulness will be gained from this text if the reader is familiar with mathematics up to calculus with some knowledge of basic physics and chemistry. Partial differential equations, operational calculus, and statistics are touched on in passing. Some training in chemical unit operations or experience in the petrochemical industry will be helpful. Dimensions are a problem, and stress is laid on carrying dimensions with all numerical factors in order to verify the dimensions of the result. Having developed the mathematical relationships, all calculations can be made with a hand-held calculator.

1-4 LEARNING OBJECTIVES

The principal objective of this text is to develop in each reader a sense of judgment about the adequacy of process equipment design, controller choice, tuning parameters, and valve characteristics for a control system that responds well and is stable. Let it be acknowledged that the broad use of the guidelines contained herein will result in applications that are entirely adequate without further analysis for about 95 percent of control systems. A second objective is to recognize control systems that do present difficulty, that do require analysis, and that might well require more sophisticated control configurations.

1-5 DEFINITION OF TERMS

The following terms are used throughout the book. (Definitions have been taken from SAMA Standard PMC 20-2-1970 Process Measurement and Control Terminology, with the permission of the publisher, Process Measurement and Control Section, SAMA, 370 Lexington Avenue, New York, N.Y. 10017.)

attenuation. (1) A decrease in signal magnitude between two points, or between two frequencies. (2) The reciprocal of gain when the gain is less than one.

Bode diagram. A plot of log amplitude ratio and phase angle values on a log frequency base for a transfer function.

calibrate. (1) To ascertain by the use of a standard the locations at which scale or chart graduations of a device should be placed to correspond to a series of values of the quantity that the device is to measure, receive, or transmit. (2) To adjust the output of a device, to bring it to a desired value, within a specified tolerance, for a particular value of the input. (3) To ascertain the error in the output of a device by measuring or comparing against a standard.

control action. Of a controller or a controlling system, the nature of the change of the output effected by the input.

control action, adaptive. Control action whereby automatic means are used to change the type or influence (or both) of control parameters in such a way as to improve the performance of the control system.

control action, cascade. Control action where the output of one controller is the set point for another controller.

control action, derivative (rate). Control action in which the output is proportional to the rate of change of the input.

control action, feedback. Control action in which a measured variable is compared to its desired value to produce an actuating error signal, which is acted upon in such a way as to reduce the magnitude of the error.

control action, feedforward. Control action in which information concerning one or more conditions that can disturb the controlled variable is converted into corrective action to minimize deviations of the controlled variable.

control action, integral (reset). Control action in which the output is proportional to the time integral of the input; i.e., the rate of change of output is proportional to the input.

control action, proportional. Control action in which there is a continuous linear relation between the output and the input.

control mode. A specific type of control action such as proportional, integral, or derivative.

control system. A system in which deliberate guidance or manipulation is used to achieve a prescribed value of a variable.

controller. A device which operates automatically to regulate a controlled variable.

controller, floating. A controller in which the rate of change of the output is a continuous (or at least a piecewise continuous) function of the actuating error signal.

controller, integral (reset) (I). A controller which produces integral control action only.

controller, proportional (P). A controller which produces proportional control action only.

controller, proportional-plus-integral (reset), (PI). A controller which produces proportional-plus-integral (reset) control action.

frequency, undamped (frequency, natural). (1) Of a second-order linear system without damping, the frequency of free oscillation in radians or cycles per unit of time. (2) Of any system whose transfer function contains the quadratic factor $s^2 + 2\zeta\omega_n s + \omega^2_n$, the value ω_n.

where:

s = complex variable
ζ = constant
ω_n = natural frequency in radians per second

(3) Of a closed-loop control system or controlled system, a frequency at which continuous oscillation (hunting) can occur without periodic stimuli.

gain (magnitude ratio). For a linear system or element, the ratio of the magnitude (amplitude) of a steady-state sinusoidal output relative to the causal input; the length of a phasor from the origin to a point of the transfer locus in a complex plane.

gain, loop. The ratio of the change in the return signal to the change in its corresponding error signal at a specified frequency. (Note: The gain of the loop elements is frequently measured by opening the loop, with appropriate terminations. The gain so measured is often called the open-loop gain.)

gain, proportional. The ratio of the change in output due to proportional control action to the change in input.

integral action rate (reset rate). (1) Of proportional-plus-integral or proportional-plus-integral-plus-derivative control action devices; for a step input, the ratio of the initial rate of change of output due to integral control action to the change in steady-state output due to proportional control action. (Note: Integral action rate is often expressed as the number of repeats per minute because it is equal to the number of times per minute the proportional response to a step input is repeated by the initial integral response.) (2) Of integral control action devices; for a step input, the ratio of the initial rate of change of output to the input change.

Laplace transform — unilateral. Of a function $f(t)$, the quantity obtained by performing the operation.

$$f(s) = \int_0^\infty f(t)e^{-st}dt$$

where:

$s = \sigma + j\omega$

$f(s)$ = function of s

s = complex variable

$f(t)$ = function of t

t = time, seconds

σ = real part of the complex variable s

$j = \sqrt{-1}$

ω = frequency, rad/sec

linearity. The closeness to which a curve approximates a straight line.

loop, closed (feedback loop). A signal path which includes a forward path, a feedback path, and a summing point and which forms a closed circuit.

loop, open. A signal path without feedback.

measured variable. The physical quantity, property, or condition which is to be measured.

offset. The steady-state deviation when the set point is fixed.

parameter. A controllable or variable characteristic of a system or device, temporarily regarded as a constant, the respective values of which serve to distinguish the various specific states of a (the) system or device.

phase difference. (1) Between sinusoidal input and output of the same frequency, phase angle of the output minus phase angle of the input. (2) Of two periodic phenomena (e.g., in nonlinear systems), the difference between the phase angles of their two fundamental waveforms.

primary element. The system element that quantitatively converts measured variable energy into a form suitable for measurement.

process. The collective functions performed in and by the equipment in which the variable(s) is (are) to be controlled.

proportional band. The change in input required to produce a full range change in output, due to proportional control action. (Note: It is reciprocally related to proportional gain.)

response, step. The time response of an instrument when subjected to an instantaneous change in input from one steady-state value to another.

response, time. An output, expressed as a function of time, resulting from the application of a specified input under specified operating conditions.

sensitivity. The ratio of a change in output magnitude to the change of input which causes it after the steady state has been reached.

set point (command). An input variable which sets the desired value of the controlled variable.

signal. Information about a variable that can be transmitted.

signal, error. In a closed loop, the signal resulting from subtracting a particular return signal from its corresponding input signal.

steady state. A characteristic of a condition, such as value, rate, periodicity, or amplitude, exhibiting only negligible change over an arbitrary long period of time.

time, dead. The interval of time between initiation of an input change or stimulus and the start of the resulting response.

time, step response. Of a system or an element, the time required for an output to make the change from an initial value to a large specified percentage of the final steady-state value either before or in the absence of overshoot, as a result of a step change to the input. (Note: Usually stated for 90, 95, or 99 percent change. See *time constant* for use of 63.2 percent value.)

time constant. For the output of a first-order (lag or lead) system forced by a step or an impulse, τ is the time required to complete 63.2 percent of the total rise or decay; at any instant during the process, τ is the quotient of the instantaneous rate of change divided into the change to be completed. In higher-order systems, there is a time constant for each of the first-order components of the process. In a Bode diagram, breakpoints occur at $\omega = 1/\tau$.

time constant, derivative action. Of proportional-plus-derivative control action, a parameter whose value is equal to $1/2\pi f_d$ where f_d is the frequency (cycles per unit time) on a Bode diagram of the lowest frequency gain corner resulting from derivative control action.

time constant, integral action. Of proportional-plus-integral control action, a parameter whose value is equal to $1/2\pi f_i$ where f_i is the frequency (cycles per unit time) on a Bode diagram of the highest frequency gain corner resulting from integral control action.

transducer. An element or device which receives information in the form of one physical quantity and converts it to information in the form of the same or some other physical quantity.

transfer function. A mathematical, graphical, or tabular statement of the influence which a system or element has on a signal or action compared at input and at output terminals.

variable, manipulated. A quantity or condition which is varied as a function of the actuating error signal so as to change the value of the directly controlled variable.

**STUDENT SUMMARY NOTES
and QUESTIONS FOR INSTRUCTOR**

SECTION **2**

JUSTIFICATION FOR AUTOMATIC CONTROL

2-1 INTRODUCTION

Automatic control has played a major role in the evolution of our modern way of life by making more goods available for everyone through increased productivity, by increasing leisure time, and by eliminating many tedious or dangerous jobs. Automation can be found in our homes, our cars, and our workplaces. It is so prevalent that it has become an almost invisible part of our surroundings.

The automatic home heating system is a familiar example of automation in our daily lives. It is difficult to recall fairly recent times when fuel (wood or coal) was piled near the furnace to be added at regular intervals as it burned; the adjusting of dampers for more or less heat; the elimination of ashes from the furnace; and the removal of ashes from the premises. The simple adjustment of a thermostat to the desired temperature not only eliminates constant attention to fuel supply but also the manual labor of fuel and ash transportation. Automatic home heating is widely justified by these conveniences.

The thermostat acts as both sensor and controller for the home heating system. It senses the temperature at a representative location in the house and compares the house temperature with the desired temperature, called the set point temperature. The difference between the sensed temperature and the set point temperature is called the controller error. If the house temperature is below the set point temperature, an electrical circuit is completed that starts a flow of fuel to the furnace and then ignites the fuel.

The fire in the furnace combustion chamber supplies heat to the house until the house temperature rises above the set point temperature, at which time the thermostat shuts off the supply of fuel; the fire goes out, and the house begins to cool. It cools until the house temperature decreases past the set point, at which time the heating cycle starts over again.

2-2 HOME HEATING SYSTEM — ON-OFF CONTROL

The familiar automatic home heating system encompasses many of the basic tenets of automatic control. First, it is an on-off type of control system. This designation results from the manipulated variable (fuel flow to the furnace) being either fully on or completely off. The performance of the system in regulating temperature reflects the type of control, wherein house temperature varies above and below the set point temperature but almost never remains at the set point temperature.

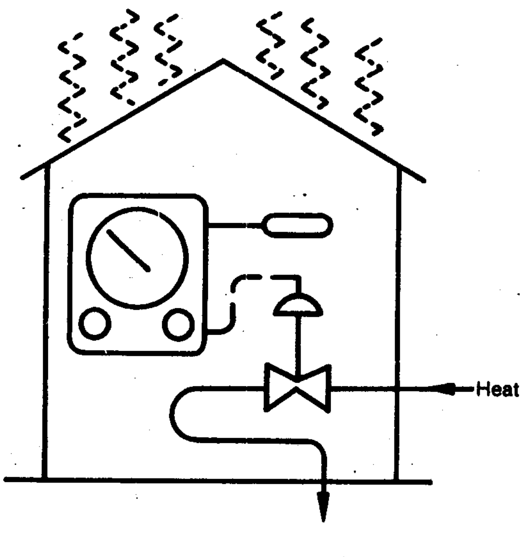

Figure 2-1. Home Heating System[3]
(Courtesy E. I. du Pont de Nemours & Company)

The home heating automatic control system also illustrates the difference between the two basic objectives of feedback control systems, one of which is regulation. To meet this objective, the control system must maintain temperature close to a constant set point with changing external conditions. For example, suppose the temperature outside the house dropped suddenly. House temperature would change its characteristics by decreasing more quickly when the furnace was turned off and increasing more slowly when the furnace was on. The temperature control system must regulate temperature near the set point despite disturbances such as a change in outside temperature. This is the regulatory objective.

The second objective is to follow changes in set point, or to respond as a servomechanism. Should someone in the house feel cold and raise the set point of the thermostat, the control system would be expected to cause the house temperature to follow the set point change. The system would call for the furnace to start and to stay on until the house temperature reached the new set point temperature, at which point the on-off action would again start to maintain the temperature near the new set point.

Lastly, automatic home heating is an example of the type of process that can be well regulated by on-off control. When the furnace is first turned on, the house volume is so large that temperature rises slowly even though heat is being supplied at the maximum furnace capacity. Finally, the temperature passes the set point of the thermostat, which then turns off the furnace. Then, because of the heat contained in the house and the low rate of heat loss, temperature decreases very slowly until it falls far enough to cause the thermostat to actuate the furnace. Thus the characteristic of this on-off control is a temperature that varies between maximum and minimum limits, with a period (elapsed time from one maximum temperature to the next) of many minutes or even hours.

On-off control is less applicable as houses become progressively smaller and less well insulated. Then temperature will rise and fall faster with the furnace being switched on and off more and more frequently. Finally, the furnace would be switched so rapidly as to cause excessive electrical contact wear, and on-off control should be replaced by a continuous type of control.

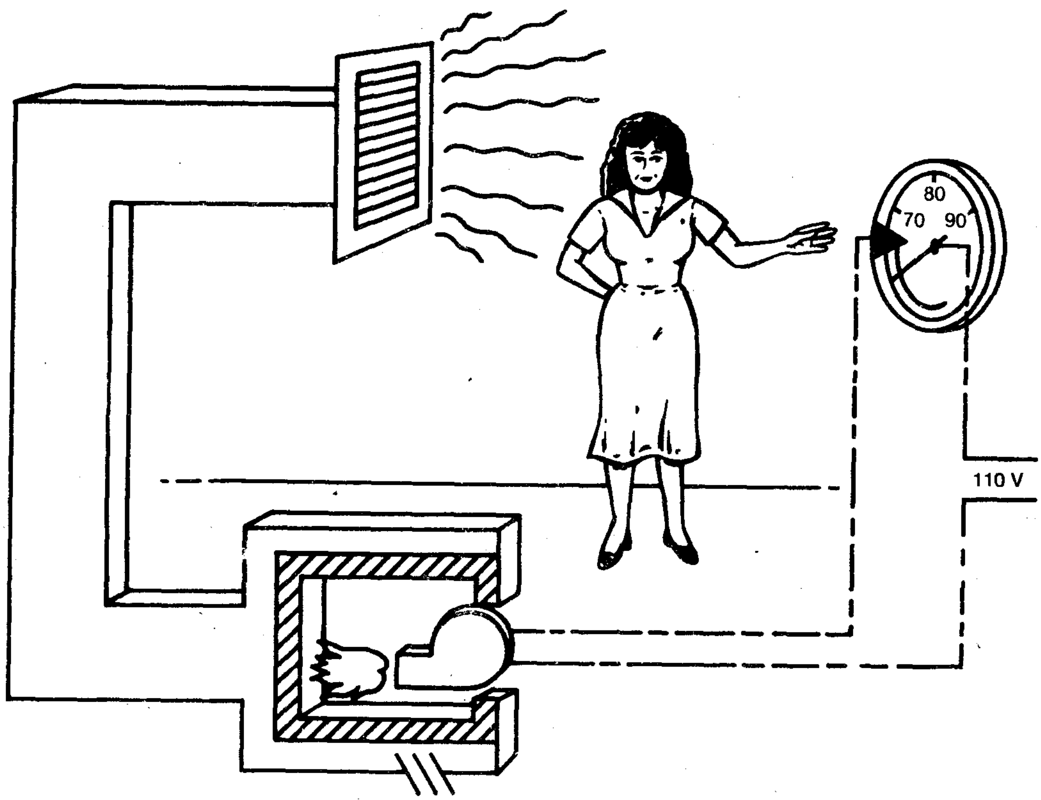

Figure 2-2. Automatic Home Heating System

2-3 HOME HEATING SYSTEM — ON-OFF PLUS DERIVATIVE CONTROL

The home heating system previously described will regulate temperature in such a manner that it will first be a couple of degrees above set point and then a couple of degrees below set point, or it will cycle by plus or minus a couple of degrees. Consider an increasing house temperature with the furnace running. The furnace will shut off as the house temperature crosses the thermostat set point. However, heated air will exist in the furnace and the duct system, and house temperature will continue to increase for a short time after the furnace shuts off. The temperature will increase, reach a maximum, and begin to decrease, at which point it will again cross the set point and start the furnace.

However, the furnace and duct system are cold when the furnace starts, and house temperature will continue to decrease for a short while until enough warm air is available to displace the cooling air in the house. At that point, temperature will reach a minimum and begin increasing, starting the cycle all over again.

The amplitude of the temperature cycle can be reduced by placing a small electrical heating element in the thermostat housing. The heater is turned on by the same switch that starts the furnace. The heater then maintains the temperature sensor inside the thermostat housing at a temperature slightly higher than the house temperature. As the house temperature rises to approach the set point, the sensor temperature is slightly higher, due to the heater, and crosses the set point while the house temperature is still slightly below the set point. The furnace is shut off before the set point is reached, and the overshoot due to residual hot air is reduced.

The thermostat with the heater thus anticipates the reaching of the set point by the house temperature and acts previously (pre-acts) to shut off the furnace. This control action has been called anticipatory or pre-act control, but the modern term is derivative action.

2-4 OPERATING AN AUTOMOBILE — MANUAL CONTROL

A human being can perform well as an automatic controller. Consider the steering of an automobile.(1) The set point is an imaginary line down the center of the driving lane. The eyes act as an error-detecting element by comparing the position of the car with the imaginary line. As the road curves, the imaginary line curves, and the eyes detect the error between the direction of the car and the curving line. The brain represents the controller modes. It decides the amount of correction and transmits this information to the manipulated mechanism, the arms. The arms then reposition the wheels through the steering mechanism. The arms do not necessarily have the strength to move the wheels, but a gain in force between steering wheel and the car wheels is supplied by the gearing or by power steering (another servomechanism).

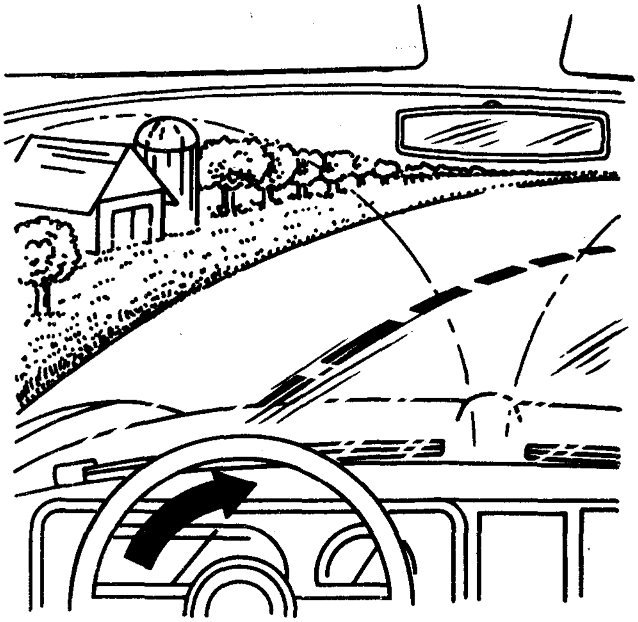

Figure 2-3. Steering an Automobile

However, the operation of an automobile illustrates some of the weaknesses of the human being as a controller. Continued driving becomes tedious and leads to boredom, which in turn leads to inattention and poor performance. A mechanism, on the other hand, will do precisely the same thing repeatedly for long periods of time.

Another human limitation lies in the ability to discern whether the center of the automobile is over the imaginary line in the center of the driving lane. Precision is of little importance on a modern highway where the driving lane is several feet wider than the automobile. An error of a foot or more can exist with little consequence. But suppose the automobile is to be driven over an old-fashioned narrow bridge. Steering gets progressively more difficult when only a few inches of clearance exist on the sides of the car.

Finally, speed of response is definitely a human limitation. Again, driving is easy when traffic is flowing smoothly. But suddenly the unexpected happens, and an accident occurs before the brakes can be applied or the steering wheel can be turned. Worse yet, speed of response varies with the condition of the driver — age, fatigue, or the effects of medication. Automatic controls will outperform human beings in the areas of repetition, precision, and speed of response whether in the operation of a vehicle or the regulation of an industrial process.

2-5 THE WATER CLOSET — PROPORTIONAL CONTROL

The filling of the common bath room fixture[2] serves to illustrate automatic control in the proportional mode. Water is retained in the tank by a rubber stopper in an opening at the bottom. The stopper is removed by a linkage connected to an external handle. Upon actuation, water runs from the tank very rapidly, and a ball float drops as the water level decreases. The inlet valve plug is lifted from its seat by the linkage that connects it to the ball. Incoming water is admitted as the plug is lifted. The rubber ball reseats itself when the tank is nearly empty. Then the tank begins to refill.

The flow of incoming water gradually decreases as the ball rises. Finally, when the water is at the desired level, the ball closes the valve entirely, and this simple proportional device (the valve opening is proportional to the valve position) has automatically refilled the tank.

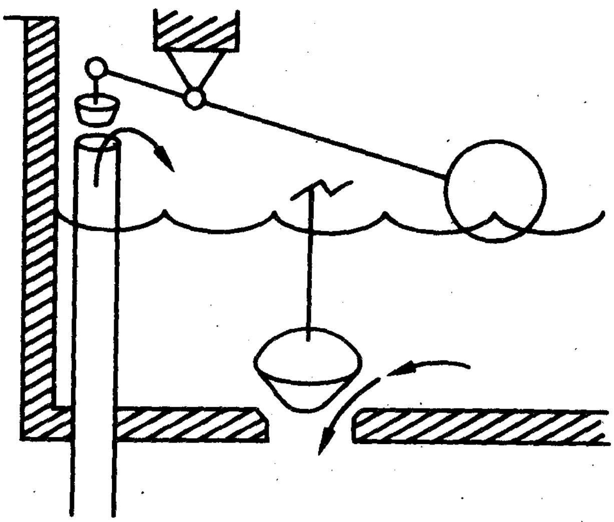

Figure 2-4. Water Closet Level

The water closet float valve illustrates one of the disconcerting characteristics of proportional control. Suppose the rubber stopper developed a small leak. The level would drop and the inlet valve would open until the inlet water flow was equal to the leak rate. At that point the level would remain stationary. Note that it would not return to the desired level because that would close the inlet valve and level would again begin to fall. This characteristic of a proportional control system is called offset, because the controlled variable (level) is offset from the desired condition (the set point) when the system is loaded (by the leak).

2-6 TANK LEVEL — MANUAL CONTROL

Most vessels used in industrial service have liquids flowing into them and out of them continuously. Generally, the tank must take whatever incoming flow it receives, and an exit flow must be manipulated to regulate the level in the tank. The flow can be manipulated by a person adjusting a manual valve. The person would watch the level in a sight glass attached to the tank and would close the valve when level decreases or open it should the level rise.

The difficulty in maintaining tank level increases significantly should the flows be large and the tank small. Under these conditions, a sudden decrease in one of the flows could cause all of the liquid to drain from the tank before the person could close the valve. In this situation, an indication of the incoming flow rate would be an invaluable aid in maintaining level. Then the person regulating the level could watch the flow gage as well as the level. The flow gage would represent feedforward, wherein the regulator (person) would be forewarned of a level change by the change in flow, and could begin adjusting the valve to compensate even before level began to change. Then the level indication is a feedback, permitting the regulator to bring the variable of interest to precisely the desired value.

Quite obviously, the technique used by the person acting as a regulator to cause level in the tank to remain stationary is to manipulate the valve until the outflow equals the inflow. However, if the flows are rematched after a change in the inlet flow, the level will not be at the desired set point. Thus an offset will exist, similar to that in proportional-only control. To bring the level back to the set point from a low level condition, the outlet flow must be decreased to a rate less than the incoming flow until the level is at the set point, then be increased to equal the inflow. More generally, this control strategy would continue to close the control valve (in this example) until the level was at the set point. In this sense, it would reset the level to the set point and, appropriately, is called reset control.

2-7 TANK LEVEL — PROPORTIONAL CONTROL

While maintaining tank level by manipulating a valve is a simple task, not only would the person to whom the task is given soon be overcome by tedium, but a simple mechanism can do the job more reliably. The simplest mechanism is a ball float inside the tank, attached to a rod that is pivoted somewhere along its length. The movement of the float up and down with level causes the opposite end of the rod to move up and down by a proportionate amount. If the stem of a control valve is attached to the opposite end of the rod, the movement will open and close the valve. Thus a device has been constructed that operates in the