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MEMORANDUM REPORT NO. 2266

EFFECTS OF REDUNDANCY ON SURVIVAL OF
CRITICAL AVIONICS EQUIPMENT

by

Keats A. Pullen

January 1973

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USA BALLISTIC RESEARCH LABORATORIES
ABERDEEN PROVING GROUND, MARYLAND

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B A L L I S T I C R E S E A R C H L A B O R A T O R I E S

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JANUARY 1973

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CRITICAL AVIONICS EQUIPMENT

Keats A. Pullen

Vulnerability Laboratory

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RDT&E Project No. 1T662708.A068

A B E R D E E N P R O V I N G G R O U N D , M A R Y L A N D

B A L L I S T I C R E S E A R C H L A B O R A T O R I E S

MEMORANDUM REPORT NO. 2266

KAPullen/bg
Aberdeen Proving Ground, Md.
January 1973

EFFECTS OF REDUNDANCY ON SURVIVAL OF
CRITICAL AVIONICS EQUIPMENT

ABSTRACT

The design of simple circuits capable of keeping communications equipment in operation under conditions of failure of vital sections or sub-units of a system are described. Analyses are included which indicate possible routes for improvement of equipment survivability in a battlefield-type environment.

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I. INTRODUCTION

The survivability of any system, be it electronic, mechanical, hydraulic, chemical or other, in a military environment, is measured in terms of its ability to continue to function in the face of destructive damage to vital parts. In a system whose configuration consists of a set of basic components operating "in series", the failure of any one vital link can cause loss of function. This condition is often described by the truism that "a chain is no stronger than its weakest link." For this reason, it is vital that all systems be studied first to establish a "priority" for each unit or subsection, this priority to be a measure of the degrees of dependence which must be placed on the given section or system in accomplishing a given mission. Typically, with avionics or vehicle electronics, alternatives are available for many functions performed by electronics, albeit the alternatives may be substantially less satisfactory than the basic equipment. (For example, under visual flight rules, map navigation may be used instead of variable omni range (VOR) navigation which is vital under conditions of instrument flying rules.)

Because of the nature of electronics, the impact of a projectile or fragments on it will usually either produce an immediate (less than one second) K-kill for the instrument or the unit will survive. Similarly, a K-kill in an avionics package normally will not lead to an aircraft K-kill, but it may lead to a mission abort. Whether or not an abort becomes necessary depends upon the specific mission and the mission environmental conditions. Different missions have different levels of dependency on electronics and navigational equipment. (Under rare conditions, a K-kill on an autopilot might render an aircraft uncontrollable and cause a crash. Usually, however, a pilot will be able to wrest control from the autopilot and complete his missions if only the autopilot itself has been damaged.)

In vulnerability parlance, it is common to speak of the vulnerable area, for a given impact condition, and typically the ratio of the vulnerable area to the total area is classed as the probability of kill

given a hit in that area. Customarily this ratio has been called $P_{K/H}$ in discussing the physical vulnerability of ordinary targets.

With electronics the kill of a component is normally of the K-class; that is, an immediate failure results (less than one second). In this sense, a vulnerability ratio may be defined which is essentially the same as the corresponding kill probability. In terms of equations, this may be stated as:

$$V = P_{K/H}; \quad S = 1-V = \frac{A_p - A_v}{A_p} \quad (1)$$

where,

V is the vulnerability ratio or vulnerability

$P_{K/H}$ is the probability of a kill given a hit

A_v is the vulnerable area

A_p is the total projected area.

As is noted later, the sum of the vulnerability ratio (or vulnerability) and the survivability ratio (or survivability) is unity. Where reduction of vulnerability through redundancy is an important consideration, the use of survivability as defined above is vital.

II. KINDS OF REDUNDANCY

As a practical matter, improvement of survivability is conveniently achieved by use of parallel processing paths thereby making the target multiply vulnerable. In aircraft, a multiplicity of engines is commonly used, multiple control linkages, multiple hydraulic systems, etc. Even with automobiles, redundancy in braking systems has helped reduce the number of brake-failure accidents in recent years.

Electrical failures are not common with automobiles, and are seldom serious, although on occasion batteries and alternators do fail. An electrical failure on a car normally leads to a stalled vehicle, whereas electrical failure in an aircraft might lead to the crash of the aircraft. (Dual magnetos are used on reciprocating aircraft engines since engine failure due to loss of electrical power cannot be tolerated.)

Electrical power systems are very costly weight-wise since they require both heavy batteries and heavy generators. As a result, any provision of redundancy in the electrical supply system can introduce difficult and costly problems.

Development of a redundancy plan for electrical systems in aircraft requires first an examination of the importance of different electrical functions under different operating conditions. A possible classification by function follows:

- a. Use for radio communication and navigation
- b. Use for lights and lighting and for de-icing
- c. Use for radar
- d. Use for autopilot-type functions
- e. Use for heating, ventilating, and air conditioning
- f. Use for engine starting.

The above list, which probably is not all-inclusive, appears to be roughly in descending order of importance to the airborne pilot. Curiously, the power requirements in this list appear to be in roughly ascending order. (The priority positions of some elements like the radar depend on the mission.)

The above considerations indicate that some of the more critical equipments probably use the least power, and this would strongly suggest that provision of one or more redundant sources of power for specialized pieces of equipment could be of vital importance.

There are several alternative approaches to achieving power redundancy for the communications and navigation equipment. These include:

- a. Additional small generator on an alternate engine (or inclusion of a small supplemental wind-driven generator as on the F8U, F-100 and other fixed wing aircraft).
- b. Special low-capacity storage battery floating on the line which will take over in case of failure of main power system. This battery could be armored.
- c. Provision of emergency reserve supplies in individual

equipments as an alternate or supplement to (b.).

How these functions may be achieved in cost and weight-effective ways is discussed in a later section.

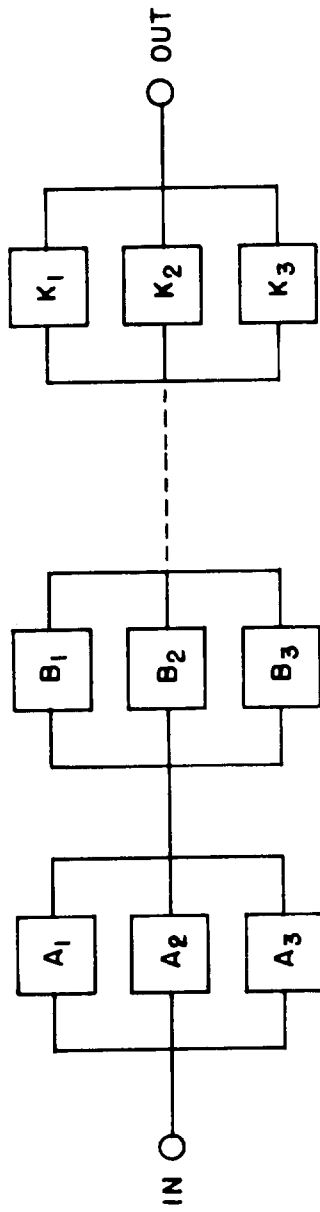
There are basically two kinds of redundancy which in theory can be developed within systems; namely, series redundancy and parallel redundancy. With series, groups of equivalent parallel subsections are connected in series to provide a complete system, whereas with the parallel, individual series chains of subsystems are connected in parallel, Figure 1. For practical purposes, the latter system has been used almost exclusively in aircraft for reasons which will become apparent in later paragraphs.

The paralleling of complete sets has generally been used for reasons of convenience even though the redundancy advantage achieved with it is rather limited. With it, two different units serving the same function can be placed at different locations and advantage taken of dispersion effects. This advantage may be highly important where damage is closely localized.

The advantage of series, or subsystem, redundancy is that if switching problems can be solved and the redundant units are dispersed in location, a substantially higher degree of survivability should be available from a specific total number of elements. The problem of protecting the interties between the subsystems of course must be solved as well.

In the past, series redundancy could only be achieved by co-locating the paralleled subsystems of the two or more sets. This could lead to multiple failures, and typically might destroy the advantages otherwise available. Solid-state developments of the past ten years have modified conditions to the point that at least a limited amount of series redundancy can today be used. Stripline cable, as it is sometimes called, can be used for a limited number of interties, and silicon diode steering circuits can be used to provide the required switching action to assure operation, steering, and isolation of the interties as required. Some of the criteria which must be satisfied by the intertie circuits are discussed in a later section.

(a) SERIES REDUNDANCY - PARALLEL GROUP CONNECTED IN SERIES.



(b) PARALLEL REDUNDANCY - INDIVIDUAL ELEMENT CHAINS CONNECTED IN PARALLEL.

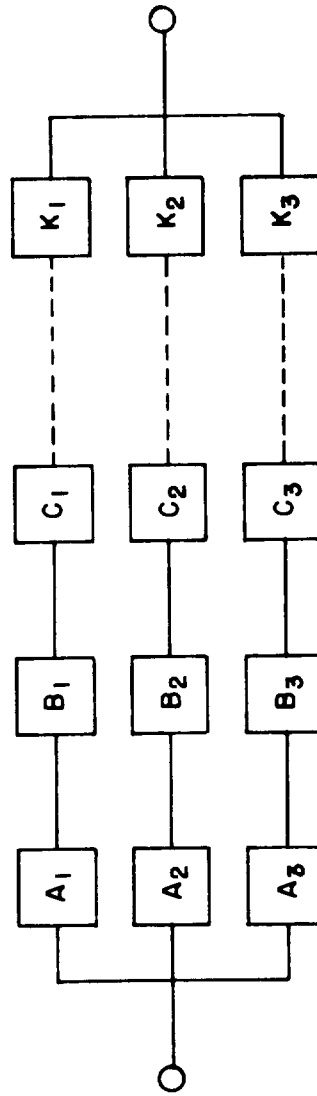


FIGURE 1. REDUNDANCY CONFIGURATIONS

III. POWER SUPPLY REDUNDANCY

With typical helicopters like the light observation helicopter, there are normally two locations where the primary battery may be located: the front bulge ahead of the pilot's seat and adjacent to the engine. The electrical generator itself is located near the main drive shaft of the engine. The battery is used to start the engine when the vehicle is on the ground and to power lights and avionics when airborne. The battery is used for operating gauges and function indicators for the pilots as well.

It is clearly evident that reliability of dc power is of considerable concern for the pilot of an aircraft, and for that reason a maximum of survivability of certain parts of the electrical system is a critical consideration in system design. This means that provision of at least a limited amount of power supply and intertie redundancy is vital.

That this is essential is further indicated by the fact that a limited amount of redundancy presently exists in typical helicopter electrical systems. Normally at least two separate alternators are coupled to the main transmission on a helicopter, and each alternator has its own independent power converter for developing dc power for storage in a battery or for direct use. In addition, a converter may be available for transforming battery power into ac power.

Nonetheless, complete loss of electrical power apparently does occur on occasion in helicopters on troop-support missions. Such a loss of power naturally makes navigation somewhat difficult, and it makes communication with both ground forces and base of operations difficult. The question then becomes, "Can a reserve power supply and emergency interties be added in a cost-space-weight-effective way to provide additional protection against failure?"

The answer to the power-supply part of the above question appears to be a definitive "YES". Depending on the kind of aircraft and the mission, between a half-hour and possibly as much as ten hours of emergency service may be required. The typical battery used for home

entertainment radio receivers is a nine-volt unit having capacity between 100 and 300 milliampere hours, depending on the load. Such a battery should be able to deliver a half-watt of power continuously for an hour in such a service. As a result, these batteries should be more than adequate for communication receivers.

The fact that avionics equipment is normally designed for 24 to 28 volt service means that at least two of these batteries should be used in series connection. Examination of the fundamental design equations for use with transistors shows quickly that voltages as high as 24 volts may be typically an order-of-magnitude higher than is necessary for collector supplies, although only about 2.5 to 3 times the required base supply voltage. Nonetheless, with existing equipment designs, the emergency supply would be required to be somewhat less than the minimum voltage reached by the battery-generator system aboard the helicopter or plane.

The emergency supply would have to satisfy several requirements to be useful. First, it would have to be in "standby-ready" at all times when the vehicle was in use. In fact, it would be advantageous for it to be "trickle-charged" under these conditions, and be automatically switched "on" when a failure of supply occurred. Further, it should be mounted either within the avionics package (preferred), or immediately adjacent to it. It should fit in the "interstices" and have a maximum weight of a few ounces.

The entire control electronics for the unit, other than the battery, can be placed in a container or package no larger than a TO-46 transistor package (either metal or plastic) or possibly in the TO-18 or TO-92 size. Since the weight of one of these packages is at most a few grams, and the volume less than 100 cubic millimeters, there is obviously no problem in control unit weight or size. In fact, a control unit of this size should be able to control power levels up to five watts with no more than 100 milliwatts dissipated within the control unit itself. A similar unit in a TO-3 style case could be used for higher-power circuits.

Simplicity and reliability are the key requirements in addition to minimum weight and volume for a control unit of the kind described. A suitable circuit for the required function is shown in Figure 2a. A modification to provide a warning light to show that emergency power is in use is shown in Figure 2b. Other alternative designs to minimize consumption of emergency power can readily be developed. In the circuit shown, resistance values are adjusted so that the transistor is cut off when input power is present, but the transistor and the light-emitting-diode (LED) are both on when only the emergency supply is on and the radio is running. The main on-off switch with this arrangement would have to turn on both the avionics equipment and the emergency battery, Figure 2c. System test is accomplished by switching off the appropriate circuit breaker to see if the unit continues to function and the LED lights up.

IV. EMERGENCY SUPPLY TESTS

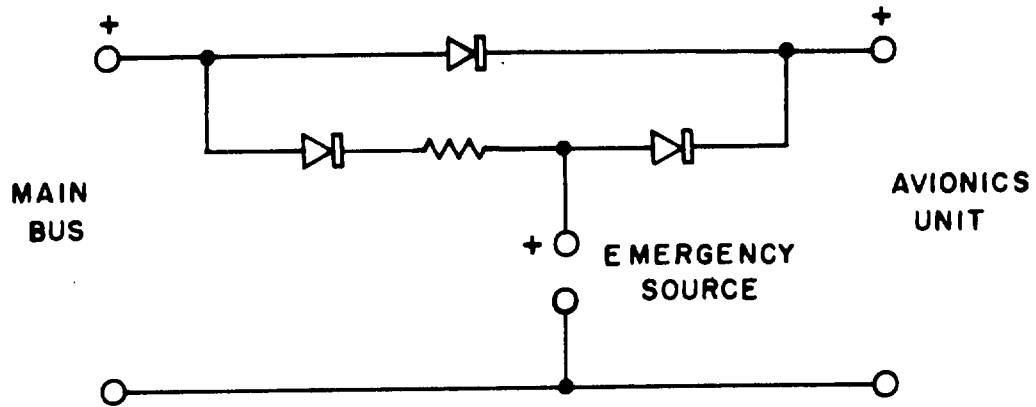
Tests have been made based on the circuit configuration of Figure 2a. A group of "C" cells, seven in number, was wired to provide the "bus supply" for the main power input. A simple nine-volt transistor battery was chosen to be the "emergency supply", and a transistorized radio receiver of conventional type (AM) was used to simulate the avionics.

Interruption of the bus supply without the emergency supply present in the circuit led to an immediate cessation of operation of the transistor radio. When the emergency supply was placed in use (by throwing a switch), however, radio function continued, although sensitivity was reduced slightly. The opinion of all who observed the test was that the resulting operation would prove to be completely satisfactory.

V. THE SERIES REDUNDANCY PROBLEM

Any piece of avionics equipment can be sectionalized into "building blocks" or sections which perform specific functions. Typically, in a group of different avionics equipments, there will be duplication both of equipments and of circuit sections. For example, all radio receivers

(a) BASIC FORM.



(b) BASIC FORM WITH EMERGENCY INDICATORS.

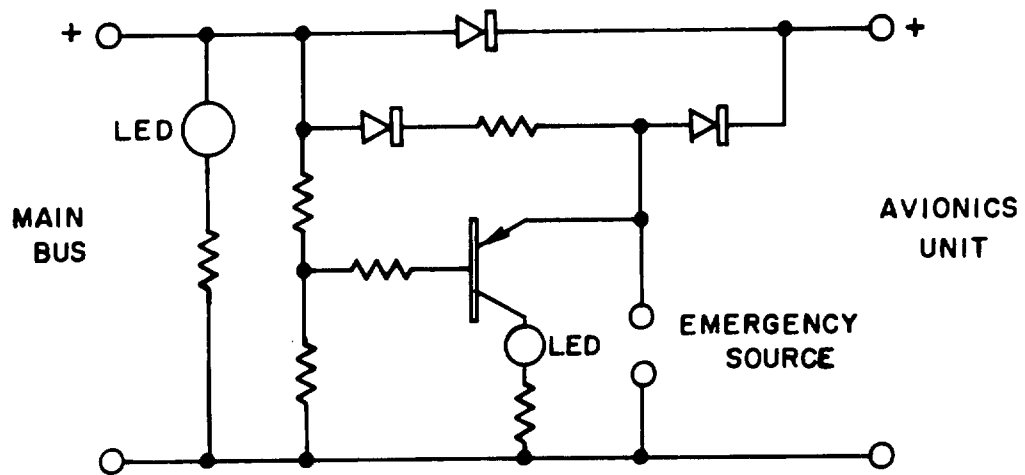


Figure 2. Power Supply Redundancy Circuits.

(c) PRACTICAL FORM.

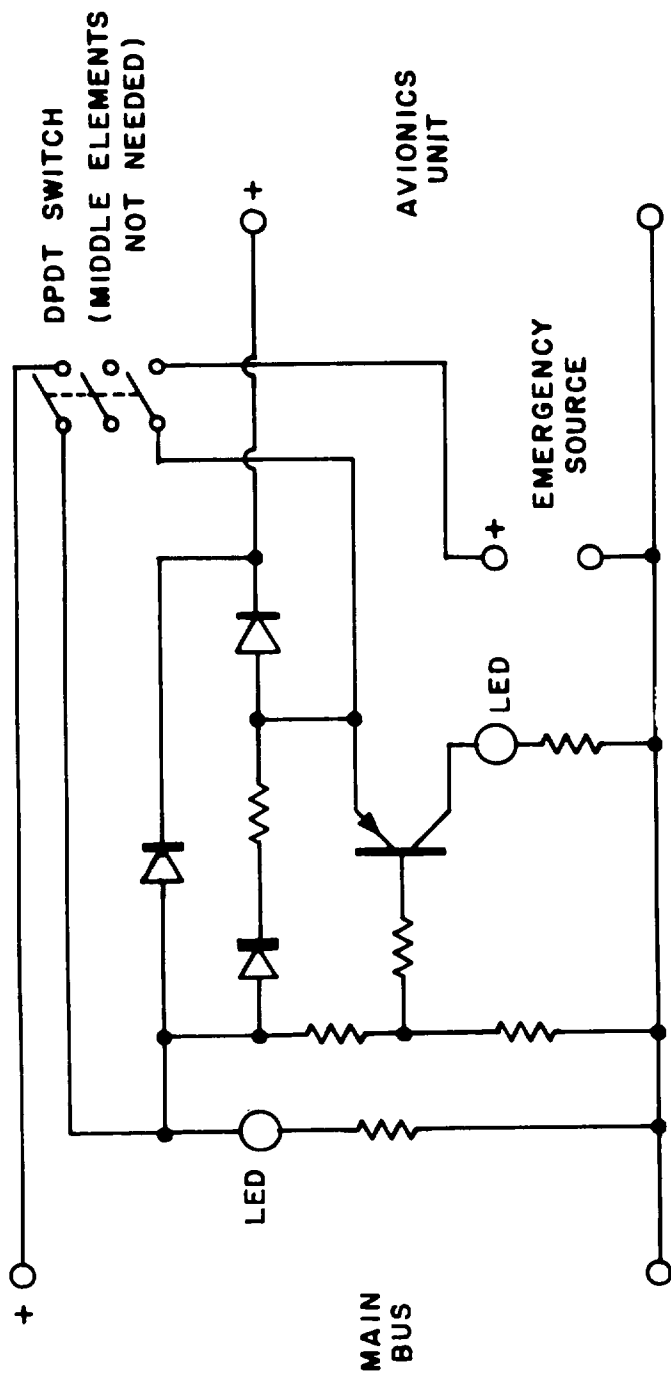


Figure 2. Power Supply Redundancy Circuits.

of necessity must have audio or video amplifiers for processing the intelligence conveyed by the received signal. Clearly, UHF, VHF, weather, and other kinds of communications receivers all have audio voice channels having largely equivalent characteristics. Some other circuits can be made mutually compatible as well.

Problems in establishing useful interties include not just the signal transfer problem, but also isolation problems, noise injection problems, and other related problems. Electrical ground-loop problems can be particularly serious since they can introduce external noise into signals. Under adverse conditions, such noise signals can degrade performance rather than enhance it. As a consequence, it is essential to consider each phase of the problem separately, and then to consider what the effects of interactions might be. (It should be noted that the ground-loop problem can be serious even in present day aircraft systems without interties.)

In a sense, it is not possible to separate the transfer and the isolation problems entirely. It is essential that intertie coupling circuits be so designed that in case of cable failure, the probability of isolation is high, yet in the absence of failure, the probability of satisfactory operation is correspondingly high. At the same time, the tie lines must be so configured that failure in the tie will lead to isolation of the units coupled by the intertie.

A basic or typical circuit which can be used for intertie control is shown in Figure 3. In this configuration, the intertie can be activated by applying a positive five volts at the control point A. This voltage may be carried over the intertie cable, and is controlled in the avionics equipment itself. The cable should be so planned that any short applied to either control or signal wire will lead to a grounding condition, and an automatic isolation action. Variants for other conditions are shown in Figures 4-6.

The switching circuit is required to detect both a short circuit to "ground" and an open-circuit or break resulting from battle damage

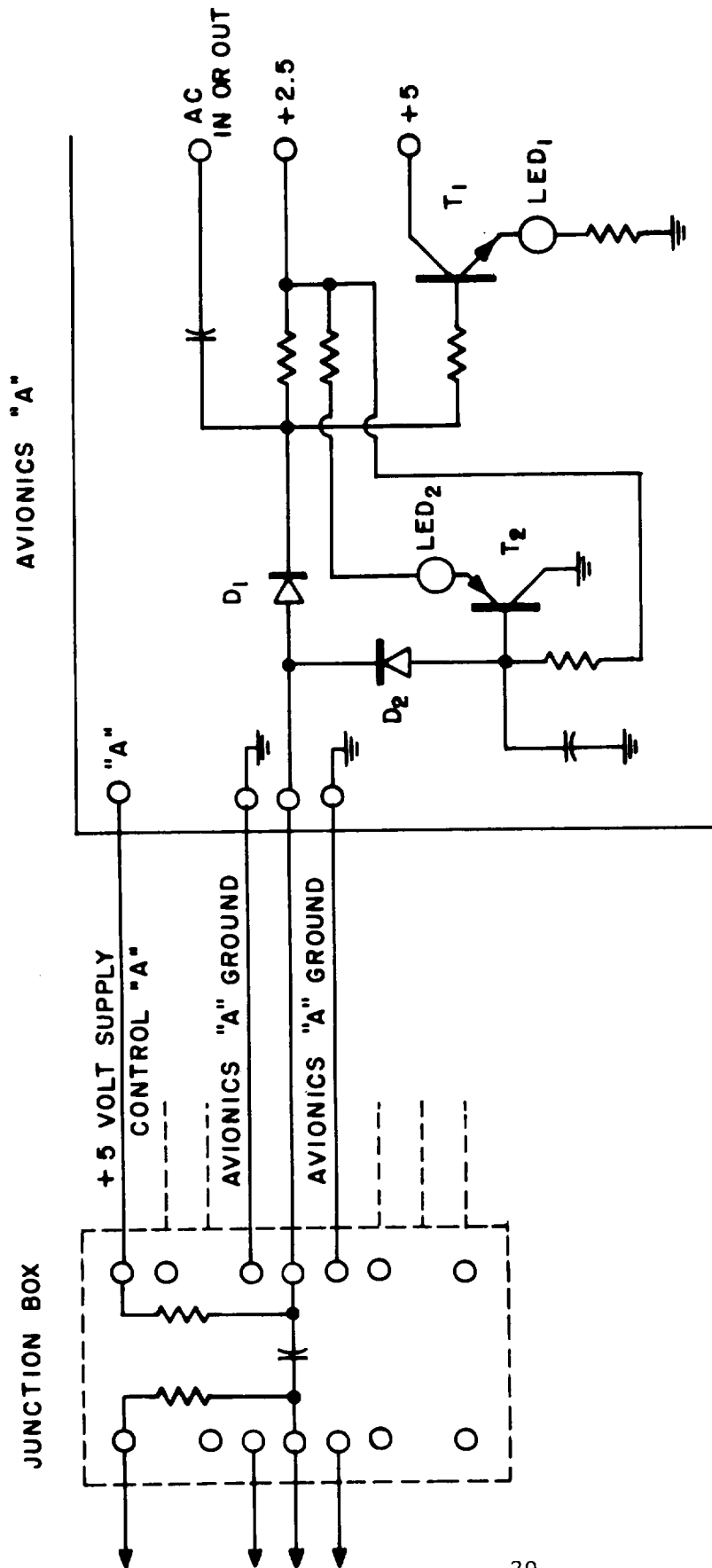


Figure 3. Basic Inter-tie Switching Circuit.

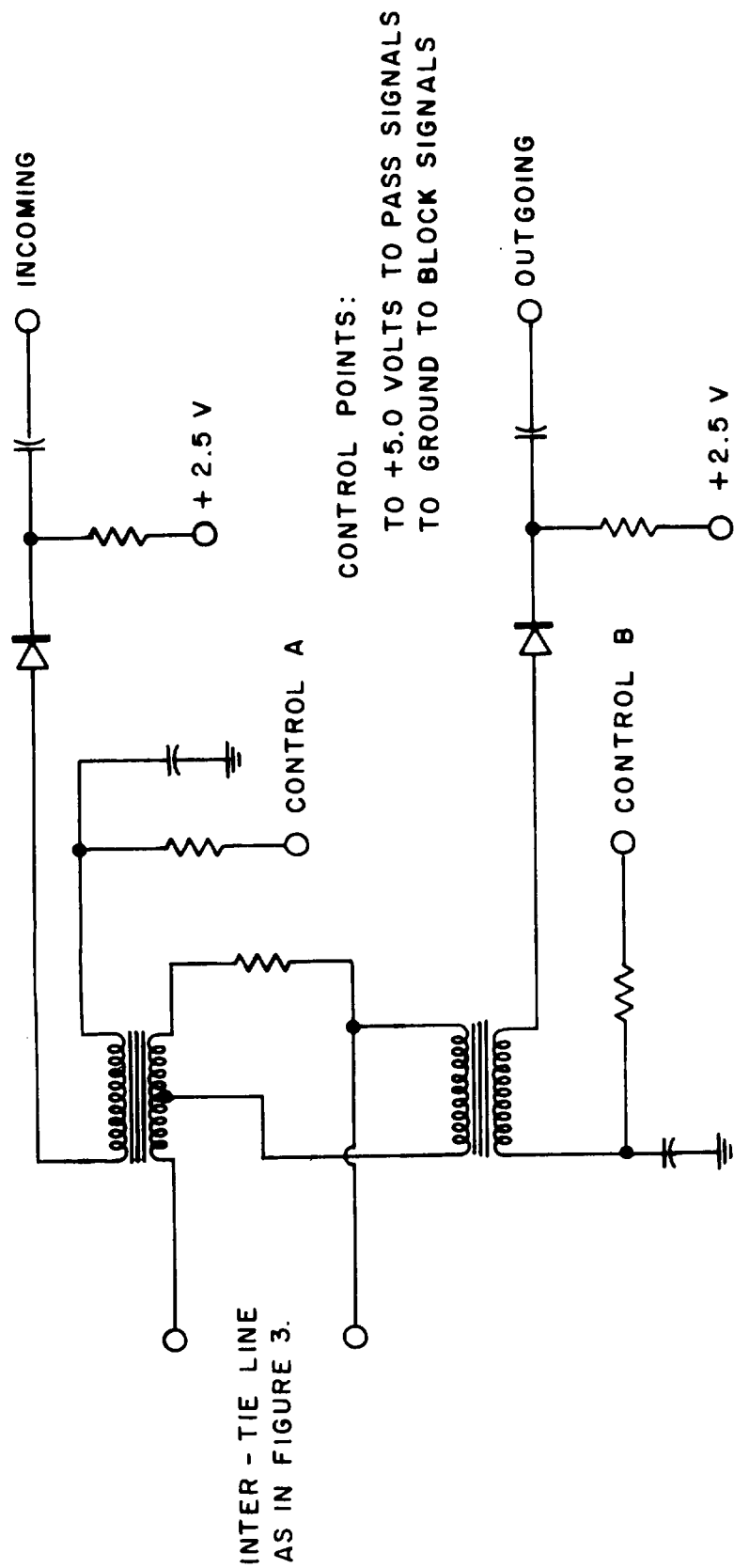


Figure 4. Signal Direction Switching Arrangement.

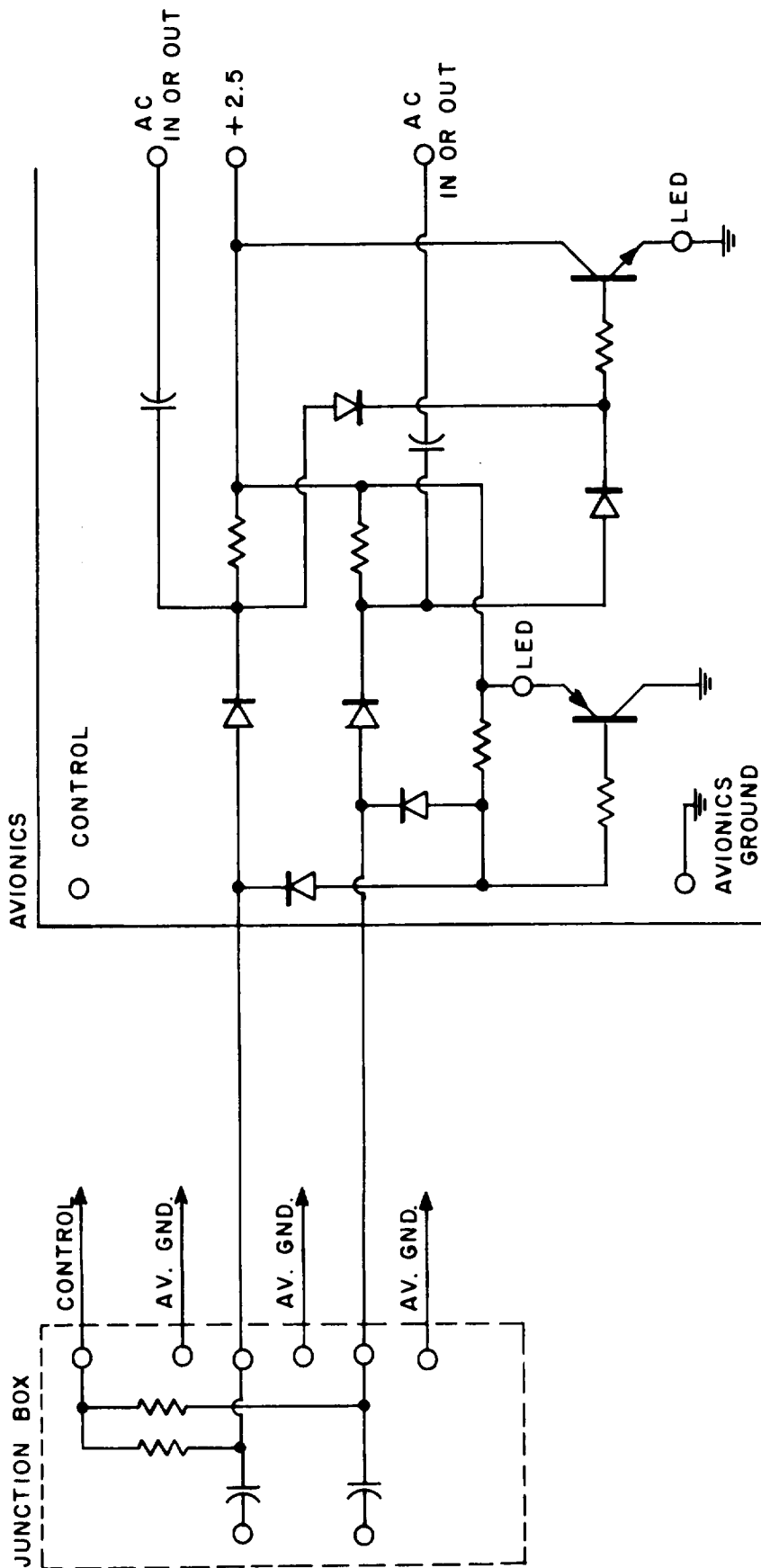


Figure 5. Balanced Switching Circuit.

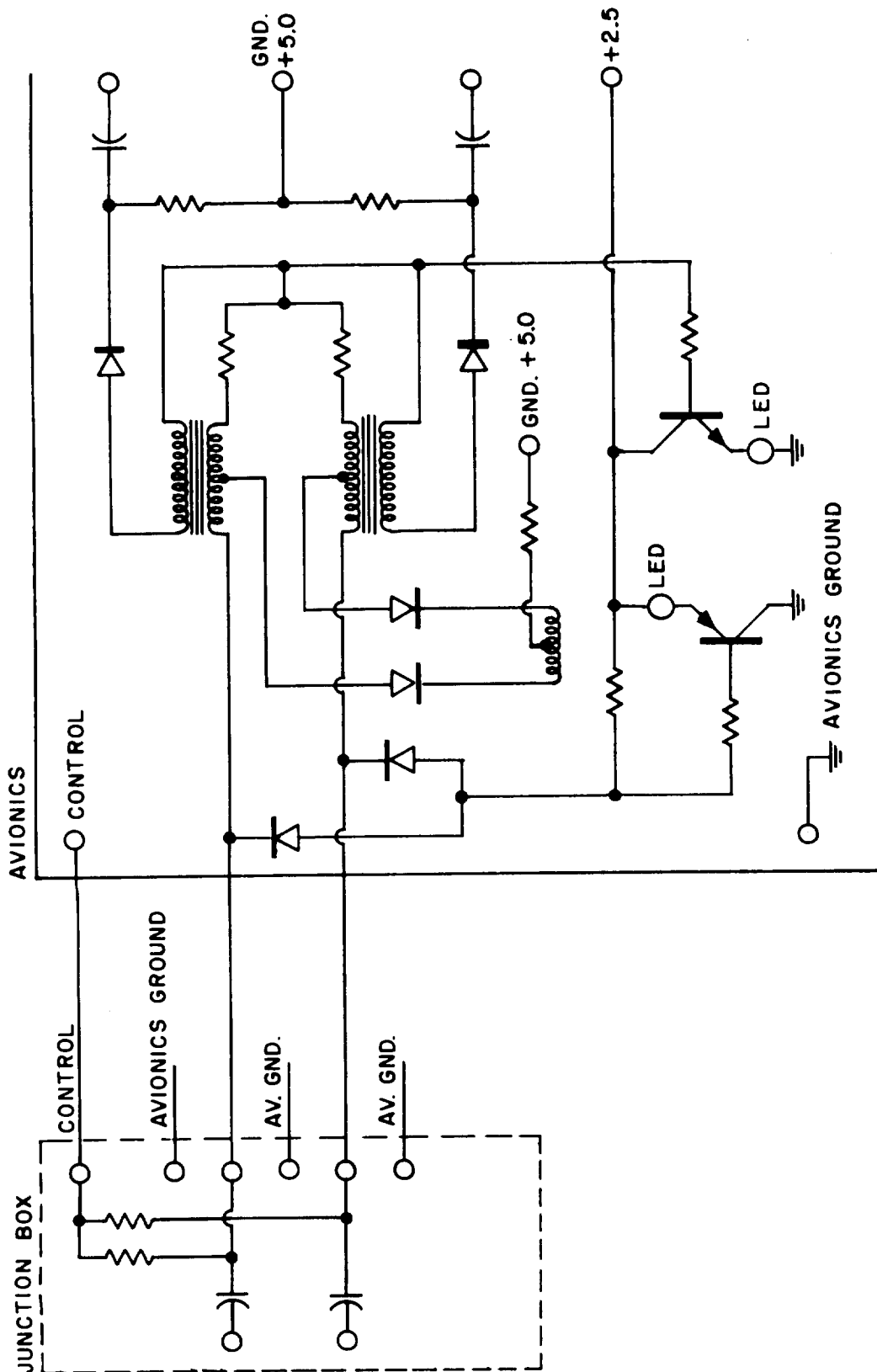


Figure 6. Balanced Line Configuration With Isolated Input and Output.

or other sources, and to isolate the circuits in an appropriate manner with either kind of failure. As long as the five-volt signal is applied at control point A and the intertie is working properly, diode D_1 is forward-biased and functions as a closed switch, and diode D_2 is back-biased, disconnecting the signal-shortening circuit and turning OFF the line-short indicator circuit. In case the line is shorted to ground, diode D_2 conducts and LED_2 lights, indicating a line problem.

When the line is operating normally, LED_1 will glow indicating that bias from control point A is reaching diode D_1 and causing it to conduct. When D_1 conducts, signals may be received or sent over the intertie. Otherwise, the tie is inactive, either because it is turned off or because a failure condition exists.

The intertie may be placed in an inactive condition by grounding the control point A; this may readily be done by a switch in the avionics unit itself. Under that condition, the diode D_2 will be in the conducting state, and diode D_1 will be weakly conducting at most. The combination of states provides for convenient testing of the availability of the tie line.

The presence of a sectioning arrangement in the intertie with the capacitor may not always be either necessary or desirable. Where more than two units are being interfaced by a tie, as might be the case with an audio-level circuit, this kind of an arrangement could easily prove valuable, but in RF or IF interties, the number of units operating on a common frequency with compatible kinds of signals is likely to be small, often two, and seldom more than three.

With isolated input and output configurations, one or the other (or both) of the ports may be inactivated by returning the appropriate diode control bus to plus five volts instead of plus 2.5 volts, Figure 6. In this way, signals may be transferred either in or out or both in and out. It is probable that certain types of failure (due to fragment damage, for example) can be caused to initiate the appropriate switching automatically. To assure this, each signal line in the inter-

tie should be "surrounded" by ground lines, and other required returns so arranged that failure will switch the appropriate diodes.

It is possible to build an integrated circuit (I-C) failure detection package which will detect failure to either ground or failure to positive or negative supply voltage. A possible circuit for use with a positive supply voltage is shown in Figure 7. This circuit achieves control by suppressing the control signal for control point A whenever one of a group of test points is either grounded or at the five-volt level. As long as all the sense voltages lie between one and four volts, the disabling circuit is inactive. The network can be used to inactivate a defective unit without interfering with other connected units if so desired.

When a unit is defective, it is desirable that it be completely disconnected from associated circuitry. Such a goal may usually be achieved by including switching diodes in the junction box as well as at the avionics equipments themselves. As long as failures in the cables are restricted to opens and shorts to ground (a condition usually existing), this configuration will isolate interties whenever a failure occurs.

VI. GROUND-LOOP CONTROL

Examination of the switching circuits shows that the amplitude of the signal voltage which may be applied to an intertie is limited to a peak-to-peak voltage of somewhat over one volt maximum. Since it is entirely possible for ground-coupling voltages to be several volts, it is important to determine how such voltages may be prevented from introducing noise.

Possibly the main source of ground-coupling voltage is ground loops (voltage differences introduced between different points of reference in a piece of avionics equipment), so that elimination of these ground loops is a vital problem in avionics either with or without redundancy. There are basically three ways of doing this.

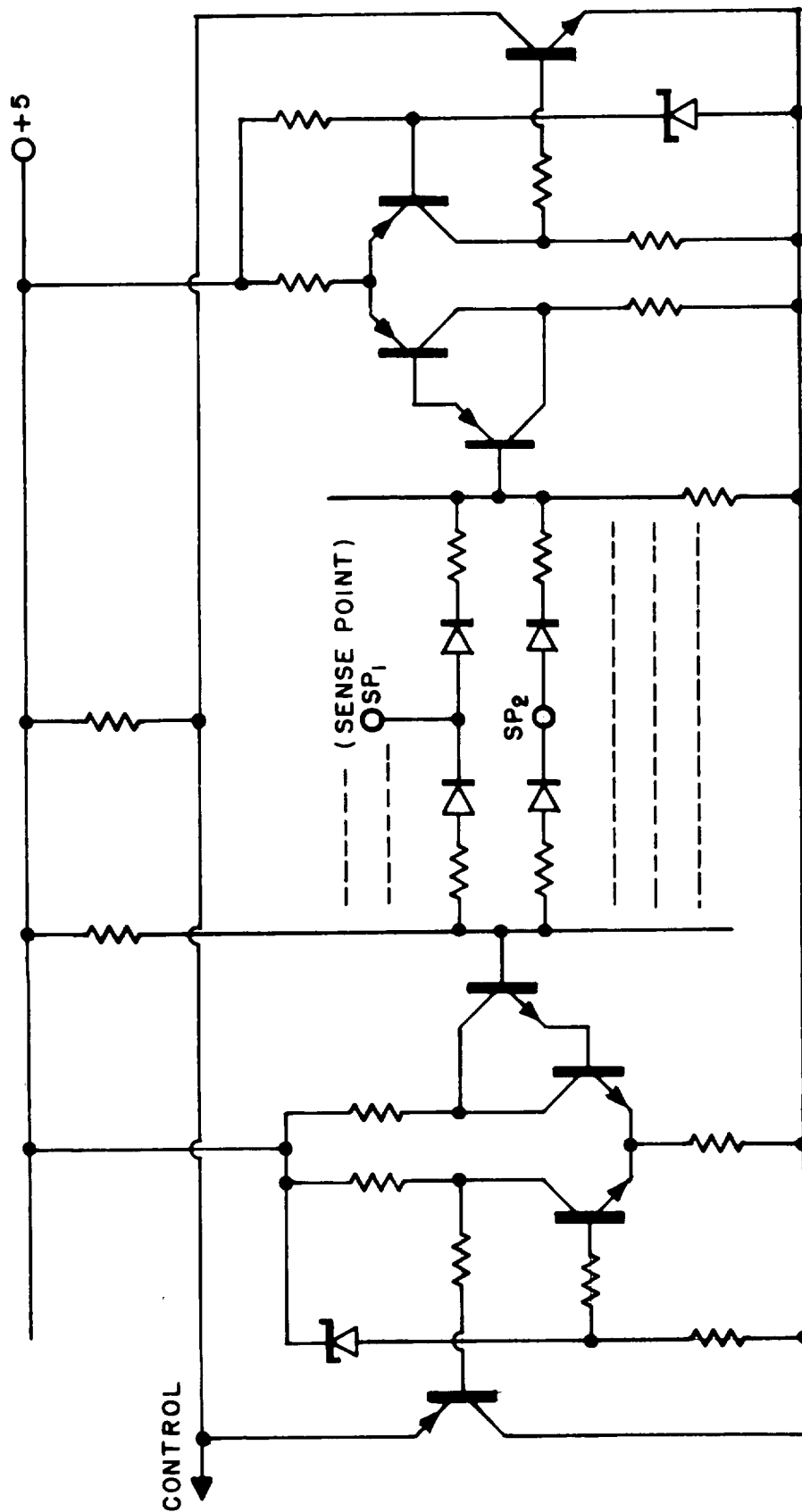


Figure 7. Avionics Failure Isolation Circuit

- a. Eliminate ground loops through careful use of ground returns.
- b. Use isolating transformers.
- c. Use balanced transmission lines.

The manner of use of these techniques in a weight-limited structure like an aircraft is of vital concern to engineers whose duty is to install avionics equipment, because of the relation of intertie noise to the ordinary noise environment problems encountered.

Ground-loop voltages are developed by the flow of "heavy" currents through relatively conducting "ground structure", which in the case of a radar site may actually be the ground, but with an aircraft or ship it typically will be the metal framework or hull. Part of the noise problem can be minimized by the use of a structural member as a return conductor. If at all possible, this member should be electrically isolated from the balance of the structure at all but one point. Otherwise, currents will leak off the member and flow haphazardly through the balance of the structure, leading to an unpredictable noise background condition. (In an aircraft, one wing spar in each wing and one body structural member should be used in this manner, and all heavy electrical loads then would be returned to these members; a completely separate instrument ground system should be used which commons to the main ground at the common point.) Molded fiberglass insulators could possibly be used to assure that the ground member behaved properly structurally.

Proper design of the ground system to keep heavy motor load currents (for control-surface positioning motors, air conditioning, and the like) out of the main structure is vital either in the presence or absence of intertie redundancy. Control of ground-loop voltages can lead to an almost unbelievable amount of improvement in the communications environment, and simplifies the use of isolating transformers and balanced lines for further reduction of intertie noise.

The use of the isolating transformer permits the ground "reference plane" for one circuit to be different than that for another without introduction of reference voltage differences into the transferred

signal voltages. It does require the use of transformers built with internal Faraday shields, however. Otherwise, there may be some high-frequency noise coupled capacitively between the windings. With proper shielding, however, this signal transfer may be kept to a minimum. Either audio, video, or high-frequency signals can be transferred with properly designed shielded transformers. The audio-frequency transformer may be a multi-winding device for coupling more than two circuits. Because all such transformers contain very fine wire, they should be well protected by placement and by appropriate use of armor.

Balanced circuits or coaxial and triaxial cable circuits will be required extensively for input RF signals, and they may be used with special preamplifiers located adjacent to the appropriate antennas to assure a maximum signal-to-noise ratio. With the balanced circuit, shielding will typically be carried with the balanced pair. Normally, this shield will attach to the receiver ground, and it is essential that an R-F transformer of suitable design be used to excite the circuit. The effective ground for the antenna must be adjacent to the antenna, and the separate receiver input ground must be isolated from it with either balanced line or coaxial or triaxial cable.

VII. ANALYTIC CONSIDERATIONS

It is desirable to place the above discussion in proper perspective through an examination of the theory of vulnerability and survivability of redundant systems. For the purpose of this discussion, the terms "system", "unit", and "component" are defined below.

System: a configuration of equipment so arranged as to perform a specified task.

Unit (of a redundant system): any one of a number of paralleled subsystems such that each unit, when intact, has the capability of fully performing the system task.

Component: a part of a unit which performs some function vital to the operation of the unit.

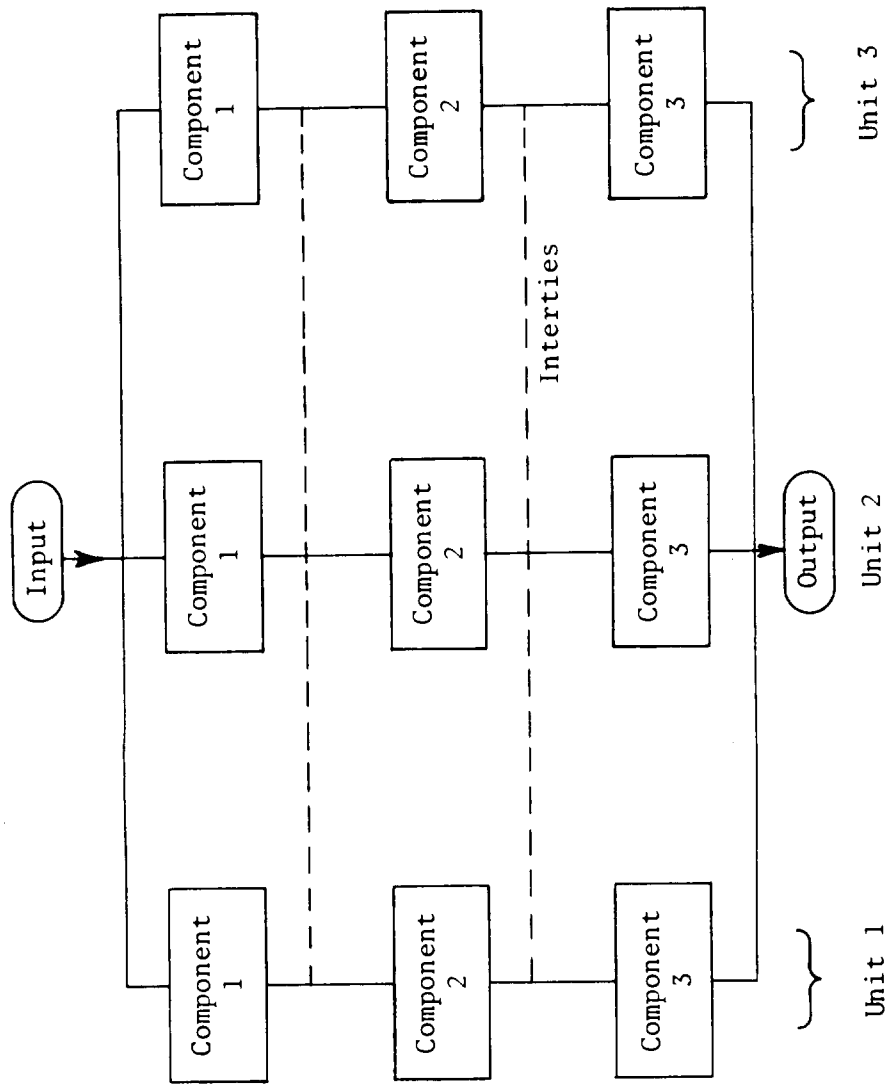


Figure 8. Schematic of Typical Redundant System

A typical redundant system is illustrated schematically in Figure 8. The theory is developed below under the assumption that failure of any one unit will not result in the simultaneous failure of any other unit. Furthermore, no provision is made for partial failure or performance degradation short of complete disabling.

For the purpose of this report, vulnerability and survivability may be defined in terms of the independent probabilities of complete failure. The vulnerability (V) of a given component, unit, or system is defined as the probability of failure when exposed to a specified threat. Since partial failures have been ruled out, survivability (S) is simply the complement of vulnerability.

$$V + S = 1 \quad (2)$$

Since survival or failure of a unit is effectively a Bernoulli trial, the vulnerability (V_T) of two paralleled independent units is

$$V_T = V_1 \times V_2 \quad (3)$$

and the survivability of two cascaded, independent components is:

$$S_T = S_1 \times S_2. \quad (4)$$

Now, if one assumes that an avionics system is assembled from units consisting of n cascaded components having equal vulnerability, and that m similar units are used in parallel to assure continuity of service, one can develop a survivability theory for this redundant system. For the moment, interties between components will be neglected.

Because of the assumption of independence, the survivability of at least r out of m components is given by

$$S_{(r,m)} = \sum_{i=0}^{m-r} f_i V^i S^{m-i} \quad \text{where } f_i = \binom{m}{i} \quad (5a)$$

Equivalently,

$$S_{(r,m)} = 1 - V^m - mV^{m-1}S - \dots - \binom{m}{r-1} V^{m-r+1} S^{r-1} \quad (5b)$$

In particular, the survivability of at least one out of two components is given by:

$$S_T = S_{(1,2)} = S^2 + 2VS = 1 - V^2 \quad (6)$$

The survivability of an avionics system built of n equally vulnerable components in each of two separate units, where the survival of the system requires only the survival of any one unit, follows Equation 6, where V is the unit vulnerability.

In general, if S_{ij} represents the survivability of the j -th component of the i -th unit, then the unit survivability S_i is given by:

$$S_i = \prod_{j=1}^n S_{ij} \quad (7a)$$

$$\text{and} \quad V_i = 1 - S_i \quad (7b)$$

The survivability of the system of " m " paralleled units is then

$$S_T = 1 - \prod_{i=1}^m V_i = 1 - \prod_{i=1}^m \left(1 - \prod_{j=1}^n S_{ij} \right) \quad (8)$$

If the individual unit is sectioned into two components of equal survivability S_{ij} , then by Equation 4, the overall survivability of the unit will be $(S_{ij})^2$. If this overall unit survivability is designated by S_i , then

$$S_{ij} = \sqrt{S_i} \quad (9a)$$

For n equally vulnerable components,

$$S_{ij} = \sqrt[n]{S_i} \quad (9b)$$

The survivability of m such units in parallel is then given by:

$$S_T = 1 - \left[1 - (\sqrt[n]{S_i})^n \right]^m = 1 - \left[1 - S_i \right]^m \quad (10)$$

But since S_i is independent of i , $S_i = S$ and

$$S_T = 1 - (1 - S)^m = 1 - V^m$$

which is Equation 6.

Considering the case where $m = 2$, if the vulnerability of each unit is 0.5, the system survivability is clearly 0.75. Similarly, for a unit vulnerability of 0.25, $S_T = 0.94$.

It is the purpose of this discussion to show that when interties between components of the several units are provided, then the system

survivability may significantly exceed that of the system without interties.

With the interties in place (see Figure 1), the system is assumed to be operational provided that at least one of each type of component is undamaged. The probability that all of the j-th components in the "m" units will fail is

$$\bar{V}_j = \prod_{i=1}^m (1 - S_{ij}) \quad (11a)$$

Thus the survivability of at least one of the j-th components is

$$\bar{S}_j = 1 - \prod_{i=1}^m (1 - S_{ij}) \quad (11b)$$

The system survivability is then the probability of survival of a cascade of components, each having an effective survivability of $\bar{S}_j$.

$$\bar{S}_T = \prod_{j=1}^m \bar{S}_j = \prod_{j=1}^m \left\{ 1 - \prod_{i=1}^m (1 - S_{ij}) \right\} \quad (12)$$

In the special case where S_{ij} is independent of i and j, and S_i consequently is independent of i,

$$\begin{aligned} S_i = S \quad \text{and} \quad S_{ij} &= \sqrt[n]{S} \\ \text{Then} \quad \bar{S}_T &= \left[1 - (1 - \sqrt[n]{S})^m \right]^n \end{aligned} \quad (13)$$

The difference between $\bar{S}_T$ and S_T as given by Equation (10) for the same m and n represents the survivability gain provided by the interties.

A few numerical examples for $n = m = 2$ will show that the efficacy of the intertie when S is inherently small, can be substantial. In fact, the use of the intertie may be nearly as effective as ADDING a third redundant unit.

Table I is useful in evaluating the effectiveness of interties in the improvement of survivability.

Table I. Survivability

<u>Unit Survivability</u>	<u>Parallel</u>	<u>Parallel with Tie</u>	<u>Triple Parallel</u>
0	0	0	0
0.1	0.19	0.28	0.27
0.2	0.36	0.48	0.49
0.3	0.51	0.63	0.66
0.4	0.64	0.75	0.74
0.5	0.75	0.84	0.87

As a further indication of the value of careful use of redundancy principles, it may be noted that some aircraft are equipped with an independent wind-driven generator which may be extended into the slipstream of the plane to maintain critical communications equipment in the case of failure of main electrical power.

Possibly the most important observation which can be drawn from the discussion above is the high degree of criticality of the maintenance of electrical power supply for vital pieces of equipment. This is made abundantly clear by the replication of power sources through use of two independent generating systems and a converter system-all aboard such aircraft as helicopters, and it is further supported by the use of the wind-driven auxiliary generator on some aircraft. Fortunately, the high-drag approach of the wind-driven generator probably isn't really necessary in view of the ease and convenience of provision of auxiliary battery supplies such as those depicted in Figure 2. They can provide what amounts to multiple-redundancy, inasmuch as each piece of avionics equipment can have its own emergency supply, and it will probably be good if the unit has not been hit by fragments. Since power cables are particularly vulnerable to damage, this change alone should enhance survivability by a substantial margin.

VIII. CONCLUSIONS

It is evident that some relatively simple changes may lead to substantial improvements of survivability in electronic equipment for use on aircraft, and also that with properly designed protective equip-

ment, the arrangements for providing the redundancy should not introduce significant failure problems of their own. It would appear that a further detailed study of this problem could lead to substantially more survivable equipment for use on aircraft.

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DOCUMENT CONTROL DATA - R & D

(Security classification of title, body of abstract and indexing annotation must be entered when the overall report is classified)

1. ORIGINATING ACTIVITY (Corporate author)		2a. REPORT SECURITY CLASSIFICATION	
Ballistic Research Laboratories Aberdeen Proving Ground, MD 21005		Unclassified	
3. REPORT TITLE		2b. GROUP	
EFFECTS OF REDUNDANCY ON SURVIVAL OF CRITICAL AVIONICS EQUIPMENT			
4. DESCRIPTIVE NOTES (Type of report and inclusive dates)			
Memorandum Report			
5. AUTHOR(S) (First name, middle initial, last name)			
Keats A. Pullen			
6. REPORT DATE		7a. TOTAL NO. OF PAGES	7b. NO. OF REFS
JANUARY 1973		42	6
8a. CONTRACT OR GRANT NO.		9a. ORIGINATOR'S REPORT NUMBER(S)	
b. PROJECT NO. 1T662708.A068		BRL MEMORANDUM REPORT NO. 2266	
c.		9b. OTHER REPORT NO(S) (Any other numbers that may be assigned this report)	
d.			
10. DISTRIBUTION STATEMENT			
Approved for public release; distribution unlimited.			
11. SUPPLEMENTARY NOTES		12. SPONSORING MILITARY ACTIVITY	
		U.S. Army Materiel Command Washington, DC	
13. ABSTRACT			
The design of simple circuits capable of keeping communications equipment in operation under conditions of failure of vital sections or sub-units of a system are described. Analyses are included which indicate possible routes for improvement of equipment survivability in a battlefield-type environment.			

DD FORM 1473

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