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CONTROL SYSTEMS RELIABILITY
USING REDUNDANT INSTRUMENTATION

by

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CONTROL SYSTEMS RELIABILITY USING REDUNDANT INSTRUMENTATION

by

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ABSTRACT

This thesis examines the increase in reliability of a thermal power control system by using redundant temperature and pressure instrumentation. This improvement in reliability can be accomplished by applying various multiplexing techniques to the noisy signals from a set of redundant instrument channels. Multiplexing techniques such as averaging, mediating, and voting based on weight factors will be examined in detail along with probabilistic analysis and experimental verifications. The effect of multiplexing on noise reduction will also be discussed. And finally, the area of instrument error distribution within a real-time system is briefly introduced to provide basis for future work.

Thesis Supervisor: Dr. Henry M. Paynter
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The author's interest in control systems instrumentation stems from a comprehensive survey that he conducted on flow instruments under the supervision of Prof. Paynter the year before. It was only with Prof. Paynter's great enthusiasm at the outset of this thesis, however, that the author decided to undertake the task of writing a thesis in this area.

In addition, the author is most grateful to his wife, Angela, for all of her support during the writing of this thesis, including the typing of the entire manuscript in a most dedicated manner. Her interest in the author's work and her encouragement during difficult times greatly contributed to the author's ability in completing this thesis.

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PREFACE

An often utilized technique to increase the reliability in any control system is the use of redundancy. The art of redundancy, however, comes in many variations. It could be redundancy in the software, like a back-up computer program package in an interplanetary spacecraft; or it could be redundancy in the hardware, like a set of triply redundant signal processing channels, as is the case in this thesis.

A system that uses redundancy to increase its overall reliability is sometimes referred to as "a fault-tolerant system". Fault-tolerance is the unique attribute of a control system which makes it possible for the system to continue with its program-specified behavior as a logic machine after the occurrence of faults.

One area of engineering that the application of redundancy has been mostly neglected is the redundancy of primary instrumentation in a thermal power system. Without redundancy, if the one and only instrument fails, the entire control system will more than likely malfunction. One must recognize the tremendous amount of revenue at stake when a power plant is shutdown due to a simple instrument failure.

In this thesis the author will first present an overview of the principle of fault-tolerance, its incentives and methods of implementation (chapter 1). In chapter 2 a study will be conducted on the errors and uncertainties of

instrument measurements obtained through temperature and pressure instrumentation. The area of probabilistic logics as applied in instrumentation redundancy will be discussed in chapter 3. Next, the author will demonstrate how the techniques of averaging and voting would significantly improve the quality of the signals and increase the reliability of such redundant instrumentation system (chapter 4). In chapter 5 a case study of some of the unique and highly reliable control systems at the Deer Island Sewage Treatment Plant will be presented. And finally in chapter 6, the method of using constitutive and conservation laws to minimize measurement errors will be briefly examined.

CONCLUSIONS

Using the techniques of averaging, mediating, and voting, there is little doubt that the overall reliability has been greatly increased for a control system using redundant instrumentation. In order to maximize the full advantages of fault-tolerance, however, one must devote complete attention to the implementation of redundant hardware at the outset of system design.

It can be concluded that multiplexing techniques such as averaging and voting can indeed increase the reliability of any redundant instrumentation system, as shown by probabilistic analysis and experimental verifications. Moreover, the implementation of such techniques is easily realizable, as the author has illustrated with an example. Furthermore, due to the high frequency spectral content of a voter output, the technique of multiplexing can actually be utilized to simplify the task of noise reduction.

And finally as indicated in chapter 6, instrument error distribution within a real-time system is indeed an important aspect of redundant instrumentation. Much more work needs to be done in this area.

CHAPTER I

INTRODUCTION TO ENGINEERING OF RELIABILITY

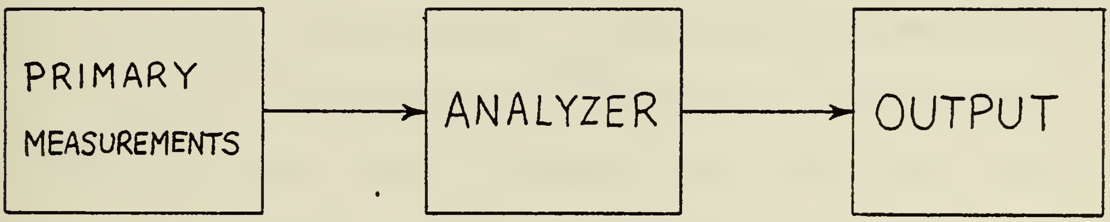
A. Introduction

If for example one simply installs a redundant instrument at the temperature sensing point in a thermal power plant, there is no question that the reliability of the temperature measurement has been increased. This is due to the simple fact that if one instrument malfunctions, a second instrument is still available to measure the parameter. However, if one ponders for a moment, he begins to wonder if he could improve the quality of the measurements at all times, even when there is no instrumentation malfunction at all. This question is especially valid if one recognizes the fact that temperature sensing devices come in many different types, e.g. RTDs, thermistors, and thermocouples; all of these instruments have their own inherent errors and uncertainties. Could one improve the quality of the measurements so that the output signal is always equal to the best of the signals from the different primary sensors? The answer is, "Yes, a fault-tolerant system can do just that". The reader will see why in the pages to follow.

Fault-tolerance is the architectural attribute of a digital system that keeps the logic machine doing its specified tasks when its host, the physical system, suffers various kinds of failure of its components.[1] A fault-tolerant

system using redundant instrumentation does more than that; even during normal operations, the logic circuitry is able to select the best possible signal using various multiplexing techniques.

A fault-tolerant control system using redundant instrumentation can be illustrated by the flowchart in Fig. 1.1.



Multiple Signals from Redundant Instruments

Process of Selecting the Most Reliable Signal

Fig. 1.1 A Control System Flowchart

Considerable research has been performed in the area of the center block, the complex process of assuring that a most reliable signal is always available. On the other hand, very little work has been done to combine the advantages of redundant instrumentation with the highly reliable techniques

of multiplexing. In fact, since Dean Karnopp and Erich Bender first reported their experimental findings for an analog system in 1966,[2] hardly any other reports have surfaced.

The entire chapter 2 has been devoted to the errors and uncertainties of primary instrumentation, so no further mention of this subject matter will be made here. Instead, the rest of this chapter will be used to introduce to the reader the concept of fault-tolerance, a term many engineers have an idea of what the final output is, but barely have any notion of the manner in which the system performs its function. Actually, the term "fault-tolerance" has only been used in connection with digital systems for the last 5 to 10 years. However, the concept of fault-tolerance, or more explicitly, the term "redundancy", has been in the standard vocabulary of most design engineers since the 1960's.

The logic circuitry mentioned in the preceding paragraphs could be basically made up of simple passive elements like AND or OR gates. They could be logic circuits that would select the upper or lower value from a set of signals; or the circuit could simply select the median from the same set of signals. In any event, when one instrument does fail, the resultant reading can be either high or low, or none at all, but the logic circuitry can take care of that by either masking the physical fault from being transmitted further downstream, or in some pre-programmed fashion, acts to continue

to provide a reasonable output, although somewhat degraded. Chapter 4 will discuss the actual multiplexing techniques in detail.

Some electrical engineers share the viewpoint that the presence of fault-tolerance features does not add any performance advantages during normal (fault-free) operation. Moreover, they state that fault-tolerance requires additional hardware that is redundant during normal operation and would be entirely superfluous in a completely fault-free logic machine.

The author wishes to point out that in a fault-tolerant control system that uses redundant instrumentation, the fault-tolerance feature actually improves the overall quality of the various signals and improves the reliability of the entire system even during normal, fault-free operation.

B. Reasons for Fault-tolerance

What are some of the incentives for implementing fault-tolerance into a control system? The objective of minimizing downtime was mentioned earlier, but there are other advantages that have not been mentioned.

In a thermal power system, if there is only one RTD at a critical temperature sensing point, or perhaps just one diaphragm at the pressure sensing point, then if the instrument malfunctions, the usual solution to the problem is a manually controlled maintenance action that results in the removal or repair of the cause of the fault. The system is then

restarted to run until the next fault strikes. The purpose of fault-tolerance is to offer an alternate solution to the fault problem in which the detection of faults and the recovery to normal operation are carried out as internal functions of the system itself. In this regard, fault-tolerance can be considered as the survival attribute of the logic machine because its function is to return the system from error states back to certain specified behavior.

Without fault-tolerance, a typical malfunction or failure usually occurs in the following sequence: The event begins with the observation of erratic behavior and a call to the maintenance expert and ends with the resumption of normal operation N hours later, with N usually found somewhere in the range of $0.1 \leq N \leq 10$. If fault-tolerance is now incorporated into the control system, human particip-ation in recovery is eliminated, and N can be lowered to the range of 10^{-9} to 10^{-6} hour.(1)

Historically, fault-avoidance has been used as the alternative to fault-tolerance. Unlike fault-tolerance, fault-avoidance requires the physical components and their assembly techniques to be as nearly perfect (fault-free) as possible. In addition, shielding must be installed to keep out all forms of external interference. The Apollo space program was an excellent example of fault-avoidance. Every single component was made to perfection; and the

result, as the reader knows, was a flawless space flight in every launch.

As one might expect, fault-avoidance has some drawbacks, and they are by no means minor.[1] First, not surprisingly to anyone, is that it is very expensive. The cost of obtaining nearly-perfect components in an instrument rises very rapidly after failure rates have been reduced to threshold values that are characteristic of the physical parameters and manufacturing technology of the components. Second, since the system will cease proper operation with the first failure or malfunction, manual-maintenance personnel must stand by continuously with appropriate fault-location and fault-removal tools and methods. This requirement represents a major budget item for the life-cycle cost of the system.

The acquisition cost of a fault-tolerant system is higher than that of a fault-avoidance system. This additional cost is due to the extra effort required to introduce fault-tolerance during system design stage and by the cost of redundant hardware and software that implement fault detection and recovery.

However, the high initial cost could be more than compensated for by the lower life-cycle cost. The reduction in life-cycle cost is a result of the following reasons. First of all, lower cost components can now be used because higher failure rates can be accepted for individual components without degrading system reliability. Secondly, a sharp decrease

in downtime will lead to a considerable lower life-cycle cost of system operation. And finally, scheduled off-line replacement of rejected parts should cost much less than providing a crew of continuously ready maintenance experts.

Without redundancy and fault-tolerance, an unpredictable shutdown in a power generation and distribution plant may represent a tremendous loss in revenue. Another example with the same result is the electronic fund transfers, or the telephone switching systems. Besides cost saving, however, there are other features of a fault-tolerant system that make it highly desirable. Human lives could be endangered if a failure occurs in some applications. Some of the examples are air traffic control, automatic control of a submarine in a diving maneuver, control of nuclear power plants and defense systems, and patient monitoring and life support systems in highly automated hospitals.

Still, a third group of control systems that would benefit immensely from fault-tolerance consists of systems in environments that do not allow access for manual maintenance, such as satellite in earth orbit; nuclear reactor instrumentation in a highly radioactive enclosure; unmanned underwater stations; and environment-monitoring stations in remote and hard-to-reach locations.

And finally, there is a strong psychological incentive for implementing fault-tolerance in any control system.

When an operator knows that the failure of a system can jeopardize a person's safety or economic well-being, or possibly the very first component failure will be fatal to the uninterrupted operation of the entire machine, the knowledge that fault-tolerance is being used is more than likely to considerably reduce his anxiety.

The author wishes to clarify one point at this time. There are distinct differences between primary sensor reliability and computer (logic circuitry) reliability. Primary sensor reliability deals with the reliability of the instruments themselves. Obviously, each instrument has its own failure rate; some are more prone to failure than others. In addition, each instrument has its own range of uncertainties and errors, inherent to any particular type of sensor. On the other hand, logic circuitry reliability deals with the failure rates of actual circuit elements. The circuit elements, almost exclusively, are passive components like diodes, resistors, and OR gates. As compared to the instruments, these passive elements are highly reliable, at least partly due to their well-controlled environments both in manufacture and in use. More discussion on this subject can be found in chapter 4.

C. Implementation of Fault-tolerance

So far in this chapter, the discussion has been almost exclusively devoted to the following two areas:

(1) The interaction between the logic circuitry and the

physical instrumentation system, and (2) the incentives for implementing fault-tolerance. It is now time to describe the common methodology for actual implementation.

Typically the control system is invariably designed for perfect components, assuming fault-free conditions. Then, fault-tolerance is introduced. This sequence implies additional provisions must be made to add more hardware and software elements. These redundant instruments and circuit elements will serve to provide the fault-handling algorithms and the spare parts needed for recovery.

Fault-tolerance can be introduced into a control system through a systematic sequence of design activities like the following:

(1) Reliability Requirements --- Reliability requirements must be specified; in other words, a set of performance specifications must be defined.

Fault-tolerance, in this case, is limited to the tolerance of physical faults in each channel. A physical fault is an out-of-specification or otherwise undersirable change in the values of one or more primary parameters in the system. It is caused by a physical failure or degradation that affects a primary sensor and may make either a permanent or temporary change in the sensed values of the corresponding physical variable.

Permanent physical faults are usually caused by irreversible changes in components, such as broken RTDs, open

connections, ruptured bellows, "bridging" between two leads, etc. Temporary faults, on the other hand, are generally results of external interferences of relatively short duration, typically in power supplies or in signal transmission. These interferences change the present values of certain measurements, but do not cause irreversible damages to the components.

After a quantitative reliability requirement has been established, the number of redundant channels needed can be determined. Each redundant primary instrument with its associated branch of the logic circuitry constitutes a redundant channel. From experimental results and other evidence, it appears likely that the triply redundant system is the optimal choice.

(2) Fault-Detection Algorithms --- The detection function is the starting point of most fault-tolerant implementations. This function usually leads to the addition of new components. The choice of fault-detection techniques is governed by the reliability specification, making certain that all relevant fault classes are detectable, and that the probability of timely detection is adequate with respect to the reliability goals. Both hardware and software techniques are applicable here.

The various methods for fault detection can be summarized as follow:

(a) Initial testing, which takes place prior to

normal use and serves to identify faulty instrument components containing imperfections introduced during the manufacturing or assembly process.[3]

(b) Concurrent (on-line) detection, which the author considers as the most important method because after all, the underlying advantage of any automatic control system is its self-checking feature. It is implemented by means of special hardware or software that operates concurrently with the regular programs of the system. Concurrent detection is important because it allows recovery to be initiated before fault-caused errors can cause extensive disruption of programs or damage to the data. Hardware methods for concurrent detection have been used for quite some time, especially in the computer and aerospace industries. These methods include error-detection codes (chapter 5), duplication and comparison, disagreement detectors with voters (chapters 3 & 4), and plant status and completion signals (chapter 5).

(c) Scheduled (off-line) detection, which takes place when normal operation is temporarily interrupted. This method is quite similar to the initial testing except that now the testing is executed by the system itself.[4,5]

(d) Redundancy testing, which serves to verify that

the various forms of protective redundancy are themselves fault-free, and takes place either concurrently or at scheduled intervals.[6]

(3) System Recovery Algorithms --- The recovery algorithm comprises all actions that are initiated by the arrival of a fault signal during normal operation and are normally completed by the resumption of normal operation (more than likely in a degraded mode), by a deliberate shutdown of the system, or by system failure.

The most fundamental difference between various recovery algorithms is whether interaction with a human maintenance operator is or is not required as part of the recovery algorithm. Recovery algorithms that do not require human decision making are automatic; all other algorithms are manually controlled, although they may contain extensive programmed sequences.

In the computer and aerospace industries, most recovery algorithms are fully automatic and require no human intervention. When a certain processor fails, full recovery simply involves with the replacement of the faulty processor with a spare. However, in the thermal power industry, in the opinion of the author, human interaction must play an important role in the recovery process, at least in the foreseeable future.

After recovery has been completed, the system can have the following three status: full recovery, degraded recovery, and safe shutdown.

Full recovery means the return of the system to a set of conditions that existed before the fault occurred. In the case of a thermal power plant, this procedure usually begins with a status light on the monitoring panel identifying one or more malfunctions have occurred; plant is operating in a degraded mode, and it is now up to the human maintenance operator to pinpoint the malfunctions and replace the damaged parts. Recovery is concluded when damaged parts have been replaced by spares.

Degraded recovery means that the system is still operating, but at a reduced capacity. In a triply redundant instrumentation system, an example of a degraded recovery is that two channels could malfunction simultaneously, while the third channel is still operating perfectly. The result is a piece of data that is not totally correct, but still within an acceptable range. The system will remain in this mode until faulty instrument or component is replaced.

Safe shutdown is the limiting case of degraded recovery. It is carried out only when the remaining computing capacity (if any) is below the minimum acceptable threshold. The objectives of shutting down a power plant are two-folded: (1) to prevent damage to remaining plant components; and (2) to stop interaction with other plant system in a deliberate and orderly manner.

A special case of hardware-controlled recovery is known

as recovery by fault masking. In such systems, faults are masked by redundant hardware, and thus remain totally invisible to the software further downstream. The masking function employs redundancy to assure that the effect of a fault is completely contained within a system module.[7,8] As long as the redundancy is not exhausted, the fault is concealed within the module and no symptoms whatsoever appear on its outputs. It is also known as a static redundancy because if viewed from the outside, separate detection and recovery functions are not identifiable.

Masking is usually accomplished by hardware redundancy, i.e. by the replication of hardware elements. The redundant elements are assumed to be permanently connected, and to fail statistically independently. They have the same failure rate and are instantaneously available to perform the masking of a failure with unity probability of success. One major drawback of static redundancy is that it must be introduced at the outset of the design phase. Total devotion must be given to fault-tolerance by the design engineers throughout the early stage. It is for this reason, as mentioned earlier, that the initial cost of a control system featuring fault-tolerance is considerably higher than that without the same feature.

D. The Author's Position on Type of Signals being Processed

This is not a thesis on signal processing, however, the principle of multiplexing as applied here deals with the processing of signals from various redundant instrumentation. Therefore, the author feels that it is appropriate to briefly comment on the type of signals being considered here.

All signals considered in this thesis are digital 16-bit parallel words. The 16-bit capacity includes a sign bit and an address bit. Moreover, these parallel words are results of distributed computing; in other words, the analog-to-digital conversion device is powered from an independent power source.

1. Why Digital?

Digital technology has indeed revolutionized the world of instrumentation. Reductions in cost of digital integrated circuits and the increase of chip complexity are rapidly making feasible the manufacturing of digital equipment at a small fraction of the cost for their analog counterparts. As a result, it is considerably easier and less expensive to find a digital system to suit one's need as compared to finding an analog system that performs the same function.

Digital systems often capitalize on having a compatible data base. This is exemplified by a large and complex process-control system in which temperatures, pressures, and flow rates are all converted into numbers.

No matter what input is considered, its value ends up in the system as a number. In this form, it can be easily added, multiplied, integrated, or otherwise processed.

2. Parallel Conversion

The best feature of this conversion approach is that conversion occurs in parallel, with speed limited only by the switching time of the comparators and gates. As the input changes, the output code changes. Therefore, this is indeed the fastest approach to conversion.

Only a few years ago, A/D conversion was done strictly in a serial format, bit by bit. Parallel conversion was not commonly practiced at the time because the number of elements needed in a parallel conversion increases geometrically with resolution. However, with the advent of LSI and VLSI technologies, it is now possible to have high resolution and fast speed at the same time.[9]

3. Distributed Computing

Distributed computing simply means that the A/D conversion and related processing will be done right at the signal source with an independent power supply. This technique, when utilized in a redundant instrumentation system, accomplishes two objectives: first, it increases system reliability because a power failure will only affect that particular channel; and secondly,

by transmitting digital data back to the data center, a considerable immunity to line-frequency (50-60-400 HZ) pickup and ground-loop interference is achieved.

The author does not intend to cover the subject of A/D conversion in any great detail here; if the reader is interested, however, reference (9) provides excellent further readings in this area.

From the general introduction in the preceding paragraphs, it is hoped that the reader has gained some knowledge of how a fault-tolerant system performs and why its implementation is important to a thermal power plant. In the next chapter, various kinds of typical power plant instruments, e.g. temperature and pressure sensors, will be described, along with the uncertainties and errors peculiar to each type of instrument.

CHAPTER II

INSTRUMENTATION ERRORS AND UNCERTAINTIES

A. Introduction

If an instrument does not seem to have malfunctioned, then why should one worry about errors and uncertainties? Likewise, if an instrument appears to be as good as the day it came off the production line, why should the measurements not be all accurate?

Of course, when an instrument becomes faulty as a result of an open connection, a mechanical failure, or a bridging of two adjacent leads, to name only a few examples, the measurement may become totally erroneous with a reading several magnitudes different from a normal reading. In this case, the instrument would simply have to be replaced at the first opportunity.

Thus, as one can see, an instrument can malfunction at any time, depending on its own failure rate; but in addition, even when it is operating under normal conditions, its reading can still be out-of-specifications simply due to inherent errors and uncertainties. The reader must realize, however, that each sensing device possesses unique characteristics that make it especially desirable in a particular application.

In this chapter, temperature and pressure sensors, the two most important and commonly found instruments in a

thermal power plant, will be explored. Their calibration drift rates, noise figures, accuracy, and other errors will be examined. In particular, platinum resistance temperature detectors (RTDs) will be discussed as a specific case-in-depth to illustrate the origins and nature of some of the instrumentation errors. Reference (10) contains a comprehensive collection of literature on various industrial thermometers. Then in chapter 4, the techniques of minimizing the effects of these errors will be explained in detail.

Even without dwelling upon the theories of probabilities and statistics, one can assume that the probability for three different types of instruments (a triply redundant case) to generate similar errors (both in sign and magnitude) is very remote. It is here that redundancy demonstrates its most salient advantage. The use of redundant instrumentation coupled with the technique of averaging or voting will yield the most reliable and least noisy signal at all times, as the reader will see in chapter 4.

B. Resistance Temperature Detectors

Two of the most widely used temperature sensing devices are resistance thermometry and thermoelectric thermometry. Resistance thermometry can be divided conveniently into two basic groups: resistance temperature detectors (RTDs) and thermally sensitive resistors (thermistors). Thermoelectric thermometry will be discussed

later. RTDs are basically electrical circuit elements formed of solid conductors (usually in wire form) that are characterized by a positive coefficient of resistivity. The RTDs of general usage are of platinum, nickel, and copper.

There is no question that platinum is one of the best materials for a resistance temperature detector, nevertheless, it exhibits certain calibration drifts and errors during both testing and normal operations. A thorough evaluation was conducted on the performance of several industrial platinum thermometers between 0° and $650^{\circ}C$ by the Oak Ridge National Laboratory, and some of the findings are briefly summarized in the following pages.[11]

1. Insulation Resistance

Consideration of insulation resistance is significant because it could indicate that measurement errors might be caused by shunting of the sensing element due to leakage of current to the sheath and between lead wires. In the experiment conducted by the Oak Ridge Laboratory, it was found that insulation resistance varied widely for similar type of thermometers, but from different manufacturers. But more importantly, it was also discovered that even for thermometers in the same group purchased from the same manufacturer, resistance differences of several decades were not uncommon.

2. Thermal Emf's

Experimental results indicate that in order to reduce thermal emf's, parallel lengths of wires in the thermometer must have similar thermoelectric properties, and thermal gradient between lead and points of lead attachment must be minimized.

3. Calibration Drift Test

A summary of the calibration drift test results is tabulated in TABLE 2.1.

TABLE 2.1

	Manufacturer		
	B	C	D
Number of thermometers tested	2	4	5
Number that failed immediately	1	1	0
Number that failed within 1000 h	2	1	0
Number that survived 6000 h	0	3	5
Maximum differential drift in °C, after 6000 h	-	1.0	0.5
Maximum absolute drift in °C after 6000 h	-	1.1	0.9

In the worst case, the absolute accuracy of the thermometers changed approximately 1°C. Some thermometers had positive errors, while others developed a negative drift.

4. Thermal Cycling

All thermometers survived 1000 cycles without breakage after they were cycled between 260°C and 50°C. When the temperature limits were changed to cycle between 760° and 80°C at a maximum rate of 8°C/sec, half of the thermometers failed within 31 cycles.

5. Effect of Crystal Defects

It is obvious from the preceding paragraphs that platinum RTD may cause certain temperature drift during service, and may even fail when subject to severe thermal cycling. Errors may also occur as a result of crystal defects or fabrication imperfection. The introduction of such physical defects into a crystalline material like platinum, will cause an increase in its electrical resistivity and therefore an error on its output.[12]

C. Thermistors

Thermistors are electrical circuit elements formed of solid semiconducting materials that are characterized by a high negative coefficient of resistivity. At any fixed temperature, a thermistor acts exactly as any ohmic con-

ductor. Typical thermistor resistance variations are from 50,000 Ω at 38°C to 200 Ω at 260°C.[13]

Some of the semiconductor materials that are commonly used to manufacture thermistors are carbon, germanium, and silicon. The author will concentrate on the application of thermistors to temperatures below 100 K or -173°C. There are two important reasons for this selection. First, materials and methods of thermometry which are well developed for higher temperatures often fail at lower temperatures. Second, problems associated with the application of thermistors become more serious as the temperature is reduced.[14]

1. Temperature Dependence

When carbon resistance thermometers are monitored at a fixed low temperature, their resistance is observed to drift with time. As the temperature is lowered, the drift becomes more serious. If one requires a stable carbon resistance thermometer, he must sacrifice temperature resolution. Part of this loss in resolution can be restored, however, by using a resistance bridge capable of a greater resolution.[15,16]

2. Power Dissipation

The measurement of resistance requires power dissipation in the thermometer. Thus, power dissipation must be kept small to avoid excessive measurement error. It has been found that a power dissipation as little as

5×10^{-12} W in a carbon resistor at 0.04 K caused about a one percent error in $\Delta T/T$.[14]

3. Self Heating

Another problem that is not so easily detected is power dissipation resulting from rf voltages induced in the leads by commerical radio transmitters. This effect is known as self-heating and is a problem common to both carbon and germanium thermistors. Error caused by such spurious power dissipation becomes much more serious as the temperature is reduced. In areas exposed to large rf fields, the electronics must be placed in a shielded enclosure; otherwise, the placement of a low pass filter in the electrical lead near the resistance thermometer may be sufficient. An efficient and adequate heat sink also appears to be an effective method to minimize such error.[17]

D. Noble Metal Thermocouples

Obviously, a perfect thermocouple would be one that produces an emf signal that is uniquely related to the temperature of the hot junction and is unaffected by time or any other factor. Although noble metals like platinum are superior to most, no materials of construction are completely stable in this regard. Mechanical failure is a major contributing factor to instrument malfunction, but in the

absence of that, thermocouple deterioration is usually caused by changes of composition which influence the emf developed over the temperature gradient to which the couple is subjected.[18]

A highly corrosive environment appears to be the major cause for compositional changes. Most environments above 1300°C are fairly hostile; in addition to vapor transport processes associated with the formation of volatile oxides, chemical reactions can also occur between the thermocouple wires and the insulating materials with which they are in contact.

1. Contamination

Mechanical failures of platinum thermocouples are sometimes caused by contamination during fabrication. The embrittlement, which sometimes occurs when platinum thermocouples are heated in contact with alumina insulators under reducing conditions at temperatures above 1200°C, is usually associated with the presence of silicious impurities in the refractory. This type of reaction results in the formation of low melting point alloys, and the thermocouple usually fails abruptly before a serious change in thermal emf has occurred.[18] Silicious impurities are usually introduced during the wire drawing process of platinum.

2. Thermal Drift

Thermoelectric stability becomes an important issue when an instrument operates continuously for thousands of hours. Experimental results indicate that thermal drift is related to compositional changes because the drift has been found to be a direct result of change in the chemical composition or metallurgical structure of the thermocouple materials after exposing to a thermal gradient.[19]

Some of the operating conditions that affect the amount of thermoelectric drift are as follow: (a) temperature level, (b) time, (c) temperature gradient, (d) environmental gas, (e) pressure level, (f) thermal cycling, and (g) nuclear radiation.[19]

3. Temperature Errors due to Catalytic Surface Burning

When a metal thermocouple is exposed to various incompletely-burned gases that exist in some engine exhaust gases, it is entirely possible for catalytic burning to occur on the surface of the thermocouple. This burning will raise the temperature of the thermocouple to a value that is higher than that of the surrounding gas medium.[20,21]

In order to eliminate catalytic reaction, design engineers have recommended coating the temperature probe with a non-catalytic material. Some of these

non-catalytic coatings include potassium-chloride and oxidized chromium.[22]

E. Variable Resistance Pressure Transducers

1. Potentiometric Pressure Transducers

A potentiometric pressure transducer is a device consists of three main components: the force collector, the sliding contact wiper, and the resistance wire winding. The pressure to be measured is applied to the force collector which, through a linkage rod, moves a sliding contact across the electrical resistance wire windings, thus producing a voltage proportional to the pressure. A diagram that illustrates the basic operating principles of such transducer is shown in appendix I. For more detailed descriptions and specifications of various commercially available pressure transducers, the AGARD publication "Wind Tunnel Pressure Measuring Techniques" (23) and the ISA "Transducer Compendium" (24) may be consulted.

Resolution and electrical noise are the two most severe problem areas associated with the use of potentiometric transducers, especially those employing wire winding resistance elements. As the wiper moves across the windings, a step resistance change is generated when the wiper disconnects with one winding or

makes contact with another. The amplitude of this step change, and therefore the resolution, depends mainly upon the geometry of the wire windings and wiper. A nominal value of resolution for most potentiometric transducers is 0.2 percent of full scale.[25,26]

Electrical noise is generated due to variation in contact resistance as the wiper travels over the resistance element. Contact pressure fluctuations and particle contamination at the wiper-wire contact are usually the causes for these variations. This noise generation tends to increase with the life of the instrument because of wear and misalignment of the wiper and track. Noise spikes may also be caused by variations which tend to lift the wiper from the resistance element. In addition, any linkage required in the transducing system will cause the instrument to be more sensitive to vibration. Recent transducer designs use the method of oil damping on the linkages and elastic elements to reduce the harmful effects of vibration.

In general, the potentiometric transducers should be used in areas of low acceleration primarily for the measurement of static pressures.

2. Strain-Gage Pressure Transducers

A strain-gage pressure transducer is an instrument in which a pressure change caused by the strain in a strain gage is converted into a change in resistance. More details on this type of transducers and their electrical schematic diagrams can be found in appendix I.

Full-scale pressure ranges from 0 to 0.1 psi to 0 to 100,000 psi are provided from various types of strain-gage transducers. In some models, static error bands as low as 0.1 percent of full scale can be achieved. If temperature compensation technique is used, transducers with temperature sensitivities as low as 0.25 percent of full scale can be fabricated. Most strain-gage transducers are somewhat sensitive to acceleration and vibration. Moreover, in pressure ranges below 10 psi, errors of 0.5 percent of full scale per g are not uncommon.[23]

F. Diaphragm-Type Variable Reluctance Transducers

A variable reluctance pressure transducer commonly used in the power industry employs a magnetic diaphragm as the sensing element, supported between two inductance core assemblies. The diaphragm deflects when a differential pressure is applied to the pressure ports, thus changing the magnetic flux. A detailed diagram of such transducer

is shown in appendix I.

One of the major advantages offered by this type of transducer is its sensitivity and acceleration capabilities. Pressure sensitivities as high as one volt per psi are available, and pressures down to 0.00003 psi may be measured. In addition, due to the extremely low seismic mass of this sensing device, it is capable of withstanding high levels of acceleration.[27]

A major disadvantage of this transducer is its susceptibility to particle contamination. If the fluid contains particles, they may easily become lodged in the small air gap ($\sim$ 0.001 in) between the core and the diaphragm. Consequently, the performance of the instrument is degraded either by mechanical or magnetic interference. A second disadvantage of using this type of inductive transducer is that AC excitation must be used.

G. Piezoelectric Pressure Transducers

Piezoelectricity is defined as an electrical polarization produced by mechanical strain in crystals belong to certain classes, the polarization being proportional to the strain and its sign related to the direction of the strain. If a piezoelectric element is stressed mechanically, its dimensions change and an electric charge is generated.[28] This type of sensor does not require external electrical

power as does the variable resistance or the variable reluctance transducer. A variety of piezoelectric materials are used, with quartz, barium titanate, lead zirconate titanate, and ceramic elements being some of the more common choices.[25]

Piezoelectric elements have an inherent high internal resistance (10^{10} to 10^{14} ohms) and a low capacitance (5 to 500 pF); thus, a slight leakage resistance path across the element electrodes or across the electrical connector pins can cause erratic operation and limit the low frequency response of the sensor. Therefore, it is important to carefully protect the piezoelectric element and all connectors from moisture or other contaminants that might create conduction paths.[23]

H. Vibration Type Liquid Densitometer

In the vibration type liquid density measuring system, the vibrating tuning fork is the basic principle of operation. The density device uses a hollow vibrator element, similar to a tuning fork, through which the measured liquid flows. As the density of the measured liquid changes, the mass and the resonant frequency also change. In fact, the frequency is inversely proportional to the square root of the density, $\omega = K/\sqrt{\rho}$. An electrostatic capacitive pickup electrode connected to an amplifier converts the vibrator displacement to an alternating voltage output, which corres-

ponds to the density of the liquid.

Hardly any study has been conducted on the vibration type liquid densitometer, thus the origins and nature of errors associated with this type of densitometry are not commonly known. One can, however, obtain an idea of the capabilities of such an instrument by the following specifications:[29]

Measuring range:	0.5 to 1.5 g/cm^3
Span:	0.05 to 0.5g/cm^3
Repeatability:	1% of span
Linearity:	$\pm$ 0.5% of span
Working Pressure:	20 kg/cm^2 G or less
Working Temperature:	-10 to 100°C

I. Concluding Remarks

In this chapter the author has not attempted to cover any particular instrument in great detail; in fact, that would be beyond the scope of this thesis. If more detailed descriptions are desired, the reader is advised to consult appendix I and some of the references listed.

If the reader has learned nothing else in this chapter, the author hopes that he is now at least more aware of the fact that different instruments behave so differently under the same environmental conditions. One instrument may yield a higher than normal reading, whereas a second one may produce an unusually low measurement; yet a third sensor

may simply fail completely.

In chapters 3 and 4, the author will discuss the principles and advantages of averaging, mediating, and voting, as applied to a control system using redundant instrumentation.

CHAPTER III

PROBABILISTIC LOGICS

A. Introduction

Probabilistic logics entail the study of error in logics, or in the physical implementation of logics. Error is viewed, according to J. von Neumann, not as an extraneous or misdirecting accident, but as an essential part of the process under consideration.[30] Actually, the study of probabilistic logics has a far greater influence; its implementation can be considered as the predecessor of all multiplexing techniques (a fundamental concept for voting) and coding methodologies (encoder and decoder), as the reader will see more clearly in the paragraphs to follow.

B. Logics and Automata

A. M. Turing[31] in 1937 and W. S. McCulloch[32] in 1943 suggested that probabilistic logics can be best studied in terms of automata. An automaton, as defined by von Neumann, is essentially a "black box" with a finite number of inputs and a finite number of outputs. Each input and each output is capable of exactly two states, to be designated as the "stimulated" state and the "unstimulated" state, respectively.

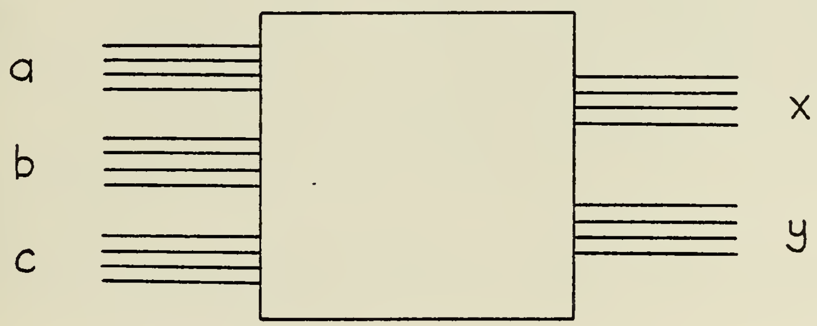
The internal functioning of such a "black box" is equivalent to a set of specifications determining which

outputs will be stimulated in response to stimulation of any group of inputs. The definition just mentioned is precisely the concept that an averager or a voting circuitry (two of the most commonly used multiplexing techniques) is based upon. In addition, the theory of automata can also be applied to the tasks of encoding and decoding in which a specific number of inputs can be converted into either fewer, same, or greater number of outputs, depending upon the specifications of a particular "black box". Therefore, an understanding of probabilistic logics is useful if one wishes to learn more about the never-ending quest of higher reliability in a control system.

C. The Technique of Multiplexing

If the inputs and outputs are bundled together, an automaton can now be represented like that in Fig. 3.1. All messages will be carried simultaneously on a bundle of N lines (N being a large integer) instead of just a single or double strand. Instead of requiring that all or none of the lines of the bundle be stimulated, a certain critical (or fiduciary) level Δ is set: $0 < \Delta < \frac{1}{2}$. The stimulation of $\geq (1-\Delta)$ N lines of a bundle is interpreted as a positive state of the bundle. The stimulation of $\leq \Delta$ N lines is considered as a negative state. Any other number of stimulated

line is interpreted as a malfunction. By constructing the automaton appropriately, it can be shown that the number of lines deviating from the "correctly functioning" majorities of their bundles may be kept at or below the critical level Δ N (with arbitrarily high probability). J. von Neumann called such a system of construction "multiplexing".(30)



Each group ≡ represents
a bundle of N lines.

Fig. 3.1 Automaton as A Black Box

The technique of multiplexing requires that the complete system must be organized in such a manner, that a malfunction of the entire automaton cannot be caused by the malfunctioning of a single component, or of a small number of components, but only by the malfunctioning of a large number of them. As the reader may observe, the probability of such occurrence can be made arbitrarily small provided the

number of lines in each bundle is made sufficiently large.

D. Von Neumann's Majority Organ

1. The Basic Executive Organ

The criterion that a control system fails only if the majority of the inputs malfunction led to the invention of the majority organ by von Neumann in 1952. The majority organ will be able to handle bundle of inputs and outputs as well as single lines. For the sake of simplicity, however, the majority organ will be modelled as a black box with three single line inputs a, b, and c of similar characteristics, as shown in Fig. 3.2.

$$m(a,b,c) \equiv ab + ac + bc \equiv (a+b)(a+c)(b+c) \qquad (3.1)$$

The Majority Organ

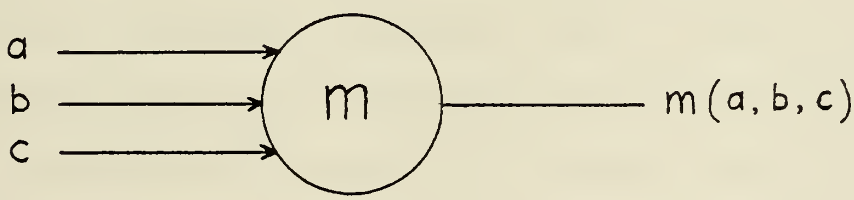


Fig. 3.2

Here m(a,b,c) represents the majority of the input signals a, b, and c; ab denotes a and b, whereas a+b defines a or b. Using the majority organ, it is clear that if any

two of the three inputs are stimulated, the output will be stimulated. Similarly, if any two of the inputs are not stimulated, the mechanism will not stimulate any output at all.

Thus, it appears that the majority organ can also be called the basic executive organ because it executes the desired basic operations on the bundles. After the execution, however, the degradation caused by the executive organ must be erased; moreover, the stimulation level of the inputs has to be restored. These two requirements necessitate the creation of a second organ --- the restoring organ.

2. The Restoring Organ

a. Construction

The restoring organ can be constructed with little difficulties and in fact, the ordinary majority organ already performs this task in a crude way. If one considers the simple case of having three signals at the input like that shown in Fig. 3.2, it should be obvious to the reader that the majority organ suppresses a single incoming impulse as well as a single incoming non-impulse. In other words, it amplifies the presence as well as the absence of the incoming impulses.

Before continuing any further, one note of

importance that should be emphasized here is the following: In order to apply the theories of probability and statistics to the majority organ concept in various applications, all inputs must be considered as statistically independent.

What are the advantages of multiplexing? As mentioned earlier, the most desirable feature of a multiplexed system is its ability to control errors. It can be shown by statistical analysis that, by using large enough bundles of lines (N being the size of the bundle), any desired degree of accuracy can be obtained with a multiplexed automaton. Of course, economics and implementation difficulties may dictate the largest number that N can take on.

b. Numerical Evaluation

Does the majority organ really perform the task of a restoring organ? The following evaluation will attempt to prove just that.

If there are N incoming lines and αN of them are stimulated, then the probability of any majority organ being stimulated is

$$\alpha^* = 3\alpha^2 - 2\alpha^3 . \qquad (3.2)$$

Provided N is large, approximately $\alpha^* N$ outputs will be stimulated. A curve of α^* against α

is plotted in Fig. 3.3.

Numerical Evaluation of
the Majority Organ

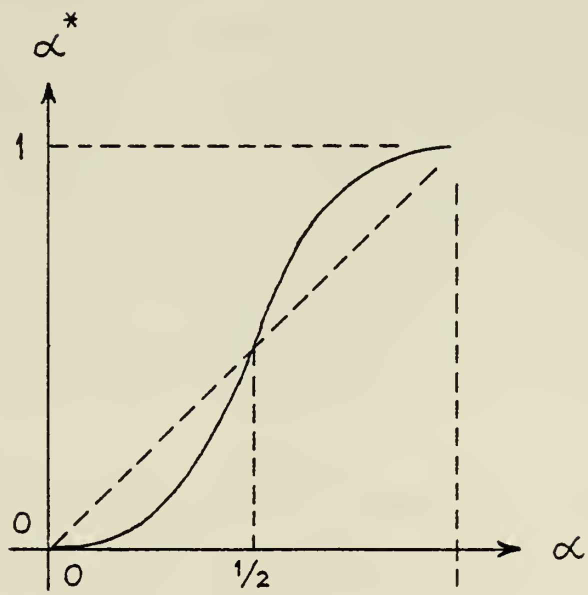


Fig. 3.3

The curve intersects the diagonal $\alpha^* = \alpha$ three times, at $\alpha = 0$, ½, and 1. For $0 < \alpha < ½$, the curve indicates $0 < \alpha^* < \alpha$; for $½ < \alpha < 1$, the plot shows that $\alpha < \alpha^* < 1$. In fact, successive iteration of this process converges α^* to the asymptote at 0 if the original $\alpha < ½$ and to the asymptote at 1 if the initial $\alpha > ½$. This is precisely the process of restoration for a digital system, to bring α nearer to either 0 or 1, to which

it was nearer originally. Thus it is shown that the majority organ does possess the desired characteristics of a restoring element.

E. Majority Organ Operations in a Digital System

Professor H. M. Paynter of M. I. T. went one step further to develop the AND and OR logic elements in more detail.[33] In digital or binary logic, the output can only take on the value of either 0 or 1. As in set theory, one can represent the AND operator with the intersection symbol $\wedge$, and the OR operator with the union symbol $\vee$.[34]

If there are two independent variables X_1 and X_2, then the operations of union and intersection may be represented in the functional matrix form as shown in Fig. 3.4.

Operations of Union & Intersection

$X_1 \vee X_2$	X_1 = 0	X_1 = 1
X_2 = 0	0	1
X_2 = 1	1	1

$X_1 \wedge X_2$	X_1 = 0	X_1 = 1
X_2 = 0	0	0
X_2 = 1	0	1

Fig. 3.4

The reader might notice the similarity between the above matrix and a conventional truth table. In fact, if the symbols T (truth) and F (falsity) are substituted for 1 and 0, respectively, a truth table would have been constructed.

If the inputs are 3-bit binary words, the operations of union and intersection produce some fairly interesting results. For example, if X_1 = 011 (3 in base 10) and X_2 = 100 (4 in base 10), then the operations of $\vee$ and $\wedge$ may be represented in Fig. 3.5.

	$X_1 \vee X_2$	$X_1 \wedge X_2$
X_1 = 0 1 1	1 0 0	0 1 1
X_2 = 1 0 0		

Union & Intersection of a Binary word

Fig. 3.5

The results in Fig. 3.5 indicate that the operation of union produces the larger of the two 3-bit words, whereas the operation of intersection yields the smaller of the two words. This concept will be developed further when continuum logic is discussed.

F. Multi-valued Logic

One may conceive a spectrum of multi-valued or n-valued logics with binary and continuum logics occupying the extreme positions. This concept was first introduced by H. Reichenbach[35] in 1932, then evaluated further by P. C. Rosenbloom[36] in 1950. It was not until 1960, however, that the idea of multi-valued logics was linked to the study of control systems by H. M. Paynter.

In two valued logic, absolute falsity is designated by the value 0, whereas absolute truth is assigned the value of 1. On this line of continuum logic, any other values that lie between 0 and 1 may be interpreted as "partial truth" as proposed by Paynter. In a four valued logic, for example, the truth values might be viewed as "truth", "plausibility", "implausibility", and "falsity".

In the system proposed by E. L. Post,[37] there are n truth values which may be denoted by 1,2,3,..., (n-1), and n. The operation of the intersection $\wedge$ can be defined by the matrix shown in Fig. 3.6.

This logic of propositions for the case of multi-valued logics is known as Post algebra, as opposed to the Boolean algebra for the two valued case.

X_1

$X_1 \wedge X_2$	1	2	3	...	n
1	1	1	1	...	1
2	1	2	2	...	2
3	1	2	3	...	3
.	.	.	.	...	.
.	.	.	.	...	.
.	.	.	.	...	.
n	1	2	3	...	n

X_2

Post Logics

Fig. 3.6

G. <u>Analogy Among Binary, Multi-valued, and Continuous Logics</u>

Binary logic can be defined as discrete logic, one that consists of only 0's and 1's. A three-valued logic is composed of 0's, ½'s, and 1's. On the other hand, an analog logic or continuous logic can take on infinitely many values between 0 and 1. Fig. 3.7 shows undeniable similarities among binary, three-valued, and continuous logics.[38]

$$Z = V(x, y)$$

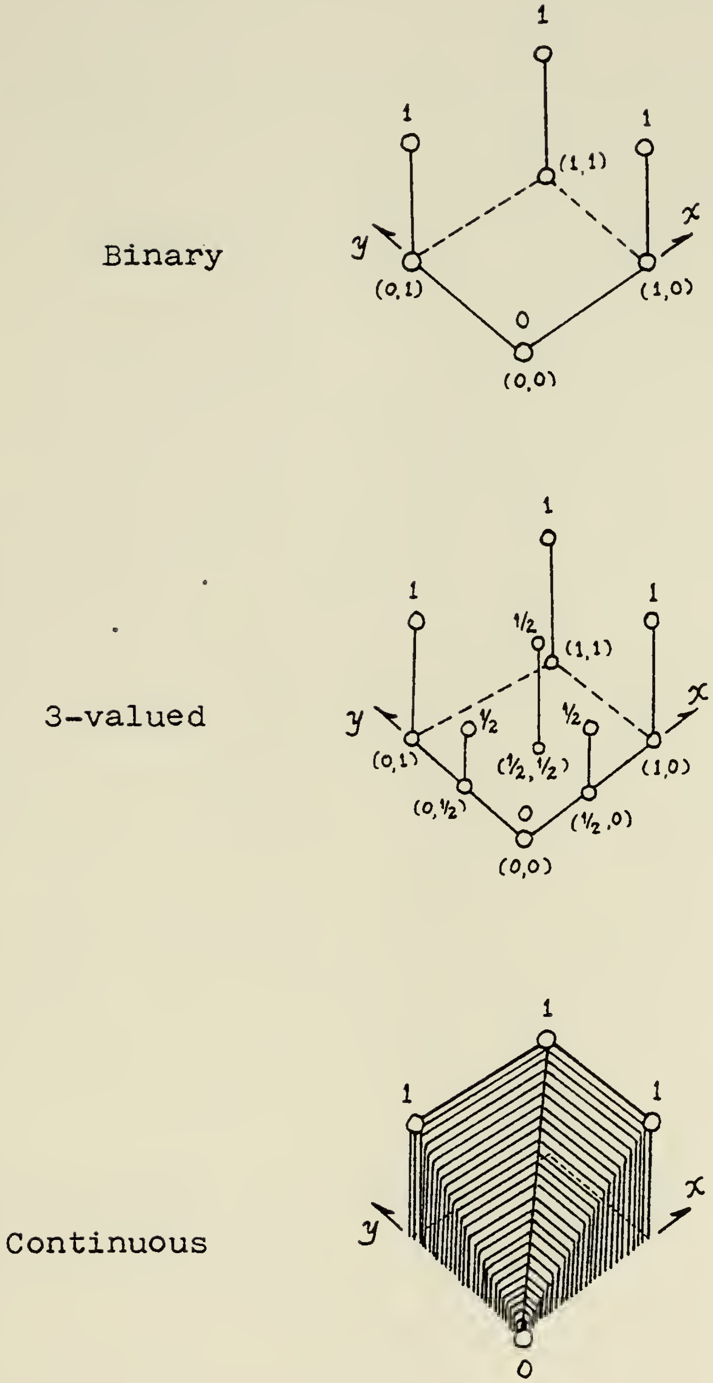
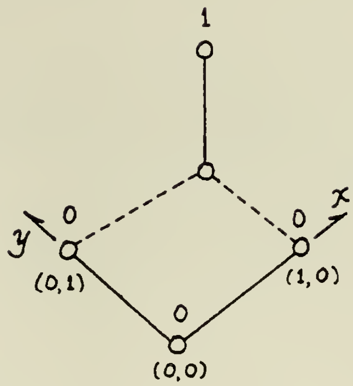


Fig. 3.7 a

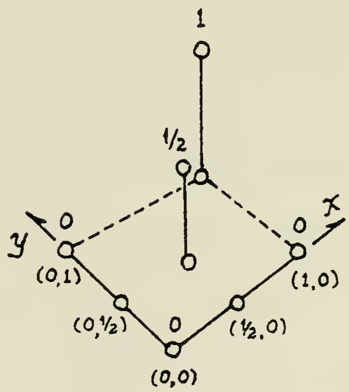
Fig. 3.7 Similaries Among Different Logics

$$Z = \Lambda(x, y)$$

Binary



3-valued



Continuous

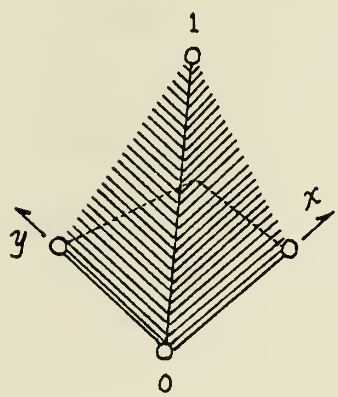


Fig. 3.7 b

Fig. 3.7 Similaries Among Different Logics

An analog analogy of the majority organ as first proposed by H. M. Paynter will be presented later in this chapter.

H. From Digital to Analog via Multi-valued Post Logics

Since the concept of multiplexing and the principle of the majority organ were first introduced by von Neumann, a great deal of contributions has been made by others in the area of reliability of binary system composed by subsystems interconnected in various ways by different kinds of restoring elements. However, primary signals from many instrumentation, control, and communication systems are still in a continuous or analog form. It is true that much of the work dealing with redundant digital systems can be carried over to analog systems, but the unique characteristics of a continuous analog signal necessitate a separate study.

Unlike the simplicity of a digital system with its strings of 0's and 1's, or the multi-valued system with its finite set of values, an analog signal is much more complex with its infinitely many forms and values. It was Paynter who first formulated an analogy between digital restoring elements and the upper and lower selectors used in an analog system.

I. Continuum Logic

In the world of digital 0's and 1's, von Neumann used the AND and OR organs as the two building blocks for his majority organ. Similarly, H. M. Paynter uses the upper and lower selectors to construct his median-taking element for an analog system.[33] Paynter defines the union operator $\vee$ as the upper selector:

$$\vee \; X(k) \equiv X(k_{max}) \tag{3.3}$$

and the intersection $\wedge$ as the lower selector:

$$\wedge \; X(k) \equiv X(k_{min}) \tag{3.4}$$

where $\{X(k)\}$ is defined as an aggregate of classes such that $X_k \big| k = 1,2,3,\ldots,n$. Fig. 3.8 shows the upper and lower selectors in symbols.

If X represents a group of time-varying functions, the following will hold true:

$$X \equiv X(t) \equiv \left\{ X_k(t) \;\middle|\; k = 1,2,3,\ldots,n \right\} \tag{3.5}$$

If the upper and lower selector operators are now performed on a set of signals as shown in Fig. 3.9, $\vee \{X(t)\}$ will represent the greatest of the X_k at time t, whereas $\wedge \{X(t)\}$ will depict the least.

J. Operations of the Majority Organ in an Analog System

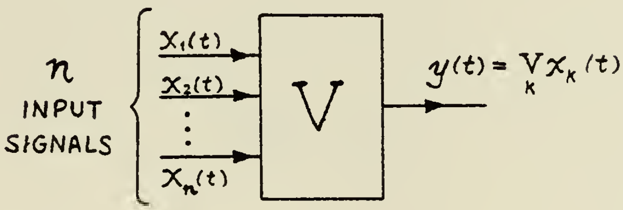
As suggested in section D of this chapter, the majority organ can be represented in the following Boolean relationships:[38]

$$\mathbb{M}\ (X_1,X_2,X_3) \equiv (X_1 \wedge X_2) \vee (X_1 \wedge X_3) \vee (X_2 \wedge X_3)$$
$$\equiv (X_1 \vee X_2) \wedge (X_1 \vee X_3) \wedge (X_2 \vee X_3)$$

In symbols, these relationships are modelled in the configurations shown in Fig. 3.10.

Selection as a Process

Upper Selector



Lower Selector

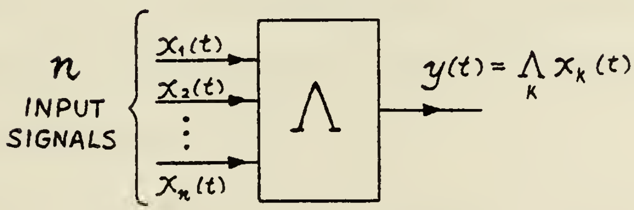


Fig. 3.8

Operations of the Upper and Lower Selectors

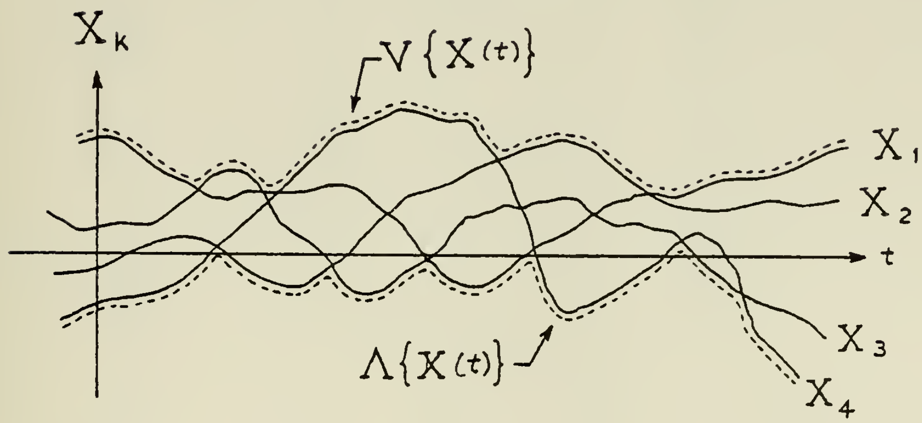


Fig. 3.9

If $X_1(t)$, $X_2(t)$, and $X_3(t)$ represent three similar sinusoidal signals but saturated with different noise and distortion like that shown in Fig. 3.11, then $\mathbb{M}(X_1,X_2,X_3)$ actually takes on the median value at any time t. Using the same symbols as shown in Fig. 3.11, y represents a continuous median signal.(38)

In chapter 4, averaging and voting, the two multiplexing techniques that are most widely used, will be discussed in detail.

The Modelling of the Majority Organ

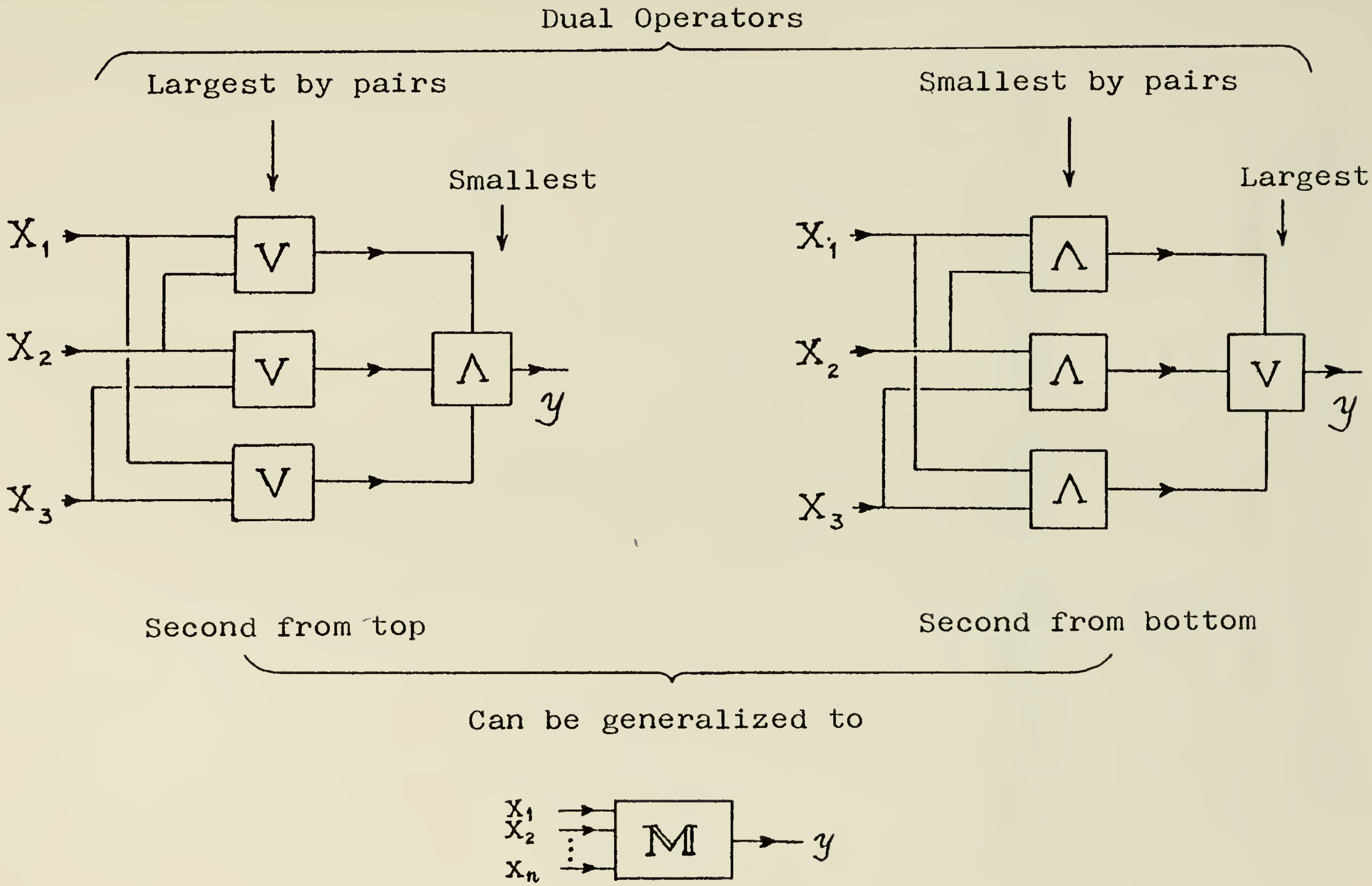


Fig. 3.10

Selection of Continuous Median Signal

Special Case of Three Signals

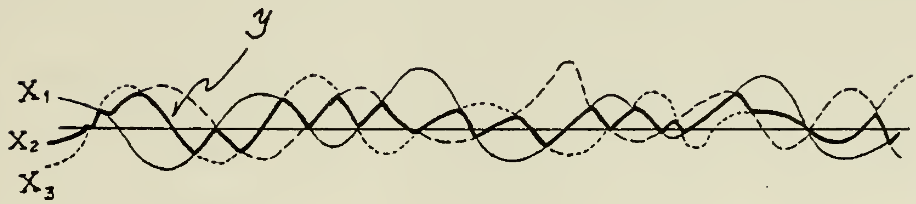


Fig. 3.11

CHAPTER IV

AVERAGING, MEDIATING, AND OTHER VOTING SYSTEMS

A. A Need for Redundancy

A control system needs to be monitored on a continuous basis; but if the instruments that monitor the system performance are themselves not completely reliable, then the system reliability is jeopardized. The control system must act on the basis of signals transmitted from the measuring instruments. If, however, these signals are faulty or inaccurate, then the system can no longer achieve optimal or even safe operation.

The importance of redundant instruments in a control system cannot be overemphasized. As already mentioned in chapter 1, if only one instrument is used to monitor a critical parameter, the failure of that instrument could often lead to catastrophe.

Obviously, if a second instrument is installed to monitor the same parameter, the probability of system failure is considerably decreased. For example, if an averager is used to process the signals from two redundant instruments, the output is clearly more reliable than the output from a single sensor. The difficulty arises, however, when the two transducer signals are vastly different from each other. Here the dilemma leads to the following question: Which signal should one choose? In addition,

even when the faulty instrument is identified, a doubly redundant system does not allow for hot-repair.

Here, the advantages of a triply redundant instrumentation system become highly significant. In the technique of averaging, with one signal going astray, the output is only slightly in error. In the method of voting, however, as long as only one signal is erroneous, the output remains correct. Furthermore, even when two signals have failed, but if one failed high while a second one failed low, the output still maintained a correct value. And finally, in view of the tremendous economic penalty for downtime, the fact that voting allows for hot-repair of a faulty instrument makes it especially attractive for a thermal power system.

The reader will learn more about a triply redundant instrumentation system in the paragraphs to follow.

B. Transition from Digital to Analog to Digital

John von Neumann's majority organ for a binary system was first introduced in chapter 3. In a binary system, as already illustrated in the last chapter, the input and output signals can be easily represented by strings of 0's and 1's. The majority-vote logic element can be constructed with a combination of two basic elements --- AND and OR gates. In fact, it is a relatively straightforward task to demonstrate the operations of the

majority organ in a binary system, as already done in chapter 3 for a simple case.

Since the majority-vote logic was first introduced by von Neumann in his series of lectures at Caltech (California Institute of Technology) in 1952,[30] a tremendous amount of works, both theoretical and experimental, has been conducted in the 1960's and 1970's to evaluate the reliability of digital systems using redundancy. It was in 1958, only 6 years after von Neumann presented his majority logic concept, Paynter formulated an analogy between digital restoring elements and the upper and lower selectors used in an analog system.[33] As mentioned in chapter 3, the unique characteristics of analog signals from most instrumentation make it necessary to conduct a separate study to analyze the application of mediation to an analog system. The experimental work conducted by Karnopp and Bender in 1966 verified the advantages that one would gain in the utilization of averaging and mediation in an analog system.[2]

A symposium on digital redundancy in 1962 may very well have started the transition from analog to digital with full speed. In February, 1962, a two day symposium was held in Washington, D.C. on Redundancy Techniques for Computing Systems[39] in which a total of more than 20 papers were presented by various design engineers and mathematicians. The collection of papers was fabulous; it represented the

hard work and dedication of numerous distinguished people.

With the advent of digital technology in the 1960's, digital redundancy using the voting technique began to be found in various applications. The idea of a voting circuitry is not new, but its implementation in the industries has definitely been an area full of innovations. During the past few years in particular, industrial implementations of redundancy are becoming more and more common everyday. Among some of the more prominent examples are the Space Shuttle program, the strapdown redundant inertial instruments for military ballistic missiles,(40) and the Bell System Electronic Switching Systems (ESS).(41) In fact, reports in this area have appeared on a regular basis in journals such as the IEEE Proceedings, AIAA Guidance and Control Conference Transactions, Electronics, etc.

C. Averaging Multiplexing Technique

1. Introduction

The averaging method can be considered as one of the oldest yet extremely useful techniques to improve the reliability of a signal or data. One is familiar with the situation in which a photographer takes two or three spot readings with his light meter, then uses the average of the readings to set the aperture and shutter speed on his camera.

A straightforward averaging technique involves

simply taking the arithmetic mean of a series of readings; in other words, the weight factor is equal for all channels. This operation, performed by a device to be called an averager, reduces the failure rate of the measuring system according to the total number of sensors. However, noise or error in any one of the inputs still affects the averaging output. If one knows a priori that a certain channel is more reliable than others, then a heavier weight factor can be assigned to that channel, thus increasing the overall reliability.[42]

An even more elaborate "average" method is also available as a multiplexing technique. Here the word "average" is in parenthesis because this method resembles the voting technique more than the ordinary averaging method. In this methodology, weight factors for each channel are continuously changing based on cross-channel differences among the several channels.[43] More on this method later in this chapter.

2. <u>Functional Block Diagram</u>

A typical multiplexed system can be represented by means of a block diagram like that shown in Fig. 4.1. Here the actual multiplexing technique can be averaging, vote-taking, or something more complex. The physical variable can be temperature, pressure, or any other engineering parameter. The noise at each channel may

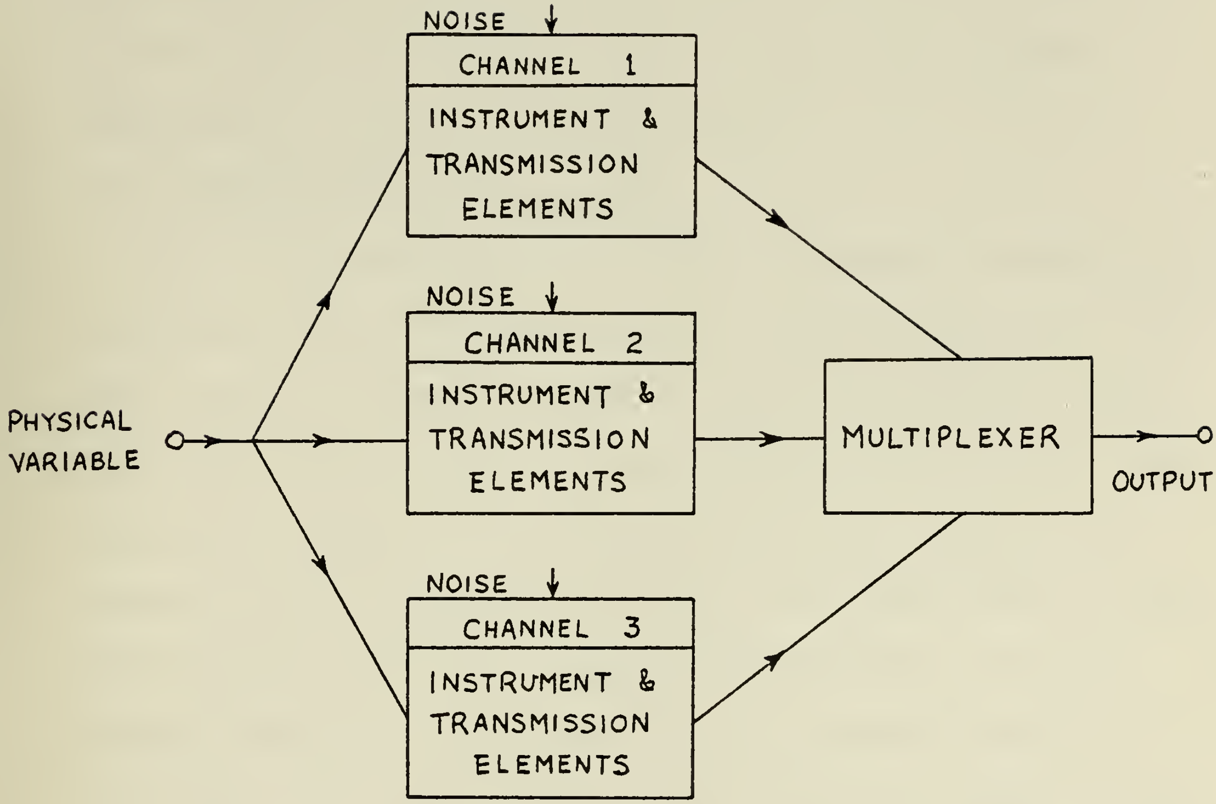


Fig. 4.1 Typical Multiplexed System

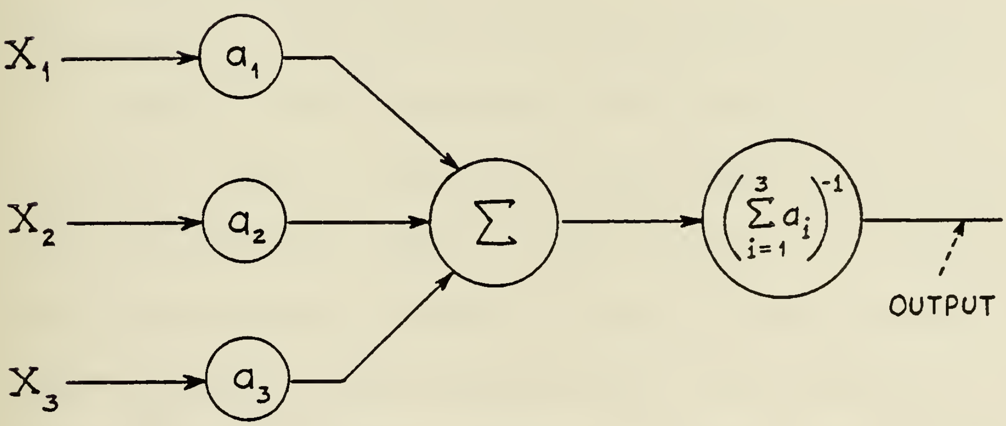


Fig. 4.2 A Linear Vote-taker

be one of the following types: transmitted noise, inherent noise, or induced noise. The block diagram represents a triply redundant case.

3. Principles of Operations

An averager which takes a linear combination of its inputs to form its output is shown in Fig. 4.2.[42] Once again, a triply redundant case is presented here; obviously, one may extend the technique for higher order redundant systems. Here the three input signals are assumed to be identical, but with different noise levels superimposed on them. As mentioned earlier, if the weight factors, a_1, a_2, and a_3 all have the value of 1/3, then the output simply will be the arithmetic mean of the input signals. If we designate the output as X_{out}, then the output of the averager is given by the relation:

$$X_{out} = \frac{1}{3} \sum_{n=1}^{3} X_n$$

which can be generalized to any number of signals.

One of the limitations of a straightforward averaging method is that a number of consistently unreliable channels may degrade the quality of the output. This limitation may be overcome, however, if the reliable inputs are given heavier weight factors and the unreliable inputs are given lighter weight factors. Clearly, the reliability of such tailormade system must be determined on an

individual basis.

4. Reliability Calculations

In the averaging method, the output will be somewhat faulty if any one or more of the inputs is faulty. It is clear that the probability of a faulty output is higher than the probability of failure at any individual channel. This shows that if the control system requires that the output must always be exactly correct, then the averaging method may not be the optimal choice due to its high failure probability. Nevertheless, one must keep in mind that the averager output signal will not deviate as much as a single signal. Detailed reliability calculations and analysis for the averager will be performed in section F, along with those of the voting element for ease of comparison.

5. Experimental Verification

a. Statistical Analysis

An experiment was conducted by dePian and Grisamore to show the advantages of an averaging circuit over a non-averaging single circuit.[44] A distribution of output values was obtained by applying the same input signal to both the averaging and the non-averaging circuits. After elaborate manipulation of the output data, the following relations were found:

For the non-averaging circuit (139 samples)

$\sigma = 0.075$

$\bar{x} = 0.174$

For the averaging circuit (44 samples)

$\sigma = 0.025$

$\bar{x} = 0.187$

The distribution curves for the two types of circuits are shown in Fig. 4.3. As one can interpret from the plot of normalized distribution of output signals (x) in Fig. 4.3, the average circuit has a considerably smaller standard deviation. It can be concluded that in general, the averaging technique provides more reliable output signals.

b. Output Waveforms

The improvement in signal quality of an averager output can be best seen from a set of analog signals. Time plots of three noisy input signals and the resulting output are shown in Fig. 4.4.[45] When only one input is noisy, the averager output has the same noise function as the input, but reduced to one-third.

If two of the input signals are noisy, the output noise level depends on the amount of correlation between the noisy functions on each

input. When all three inputs are noisy, the output noise levels increase but are still less than those of any of the inputs.

Normalized distribution of output signals (x)

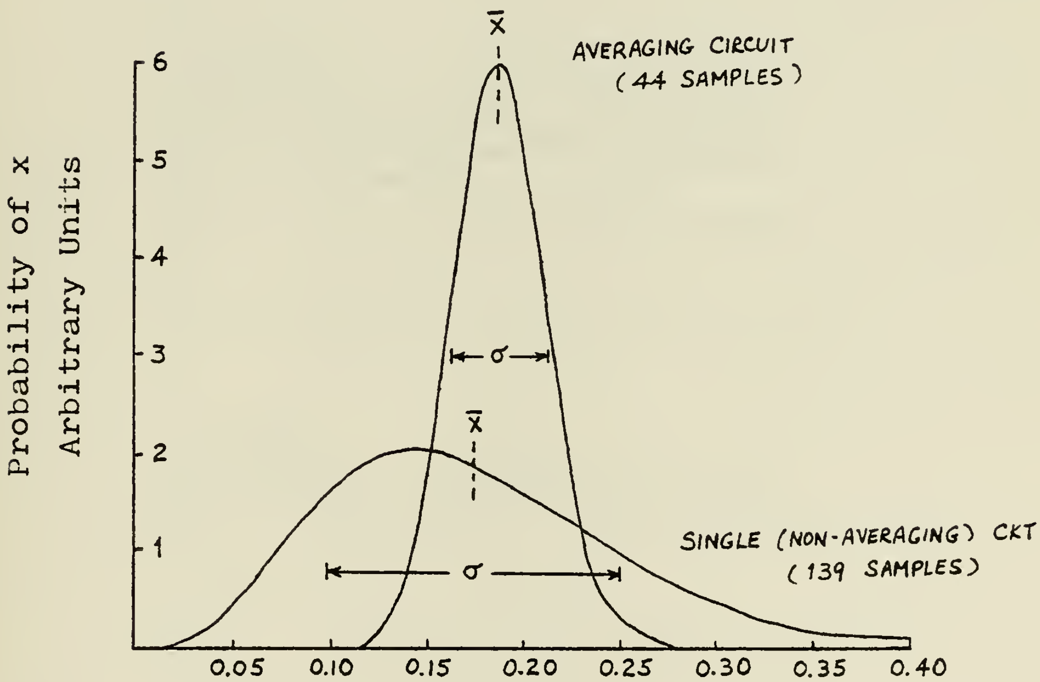


Fig. 4.3

Averager Output

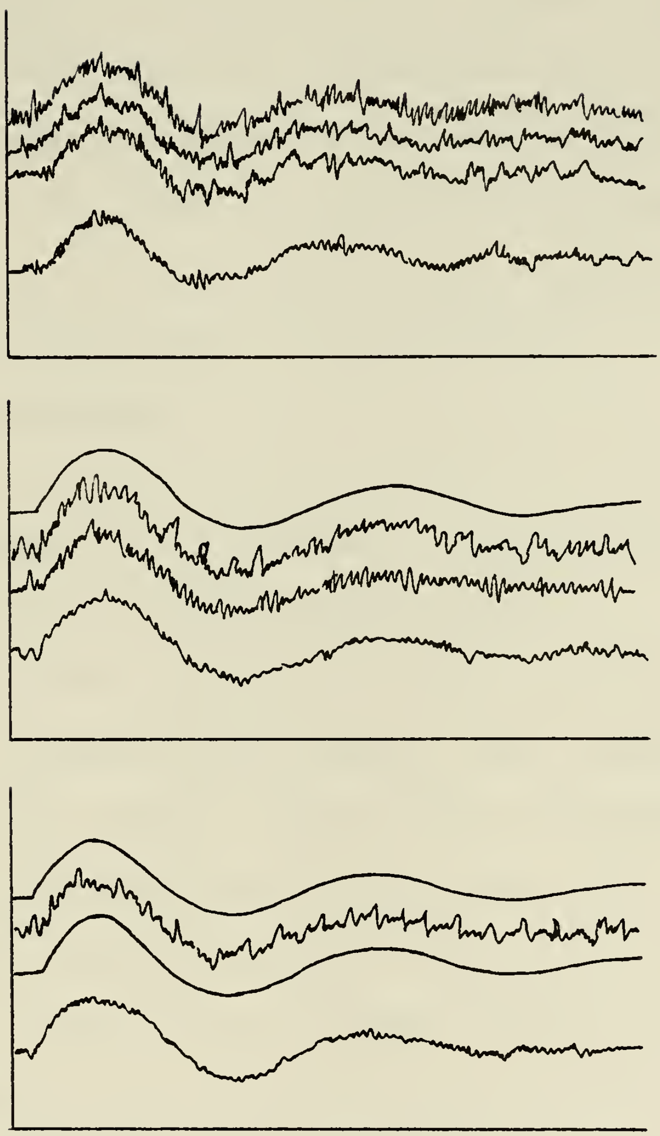


Fig. 4.4

Experimental time plots of averager output when one, two, or three input signals are noisy. In each case the upper three signals are the inputs and the lower signal is the output.

D. Voting Technique

1. Introduction

A vote-taker is a generalization of the majority organ introduced by von Neumann. The output of a voter will always be the median value of the inputs. Voting operations in an analog system have already been performed in chapter 3. The operations of a voter circuitry on three 3-bit digital words will be conducted later in this section.

2. Implementation

As already stated in the last chapter, the voting concept can be defined, in terms of Boolean algebra, as the following relations:[38]

$$\mathbb{M}(X_1,X_2,X_3) \equiv (X_1 \vee X_2) \wedge (X_1 \vee X_3) \wedge (X_2 \vee X_3) \quad (4.1)$$

where X_1, X_2, and X_3 are digital input signals.

The above concept can be easily implemented using the voter circuitry shown in Fig. 4.5. The circuit, in essence, produces an output which remains correct no matter in what manner a single channel fails.

Critics of the voting principle often ask the following question: How does the failure rate of the voter affect the overall probability of error in a system? Obviously, if the voter is constructed of the same components as used in the rest of the system, no improvement occurs. The next step is to consider using

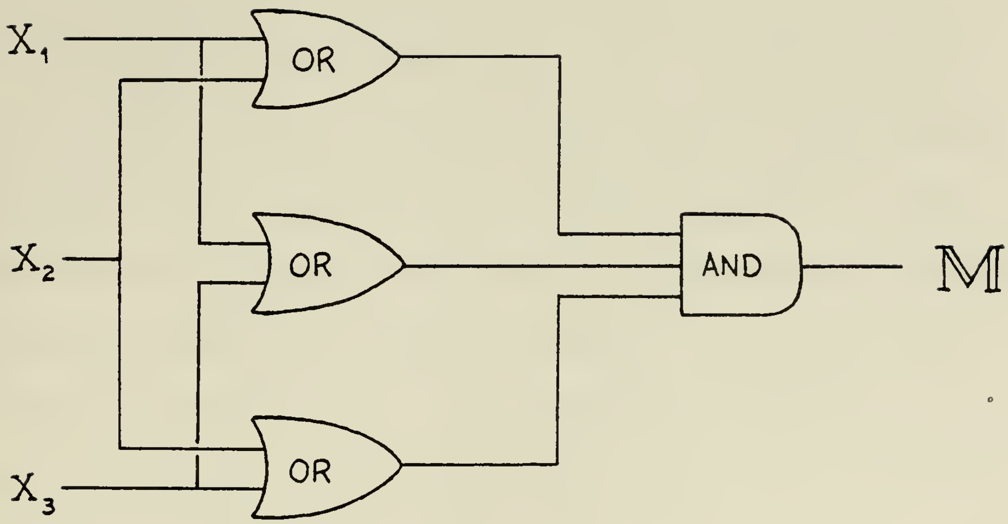


Fig. 4.5 Voter Circuitry

extremely reliable parts for the voter. This in turn is followed by the suggestion that one should use these extremely reliable parts for the rest of the system, thereby creating the original condition with no increase in reliability over the non-redundant case. The last suggestion is highly impractical, however, because complexities of modern circuitries and economic considerations often prohibit the use of ultra reliable components throughout the entire system.

Therefore, it can be concluded that if only the voting circuitries are made of highly reliable components, the overall system reliability will still improve.

A detailed calculation of the improved reliability will be presented in the next section.

One must realize that the voter in Fig. 4.5 is only a 1-bit machine. It is true that in this thesis all signals are assumed to be 16-bit parallel words; but a 16-bit parallel word voting circuitry will take up several pages of circuit diagrams. In order to provide the reader with the perception of what a 16-bit vote-taker would look like, however, a simpler 3-bit voter is shown in Fig. 4.6.

In Fig. 4.6 the binary words 011, 100, and 101 are used to illustrate the operations of such 3-bit voter. The purpose of the comparator is to assist the three OR gates to find the larger of any two 3-bit words. As soon as any two bits have different values, the comparator will identify which bit has a value of 1, then command the converters to convert the rest of the 3 bits of the smaller binary word to have the same values as those of the larger binary word. In this way, the output at the OR gates will always be the larger of the two 3-bit words. The key to Fig. 4.6 provides an example for such operations.

If one compares the three inputs with the output bit by bit, he would notice that the output bits do not represent the majority of the input bits. For example,

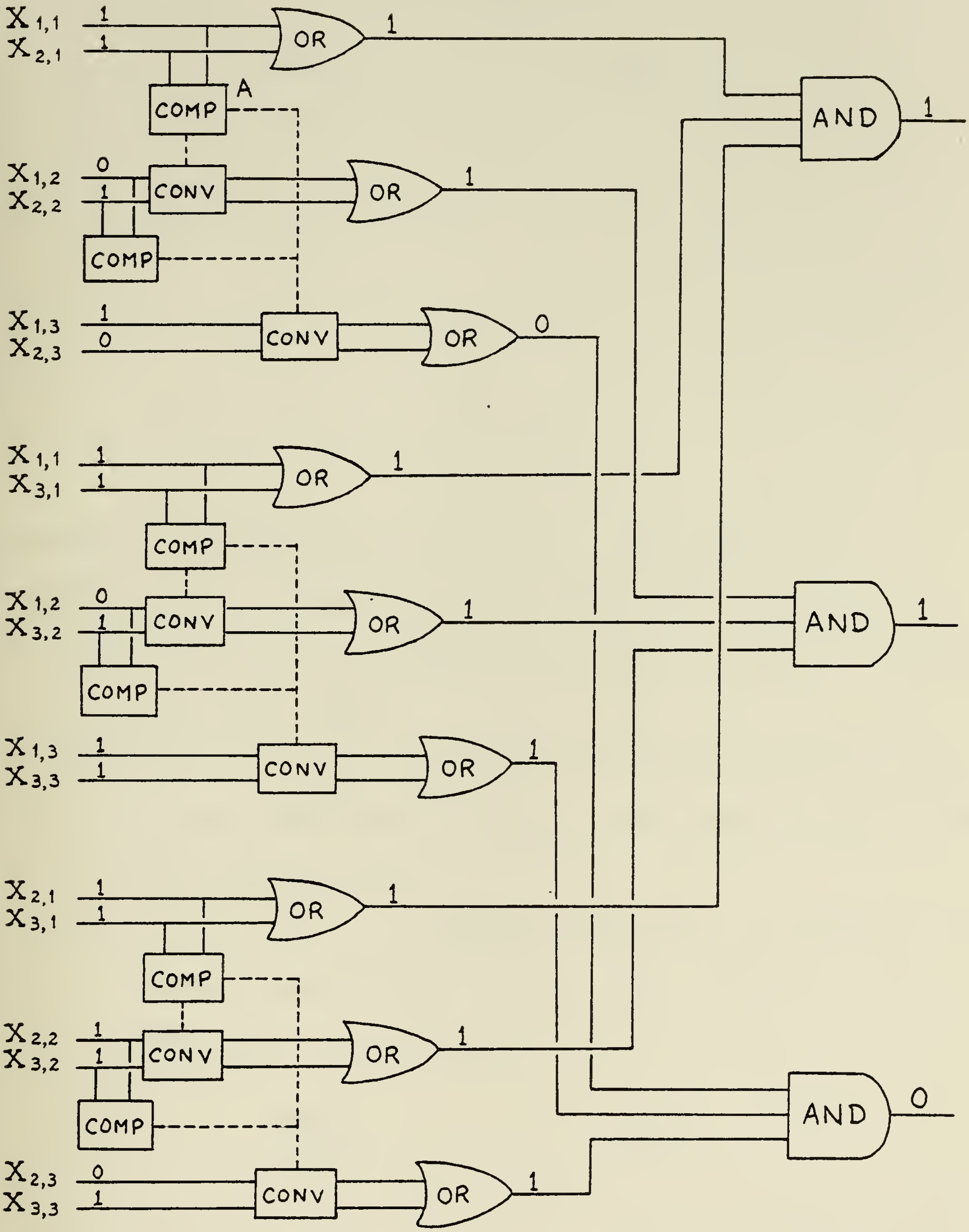


Fig. 4.6 A 3-Bit Voter

KEY to Fig. 4.6

	Binary	Base 10
X_1 =	1 0 1	5
X_2 =	1 1 0	6
X_3 =	1 1 1	7

$X_{1,1} = 1$; $X_{1,2} = 0$; $X_{1,3} = 1$

$X_{2,1} = 1$; $X_{2,2} = 1$; $X_{2,3} = 0$

$X_{3,1} = 1$; $X_{3,2} = 1$; $X_{3,3} = 1$.

Operations of COMPARATOR at point A , 1st comparator in top voter (other comparators operate in similar fashion):

1. If $X_{1,1} \neq X_{2,1}$, identify which is larger, otherwise no action taken.

2a. If $X_{1,1} > X_{2,1}$, command converters to convert $X_{2,2}$ to have same value as $X_{1,2}$; and convert $X_{2,3}$ to have same value as $X_{1,3}$.

b. If $X_{2,1} > X_{1,1}$, command converters to convert $X_{1,2}$ to have same value as $X_{2,2}$; and convert $X_{1,3}$ to have same value as $X_{2,3}$.

INPUTS	OUTPUT
1 0 1	
1 1 0	1 1 0 (Median Value)
1 1 1	

the most significant bit on the output does not represent the majority of the most significant bits on the three inputs. The reader may have noticed, however, that the output represents the median value of the three inputs. Other examples performed by the author show similar results. In this regard, the voter in a digital system is identical to the mediator used in an analog system, as discussed in chapter 3.

3. Reliability and Maintainability

Here the reliability study is conducted for both the averaging and the voting techniques for comparison. One of the major advantages of the voting concept is that it does not require any failure detection. Failure detection, on the other hand, is essential for some fault-tolerant systems that use a tolerance renewal scheme to reconfigure the system around a faulty module using spare units, once the failed module has been isolated.

When a channel fails by outputing a faulty signal, it is sometimes not easy to determine the exact cause of the fault; it can be a short or an open circuit, or a limit value such as a supply voltage. As long as only a single channel has failed, there will be no effect on the output signal (for a triply redundant case). Moreover, monitoring equipment can be set up

to pinpoint the faulty channel when a particular signal deviates from the other two. Once the faulty channel is located, it can be serviced on line without affecting the overall operation of the control system, provided only that a second channel does not fail during the service period. As long as maintenance is available to replace the faulty unit, the probability of continuous failure-free service is greatly increased.

In this reliability analysis, all input signals are considered to be noise-free, but to have the possibility of being at false value. A false value at the input is defined as a failure of an input signal. A clear definition of an output failure is not established; instead, the probability that at least one, two, or three input signals have failed will be plotted as a function of individual signal failure probability.

The probability that at least f out of 3 inputs fail, Pr(f), is the probability that f, f-1, etc. signals fail; based on the binomial expansion theorem, Pr(f) can then be defined as follows:[45,46]

$$Pr(f) = \sum_{i=f}^{3} \frac{3!}{(3-i)!\ i!} P^{i} (1-P)^{3-i} \qquad (4.2)$$

where P is the probability of an individual input failure.

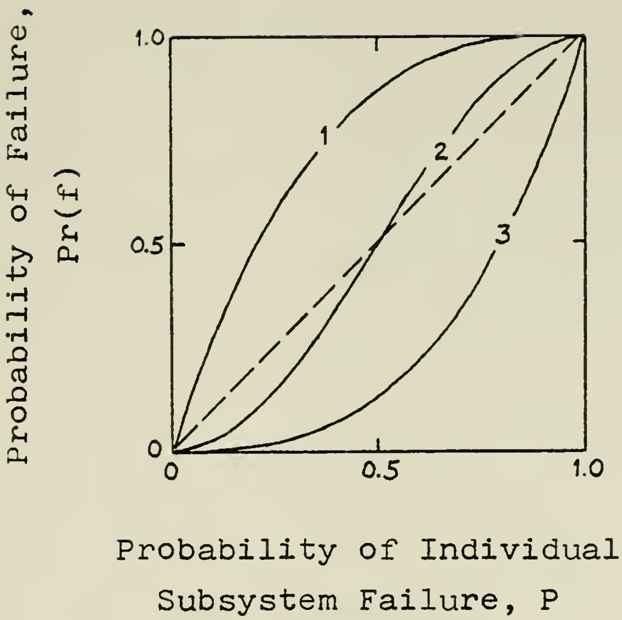


Fig. 4.7

Probability that at least (1), (2) or (3) signals are faulty vs. individual signal failure probability

In Fig. 4.7 the probability, Pr(f), that at least f of 3 channels fail is plotted against the constant probability, P, that any one of the signals may be faulty, for f = 1, 2, 3. From this graph, one can obtain an indication of the failure probabilities for the averaging and the vote-taking techniques.[45]

Curve 1 applies only to the averager since one of three channels fails for the voter has no effect on the output. For the averager, however, the output will be

faulty if any one of the inputs is faulty. Curve 1 indicates that the probability of a faulty output of an averager is worse than the probability of failure at any single channel. Of course, the averager output signal will not deviate as much as an individual signal.

Curve 2 of Fig. 4.7 represents the case of the vote-taker in which a faulty output will result whenever any two of its three inputs are faulty. If the channel fails by open circuiting, however, the output will not be affected. From the S shape of curve 2, it becomes quite clear that for well-designed channels with $P << \frac{1}{2}$, the probability of a faulty output for the voter is very small compared with that for a single channel.

Finally, curve 3 indicates the worst case when all three channels are faulty. Until all three inputs are faulty, an averager will still react to some extent to the correct signal as long as some information from the correct signal get through. The voter, on the other hand, will simply neglect the correct signal altogether as soon as two signals are faulty.

Since the vote-taker can operate perfectly with a minority of channels failed, fast repair or replacement of a malfunctioned channel will sharply reduce the probability of system failure. This feature is especially

desirable in a thermal power plant if one considers the economic penalty associated with the shutdown of the plant for maintenance of instrumentation.

Incidentally, the fact that a voter maintains a correct output even when a minority of its channels are faulty is a simple example of fault-masking, the ability to prevent the fault from being transmitted further downstream.

4. Experimental Verification

As in the case of the averager, it is considerably easier to visualize the sharp improvement in signal quality of a voter output from analog signals. Time plots of three noisy input signals and the voter output can be seen in Fig. 4.8.[45] When only one input is noisy, the voter output is completely clean.

If two of the input signals are noisy, the output noise level is directly related to the amount of correlation between the noise functions on each input. Careful examination of the output shows that the output waveform is identical with the noise-free signal for one-third of the time.

Finally, when all three inputs are noisy, the output noise levels increase, but similar to the averaging technique, the noise levels are still less than those of the inputs.

Voter Output

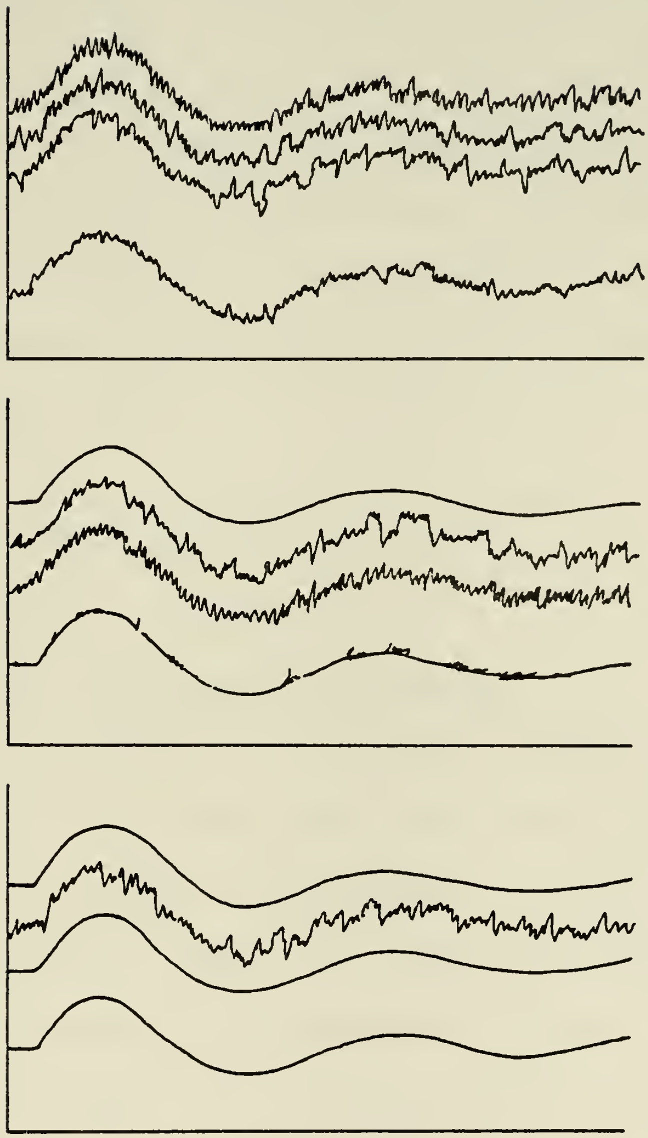


Fig. 4.8

Experimental time plots of voter outputs when one, two, or three input signals are noisy. In each case the upper three signals are the inputs and the lower signal is the output.

5. Reliability for Higher Order Redundancy

The triply redundant case has been used throughout the analysis. One must realize that higher order of redundancy is also used. However, the triply redundant case is felt to be the most practical case because it is the lowest order of redundancy to which the voting concept may be applied. Obviously, one may easily extend all of the results for higher order redundant system in which Pr(f) may be represented by the following formula:

$$\Pr(f) = \sum_{i=f}^{n} \frac{n!}{(n-i)!\ i!} P^{i} (1-P)^{n-i} \qquad (4.3)$$

where n = order of redundancy.

6. Multiple Line Restoring Element

In addition to the simple voter configuration shown in Fig. 4.5, there are other voter configurations that will yield higher reliability. Such an improved version is shown in Fig. 4.9. This arrangement is called the multiple line restoring element.(47) It consists of a group of N voting elements, each with N inputs. All of the lines from the input bundle enter each of the restoring elements, M_1, M_2, and M_3 .

A more sophisticated technique is the triplicated voting method shown in Fig. 4.10.(48) By dividing each of the parallel channels into a large number of

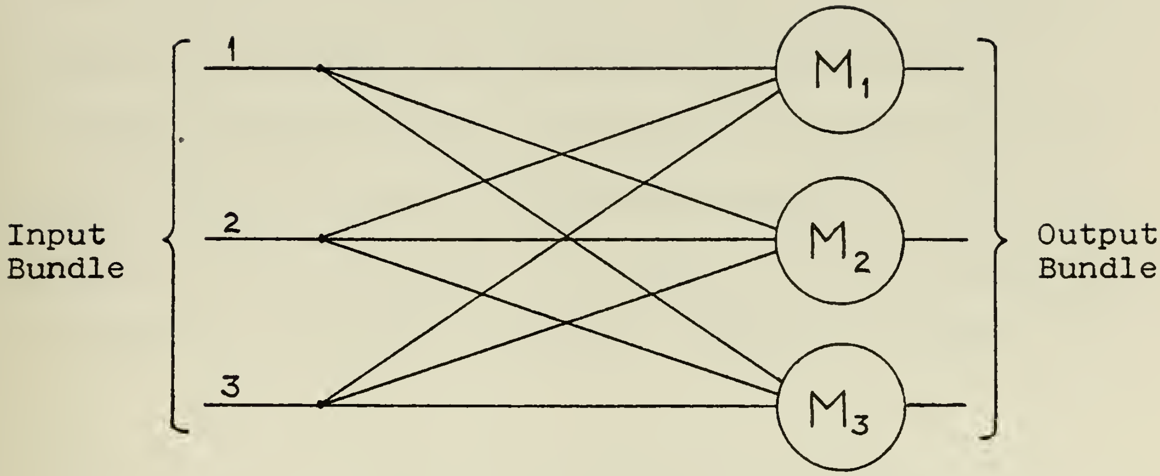


Fig. 4.9 Multiple line Restoring Organ

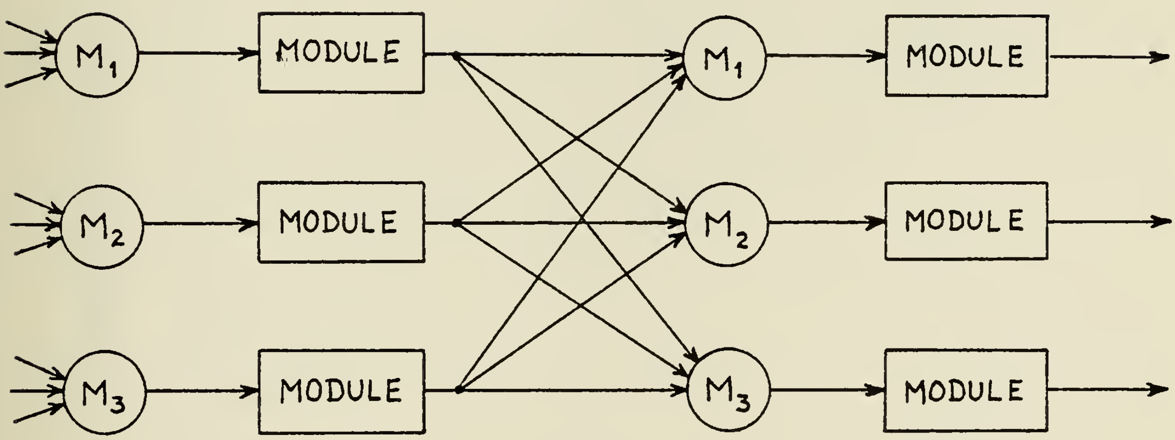


Fig. 4.10 Triplicated Voting Technique

segments and taking a vote after each segment, it is now possible for the system to experience a sizable number of faults in all three channels and still perform satisfactorily, as long as the faults do not occur simultaneously in identical segments of two out of the three channels. The number of such segments in a system is referred to as the "level of voting".[48]

MTBF's vs. Levels of Voting

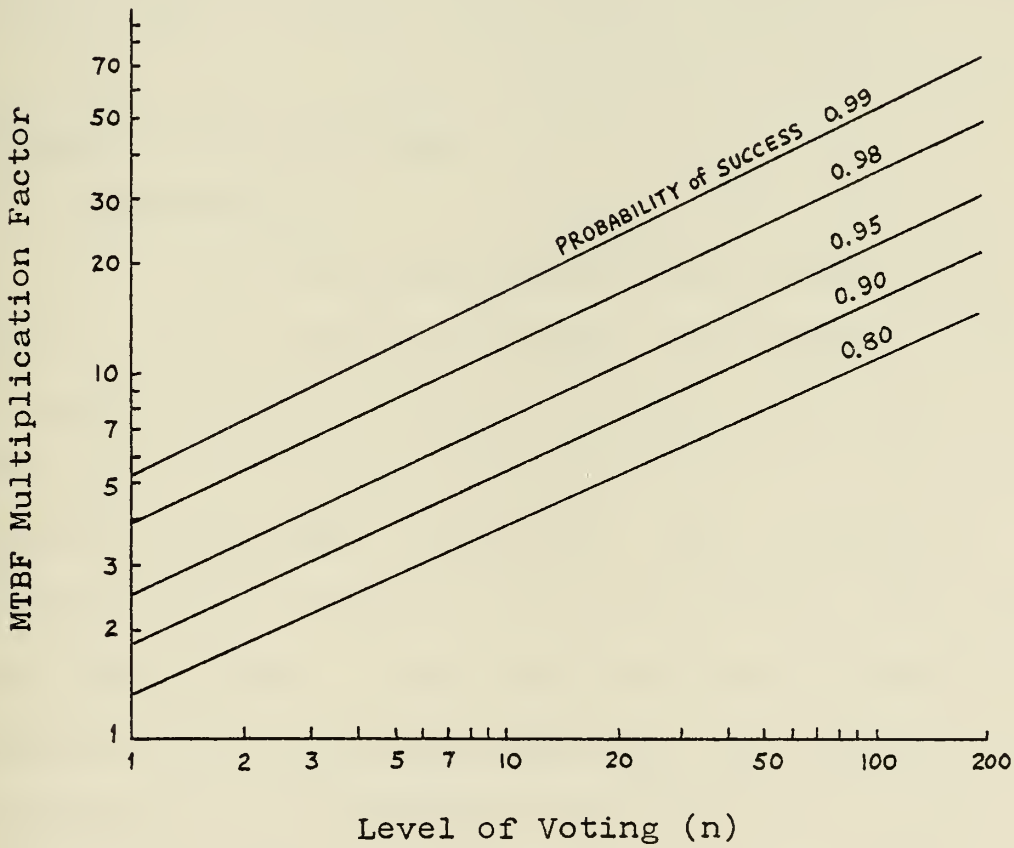


Fig. 4.11

Fig. 4.11 shows the improvement in reliability as the voting levels are increased in a parallel channel voter system. Assuming a non-redundant system with a 98% probability of non-failure, a three channel redundant system with two levels of voting should have its MTBF (mean time between failure) increased by more than 5 times. Of course, the higher the levels of voting, the greater will be the MTBF's, as indicated from Fig. 4.11. One must realize, however, that cost is an important factor in determining the maximum level of voting that an engineer can design a system.

E. Advanced Voter Technique

1. Introduction

In an instrumentation control system that uses a voting circuitry like the one examined in the preceding section, whenever a channel fails, the output will show considerable transient due to the switching action of the voter. Sometimes, these transients could be severe enough to cause an adverse response in the total system. A new voter has been proposed to minimize such switching transients; the output is determined as a continuous smooth function of the redundant inputs using a weighted "average".[43]

2. Principles of Operations

This type of voter minimizes switching

transients on the output because the isolation of a faulty channel is accomplished through a continuous numerical weighting. The output is determined in such a fashion that the outlying (faulty) signals are heavily discriminated against, in favor of the signals that are fairly close.

In section C the author briefly mentioned an averaging method that assigns heavier weight factors to more reliable channels. These weight factors, however, were determined a priori. The voter described in this section, on the other hand, uses weight factors that are dynamic and are continuously changing based on cross-channel differences.[43]

A block diagram of such voter is shown in Fig. 4.12.

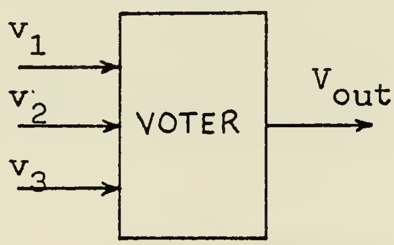


Fig. 4.12 Advanced Voter

V_{out} is defined as

$$V_{out} = \frac{W_1V_1 + W_2V_2 + W_3V_3}{W_1 + W_2 + W_3} \qquad (4.4)$$

Obviously, if $W_1 = W_2 = W_3 = 1/3$, then V_{out} will simply be a mean value voter, or a simple averager, as already examined in section C. In any event, regardless of what values W_1, W_2, and W_3 take on, V_{out} is always a continuous smooth function of V_1, V_2, and V_3.

Reference (43) provides a family of weight factors for a triply redundant voter. Some weight factors involve the exponential functions, whereas others are defined in terms of the hyperbolic functions. One group of weight factors that is of particular interest is the following:

$$W_1 = \left[1 + \left(\frac{V_1 - V_2}{a} \right)^2 \left(\frac{V_1 - V_3}{a} \right)^2 \right]^{-1}$$

$$W_2 = \left[1 + \left(\frac{V_2 - V_1}{a} \right)^2 \left(\frac{V_2 - V_3}{a} \right)^2 \right]^{-1} \qquad (4.5)$$

$$W_3 = \left[1 + \left(\frac{V_3 - V_1}{a} \right)^2 \left(\frac{V_3 - V_2}{a} \right)^2 \right]^{-1}$$

The constant a is the tolerance parameter which is a measure of the allowable noise level in a given channel.

Note that if the square of the cross-channel differences, $(V_i - V_j)^2$, are all small, then the equation of V_{out} will approach the following:

$$V_{out} = \frac{V_1 + V_2 + V_3}{3}$$

On the other hand, if $\left(\frac{V_1 - V_2}{a}\right)^2 << 1$ and both $\left(\frac{V_2 - V_3}{2}\right)^2$ and $\left(\frac{V_1 - V_3}{2}\right)^2 >> 1$, then the equation of V_{out} reduces to $V_{out} \cong \frac{V_1 + V_2}{2}$.

From the above analysis, it becomes clear that if V_3 is indeed the erroneous signal, then the weight factors will computationally vote out V_3 in favor of the two nearly identical signals V_1 and V_2. Table 4.1 can be used to demonstrate just that. In this table computed values of V_{out} for a range of values of V_1, V_2, and V_3 are tabulated. Formulas used for V_{out} and W_1 to W_3 are equations 4.4 and 4.5, respectively.

As the reader can see, these weight factors are constructed to discriminate against a possible failed signal in favor of the remaining good signals. In this regard, it is similar to the voter described in section D.

F. Functional Redundancy

1. Introduction

This section deals with a reliability problem that is somewhat different from that of a voting element. Here the major concern is the improvement of the overall reliability of the entire system by partitioning the system into functional blocks and making each block

INPUTS			OUTPUT
V_1	V_2	V_3	V_{out}
0	0	0.1	0.033
0	0	0.5	0.180
0	0	0.8	0.210
0	0	1.0	0.200
0	0	1.2	0.174
0	0	1.5	0.114
0	0	2.0	0.060
0	0	3.0	0.018
1.0	1.0	1.0	1.000
1.0	1.0	1.1	1.033
1.0	1.0	1.2	1.066
1.0	1.0	1.5	1.180
1.0	1.0	2.0	1.200
1.0	1.0	3.0	1.067
1.0	1.0	4.0	1.018

Table 4.1 Voter Output for Triply Redundant Signals

parallel-redundant.

2. Principles of Operations

The usual method for improving the reliability of a system is to establish a parallel configuration of two identical units, either both operational or one operational and the other in standby. The disadvantage of this arrangement is that the failure of any one component within the unit would place that entire unit out of action.

If the system is partitioned into functional blocks, and each block is parallel redundant, this would significantly increase system reliability because now even if one block in a set fails, the other blocks in the set can still be used.(49) The outputs of each functional block are cross-strapped to the inputs of the succeeding pair. A block diagram of such system is shown in Fig. 4.13. The system may be an encoder, decoder, or any other functional device in a control scheme.

With the system partitioned into five parallel-redundant functional blocks, it can now be configured into 2^5, or 32 possible combinations of functions to circumvent failures should they occur. Functional sections are activated by power switching. With 32 possible configurations, there is little doubt that

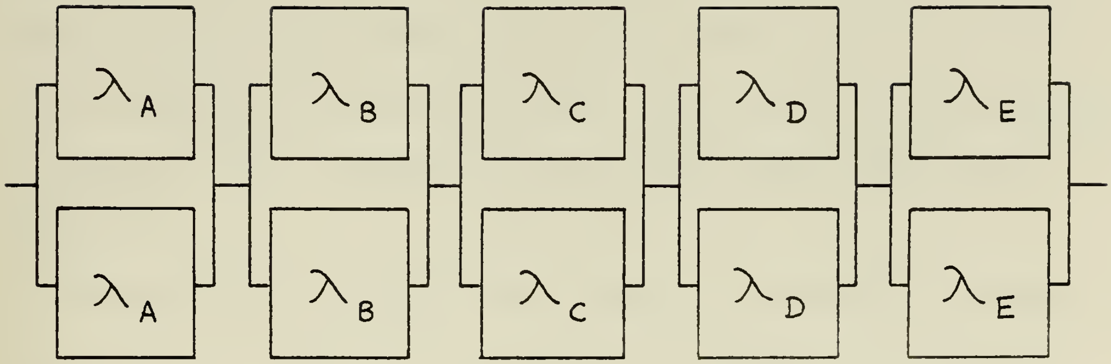


Fig. 4.13 Functional Redundancy

the overall reliability of the system has been greatly improved.

G. Noise Reduction

1. Introduction

Signals from various instruments are usually superimposed with noise. The extraneous noise may be a result of thermal emf from an RTD; or it may be caused by self-heating in a thermistor, to name only two of the many sources. Chapter 2 contains a detailed description of many of the sources that can generate noise in an instrumentation system.

2. Noise Reduction Methodologies

Noise can be categorized into two groups: random or coherent. Random noise is usually generated

within components, such as RTDs, transformer cores, or semiconductor junctions, whereas coherent noise is either locally-generated by processes, such as voter switching, or coupled in. Coherent noise often takes the form of "spikes".

Regardless of the noise origins, several methods are commonly used to retrieve the original waveforms. Some of these noise reduction techniques are analog-to-digital conversion, shielding and guarding, signal compression and filtering, and where possible, an information rate that has enough redundancy to allow the digital processor to retrieve data via correlation and summation.[9]

Where noise is likely to have large spikes as a major component, the integrating-type A/D converter (dual-slope) usually provides additional filtering. For random noise, if there are sufficient samples taken of a given signal channel, the technique of averaging may be used as a filtering device.

3. Technique of Averaging

Averaging is a noise reduction technique often used in a digital system. A digital averager is basically a device used for averaging repetitive noisy signals. Signal averaging has the ability to recover the signal's original waveshape from the noise. In

this way, the signal-to-noise ratio can be improved by several orders of magnitude.

The author would like to point out that the averager mentioned here is different from the averaging multiplexing technique examined in section C. In section C the averager is a device that takes an average value of the signals from three redundant channels. Here, averaging is a technique that reconstructs a signal waveform by taking the average of a sufficient number of repetitive noisy signals. In this regard, the averager described in section C, in addition to improve the reliability of the signal, also acts as a noise reduction device. Of course, the degree of noise reduction is not as extensive as compared to the averager in this section since only three samples are taken (in a triply redundant case).

Provided the waveform is repeated over and over again, any signal waveform which is corrupted by noise can be reconstructed. For a weak periodic signal that is buried in noise, the technique enhances it by overlaying successive segments of the noisy signal, where the segment length equals the period of the signal.[50]

Even when the waveform repeats itself at irregular intervals, but if some characteristics of the signal can be used to align the successive, noisy waveforms, aver-

aging can still be used. Fig. 4.14a and Fig. 4.14b illustrate such an example. The signal in Fig. 4.14a has a rather poor signal to noise ratio, but it contains a sharp peak which rises above the noise. By aligning the peaks and then averaging the noisy waveforms together, the noise will tend to cancel itself out whereas the signal reinforces itself; the result is shown in Fig. 4.14b.

Averaging An Aperiodic Waveform

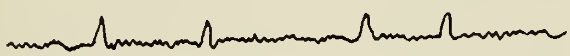


Fig. 4.14 a

Fig. 4.14 b

The averager uses each new noisy signal to update a partial average formed from previous waveforms, thus forming a new partial average. The sequence of events can be seen in Fig. 4.15. The symbols in Fig. 4.15 are defined as follow:[50]

- e is the present noisy waveform to be averaged
- E is a sampled and quantized version of e
- A is a sampled and quantized version of the present partial average before it is modified by E.

Averaging System Waveforms

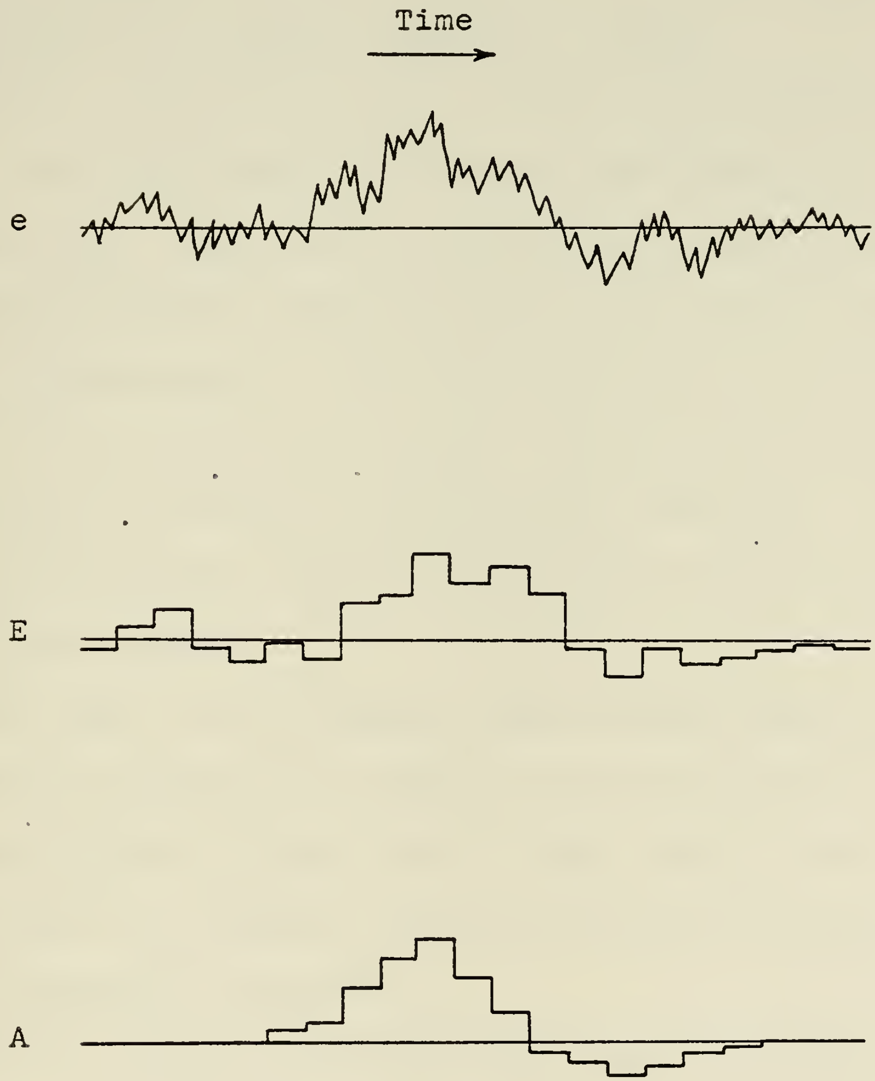


Fig. 4.15

4. Low-pass Filter for the Vote-taker

It was shown in the discussion in section D that the output of a voter is rather jagged; the switching action of the voting circuitry is the cause for this high frequency spectral content.

Fig. 4.16a represents a digital input with a broad band noise spectrum.[2] Note that the abscissa is in a log scale. Three input signals with similar noise spectrum like that shown in Fig. 4.16a are fed into a voting multiplexer. The output after multiplexing (Fig. 4.16b) shows some fairly interesting effects. The overall waveform is considerably smoother. At high frequencies, however, substantial harmonic contents are still present.

In Fig. 4.17a a digital input signal with a narrow band noise spectrum is shown. The output after a voter is illustrated in Fig. 4.17b. Here, one can see clearly that there are definite peaks at integer multiples of the fundamental frequency.

In a practical situation the signal spectrum and the noise spectrum often overlap, therefore, considerable noise can be filtered out by using a simple low-pass RC filter like that shown in Fig. 4.18.

5. Buffering of Data

In the digital mode, one can conveniently

Broad Band Noise

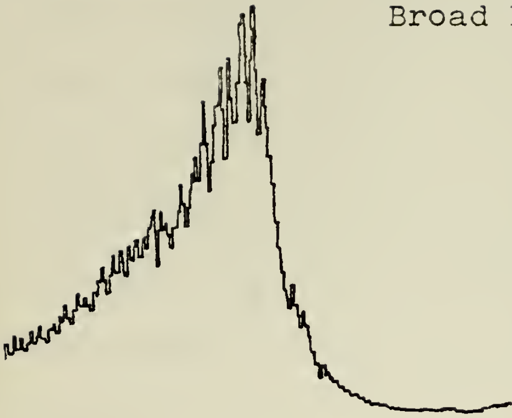


Fig. 4.16 a

Fig. 4.16 b

Narrow Band Noise

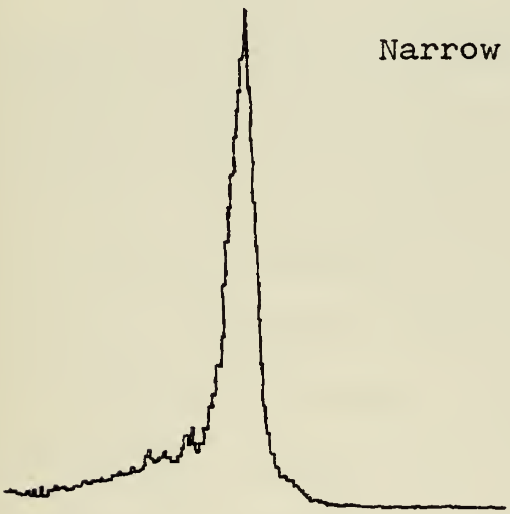


Fig. 4.17 a

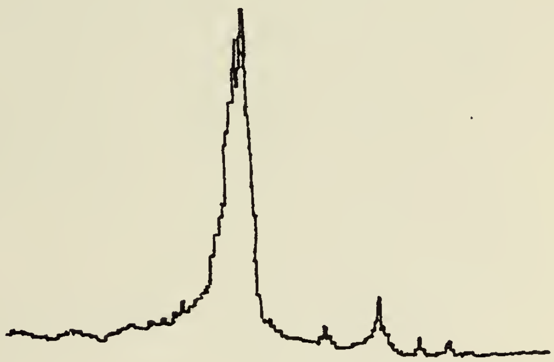


Fig. 4.17 b

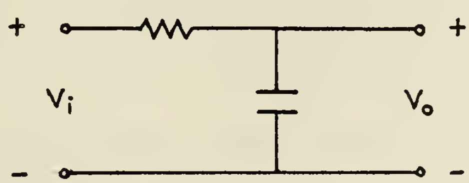


Fig. 4.18 RC Filter

manipulate the time variable under various circumstances. After an analog signal has been converted to its digital form, time is no more constrained than any other characteristic of the signal. In fact, time can be compressed. This process permits the collection of data at a slow rate and the output of this collected data in a fast burst. For example, when temperature signals are picked up by an RTD over an interval of a few seconds, they can be compressed and repeatedly processed or displaced every few milliseconds.[50]

If certain Gaussian noise is always present in a particular frequency band, while the signal itself spreads out in the entire frequency spectrum, then one may wish to use a band-pass filter for noise reduction. In digital telemetry, in addition to increase transmission efficiency, data compression is often used as a technique to reduce noise. By using data compression, the amount of data to be transmitted is now reduced, usually in the form of redundancy reduction, variable-length encoding, or parameter extraction. If the remaining important data are reorganized at constant time intervals, a bandwidth compression is also achieved.[51,52] Thus, the technique of data compression is now also acting as a band-pass filter.

6. Software Digital Filters

Software digital filters refer to the different algorithms that one can use to implement a filtering operation on a general purpose digital computer. Some of the better known procedures include the Fourier Transform, the Walsh Functions, and the Wiener filtering technique. The Walsh Functions are particularly useful for non-linear signals. Reference (53) provides more details in this area.

H. A Simple Example in Multiplexing

In Fig. 4.19 the author has designed a simple triply redundant multiplexing system to illustrate many of the topics already discussed in the preceding sections of chapter 4.[50,54] The design is intended to be general enough so that its methodologies can be applied to most engineering systems.

The signal levels out of many transducers are usually in the millivolt range, possibly 10 or 100 mV full scale. In addition, the transducers are often located in a noisy environment. In Fig. 4.19 it is assumed that the transducer output is about 10 mV and that its two output leads are electrically isolated from ground. The cable leading from the transducer, however, is subject to capacitive and inductive noise pickup.

By using shielded cable, most noise pickup can be

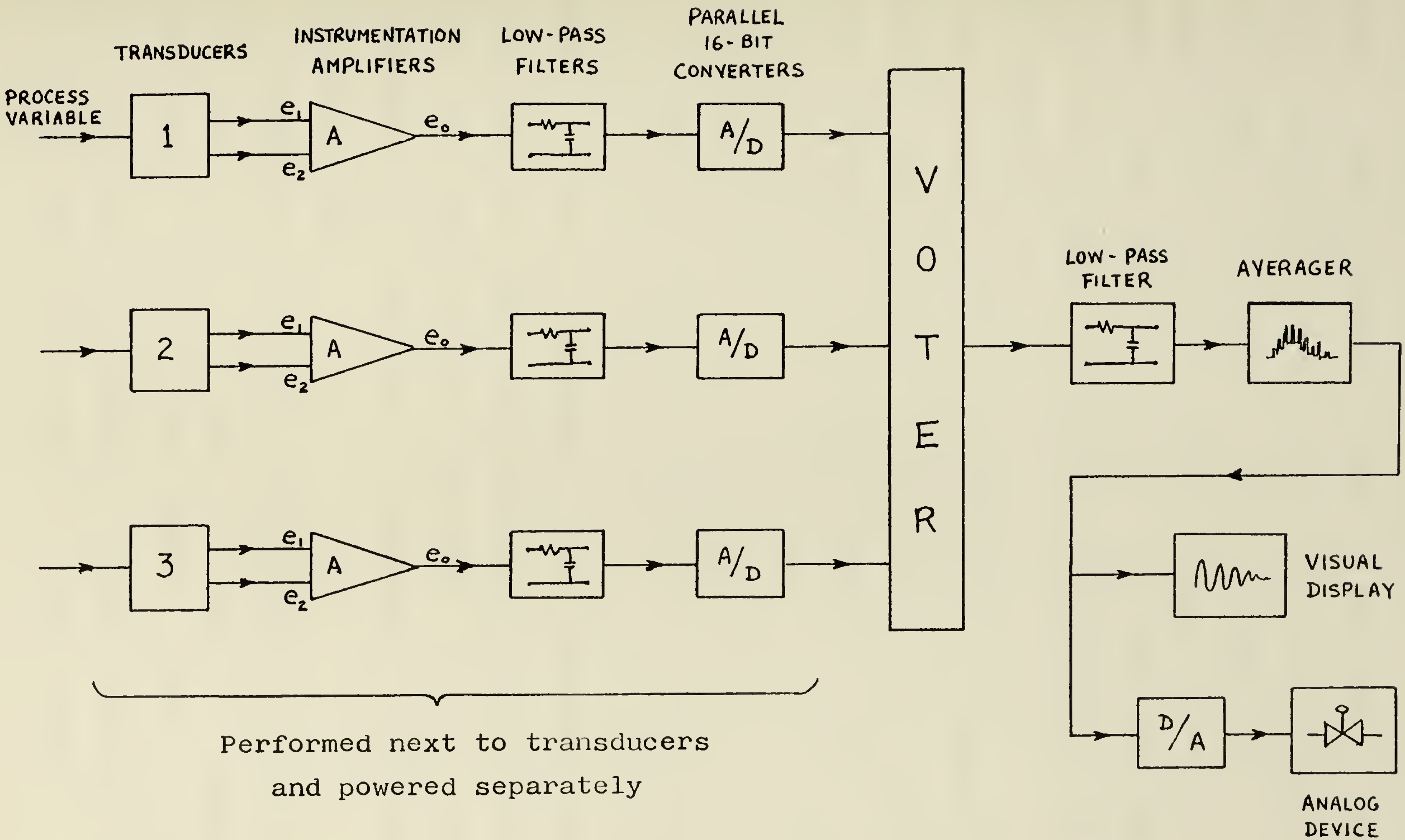


Fig. 4.19 A Simple Example in Multiplexing

minimized; however, common-mode noise may still exceed the transducer output by several orders of magnitude. Common-mode noise is that component of the total noise picked up which is common to e_1 and e_2. It is the major role of the instrumentation amplifier to provide common-mode-noise rejection. Moreover, the amplifier amplifies the signal $e_1 - e_2$, and provides a high input impedance and a low output impedance.

The low-pass filter just upstream of the parallel A/D converter is used simply to filter out any high frequency spectral contents in the original transducer signal. Sometimes, no filtering is needed because of the low-pass characteristics of the signal and noise or the input cable.

The parallel 16-bit A/D converter used here has already been discussed at the end of chapter 1. The most evident advantage of parallel conversion is its tremendous speed. The information no longer has to be converted bit by bit because as the input changes, the output code also changes. With a parallel A/D converter, a sample and hold circuit is no longer needed.

As mentioned in chapter 1, A/D conversion is performed near the signal source, and each instrumentation package is powered from a separate power source. After the signals have been converted from analog to digital, they are then transmitted to the control center for multiplexing.

Here, the three redundant signals are processed by the vote-taker; the output will simply be the median value of the three input signals. The switching action of the voting element will inevitably produce considerable spikes on its output, so a low-pass filter is needed here.

Before the signal is sent on its last leg to the digital meter for display, it is processed through an averager (already examined in detail in section G) for further noise reduction. The digital signal can also be sent to a D/A converter so that the analog output can be used in an analog control scheme, like the positioning of a valve based on flow signals.

The author hopes that with the above example, the reader has acquired a better understanding of the various functions of a control system that uses redundant instrumentation, and more importantly, how all of the components perform together to enhance the reliability of any noisy signal.

In chapter 5 a case study of some of the control systems at the Deer Island Sewage Treatment Plant will be presented.

CHAPTER V

DEER ISLAND SEWAGE TREATMENT PLANT - A REVISITED CASE STUDY

A. Introduction

The Deer Island Sewage Treatment Plant in Boston, Massachusetts presents a very unique case study in control systems engineering. In order to control pump speed at the Deer Island plant, flow and level signals from the three headworks must be transmitted to the pumping station at Deer Island. These telemetered variables must be extremely reliable to prevent any massive overflows or even flooding at the pumping station. The control system at Deer Island employs an unique method to assure transmission reliability by checking for any differences between the transmitted and returned signals. Here, "returned signal" refers to a signal that has reached its destination, but has now returned to its source. The reader will be introduced to this clever control scheme in the following pages.

B. System Description

The Deer Island Sewage Treatment Plant is the larger of the two sewage treatment plants within the Metropolitan Sewerage District (MSD) in the Boston Harbor-Eastern Massachusetts Metropolitan Area. The Metropolitan Sewerage District comprises of 43 cities and towns, and 225-mile

network of interceptor sewers leading to processing facilities at the Deer Island and Nut Island (the 2nd plant) sewage treatment plants.[55] Here, primary treatment is given to a combined average daily flow of 450 million gallons and a maximum daily flow of 1.2 billion gallons at these two plants. Wastewater from almost two million people and stormwater runoff from rainfall are processed to remove suspended solid matter and chlorinated to destruct bacteria, prior to discharge into Outer Boston Harbor.

The next paragraph briefly describes the basic functions of the pumping station at Deer Island.

A major portion of the flow from communities in the Boston metropolitan area located near the Mystic and Charles rivers empties into deep rock tunnels under Boston Harbor which carry it to the Deer Island Treatment Plant. The pumping station at Deer Island is required to lift flows from the deep rock tunnels, which are some 300 feet under Boston Harbor, into the treatment plant. The pumping station has a capacity of 810 million gallons per day.

Professor Henry M. Paynter of M.I.T. has long been closely associated with the pumping station and its control systems at the Deer Island plant. In January 1982, the author visited the Deer Island plant and the Chelsea Creek Headworks for the first time. The visit was made possible only with the most congenial cooperation from Messrs.

Ken Donavon and Paul Sullivan of the Deer Island plant and with Professor Paynter as a most knowledgeable guide. Fig. 5.1 shows a diagram of the entire Deer Island plant and basically how it works.[55]

One must be selective in making a case study of a complex system like the Deer Island plant; therefore, the author intends to cover only some of the control systems which are relevant to this thesis. In particular, the areas that will be covered are the followings:

1. Sewage Tunnel System
2. Central Control Panel
3. Digital telemetry vs. aging analog system
4. Instrumentation for electric-driven pumps
5. Instrumentation for future electrical generators

C. Sewage Tunnel System

The Metropolitan Sewerage District tunnel system is shown in a simplified schematic form in Fig. 5.2a. Here the dash components denote the flow and level-control action. The block diagram in Fig. 5.2b can be used to investigate hydraulic transients in such sewage-disposal system, as Paynter was called upon to perform at one time. The physical elements are interconnected as shown in Fig. 5.2c.[56,57]

If a control scheme is designed so that the downstream flow Qc simply follows the inflow Qa, rather violent surges

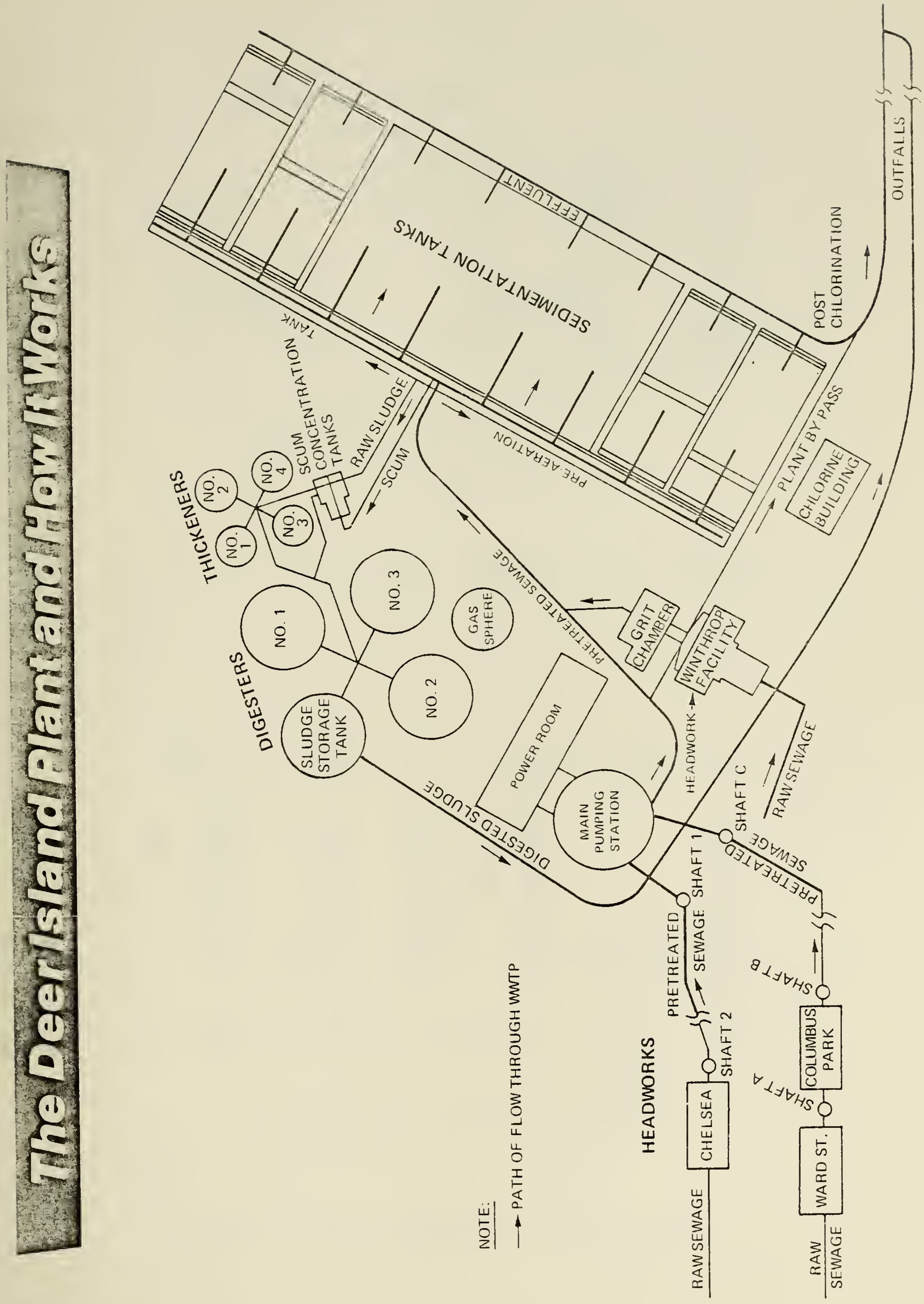

The Deer Island Plant and How It Works
NOTE:
PATH OF FLOW THROUGH WWTP
HEADWORKS
RAW SEWAGE
CHELSEA
SHAFT 2
PRETREATED SEWAGE
SHAFT 1
RAW SEWAGE
WARD ST.
SHAFT A
COLUMBUS PARK
SHAFT B
PRETREATED SEWAGE
SHAFT C
RAW SEWAGE
HEADWORKS
WINTHROP FACILITY
MAIN PUMPING STATION
POWER ROOM
DIGESTED SLUDGE
SLUDGE STORAGE TANK
DIGESTERS
NO. 1
NO. 2
NO. 3
GAS SPHERE
THICKENERS
NO. 1
NO. 2
NO. 3
NO. 4
SCUM CONCENTRATION TANKS
RAW SLUDGE
SCUM
TANK
PRETREATED SEWAGE
GRIT CHAMBER
PRE-AERATION
SEDIMENTATION TANKS
EFFLUENT
PLANT BY-PASS
CHLORINE BUILDING
POST CHLORINATION
OUTFALLS

Fig. 5.1

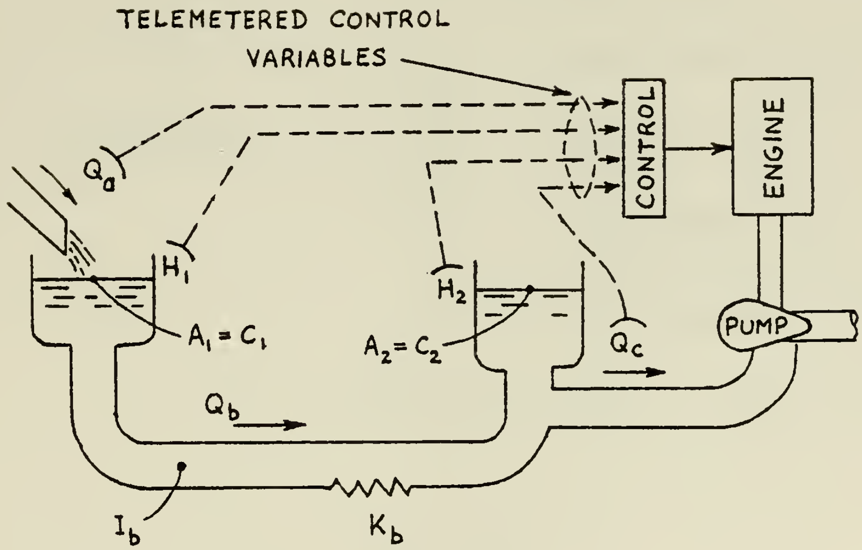


Fig. 5.2 a Sewage Tunnel System

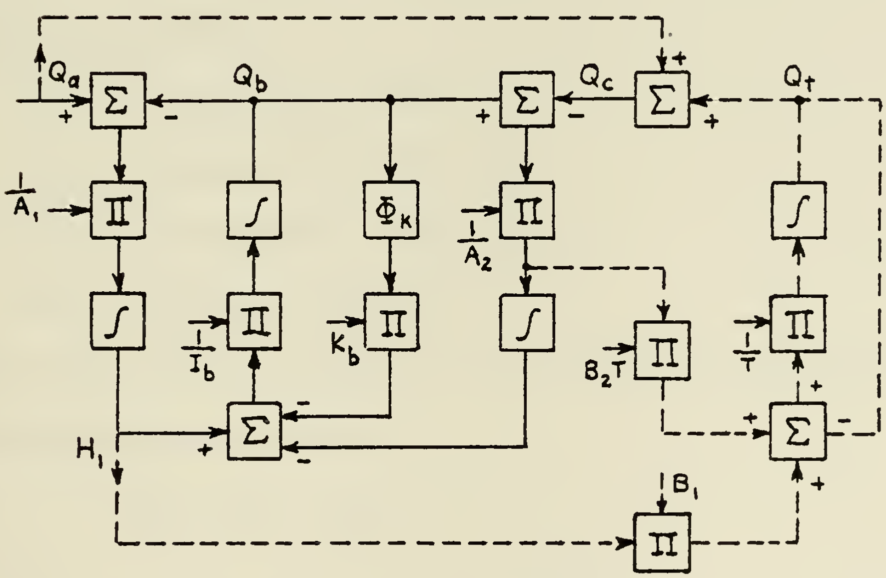


Fig. 5.2 b Computer Block Diagram

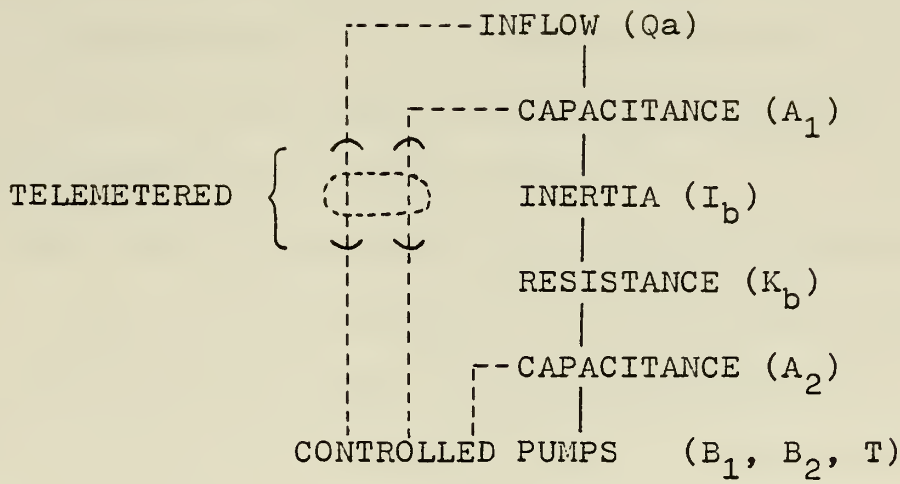


Fig. 5.2c

will occur whenever the flow is disturbed. Such heavy transients cannot be tolerated; thus the pumps at the Deer Island plant are placed under control of the following telemetered variables:

(a) Input flow Qa

(b) Upstream level H_1

(c) Downstream level H_2

(d) Output flow Qc

Using the above variables, the pumps are constrained by the following relations:

$$Qc = Qa + Q_t$$

$$T \frac{d\ Q_t}{dt} + Q_t = B_1\ H_1 + B_2\ T\ \frac{d\ H_2}{dt}$$

where B_1, B_2, and T are controller adjustments.

An ASME publication entitled "The Dynamics and Control of Eulerian Turbomachines"[58] by Paynter provides an in-depth study of the actual control scheme for individual pumping units (inner loop of Fig. 5.2c).

As one can see, the reliability of the four telemetered variables is vital to the operations of the pumping station. In the next section, the reader will be introduced to a sophisticated control panel (even in today's perspective) that monitors the reliability of the flow and level signals.

D. Central Control Panel

As mentioned in section C, flow and level signals are continuously used as part of a control scheme to regulate the speed of the pumps. A highly visible control panel that shows the quality of each flow and level signal is located in the main pumping station control room. From Fig. 5.1, it is clear that the Deer Island plant receives pretreated sewage from the three headworks, namely Ward Street, Columbus Park, and Chelsea Creek. Accordingly, flow and level readings from the three headworks must be closely monitored.

Since the six telemetered control variables must be transmitted from the headworks to the Deer Island plant, transmission reliability cannot be overemphasized. The Deer Island plant uses an elaborate control scheme to monitor the reliability of the transmitted signals. Fig. 5.3

shows the operations of such monitoring system.[59]

At one of the headworks analog signal from the flow instrument (Parshall flume) or level indicator (bubbler tube) is first converted into an air signal, ranging from 3 to 15 lb. pressure. The air signal is in turn used to modulate a carrier frequency; this process is performed in the block labeled modulator. The modulated wave is then sent to the multiplexer for multiplexing before transmitted to the Deer Island plant. Here, the term "multiplexing" refers to the simultaneous transmission of several messages at different frequency bands over a common line. The signals from the headworks to the Deer Island plant are transmitted simultaneously on microwave and leased line.

At the receiving end at Deer Island, the received signal is first recovered by using band-pass filters in the de-multiplexer; the signal is then demodulated to retrieve the original signal. This analog signal is in turn converted to an air signal to be used as part of the pneumatic pump speed control system.

The air signal mentioned above, in addition to being used to regulate pump speeds, is sent back to another set of modulator and multiplexer so that the signal can now be transmitted back to the headworks for comparison.

At the headworks, the returned analog signal is

Deer Island Telemetry System (Currently in use)

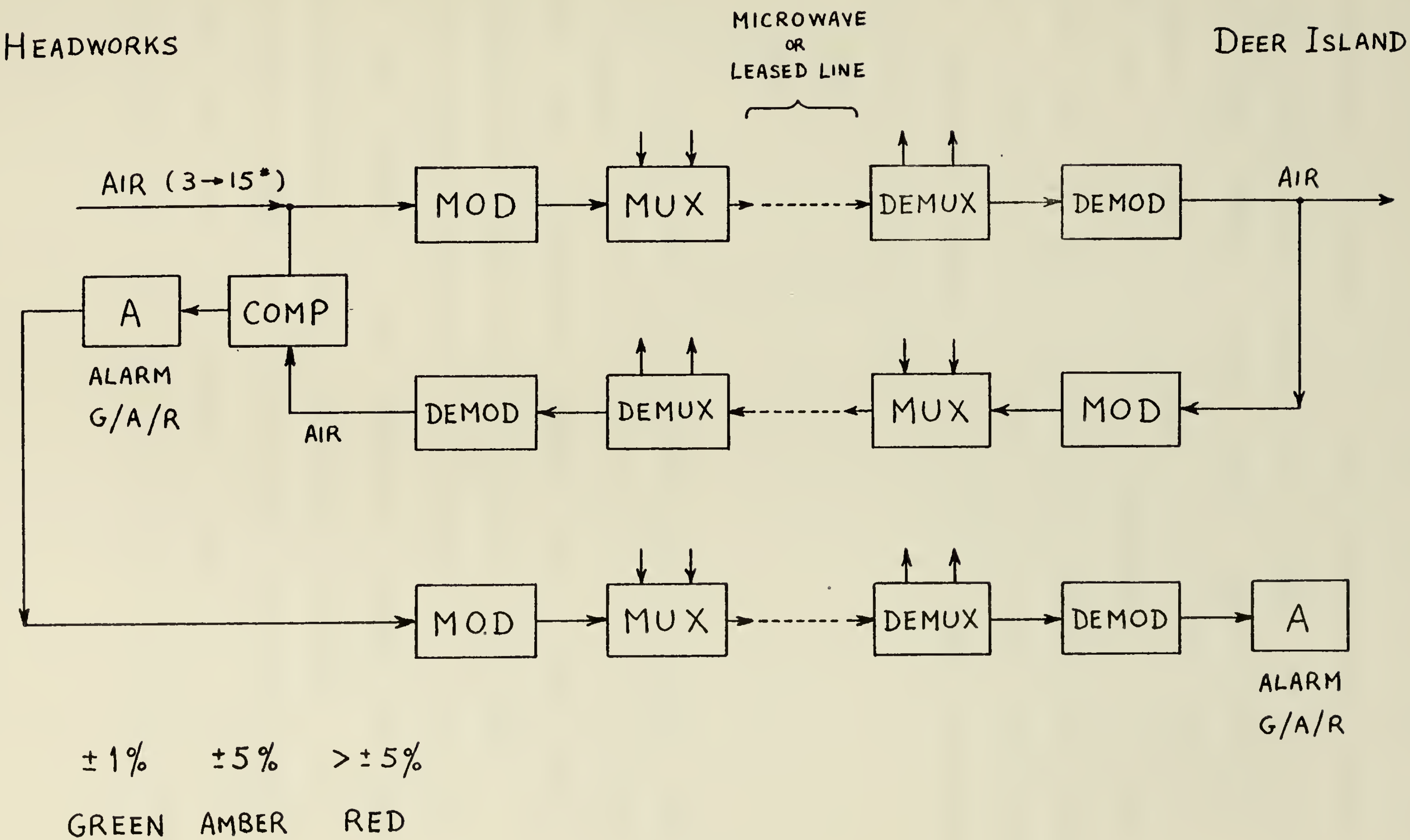


Fig. 5.3

converted back to an air signal. Here, the air signal that has just returned is compared with the original air signal for any differences. The differences, if any, are indicated by a set of GREEN, AMBER, and RED lights. The differences in air signals are next transmitted back to Deer Island so that the control panels at both the headworks and the Deer Island plant have the same indications on their status boards.

Fig. 5.4 shows the status board at the Deer Island plant. The three lights are defined as follow[60] (where tolerances are representative values only):

GREEN --- $< \pm 1\%$

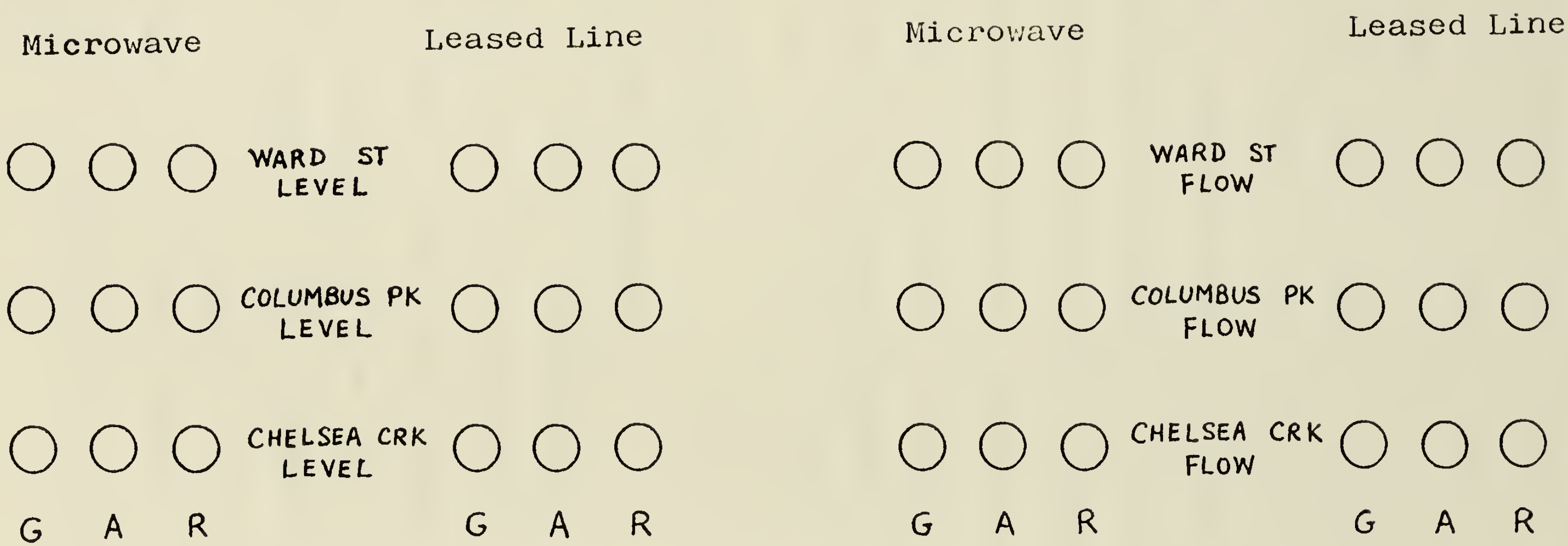
AMBER --- $< \pm 5\%$

RED --- $> \pm 5\%$

If a red light stays on for more than one second, the system is designed to automatically switch to the alternate mode, either from microwave to leased line, or vice versa.

A control panel such as the one used at the Deer Island plant greatly improves the confidence level of the operator. For example, if all lights are green, the operator knows that transmission quality is almost flawless. Even when one light is amber, as was the case during the author's visit, there is no need for urgency or immediate action; it may be the result of a minor problem, such as a faulty module.

Color Coded Status Board



G = Green

A = Amber

R = Red

Fig. 5.4

E. A Need for Newer Design

As in any aging system, replacement parts often present the most insurmountable problem. Analog transmission equipment can still be replaced, although their digital counterparts usually have much higher availability and at considerably lower cost. Pneumatic control devices, on the other hand, are almost vanished from the open market. Replacement parts are extremely difficult to be found. It would be economically infeasible to have each replacement made to its own specifications by a manufacturer.

A digital system has many desirable features that make it a natural choice eventually to replace the analog system. The technique of pulse-code modulation is particularly attractive, as the reader will see why in the next section.

F. Digital Telemetry

1. Pulse-Code Modulation

In digital communications, a multiplexed system often used is the technique of time division-multiplex (TDM) in which the signal messages are organized in subsequent time intervals, usually by sending one sample of each message after the other in a cycle or frame and sending one frame after the other. If each sample in the TDM system is represented in digital form, a pulse-code modulation (PCM) multiplex is obtained.

The author feels that a digital telemetry system using pulse-code modulation deserves careful consideration as a replacement for the aging analog system. Some of the characteristics that are inherent in a digital communication system make the PCM system considerably more desirable as compared to its analog counterpart. In addition, a decreasing cost of implementation due to the technological evolution in solid state digital integrated circuits makes such communication system all the more attractive.

One of the important advantages of a digital system is its relative immunity to noise pickup. Any noise picked up in transmission will ride on top of the pulse and / or produce grass between the pulses. However, as long as a pulse can be distinguished from the noise, there is no problem.[61]

Pulse-code modulation uses a binary digital code. The peak-to-peak value of the signal to be transmitted is divided into a number of discrete steps. The number of bits used in the binary code determines the total number of steps available and the accuracy of the transmitted values. For example, a 16-bit digital word provides 2^{16} or 65,536 steps. Clearly, the smaller the value each step corresponds to, the higher the accuracy. Reference (61) provides a more in-depth explanation on

PCM.

Obviously, a 16-bit word provides considerably more accuracy than, for example, a 3-bit word. However, the transmission of 16-bit signals require a much greater bandwidth. In order to minimize bandwidth while maintaining accuracy, several techniques have been employed. One method involves the use of adaptive data compression, also referred to as "redundancy reduction". In this technique, any sampled data which would not add significant value to the received information is considered redundant and need not be transmitted. As a result, the sampling rate is sharply reduced and so is the bandwidth. More on this subject in the actual implementation of such system.

2. Implementation

Fig. 5.5 shows a block diagram of a digital telemetry system using digital filtering, data compression, and error control coding. The author considers such system a viable choice to replace the aging analog system.[51] As before, flow and level signals will be transmitted from the three headworks to the Deer Island plant, except now that transmission is via digital telemetry with pulse-code modulation.

Even with the new digital system, there is no reason to replace the color coded status light panel.

New Digital Telemetry System

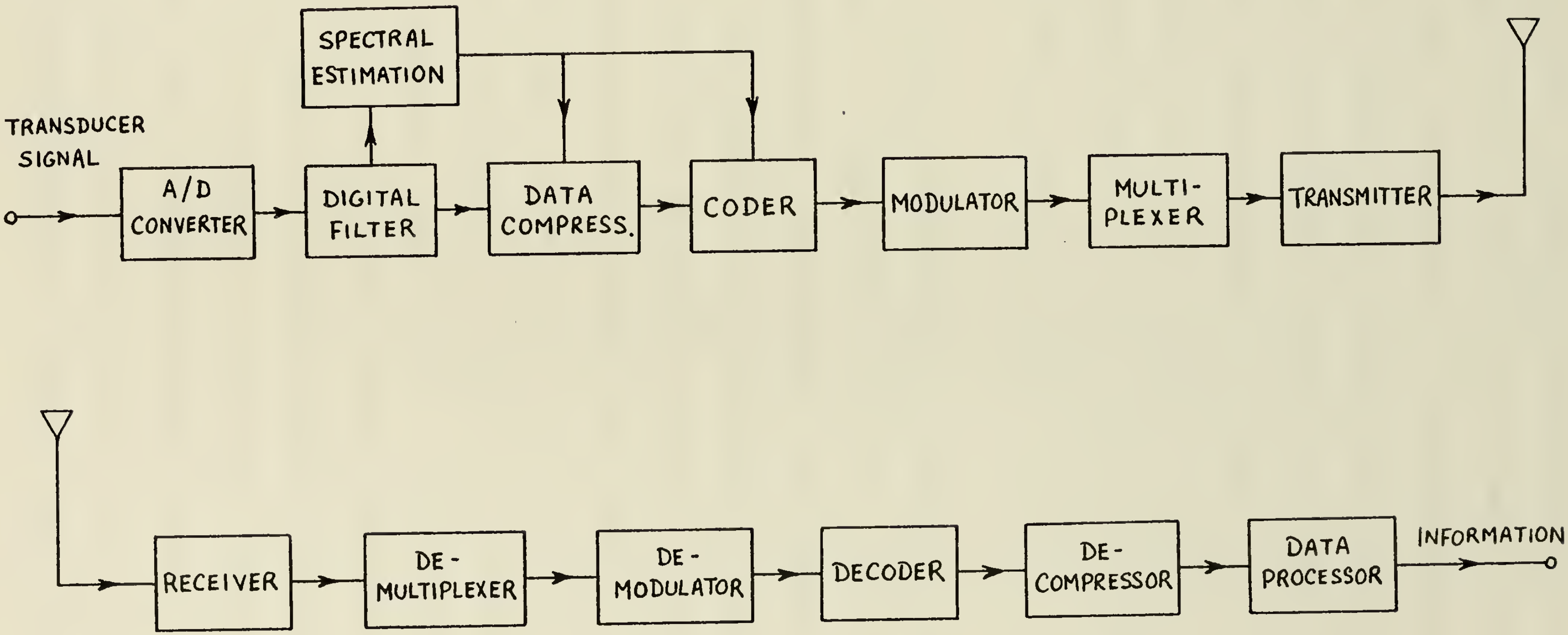


Fig. 5.5

Actually, the status lights are so useful, yet so simple, that the people at Deer Island have become quite fond of them. Thus, the status board will be incorporated into the new digital system, still indicating the differences, if any, between the original signal (no longer an air signal) and the returned signal. In fact, it is practical to simply connect the digital system in parallel with the analog system; then, with the flip of a switch, the operator can have the control system operate on either mode.

In Fig. 5.5 the three blocks: digital filter, data compression, and spectral estimation all perform as a team to regulate the bandwidth of the signals being transmitted. The digital filter (usually a low-pass filter) prefilters the telemetry signals in such a way that the following data compressor can operate in the most efficient way. As mentioned earlier, data compression reduces the amount of data to be transmitted by removing all redundant information. If the remaining important data are reorganized at constant time intervals, the number of sampled points are greatly reduced. By this technique, it has been found possible to reduce the number of sampled points by at least a 5 to 1 ratio, and in some cases by as much as 160 to 1. By reducing the number of samples taken, the pulses

per second of modulation are reduced, and the bandwidth required is decreased.

Spectral estimation is a rather useful method to perform short-time spectral estimation, and thereby adapt the sampling frequency to a more appropriate value.[51] In general, the sampling frequency is kept at the minimum possible value consistent with the signal frequency content in order to reduce the amount of data sampled.

When pulse modulation is used, energy is transmitted only during the pulse sampling intervals. With data compression and spectral estimation, the sampling rate is sharply reduced; therefore, the transmitter duty cycle is quite low, and the overall transmission efficiency is greatly improved.

Error control coding, a technique that uses the coder and decoder, performs a protective measure on the transmitted signals. Before the data entering the communication channel, suitable control data (a given number of bits in an information word) are added by the coder. At the receiving terminal, the same control data are utilized by the decoder to detect (error detection) or correct (error correction) the errors introduced by the communication channel or other disturbances and interferences.[51]

The reader may have noticed that the technique of error control coding performs a function that is similar to that of the status lights, to assess the quality of the transmitted signals. Therefore, if the status lights remain as an integral part of the new system, coding the transmitted signals may not be needed. Of course, one can always use it as an extra redundancy.

G. Insufficient Instrumentation for the Electric-Driven Pump

Currently, there are nine pumps at the Deer Island pumping station. Eight pumps are run by diesel engines, while the ninth pump is a variable speed electric-driven pump powered by on-site generators. With the U.S. diesel engine technology in its present state, it is difficult to expect the industry to come up with new design to replace the aging machines. A few years ago, an electric-driven pump was installed so that its performance can be evaluated for possible future conversion to all electric pumps.[(60)]

If the instrumentation panel for the electric pump is intended to be a prototype for future models, it is a very disappointing one. There are only two or three instruments on the electric pump control panel as compared to almost ten instruments on the diesel instrumentation panel. The information that one can obtain from the electric pump panel

on the overall plant operations is totally insufficient. On the other hand, the diesel instrument panel shows a substantial amount of plant data. Shaft levels and flow rates from all three headworks can be seen clearly in a quick glance. In addition, whether a particular unit is pumping from Chelsea Creek or Ward St. - Columbus Park is shown in plain view on the panel. If an operator, while facing this panel, has to make a sudden decision during a plant upset, he has all of the necessary plant data to act upon.

From the above discussion, it becomes clear that adequate instrumentation similar to that on the diesel control panel must be installed on the electric pump instrumentation panel.

H. Instrumentation for Future Electrical Generators.

At the present, the five on-site generators provide just enough electrical power for the single electric pump and the auxiliaries (sewage treatment, lights, auxiliary pumps, etc.). If more electric-driven pumps are used to replace the aging diesel engines, considerable more electrical power must be needed. This in turn will require more electrical generators to be installed. One proposal involves the installation of several gas turbine generators using methane gas as fuel (methane gas is a byproduct from the decomposition of sewage sludge).

Whether one uses gas turbines or diesel engines for electrical generation, proper control systems and adequate

instrumentation must still be provided. The triply redundant multiplexing system shown in Fig. 4.19 is a good starting point for the design of such control system using redundant instrumentation. As in any thermal power plant, the parameters monitored will be temperature, pressure, flow, and possibly density.

In chapter 6, some particular aspects of instrumentation errors will be examined. Chapter 6 is different from chapter 2 in that chapter 2 dealt with instrumentation errors and uncertainties in a survey format, whereas chapter 6 will discuss some of the methods that one can use to compensate for these errors.

CHAPTER VI

PHYSICAL CONSTRAINTS IMPOSED BY CONSTITUTIVE AND CONSERVATION RELATIONSHIPS: IMPLICATION FOR INSTRUMENTATION REDUNDANCY

A. Introduction

Sometimes instrumentation readings that obviously need to be density or temperature corrected are still being used without either correction. And occasionally, instrument data that clearly violate laws of conservation are still being recorded and interpreted as if they were correct.

The area of physical constraints imposed by constitutive and conservation relationships is another promising area for redundant instrumentation. However, due to lack of time and general unavailability of sufficient literature in this area, the author will only attempt to present a cursory treatment of this subject matter. A few brief examples will be given later in this chapter.

B. Density Correction

1. Computation of Density from Pressure and Temperature

An excellent example to illustrate the fact that some instruments need density correction is the differential pressure (d/p) cell. The d/p cell is used to measure flow rate in either a liquid or gas medium. The differential pressure caused by the velocity increase

is proportional to the square of the flow rate. More specifically, the Bernoulli equation leads to the following flow rate relationship:(62)

$$\dot{V} \text{ (flow rate)} = Q = AV = A\phi\sqrt{\frac{2\Delta P}{\rho}} \qquad (6.1)$$

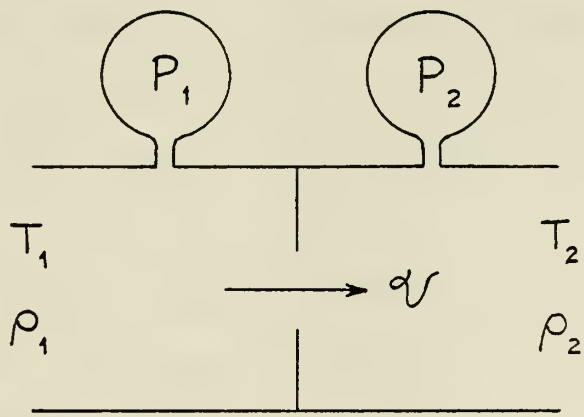


Fig. 6.1 Differential Pressure Cell

From equation 6.1, the following mass flow rate ($\dot{M}$) expression can also be established:

$$Q \sim \sqrt{\frac{\Delta P}{\rho}} \qquad (6.2)$$

$$\dot{M} = \rho_{mean}\, Q \sim \sqrt{\rho_{mean}\, \Delta P} \qquad (6.3)$$

Clearly, P_1 and P_2 can be measured experimentally, as indicated by the pressure taps in Fig. 6.1. If fluid properties are also known, one would only need temperature to compute density. With ΔP, ρ , and A (physical dimensions of orifice plate), the actual

mass flow rate can be easily calculated. Since T_2 is usually not equal to T_1, thus temperature measurement here refers to an average value of T_1 and T_2. More on temperature correction in section C.

2. Actual Measurement of Density

Since T_2 is normally not equal to T_1, ρ_1 will be different from ρ_2. Therefore, both ρ_1 and ρ_2 must be measured to obtain a more correct value for density. Again, here a more correct value could simply be the mean value of ρ_1 and ρ_2. As for density measuring device, one can use the vibration type liquid densitometer described in chapter 2 to measure the two density values.

C. Temperature Correction

As mentioned in the last section, T_1 and T_2 of Fig. 6.1 do not normally share the same value. The following paragraphs will briefly explain this phenomenon.

As the fluid passes through the orifice plate, some of the kinetic energy (no matter how infinitesimal) will be lost due to impingement of the liquid on the plate. This loss in kinetic energy is usually recovered in the form of heat, or a slight increase in temperature on the orifice plate and in the fluid. Therefore T_2 will no longer be the same as T_1.

Since some of the total energy is lost at the orifice

plate, the total energy at point 1 (H_1) must be greater than the total energy at point 2 (H_2), or $\Delta H = H_1 - H_2 > 0$. Since one can assume with reasonable accuracy that $|\Delta H|$ is proportional to the change in internal energy, $|\Delta U|$, it can be concluded that $T_2 - T_1 > 0$. In sum, the situation in Fig. 6.1 can be expressed as follows:[63]

If $\Delta H = H_1 - H_2 > 0$

and $|\Delta H| \sim |\Delta U|$

then $T_2 - T_1 > 0$.

As one can see, in order to get a more representative value for temperature, both T_1 and T_2 must be measured.

D. <u>How to Minimize Data Error in a 2-Phase Region</u>

P_v, P_L, T_v and T_L are measured values

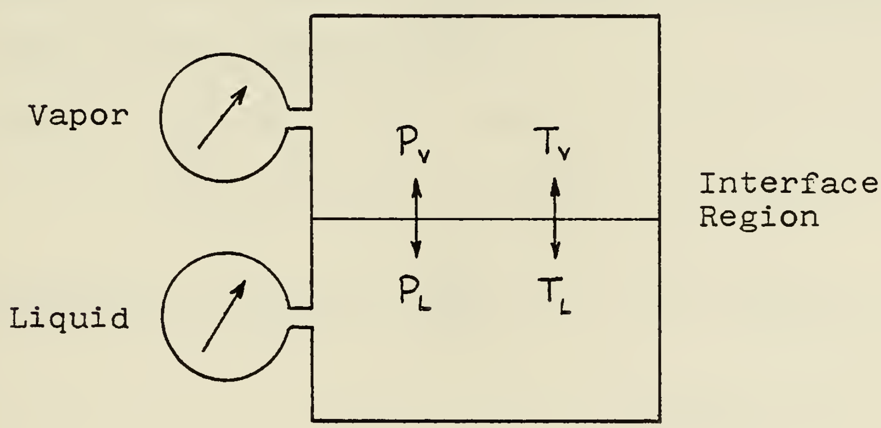


Fig. 6.2 2-Phase Region

In a 2-phase region like that shown in Fig. 6.2, it is often difficult to determine true temperature and pressure. The two procedures described in the following paragraphs should prove to be quite valuable in minimizing data error.[63] The reader should be aware of the fact that the two correlation procedures will not produce identical results. One method will normally produce a more accurate result than the other, as the author will illustrate with a simple example.

<u>Procedure 1</u>

a. Determine $T_{sat}(P_V)$ and $T_{sat}(P_L)$

b. With the four data points: $T_s(P_V)$, $T_s(P_L)$, T_V and T_L, minimize error by the following methodology:

$$\text{let } E(\text{error}) = \sum_{k=1}^{4} (W_k T_k - T)^2$$

where W_k are weight factors based on confidence level of each measurement,

$$\text{then } E = \sum_{k=1}^{4} (W_k^2 T_k^2 - 2 W_k T_k T + T^2)$$

$$= \sum W_k^2 T_k^2 - 2 T \sum W_k T_k + 4 T^2$$

$$\text{Minimizing E yields: } \frac{\partial E}{\partial T} = 0 = -2 \sum W_k T_k + 8 T$$

$$T = \frac{\sum W_k T_k}{4}$$

c. Since this is a saturated state, if T_{sat} is known, P_{sat} can be determined.

Procedure 2

a. Determine P_{sat} (T_v) and P_{sat} (T_L)

b. With P_s (T_v), P_s (T_L), P_v and P_L, repeat part b of procedure 1 to find P_{sat} .

c. If P_{sat} is known, T_{sat} can be easily found.

E. An Example in Minimization of Data Error

For this example, the 2-phase medium is assumed to be saturated vapor and liquid at 400.0°F and 247.26 psi. In the vapor region, due to the insulation effect of a steam blanket, pressure can normally be measured with greater accuracy than temperature; therefore, the following contaminated values of pressure and temperature and their weight factors (W's) are assumed:

P_v = 248.00 psi $\qquad$ T_v = 396.50°F

P_L = 246.20 psi $\qquad$ T_L = 401.50°F

$W (P_v) = 0.5$ $\qquad$ $W (T_v) = 0.1$

$W (P_L) = 0.2$ $\qquad$ $W (T_L) = 0.2$

In order to determine temperature values given pressure measurements, or vice versa (as required by procedures 1 & 2), the method of interpolation is often used if one needs to determine values that lie between tabulated data in a steam table. However, the results obtained from such method are

rarely reproducible. With the advent of digital computer, the technique of analytical curve fitting becomes practical. Moreover, the results are always reproducible.

One can use the following procedure to fit the saturation curve analytically. In this procedure an algebraic expression is determined by performing linear regression on several data points from the saturation curve. Once determined, this algebraic relationship can be used to generate pressure values based on temperature inputs, or vice versa.

If a transformation is performed on the two parameters, pressure (P) and temperature (T), two new variables can now be defined as follow:

$$X = \frac{1}{T} \quad \text{where T is absolute} \qquad (6.4)$$

$$Y = \ln P \qquad (6.5)$$

With the two new variables, one can easily use the following linear laws for curve fitting the saturation line:

$$X = a - b\,Y \qquad (6.6)$$

$$Y = c - d\,X \qquad (6.7)$$

where a, b, c and d are constants that will be determined.

The reader should be aware of the fact that if only two data points are used to fit the saturation curve, identical curves will result by either correlation method (Y vs. X or X vs. Y).

Using five data points from the saturation curve and the technique of linear regression on each of the two equations (6.6 & 6.7), the following values for constants a, b, c and d were determined:

$$a = 3.27 \times 10^{-3}$$

$$b = 2.14 \times 10^{-4}$$

$$c = 15.30$$

$$d = 4{,}676.17$$

Thus equation 6.6 and 6.7 can now be rewritten as follow:

$$\frac{1}{T} = 3.27 \times 10^{-3} - (2.14 \times 10^{-4}) \ln P \qquad (6.8)$$

$$\ln P = 15.30 - \frac{4{,}676.17}{T} \qquad (6.9)$$

With equations 6.8 and 6.9, one can proceed to procedures 1 and 2 in this example.

Procedure 1

a. Using equation 6.8, the following temperature values are found:

$$T_{sat}\ (P_v) = T_s\ (248.00 \text{ psi}) = 400.27^{\circ}F$$

$$T_{sat}\ (P_L) = T_s\ (246.20 \text{ psi}) = 399.63^{\circ}F$$

b. $T_{sat} = \dfrac{\sum W_k\ T_k}{4}$ where $T_k = T_s\ (P_v)$, $T_s\ (P_L)$, T_v and T_L

Using the weight factors assumed earlier, T_{sat} becomes $400.01^{\circ}F$.

c. With $T_{sat} = 400.01^{o}F$, using equation 6.9,

$$P_{sat} = 247.27 \text{ psi.}$$

Procedure 2

a. Using equation 6.9, the following pressure values are determined:

$$P_{sat}\ (T_V) = P_s\ (396.50^{o}F) = 237.55 \text{ psi}$$

$$P_{sat}\ (T_L) = P_s\ (401.50^{o}F) = 251.50 \text{ psi}$$

b. $Psat = \dfrac{\sum W_k\ P_k}{4}$ Where $P_k = P_s\ (T_V),\ P_s\ (T_L)$ P_V and P_L

Using the weight factors assumed earlier, P_{sat} becomes 247.29 psi.

c. With $P_{sat} = 247.29$ psi, using equation 6.8,

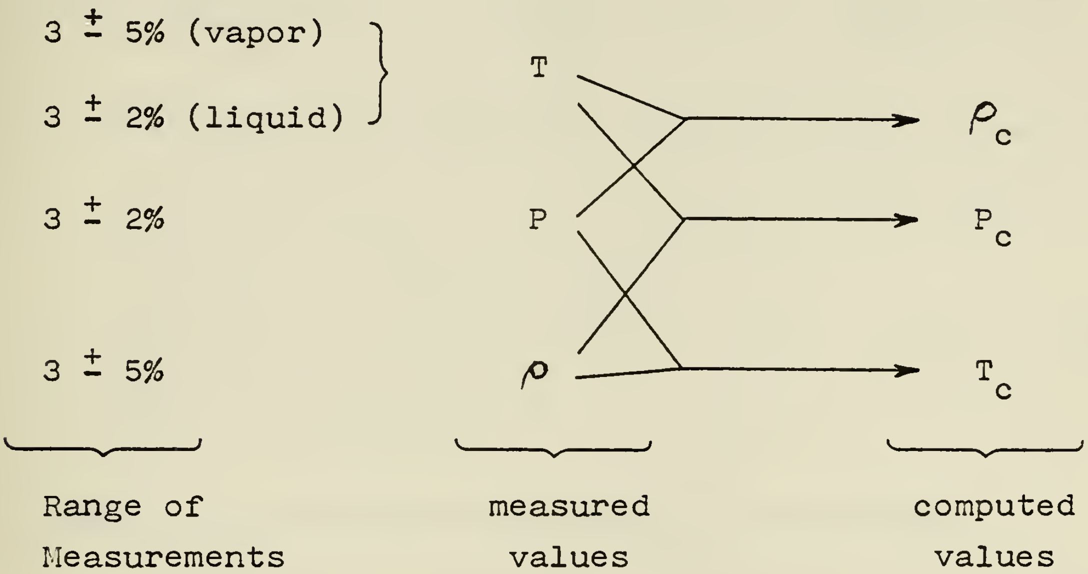
$$T_{sat} = 400.02^{o}F$$

As the reader might have observed, the temperature and pressure values deduced from both correlation procedures are almost identical to the true values. However, one should be aware that such closeness between these two sets of values has been partially due to a coincidence in correlation between the contaminated values and their respective weight factors.

F. Redundant Parameters - T, P, ρ

In this section, the technique of using redundant parameters to minimize data error will be discussed.[63]

As the reader knows, any one of the three parameters, T, P, and ρ can be considered as redundant, and any two of the three parameters can be used to compute the value of the third redundant parameter. Furthermore, the computed value can then be used to check on the accuracy of the actual measurement. This procedure is illustrated as follows:



(The range of measurements is based on readings from three redundant instruments).

A general procedure to minimize measurement errors is described as follows:

1. Measure T_m, P_m, and ρ_m experimentally
2. Compute T_c, P_c, and ρ_c and use these as the adopted values for $T_{adopted}$, $P_{adopted}$, and $\rho_{adopted}$
3. Formulate the following least squares error expression:

Let E (error) $= W_p (P_m - P_a)^2 + W_T (T_m - T_a)^2$
$+ W_\rho (\rho_m - \rho_a (T_a, P_a))^2$

where W_p, W_T, and W_ρ are weight factors based on standard deviations of instrument readings.

4. Minimize error by the following equations:

$$\frac{\partial E}{\partial P_a} = 0; \qquad \frac{\partial E}{\partial T_a} = 0; \qquad \frac{\partial E}{\partial \rho_a} = 0.$$

However, the expressions found for P_a, T_a, and ρ_a must be subject to the constraint of the state equation, $\phi (P_a, T_a, \rho_a) = 0$

5. Must distribute corrections so as to reduce errors based on constraint.

G. The Role of Conservation Laws in Measurements

All engineers know that the laws of conservation, such as mass conservation, momentum conservation, and energy conservation can never be violated. However, instrument readings that clearly violate these laws are often still being recorded.

The following three brief examples exemplify some typical situations in which the instrument readings might be left in error if the specific relationships are violated:

1. Conservation of Mass

$$\dot{M} = \sum \text{Flow}_{in} - \sum \text{Flow}_{out} \qquad (6.10)$$

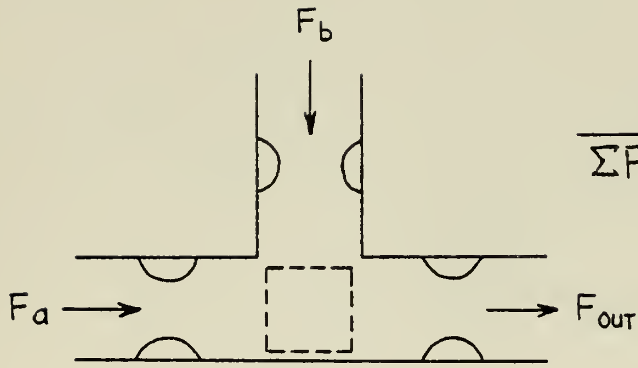


Fig. 6.3 Flow Measurement

In Figure 6.3 the sum of F_a and F_b at any time t is not necessary equal to F_{out}. However, if one takes the time-averaged measurements of the three flows, within the accuracy of the instruments, the following relationship should always hold:

$$\overline{\Sigma F_a}^T + \overline{\Sigma F_b}^T \equiv \overline{\Sigma F_{out}}^T \qquad (6.11)$$

If the above relationship is violated, then the errors must be distributed accordingly among the three flowmeters. Reference (64) provides an in-depth study of many of the commonly found flowmeters.

2. <u>Conservation of Momentum</u>

$$\dot{G} = \Sigma \, Force_{in} - \Sigma \, Force_{out} \qquad (6.12)$$

For any flow in the direction indicated as shown

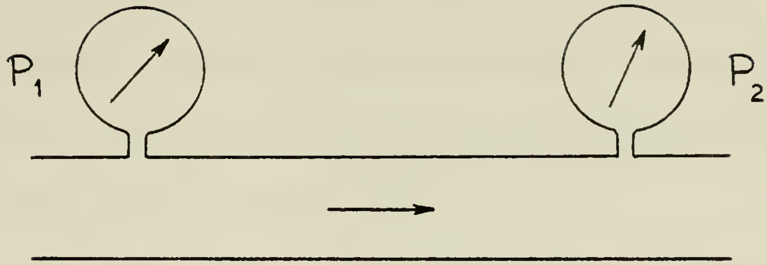


Fig. 6.4 Pressure Measurement

in Fig. 6.4, P_1 must be greater than P_2 . If the pressure sensors indicate differently, one or both instruments must be in error and need to be adjusted.

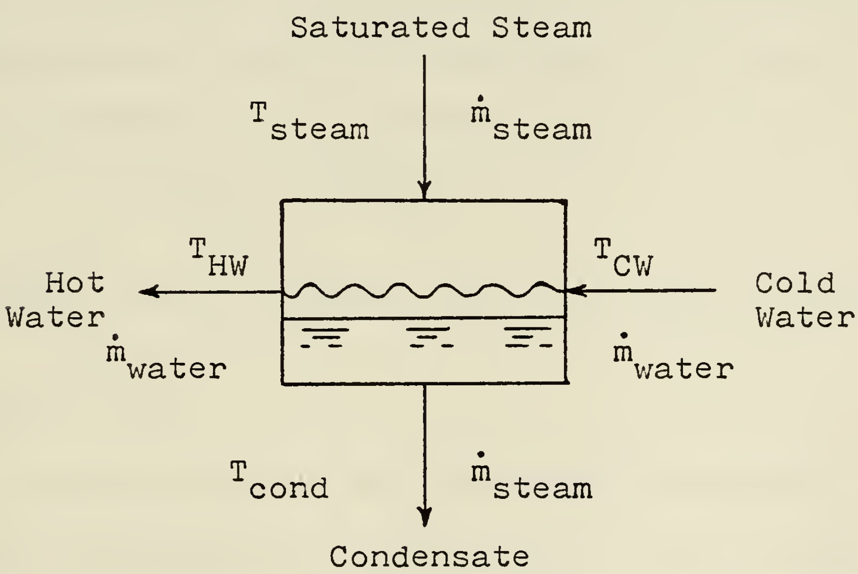


Fig. 6.5 A Simple Heat-Exchanger

3. Laws of Thermodynamics

Example 3 as illustrated in Fig. 6.5 is a much more complex case. Careful energy and heat balance calculations must be performed before any violation of thermodynamic laws can be shown.[65]

By the first law of thermodynamics, the following expression is true:

$$\dot{m}_{steam}\,(h_{steam} - h_{cond}) = \dot{m}_{water}\,(h_{HW} - h_{CW}) \qquad (6.13)$$

Clearly, specific data such as mass flow rates ($\dot{m}$'s) and enthalpies (h's) are needed for the energy balance calculations before any given instrument can be isolated as faulty.

In addition, if one considers the second law of thermodynamics, then the following relationship in terms of entropy (s) is always true:

$$\sum s_{out} > \sum s_{in} \qquad (6.14)$$

$$\left|\dot{m}_{steam}\right| s_{cond} + \left|\dot{m}_{water}\right| s_{HW} > \left|\dot{m}_{steam}\right| s_{steam} + \left|\dot{m}_{water}\right| s_{CW} \qquad (6.15)$$

One must realize that although the heat exchange between the system and surroundings can be assumed to be zero, an increase in entropy is to be expected, because the process is basically irreversible.

It should be clear to the reader that concern for

the physical constraints imposed by laws of nature is indeed an important aspect of redundant instrumentation. Only occasionally are attempts made by engineers to distribute instrument errors consistently within a real-time system. Much more work remains to be explored in this area.

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APPENDIX I

VARIOUS TEMPERATURE AND PRESSURE SENSORS

A. Platinum RTDs

Platinum, being a noble metal, is used almost exclusively for precision resistance thermometers. Platinum resists corrosion and chemical attack under most environments, so it is fairly stable. In addition, it is easily workable and can be drawn into fine wires. Moreover, platinum has a high melting point (1772°C) and in fact, shows little volatilization below 1000°C. All this is evidenced by a linear and stable resistance-temperature (R - T) relationship that characterizes the platinum sensor over a wide range of temperatures. An early example of a platinum RTD from the National Bureau of Standards is shown in Fig. 1.

B. Carbon Resistance Thermometry

1. Advantages and Disadvantages

The carbon resistance thermometer has a number of desirable qualities as a secondary thermometer, including high thermometric sensitivity, small physical size, fast response, ease of installation, and very low cost. The major drawback, however, is that there is no well-defined theoretical (or empirical) resistance-temperature relation for use in extrapolation or interpolation. As a result, a somewhat laborious

calibration procedure is usually required throughout the temperature range of interest.

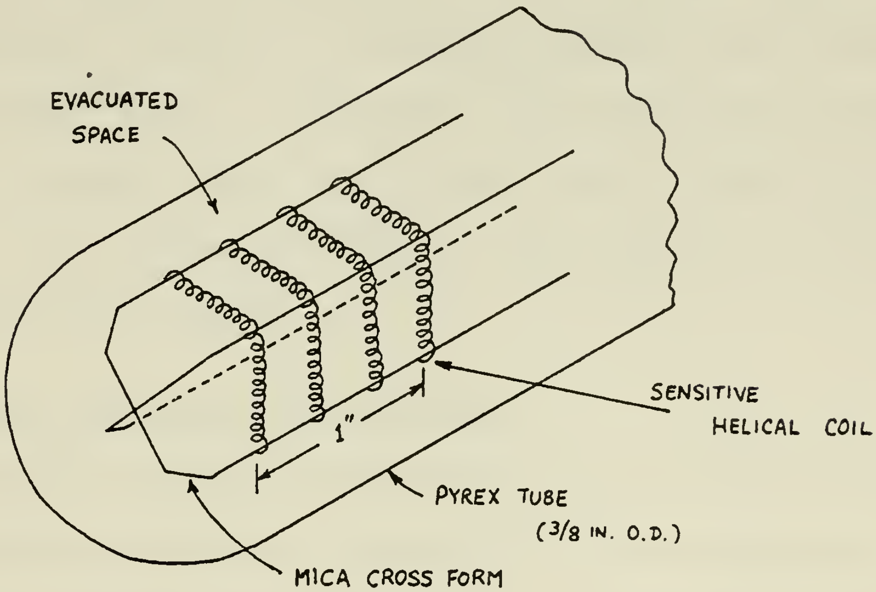

Fig. 1 Construction detail of a platinum resistance thermometer tip

2. Effects of Magnetic Field

Experimental data showed that the magnetic field effect is strongly dependent on temperature and becomes substantially larger as the temperature is reduced. It is interesting to note that the effect is independent of whether the magnetic field is applied parallel or perpendicular to the resistor axis.

In a time varying magnetic field, the effect may be considerably more severe. Eddy currents may be introduced in the leads which, by Joule heating, warm

the thermometer above the temperature of the surroundings. This is especially true if the leads have a solder coating. The solder alloy may become superconducting, but with a transition spread over a wide temperature range. Therefore, the resistance of the solder coating can be quite small over a considerable range of the magnetic field and may result in a large dissipation of power.

C. Germanium Resistance Thermometry

Besides carbon thermometry, a second major category of semiconductor resistance thermometry is the germanium resistance thermometer. The germanium thermometers share some of the inherent problems with the carbon thermometers, such as self-heating errors, but it does have its own unique characteristics.

Germanium, in its intrinsic form, is a rather poor resistance measuring device in the cryogenic region because its dR/dT is so large, and its resistance at a temperature approaching absolute zero (0 Kelvin) is so great. However, solid state physicists have utilized the idea of mixing two or more elements to form an alloy which would reduce both the near zero Kelvin resistance and the sensitivity to dR/dT. Impurities are commonly introduced into germanium in the form of pure elements. Some of these elements include phosphorus, gallium, and arsenic.

D. Noble Metal Thermocouples

1. Environmental Stability

Darling and Selman[66] conducted a series of experiments in which the environmental stability of noble metal thermocouples was investigated in a systematic manner. In particular, they studied the compatibility of the platinum metals with oxides such as alumina, magnesia, zirconia, and silica. Their experimental results indicated that the reactions between platinum and the refractory oxides are controlled by the affinity of platinum for the metal released on decomposition, by the surface area of the reacting substances, and by the rate at which oxygen and metal vapors can be removed from the reaction zone.

2. Chemical Reaction

Metal oxide decomposition involves a process of dissociation which yields both metal and oxygen in gaseous form. In the case of aluminium, the reaction can be described as follows:

$$2/3\ Al_2O_3 \longrightarrow 4/3\ Al + O_2$$

Alumina dissociates, oxygen is evolved, and platinum extracts metal from the refractory to form dilute alloys. Experimental data confirmed that platinum has a much higher affinity for zirconia and alumina than for magnesia. One proposed postulate to explain this

phenomenon is that the magnesium-magnesia dissociation pressure is higher than the vapor pressure of platinum, whereas the metallic vapor pressures of zirconium and aluminum lie well below that of platinum. Most of the reaction processes occur through a vapor phase and proceed rapidly only when oxygen is continuously removed from the reaction zone.

E. Variable Resistance Pressure Transducers

A diagram that illustrates the basic operating principle of the variable resistance pressure transducer is shown in Fig. 2. The pressure to be measured is applied to the force collector (capsule) which, through a linkage rod, moves a sliding contact (wiper) across the electrical

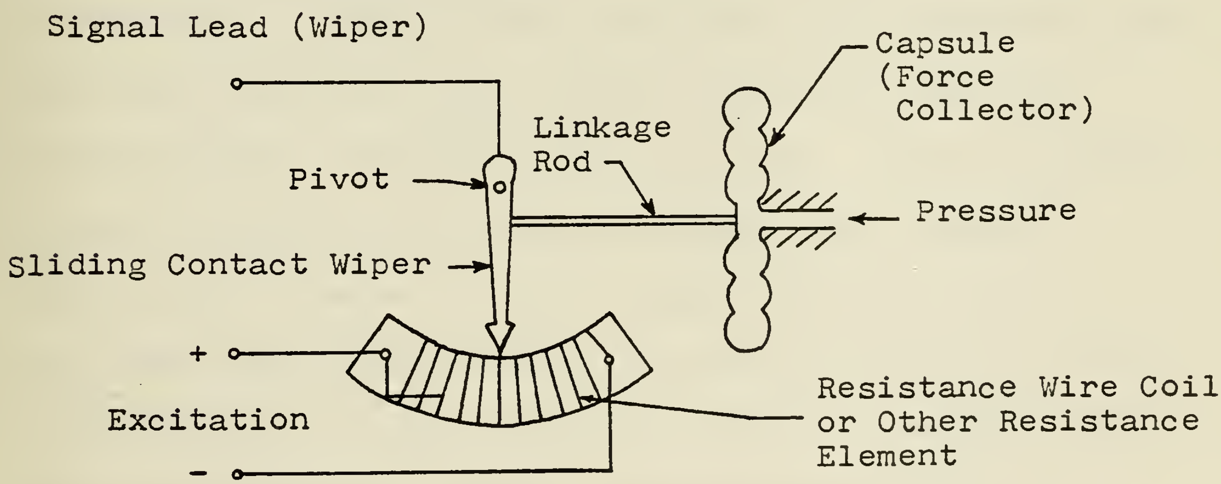

Fig. 2 Potentiometric Pressure Transducer Schematic

resistance wire windings. This action in turn produces a resistance change between the wiper signal lead and an excitation lead. Therefore, with the wire excited as shown, a voltage change between the wiper and excitation lead can be developed. This change is linear for most transducer designs. A nominal full-scale deflection for such a system is about two percent of the capsule diameter. In order to obtain large deflections, two or more capsules may be cascaded so as to add the deflections of each.

Besides using a capsule, a bourdon tube can also be used as a force collector. The bourdon tube is a spring alloy tube with an elliptical cross section which is closed at one end and is shaped in a curved or twisted configuration. When pressure is admitted into the tube, the difference in area exposed to the pressure causes the curved tube to tend to straighten. Thus, if the open end is held securely, the closed end will move. The bourdon tubes can generally provide greater deflections than capsules. Many transducer designs incorporate the spiral, helical, and C-shaped bourdon tubes because of their large deflections which in some cases permit transducers to be built without an extra linkage between the tube and the resistance element. This minimizes vibration, friction, and backlash problems.

The resistance element of a potentiometric transducer most frequently consists of electrical wire wound on a

mandrel. The wire is generally a platinum alloy on the order of 0.001 - in diameter, whereas the mandrel is an insulating material such as ceramic or phenolic.

F. Strain-Gage Pressure Transducers

Most strain-gage pressure transducers have a configuration like that shown in Fig. 3. This is the so-called bonded strain-gage technique that consists of four active strain-gage elements bonded to the elastic element (cantilever). When a force is applied as shown, the two top strain gages (1 and 2) are in tension and increase in

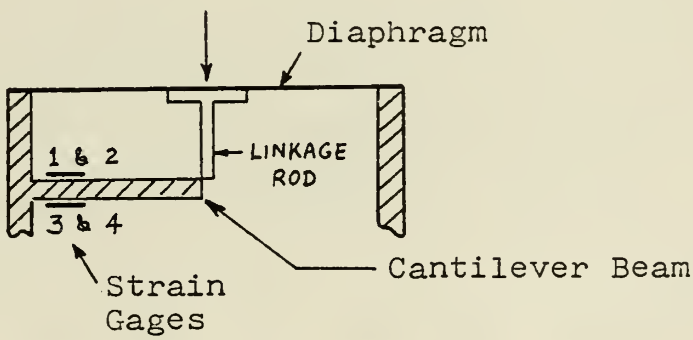

Fig. 3 Bonded Strain-Gage Cantilever Transducer

resistance while the bottom elements (3 and 4) are in compression and decrease in resistance. By connecting the two elements whose resistance increases (1 and 2) and the two whose resistance decreases (3 and 4) in diagonally opposite arms of a bridge as shown in Fig. 4, maximum output is obtained.

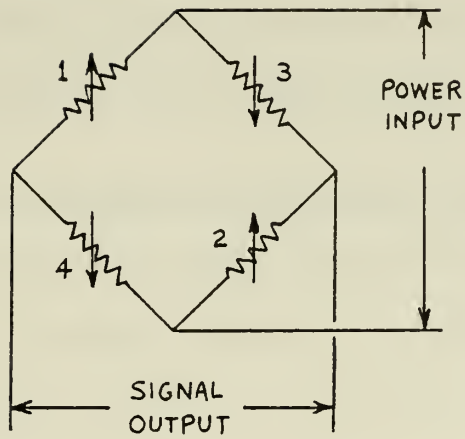

Fig. 4 Bonded Strain-Gage
Electrical Connection

In recent years, however, with the advent of semiconductor technology, it has become advantageous to manufacture strain gages from semiconductor materials. The semiconductor gages have a gage factor that is approximately 75 times greater than that of a wire gage. Gage factor is defined as the ratio of normalized resistance change to unit change of strain. With a substantially higher gage factor, manufacturers are now able to develop smaller and extremely stiff pressure sensors, allowing high frequency dynamic measurements to be made more conveniently and more accurately.

Besides the more familiar bonded metal wire strain-gage

configuration, there are several other types of strain-gages; some of the examples are gaged diaphragm pressure transducers, cantilever-type transducers, pressure vessel transducers, and unbonded strain-gage pressure transducers.

G. Diaphragm-Type Variable Reluctance Transducers

A variable reluctance pressure transducer commonly used in the power industry employs a diaphragm as the elastic element and is shown in simplified form in Fig. 5.

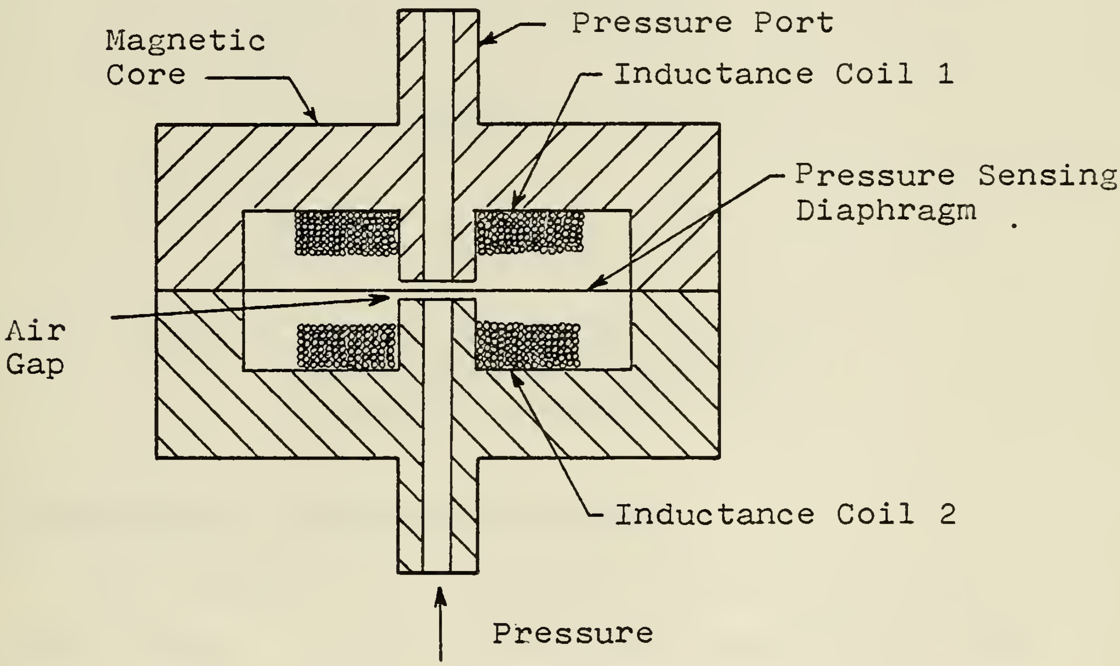

Fig. 5 Diaphragm-Type Variable Reluctance Pressure Transducer

A diaphragm of magnetic material, supported between two inductance core assemblies, completes a magnetic circuit with the cores. The diaphragm deflects when a differential

pressure is applied to the pressure ports. This increases the air gap in the magnetic flux path of one core while decreasing the gap in the other; therefore, the reluctance of each flux path is altered. The overall effect is a decrease in inductance of one of the wire wound coils and an increase in the other. A half-bridge, two-active-arm device is formed if the two coils are connected as shown in Fig. 6.

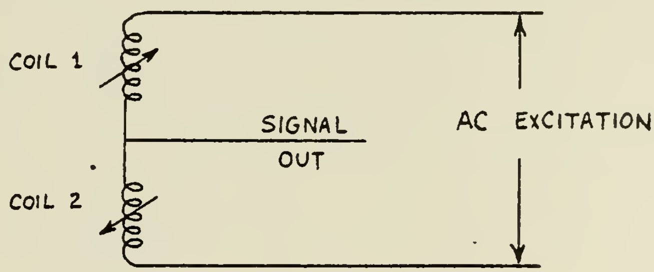

Fig. 6 Electrical Configuration for Variable Reluctance Pressure Transducer

H. Piezoelectric Pressure Transducers

Most piezoelectric elements will reach a Curie point when heated. At this Curie point temperature, the crystalline structure changes, polarization is lost, and hence the piezoelectric effect is destroyed. Quartz has a Curie point of approximately 1000^{o}F, whereas this temperature for some of the ceramic elements is as low as 250^{o}F. In addition, quartz has a negligible pyroelectric

effect which is defined as the changes in output that are proportional to the change in temperature experienced by the crystal. It is for these two reasons mentioned above that the quartz element is particularly more applicable in areas of temperature change and high operating temperatures.

Ceramic elements, on the other hand, have a charge density that is generally 10 to 100 times greater than that for quartz; as a result, ceramic elements are often used in situations where low pressures are measured.

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