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SYSTEM DATA COMMUNICATION STRUCTURES FOR ACTIVE-CONTROL TRANSPORT AIRCRAFT
Volume II

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16. Abstract

This two volume report addresses the problem of data and power distribution in advanced transport aircraft in support of the NASA Energy Efficient Transport Program. Advanced aircraft design concepts are employing active control techniques to achieve significant increases in aircraft performance and energy efficiency. The concepts depend, however, on the availability of control mechanisms, with their supporting communication and power systems, that can perform flight-crucial functions continuously. Traditional methods are likely to be inadequate for these requirements. The objective of this study is to develop the technology that will meet the challenge.

Volume I addresses several specific technology issues.

Volume II directly addresses the application of communication structures to advanced transport aircraft. First, a set of avionic functional requirements is established, and a baseline set of avionics equipment is defined that will meet the requirements. Three alternative configurations for this equipment are then identified that represent the evolution toward more dispersed systems. Candidate communication structures are proposed for each system configuration, and these are compared using trade-off analyses; these analyses emphasize reliability but also address complexity. Multiplex buses are recognized as the likely near-term choice with mesh networks being desirable for advanced, highly dispersed systems.

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PREFACE

This is the second volume of a two-volume report covering work performed in the period between June, 1978, and April, 1981, on a project entitled "Definition and Analysis of Systems Data Communication Structures." This project was sponsored by the National Aeronautics and Space Administration, Langley Research Center, Hampton, Virginia. The Technical Contract Monitor was Mr. J. Larry Spencer.

The first volume is primarily concerned with communication methodology, while this volume treats communication issues at the aircraft system level.

The authors would like to express their gratitude to the personnel of NASA Langley who, along with Mr. Spencer, have made significant technical contributions to this work, especially Messrs. Brian Lupton and Nicholas Murray. Thanks are also due to Mr. Billy Dove, whose foresight and confidence made this project possible.

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Chapter 1

INTRODUCTION

The objective of this study is to develop a technology base consisting of concepts, data, and trade-off analyses to support the design of the data communication structures for future aircraft avionic systems. For this study, avionics is broadly defined to include almost all electronic functions expected to be performed on future aircraft. These functions extend from life critical fly-by-wire active control to the maintenance support.

In this study, we assume that the design of future avionic systems will be highly integrated and that a fault-tolerant computer system will be the heart of the system. The communication system studied is thus primarily to provide the necessary data transfer between the fault-tolerant computer and the sensors, displays, controls, and actuators necessary to perform all required avionic functions. This study consists of the identification of a number of alternatives for providing this communication function, and an analysis of their relative characteristics, including: performance, cost, reliability, and maintainability.

An initial decision was made that a study of communication systems could not be effectively conducted in isolation from the systems in which they are used. The approach taken for this study is first to establish as realistic an environment as possible for the communication problem. This environment is established first by defining a set of functional and operational requirements that must be met by the avionic systems in a future target time period. Next, a set of basic hardware elements is hypothesized that would be necessary to meet these requirements. A range of potential system configurations are then studied that would organize the hardware elements. From this study, three basic system configurations are chosen to represent the system configurations most likely to emerge at various stages of future development. Communication structures are then studied in the context of these system configurations.

Alternative communication structures are designed for each system configuration. A relatively complete description for each of these total systems gives a more concise picture of of the communication problem. Each system is then analyzed to provide trade-off information among the communication alternatives. An extensive reliability and throughput capacity analysis is performed on the candidate systems to assure that each meets the requirements. These analyses establish the basis for a trade-off comparison among candidates. The alternative systems are then compared in terms of relative complexity and other factors that could affect the choice for the most effective system for a particular application.

The following chapter gives the baseline system requirements to be met by the avionics system. Chapter 3 discusses the baseline equipment requirements. Chapter 4 defines alternate system configurations that represent those to be used in the future to meet these requirements. Chapter 5 gives the alternate communication structures for each of three representative system configurations and a description of each total system. Chapter 6 presents the results of the trade-off analysis of these system alternatives. Chapter 7 provides the conclusions and recommendations.

Chapter 2

BASELINE REQUIREMENTS FOR DATA COMMUNICATION STRUCTURES

The purpose of this chapter is to establish baseline requirements for the study of data communication structures. The requirements are based on considerations in the following areas: The first consideration is the target time period where it is expected that the proposed communication structures be used. The next consideration is the definition of a representative set of functions to be performed by the avionics system and supported by the communication structure. The characteristics and requirements for these functions are discussed along with the operational ground rules for the aircraft. Finally, the system reliability requirements are discussed as well as the hazard environment in which this reliability must be achieved.

2.1 TIME PERIOD CONSIDERATIONS

It is important to establish the time periods when the results of the research program should be used. The time period is needed to determine both the functional requirements for the communication structure and the technology likely available to implement the system.

The time period considered for this study includes a range of times, beginning with the earliest time the results of this work can be applied, and extending to an indefinite time in the future when the data communication system will be used in a full flight-critical active control system. The introduction of digital communications will most likely be evolutionary. Aircraft currently being developed extensively use digital communication. In future aircraft, the percentage of the avionics system involved in digital communication and the criticality of those communications are both expected to increase. This study will contribute to the technology base necessary to develop the most effective communication system through that time period.

The communication structure cannot be developed as independently as can individual devices, such as displays or sensors. These latter items can be developed at their own pace and then introduced into a system when they are ready or required. The communication structure is integral with the total system and is thus more dependent on the functions and requirements of the total system. Therefore, it is important to estimate the time periods when the systems are used, as well as to estimate the expected requirements for those systems, to create a realistic context to develop the most effective communication structure.

The time period for this study is largely determined by the purposes of NASA research. The purpose of NASA is not usually to develop systems themselves, but rather to develop the technology base for these systems. The technology base must therefore be established sufficiently prior to the time the definition and development of the actual systems starts. This situation establishes the early bound for the target time period.

To determine the earliest time the results of this study can be used, a brief look at the primary focus of this study, the commercial aviation industry, is necessary. One factor influencing the time frame is that new aircraft developments tend to come in groups or generations and that most major new system concepts are introduced with the new aircraft. Figure 1 gives the approximate time history of most major U.S. commercial aircraft developments since the introduction of the jet engine to civil aircraft. The beginning of the bar for each aircraft is the approximate time of its development go-ahead, and the end is the time it entered service.

The standardization process will also influence the introduction of new technology in commercial avionics. The airlines find it advantageous to develop form, fit, and function characteristics for electronic equipment to enhance interchangeability and competition. These characteristics are developed by the Airline Electronic Engineering Committee (AEEC) with the support of Aeronautical Radio Inc. (ARINC). The communication structure is a key item which must be included within the standardization process. The AEEC is just completing the most extensive round of new characteristic developments to date. The primary objective of these new characteristics is the conversion to a virtually total digital aircraft. The new equipment uses dedicated broadcast digital buses as defined by the ARINC Digital Information Transfer System (DITS), Characterisitic 429. This new equipment will be used extensively in the Boeing 767 and 757 aircraft. The same equipment may also be utilized on other new and derivative aircraft for the next few years.[1] This structure may change if a new concept offers sufficient

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[1] Supercript numbers refer to the list of references at the end of the report.

Figure 1: Generations of Aircraft Development

advantage to justify the cost of developing new standards and new equipment, or if new requirements emerge that cannot be met by the current equipment. In either case, new characteristics that use a new communication structure would not be introduced before the next major new aircraft development cycle. The timing of the next major aircraft development cycle will be primarily influenced by technology and the economy. By looking at past experience, as shown in Figure 1, the go-ahead for the next generation will be around 1987 with service to begin in 1990. The technology for this new aircraft must exist and be fully demonstrated at least one to four years before the go-ahead date. Thus, around 1985 will be the beginning of the time period covered by this study.

The upper bound on the time period is more open and a function of the level of technology rather than a specific date. This bound is also influenced by the purposes of NASA research. One purpose of this research is to create the opportunity for industry to utilize technology whose technical risk is too high for any one company to undertake. The technology this research is expected to support will allow the inclusion of an entire avionics system in an integrated design to support fully flight critical functions. Such advanced technology will permit electronics to be embedded within equipment in all locations in the aircraft. The upper end of the time period is thus that time when this technology is adopted. This time will be no earlier than the second major round of new aircraft development, presumably to occur in the mid 1990's.

2.2 AIRCRAFT OPERATIONAL GROUNDRULES

The communication system should be a part of a total system to achieve as high a level of self-monitoring and self-correction as possible. This capability is necessary for both flight operations and maintenance. The design goal is that all single failures and most multiple failures be operationally invisible to the crew. The failed component should be automatically identified to a high degree of confidence so that unconfirmed removals are almost eliminated. The system should also be capable of automatically checking out and revalidating itself after repairs.

The aircraft is assumed to be certified for full Category III B autoland capability. The aircraft should be dispatchable, at least with Category II capability, with any single failure and most combinations of failures.

2.3 AIRCRAFT FUNCTIONAL REQUIREMENTS

To establish the scope of the task to be accomplished by the communication system, some idea should be obtained about the functions performed by the equipment using the system. For this purpose, a set of functions to be performed by the avionics system is presented, along with the characteristics and requirements of those functions important for the communication system. This list is not the result of a definitive design of any particular airplane, but is considered adequate to establish the requirements for the communication system.

An assumption made for the purpose of this study is that the communication system will be involved in virtually all electronic functions on the aircraft. The resulting avionics system is not necessarily highly integrated, although such integration is a strong possibility, and the communication system should be capable of supporting that possibility. In any case, the majority of all data transfer within the aircraft will use digital communication with a common format except in a few cases where dedicated links are necessary for the most effective design. Consequently, the functions listed here include all electronic functions performed now or expected to be performed in the target time period. The expected evolution of these functions during the time period is also discussed. The only major function assumed to remain independent (and is thus not included) is the passenger service and entertainment system.

The functions are discussed in the following broad categories:

1) flight control

2) flight monitoring and warning

3) flight management

4) navigation

5) communications and surveillance

6) engine control and monitoring

7) aircraft systems management

8) aircraft and systems support functions

This chapter discusses the functions themselves; the following chapter discusses the equipment and data requirements necessary to implement the functions.

2.3.1 Flight Control Functions

The flight control functions are crucial in establishing the requirements for the communication system. Flight control is presumably the most flight-critical function and has some of the most stringent requirements for data rate and transport delay. Flight control will also probably change significantly during the target time period. The extent and complexity of these functions will presumably increase, and, in particular, the degree of flight criticality will become much greater. The categories of flight control functions include: stability and command augmentation, structural load relief, flight path control, and control surface linkage (fly-by-wire). These functions are described in the following paragraphs, along with an estimate of the functional failure rate requirement for each.

2.3.1.1 Stability and Command Augmentation

The stability and command augmentation functions provide commands to the control surfaces that modify the inherent aerodynamic characteristics of the basic aircraft on the basis of inputs from flight data sensors. A typical stability augmentation function used for a number of years and expected to continue to be used, is a yaw damper that reduces undesirable Dutch roll oscillations. Stability augmentation functions are expected to increase significantly in the target time period as equipment capability and reliability make possible the design of more efficient airframes. One of the most important in this category is reduced longitudinal static stability. The reduction of the inherent static stability will allow for the reduction of both trim drag and the size of the horizontal tail. The ultimate will be a completely unstable aircraft.

Command augmentation uses sensor data to augment the commands from the pilot. These functions are also expected to increase to improve the handling qualities of increasingly more complex aircraft. These functions will impact the communication requirements in both data rate and reliability. To maintain a stable system, maintenance of a minimum data rate and minimization of the maximum total delay from sensor input to control output are necessary. These requirements will vary for different aircraft. Nominal rates of 50 samples per second with a maximum transport delay of 20 milliseconds is assumed here as representative.

The reliability requirements are likely to have the greatest impact on the communication system. At the beginning of the time period the stability augmentation functions are not totally flight critical. However, a complete failure of the augmentation function may substantially reduce the operational flight envelope of the aircraft and increase the probability of an accident. Consequently, it will be highly desirable for these functions to have a failure rate between 10^{-6} and 10^{-7} per hour. At the other end of the time period, one assumes that the aircraft is completely unstable over a significant percentage of the flight regime so that a total loss of the stability augmentation system leads to an immediate loss of the aircraft. The communication system then must support a total system that has failure rate of less than 10^{-9} per hour.

2.3.1.2 Structural Load Relief Functions

Structural load relief functions are those active control functions that allow relaxation of the basic structural requirements, making a more efficient structural design possible. The functions include: maneuver load control, gust load alleviation, elastic mode suppression, and flutter control. These functions are also expected to increase during the target time period.

These functions will not be as flight critical as the stability augmentation functions. A failure may cause operational restrictions. However, an aircraft will not be made so structurally weak that it immediately fails when the active control system fails. The only exception envisioned is a structure with a flutter mode within the normal operating speeds; however, we assume that a flutter mode with this degree of criticality will not be used during the target time period. Thus, the reliability requirement for the structural load relief functions is expected to range from 10^{-5} to 10^{-7} per hour over the time period.

Possibly the most important impact the structural relief functions will have on the communication system is the high data rate requirement for flutter control. The actual requirement will depend on the flutter frequency for the particular aircraft. The requirement placed on the communication system will also depend on the organization of the control system. The load will be greatest if the system requires that the sensor signals and actuator signals be handled by the primary communication system. The data rate requirements may be so great that dedicated signal lines are used for this function to remove the load from the primary system. Possible flutter frequencies range from 15 to 25 Hz. With required samples rates of at least twice and up to ten times the frequency, sampling rates will range from 30 to 250 times per second, with a sample rate of 100 times per second assumed here.

2.3.1.3 Flight Path Control Functions

The flight path control functions cause the aircraft to automatically follow a desired path in space and time. These functions include: the traditional autopilot modes of attitude hold, heading select/hold, altitude select/hold, speed select/hold, vertical speed hold, etc. These functions also include the automatic throttle and automatic landing functions, and, in the future, will provide complete time referenced flight path control from takeoff to landing.

These functions are not expected to place any additional critical requirements on the communication system. The data rate requirements are not expected to be high. The most flight critical function will be automatic landing. The requirements will not be any higher than those already achieved. Because of the low exposure time, the equipment failure rate requirement will range from 10^{-6} to 10^{-8} per hour.

2.3.1.4 Flight Control Linkage

Included here as a flight control function is the linkage between the automatic control system or the pilot and the control surface. Most aircraft now have dedicated analog electrical signals from the electronic system to the surface actuators. Almost all aircraft (except the F-16) retain a mechanical linkage from the pilot to the critical control surfaces. It is expected that during the target time period the advantages of removing the mechanical linkage will be significant, particularly as the control surfaces become more complex to support structural load relief functions. Future systems are also likely to locate the servo electronics integrally within the servos. As these changes occur, they are likely to put some of the most severe requirements on the communication system. A complete failure in communications will result in an immediate loss of the aircraft. The reliability requirements will thus be essentially the same for a completely unstable airplane. The communication system will have to support a total system with a failure rate of less than 10^{-9} per hour.

2.3.2 <u>Flight Monitoring and Warning Functions</u>

Flight monitoring and warning functions are presently a collection of warning functions for such conditions like: stall, overspeed, off altitude, gear up, ground proximity, etc. Warnings to be added in the near future are wind shear and mid air collision. Hopefully, during the target time period, much broader, more comprehensive and integrated functions will be performed to assure that the aircraft is always flown within a safe flight envelope, thus significantly increasing flight safety.

These functions will unlikely place any unique requirements on the communication system. The only influence will be by the addition of any unique parameters to the data that must be communicated. A high degree of confidence must be placed on the reliability of these functions, although it is improbable that a failure will be the direct cause of an accident. The required reliability is thus less than that of flight control functions.

2.3.3 Flight Management Functions

Flight management functions are those capabilities that assist the crew in conducting the flight. Included are: flight planning, navigation data handling, communication system management, optimal flight path computation, etc. These functions are not expected to place any significant reliability or data rate requirement on the communication system. The most significant requirement will be provisions for handling and updating large amounts of data. Presumably, some large capacity data storage device will be included in the system, such as tape, disk, or possibly a new technology, such as bubble memory. The data will have to be updated periodically with a a carry-on device, such as a tape cartridge, or by data link using a VHF radio. Depending on the configuration of the systems, there may be a requirement for the communication system to move this data effectively.

2.3.4 Navigation Functions

The navigation function includes all of the sensors used primarily for navigation. These sensors include all those used now, plus those expected to be added during the target time period. The present sensors are VHF omni range (VOR), distance measuring equipment (DME), automatic direction finder (ADF), marker beacon, instrument landing system (ILS), inertial, and Omega, while the new systems are the microwave landing system (MLS) and the Global Positioning System (GPS). The inertial navigation sensors are integrated into the flight control/instrumentation inertial sensors. Loran and doppler navigation are not included.

The trend during the target time period is assumed to be toward greater integration of the navigation function. Data from the various sensors will be combined to obtain the best estimate of the aircraft's position, and also to allow the sensors to calibrate and monitor each other. This integration should increase the load on the communication system, but not to a significant degree relative to the flight control functions. Also, the reliability requirements will not be as great.

2.3.5 Communication and Surveillance Functions

The traditional voice communications on VHF and HF radios will have little impact on the internal aircraft communication system. These radios will be interfaced into the system to allow centralized communication frequency management. The reliability of this radio control function must be high but not as high as the flight control functions.

A more significant impact on the aircraft communication system will come from the data link functions. During the target time period, there will be an extensive and growing utilization of digital data link. Data links are assumed both through the ARINC system using VHF and possibly HF for airline operational, maintenance, and passenger service messages, and through the Air Traffic Control (ATC) system using the Discrete Address Beacon System (DABS) data link for ATC commands, operational data, weather data, etc.

The primary impact of the ARINC data link is the gathering and transferring of the data that will make up the data link messages. Most of this data will be available for other reasons. However, a few new terminals on the communication network will most likely be dedicated to data link functions, such as a cabin teletype terminal. The ARINC VHF data link is not expected to place critical timing requirements on the communication system. A dedicated link controller and data buffer is part of the modulator/demodulator (modem), so that the internal aircraft communication system is not directly involved in the timing requirements of responding to ground interrogations.

The DABS data link will place similar requirements on the aircraft communication system. The primary requirement will be the distribution of data coming up through the link to the appropriate devices and the collection of the data to be sent back down the link. A buffer is expected to lie between the DABS modem and internal communication structure. A data communication interface has been defined as a part of the proposed technical characteristic for DABS.[2] This system can communicate DABS messages in both directions to the appropriate peripheral devices, used primarily on smaller aircraft with no other data communication system. This system has timing requirements too severe to be made directly compatible with an aircraft communication system. For example, response time to a message must be as short as 4 microseconds. Thus, a dedicated buffer is used so the internal communication system will be relieved of these extremely tight timing requirements.

2.3.6 Engine Control and Monitoring Functions

The thrust command is transmitted to current aircraft engines by mechanical linkage. During the target time period, thrust control will be transmitted electrically, similar to commands to the aerodynamic control surfaces. Electrical commands for thrust will probably be introduced sooner than for aerodynamic commands. Initially, these commands may use dedicated wire. However, by the end of the time period, these commands will presumably be handled by the communication system. The primary impact will be the reliability requirement which will be essentially the same as for flight control.

Also, there will be electronics directly associated with the engine for control and data acquisition. The communication system will be responsible for supplying the engine electronics with necessary aircraft data, such as air data, and for transferring data needed for cockpit engine instrumentation, and for safety and maintenance monitoring. These communications will have a moderate data rate and reliability requirement and thus not put constraints on the communication system.

In the future, the possibility exists that for environmental or other reasons, the engine control will be removed from the engine. In this case, the data rate and transport delay requirements from engine sensor inputs to fuel flow control outputs will be very tight; however, that this separation will be made during the target time period, for both technical and management reasons, is highly unlikely.

2.3.7 Aircraft Systems Management

The management/control, and particularly the display for all aircraft systems, are expected to become more integrated in the future. Traditionally, most of these systems were designed and built independently with separate controls and displays with dedicated wiring. As these systems grew more complex, the clutter and confusion in the cockpit became unmanageable. Thus, from the beginning of the target time period integrated displays will be used. The integration of signals required to support an advanced display system encourages the inclusion of many auxiliary functions into a more integrated system. Several new ones that cannot be easily identified will probably be added. Aircraft systems likely to be involved in the data integration include: the fuel system, electrical system, hydraulic system, landing gear and brakes, environmental control system, weight and balance, auxiliary power system, and pneumatic/anti-ice system.

The integration of this data will have a major impact on the communication system because of the sheer magnitude, the number of signals involved, and their locations. The total reliability of all these functions must be high but not as high as the flight control functions. A major question to consider in the system design is the degree to which all of these auxiliary functions can be integrated with the primary flight control functions, without degrading the reliability of the more critical flight control functions. The answers to these questions are beyond the scope of this study. The assumption made here is that the communication structure should be capable of handling completely integrated systems to allow system designers freedom to develop the most effective approach.

2.3.8 Aircraft and System Support Functions

During the target time period, an increasing reliance will be placed on electronics to optimize the operational effectiveness of aircraft. This trend will be motivated in at least two ways: The rapid development of electronic technology means that the cost of electronics relative to benefits gained is constantly shifting in favor of more electronics, and the ability to synergistically use capabilities that already exist to perform existing functions. The functions envisioned involve increased use of automatic monitoring, testing, and reconfiguration management. These capabilities will identify more easily and accurately failed equipment or degraded performance, to allow maintenance to be anticipated, and to avoid operational delays. These capabilities will also: aid in system checkout after repairs are made, assist in record keeping for maintenance control purposes, and identify more quickly troublesome areas that need basic redesign.

One of the most important elements of the maintenance support function is the avionics system itself. Efficient methods will be needed to maintain the required high level of reliability and to confirm that this reliability is reestablished after repairs are made. This automated maintenance function will be required to assist in maintaining the certifiction of the system. Some contemporary flight control systems use separate hardware for this function, but future systems are anticipated to incorporate this function into the primary system.

Much of the sensor information and processing capability to perform these functions will already exist in the system, although many more will most likely be added. The major impact on the communication system will be the large number and diversity of signals that must be handled.

2.3.9 Summary of Functional Requirements

The major factors that influence the communication system resulting from this functional requirements study are summarized here. The highest reliability requirements result from the stability augmentation and control surface linkage (fly-by-wire) flight control function. The flight control system must, at the beginning of the target time period, support a near-neutrally stable aircraft in some parts of the flight envelope, while progressing to a completely unstable aircraft by the end of the time period. During this period, the mechanical linkages are removed. The required failure rate for these functions is 10^{-7} per hour at the beginning of the time period, and decreasing to 10^{-9} by the end. The failure rate which can be apportioned to the communication system will depend on the design of the system. However, communications should only contribute a relatively small part of the total. Failure rate requirements for the probability of a complete failure to communicate the minimum information necessary to perform the flight critical functions range from 1 to 3 times 10^{-8} per hour at the beginning of the time period and 1 to 3 times 10^{-10} at the end.

The most severe data rate and transport delay requirements result from the flutter control function. The assumed maximum data rate requirement is 100 samples per second. The rate requirement is assumed to drop to 50 samples per second when the function is performed by a dedicated system.

The total capacity requirements and the extent to which the communications are localized throughout the aircraft depend on where the servo-electronics are located and how extensively the system is integrated, particularly with auxiliary functions. The following paragraphs discuss the environment in which these requirements must be met:

2.4 HAZARD ENVIRONMENT

The fundamental requirements that all candidate communication systems must meet are: first, they must perform the basic communication tasks; second, they must perform these tasks reliably; and third, the technique must be practical from the cost, operational, and maintenance points of view. The preceding section established baseline requirements for the communication tasks and the reliability that these tasks must be performed. This section discusses the hazard environment in which the reliability requirement must be met. The hazard categories include: random equipment failures, specification errors, and induced failures.

2.4.1 Random Equipment Failures

The communication system must meet the reliability requirements in an environment where the equipment malfunctions from random failures. Each component of the active and passive equipment used to perform the communication function may fail to perform its required task. These failures are normally caused by the interaction of environmental stress, or a particular operational situation with an inherent manufacturing fault in that component, or a deterioration in capability since it was manufactured. These failures are assumed to be random, with little correlation with each other. The rate of failure is determined by the quality of the original manufacturing, the extent of initial equipment burn-in, the thoroughness of initial tests, and by the environmental experience, both accumulative and instantaneous. The statistical failure rate for most of the components that will comprise the communication system are relatively well known, based on past experience with that, or similar components. The environmental stress on the components will be a function of location, and are assumed to be defined by Radio Technical Commission for Aeronautics DO-160.[3]

The reliability that can be achieved by individual electronic components does not normally approach the levels required for the system. Therefore, the system must be built to tolerate all potential faults in the electronic hardware. The system must be designed to detect and isolate any potential failure that cannot itself be shown to have a probability of occurrence significantly less than that required for the system. When a failure is detected, the system must have sufficient additional resources so that the essential functions can continue to be performed. Analysis is necessary to show that the reliability of the failure detection, isolation, and reconfiguration meets the total system reliability requirements in an environment of random equipment failure rates. For this study, the component failure rates relatively well defined and available from such sources as MIL-HNBK-217B.[4]

2.4.2 Specification Errors

The design of a communication system to meet reliability requirements approaching 10^{-11} failures per hour in the presence of random failures is a difficult but achievable task using techniques beginning to mature. As these goals are achieved, the relative importance of other potential causes of system failure increases. An important category of potential failure sources are identified here as specification errors, which include: generic faults in the design of the system hardware or software, errors in the manufacturing process itself, and errors in the operation of the system. When redundant channels provide coverage for random failures, specification errors may become a dominant source of failure because they can affect all redundant channels simultaneously to cause a complete system failure.

These faults are more difficult to define, estimate the probability of occurrence, and provide protection against. By definition, almost no actual experience can help to understand these types of failures or estimate their rate of occurrence. This situation is illustrated by the following fact: If a particular design is accepted as a standard and used on all commercial aircraft for a typical generation of 15 years, the total flight time is estimated to be between 10^8 and 10^9 hours. Thus, if no failure arises (or only one) during this time period, it will contribute little to an increased understanding and prove little about the statistics. In any case, the information will be too late since the risk will already be taken. Therefore, the system must be designed such that it is theoretically close to impossible to have a life-critical failure in the system.

Two approaches to the problem are suggested here: First, the basic design can be done so that it is extremely improbable that any error exists in the hardware or controlling software. Some of the techniques which might be used to accomplish this error free design are:

- Strict requirements specification standards
- Enforced design methods standards
- Achieving the simplest possible design
- Using a design that can be proven correct mathematically
- Using independent design verification and validation teams.

The other approach is to design the system such that there is no single link in the design which allows any one design error to cause a complete system failure. This technique means there are redundant channels, where the channels have dissimilar design, or where there is some backup means to provide all critical functions. The backup system would not use the same design as the primary system.

2.4.3 Induced Failures

The final hazards discussed here arise from external events. The probability that the communication system continues to provide critical functions after the occurrence of one of these events must be proportional to the probability of that event. The external events considered here are: physical damage, fire, lightning, and extreme deviation from the design environment, including temperature, vibration, shock, and EMI.

2.4.3.1 Physical Damage and Fire

The probability that physical damage and fire will affect the communication system can be significant relative to the very low failure rates required. Physical damage can result from the following: collision with other aircraft, birds, the ground or other stationary objects; excessive aerodynamic loads, caused by abrupt maneuver or turbulence; explosion (terrorist or accidental); massive failure of engine or other equipment, such as an air conditioning turbine, including the effects of parts thrown out; loose objects, such as cargo; and damage due to rapid decompression. Also, fire can result from many of the same causes, in addition to massive failure of electrical and electronic equipment, cargo fires, accidental trash fire, such as a cigarette in a waste container, etc. Physical damages may also include liquid damage from fuel, hydraulic, galley, and toilet leaks.

The requirement for the communication system is that it continue to provide all flight critical functions after any damage or fire that is not so severe as to prevent flight otherwise. In other words, the primary cause of an accident should not be damage to the communication system. The probability that the communication system can survive the damage is proportional to the probability of that damage.

To obtain an initial estimate of the probability that a communication system is damaged, a survey was made of all air carrier accidents between 1964 and 1977.[5] [6] The briefs of the accidents in the Annual Reviews of Aircraft Accident

Data, published by the National Transportation Safety Board (NTSB), were used. For each accident, a determination was first made on whether, if an advanced communication system were used, damage to that system could have contributed to an accident. Two classes of accidents were eliminated: those where it was judged unlikely that any part of a communication system would be damaged, and those where the results of the accident would be the same whether the communication system were damaged or not. A total of 722 accidents were included, 57 of these were considered to be ones where communicaton system damage could have been a factor.

For each of these accidents, rough estimates are made in three categories: the probability of at least one electrical cable containing a communication line or communication terminal was damaged, the probability that more than one line or terminal was damaged, and the probability that one particular area in the airplane was damaged which would correspond to a controller of the communication system. These probabilities were summed to get a total number of events. The results were: 16.7 events for one line or terminal, 5.3 for more then one, and 0.4 for a control center. The total operating hours for this time period was 70.6 million hours. The probability rates for damage events per hour are thus 2.4×10^{-7} for one line, 7.5×10^{-8} for two lines, and 6×10^{-9} for a control center. Not included are incidents which may have caused damage not serious enough to report. It is also assumed that no unusual care was taken to protect against damage. A more thorough analysis of selected accidents and incidents is necessary to increase confidence in these numbers. (A more complete description of the analysis performed to estimate these damage probabilities is given in Appendix A.)

2.4.4 Lightning

Lightning is also a significant component of the hazard environment for a communication system which achieves high reliability by redundancy and fault tolerance. Two factors must be considered: First, the probability that a lightning event with particular characteristics occurs, and second, the probability that, given lightning has these characteristics, the system fails.

The probability that an aircraft will be struck by lightning depends on the altitude, location in the world, and time of year. Data gathered by the UK for both European and world-wide operations found strike incidence rates varying from one in 780 hours to one in 19000 hours. The commonly accepted rate is once per year or once per 3000 hours. The indirect effects of lightning flashes nearby, but not striking the aircraft, may also be significant when considering any effects on the communication system. The rates for nearby strikes are not known, but are not assumed to be significantly more than double the direct strike rate.

The effects of a lightning strike on the communication system depend on the varying intensity and characteristics of the strike. The assumed distributions for these characteristics are given in NASA Reference Publication 1008, <u>Lightning Protection of Aircraft</u>, pages 21 to 16.[7] The worst case strike is the same as that used for the Space Shuttle design and given in Figure 2.

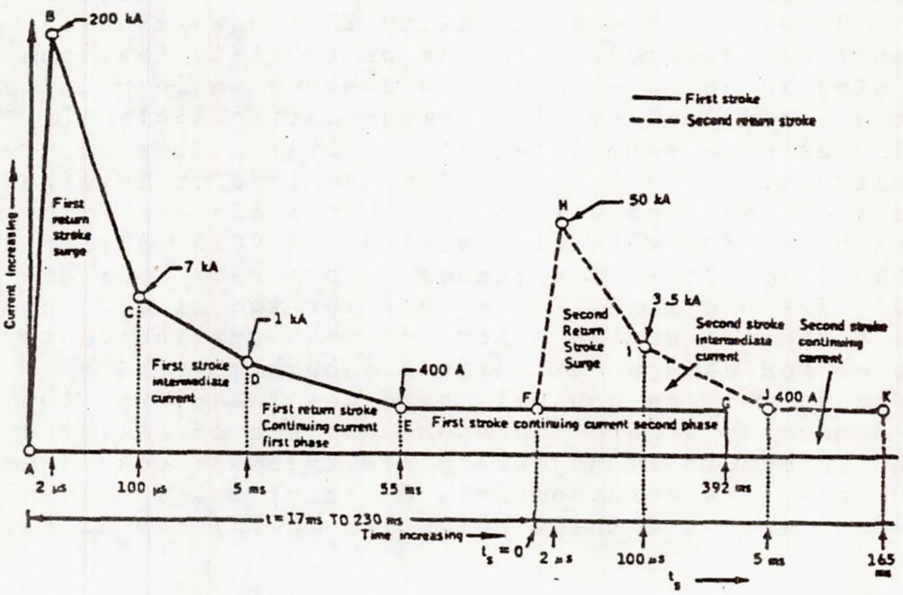


Figure 2: Diagrammatic Representation of Lightning Model

The probability that a lightning strike with certain characteristics will produce an error or cause a complete failure of a particular communication system is difficult to estimate. The mechanisms by which lightning might induce failures are not well understood, but depend on the design of the particular system, how it is installed in the aircraft, and how it is protected from the effects of lightning.

A first estimate of the probability of effects of lightning on the system is obtained from past experience of indirect effects of lightning on commercial aircraft, as reported in NASA Reference Publication 1008, page 100. The interference and outages on equipment, with direct connections outside the aircraft through antennas, etc., were assumed not to apply to the internal communication system. The total of the other cases gave interference in 12% of the strikes and outages in 7%. Thus, the first estimate gives a probability of 4×10^{-5} per hour of some interference, and a probability of 2.5×10^{-5} per hour of some damage.

Some of the candidate advanced communication systems may be more susceptible than current equipment due, for example, to the use of digital technology or wires that are more spread throughout the aircraft. On the other hand, a better understanding of interference mechanisms that allows the development of protection techniques may reduce the probability of faults. One technique that appears to offer significant protection is the use of shields grounded at both ends. Sometimes, this may be an additional overall shield, where single-ended shields are needed to protect it from other types of noise.

For this study, lightning is an unique hazard with the potential to affect diverse parts of the communication system simultaneously in unpredictable ways. The methods available to bound these effects are limited and difficult to construct. For these reasons, the candidate communication systems must be made essentially immune from the effects of lightning phenomena.

The immunity can be provided by either passive shielding or active recovery techniques. The techniques which provide immunity may vary for different candidate systems. The costs for providing the immunity must be included in the cost trade-offs for each system, for example, the weight of any additional shielding. The lightning protection for the processing system that gives the basic supervisory control of the communication system is not part of this study. It is assumed, however, that the processing system is tolerant of lightning hazards and can implement any active recovery techniques in the communication system used by a particular design.

Chapter 3

BASELINE EQUIPMENT REQUIREMENTS

The preceding chapter discussed the functions to be performed by the avionics system that must be supported by the communication structures investigated in this study. Some baseline assumptions must now be established for the electronic equipment necessary to perform these functions. This chapter identifies the basic hardware elements that: supply the required sensor information; provide the display and control interface with the crew; and interface with the actuators that control the aerodynamic surfaces, engines, and other aircraft systems. A parameter list is established corresponding to each sensor or effector to estimate the amount of data that must be communicated, along with requirements for accuracy, data rates, time delay, and reliability. The equipment set and associated parameter list are not based on a detailed design of a complete avionics system. They are assumed, however, to be sufficiently representative to define a realistic baseline for the communication system study. The next chapter identifies alternative configurations which organize these hardware elements into a total system.

The equipment and parameters discussed are primarily concerned with sensor systems and effectors. No attempt is made here to predict the communication load attributable to the computer systems themselves, or to estimate intra-computer system communications. These characteristics are too dependent on the particular system design to allow meaningful estimates.

The equipment and parameters are listed in major groupings roughly corresponding to the functional areas mentioned earlier. Table 1 depicts a typical parameter list.
The information with each parameter includes: the quantity, the required digital resolution, the data rate, the response time or allowable transport delay, the assumed criticality of that set of parameters (not necessarily of each individual parameter in a redundant set), and the typical location of that signal in the aircraft. This information comes from a variety of sources. A primary source is the ARINC DITS Specification 429.

TABLE 1

Flight Data Sensors

Parameter	Quantity	Resolution (BITS)	Samp./sec	Resp. Time	Criticality*	Location
Angular Rate	9	13	50	10 ms	VH	Avionic Bay (AB)
Acceleration	9	12	50	10 ms	VH	AB
Flutter Sensor	6	10	100	2 ms	H	Wing
Static Pressure	2	16	10	50 ms	H	AB
Total Pressure	2	14	10	50 ms	H	AB
Total Temperature	2	10	2	1 s	M	Nose
Angle-of-Attack	2	11	50	10 ms	M	Nose
Magnetic Field Sensor	2	12	50	10 ms	H	Wing

*VH Total Failure Rate less than 10^{-9}

H Total Failure Rate less than 10^{-7}

M Total Failure Rate less than 10^{-5}

L No Safety of Flight Requirement

3.1 AIRCRAFT FLIGHT DATA SENSORS

The first equipment considered is the set of aircraft flight data sensors needed primarily to support the flight control functions and used in several other functions, including flight warning and navigation. Table 1 provides the parameter list. This set of sensors is integrated to collectively produce all necessary aircraft flight data for every function. The different functions, such as flight control, navigation, and cockpit instruments, will not have separate sensors. In this list, the sensor processing is also integrated so that only the basic sensor measurements need be transmitted. This degree of integration may not occur until later in the target time period. If the sensor system integration is not implemented, Table 2 gives typical data transfer requirements for a more conventional arrangement for air data system and inertial reference system.

Table 1 includes: strapped down angular rate and acceleration sensors, flutter control sensors in the wing, air pressure and temperature sensors, angle-of-attack vanes, and flux gates. The total reliability requirement for inertial sensors is very high to support the active control of a basically unstable aircraft. Sensor redundancy achieves this high reliability. The number of sensors required depends on the basic reliability of the sensors and the redundancy scheme. A compromise is made here of nine sensors, each representative of either simple triple redundancy of high reliability sensors or a more sophisticated skewed arrangement of less reliable sensors. The reliability requirement for the other sensors is not as high because some alternate data or emergency procedures avoid a catastrophe in most cases.

3.2 FLIGHT CONTROL ACTUATORS

The parameter list for the flight control actuators is given in Table 3. There are two groups: one for the command signals going to the actuators, and the other for the surface position sensors bringing information back into the system. The parameters listed are the interface between the flight control processing system and the servo electronics. Several other signals are necessary between the servo electronics and the hydraulic actuator, including: position feedbacks, rate feedbacks, differential pressure sensors, engage discretes, etc. These signals are transferred by dedicated wires and do not involve the primary communication system. The location of the servo electronics, then, is crucial in establishing the requirements for the communication system.

TABLE 2

Independent Flight Data Computers

Parameter	Quantity	Parameters	Resolution (BITS)	Samp./sec	Resp. Time	Criticality	Location
Independent Flight Data Computers							
Inertial Reference System	3	14 (30 INC Navigation)	18(max)	50(max)	20 ms	VH	AB
Air Data System	2	13	18(max)	16(max)	50 ms	H	AB

TABLE 3

Flight Control Actuator Signals

Parameter	Quantity	Resolution (BITS)	Samp/Sec	Resp. Time	Criticality	Location
Flight Control Actuator Commands						
Wing Dynamic Control Surfaces (Roll, DLC, MLC, GLA, EMS)	18	12	50	10 ms	VH	Wing
Wing Flutter Suppression	6	12	100	2 ms	H	Wing
Wing Configuration Control (Flaps, Slats, Variable Chamber Spoilers)	20	1	10	100 ms	M	Wing
Tail Dynamic Control Surfaces	11	12	50	10 ms	VH	Tail
Landing Gear Operation	6	1	1	100 ms	H	2 Nose Gear 4 Main Gear
Steering	1	10	10	50 ms	L	Nose Gear
Brakes	5	8	10	50 ms	H	1 Nose Gear 4 Main Gear
Control Surface Position Sensors						
Wing Dynamic Surfaces	8	12	50	10 ms	H	Wing
Wing Flutter Suppression	6	12	100	2 ms	H	Wing
Wing Configuration Analog	4	10	10	100 ms	M	Wing
Wing Configuration Discrete	20	1	10	10 ms	M	Wing
Tail Surfaces	6	12	50	10 ms	H	Tail
Landing Gear Analog	1	10	10	50 ms	L	Landing Gears
Landing Gear Discrete	20	1	10	50 ms	M	Landing Gears

Servo electronics are currently included within the flight control system in the avionics bay. In the future, the electronics will most likely be included with the actuators. This will be the case by the end of the target time period, and may also be true at the beginning of the time period for some of the actuators. This shift will not significantly change the load on the communications but will affect its physical geometry. The distinction will be made when summarizing the total requirements.

The flutter control will probably be performed with a dedicated control loop, either locally or centrally. However, the data requirements are retained within the communication system to hold the option open.

3.3 NAVIGATION SENSORS

The navigation sensors are given in Table 4. Most of these data requirements are moderate and well defined. It is likely that the Global Positioning System (GPS) will be implemented at least by the end of the time period. The GPS function is assumed to be partially integrated. The basic control of the receivers will be retained in the GPS unit itself. The navigation equations, however, will be solved in the central computers where other navigation data will be combined to provide both mutual calibration and error detection functions. The highest data rate requirement will be line of sight velocity data from inertial sources that is fed back to the receiver units to improve the signal tracking loops.

Weather radar is included as a navigation sensor. An ARINC standard has been established for the weather radar data output from the transmitter-receiver unit. This data is at a very high rate so dedicated lines are assumed that are not included in the primary communication system.

3.4 COMMUNICATIONS EQUIPMENT

The parameters involved with radio communications are given in Table 5. The normal radio equipment will place a small load on the data communication system. The only significant function will be the transfer of tuning and control messages to the transceivers.

The load on the data communication system will be primarily due to the data link functions of the radio communications system. The aircraft has full capability for both ATC DABS data link and company ARINC data link throughout the

TABLE 4

Navigation Sensors

Parameter	Quantity	Resolution (BITS)	Samp/Sec	Resp. Time	Criticality	Location
VOR Angle	2	12	16	20 ms	M	AB
DME Dist	2	16	16	20 ms	M	AB
ADF Bearing	2	12	16	20 ms	M	AB
ILS Localizer	2	13	16	20 ms	H	AB
ILS Glide Slope	2	13	16	10 ms	H	AB
Marker Beacon	6	1	1	100 ms	M	AB
Radio Altitude	2	17	20	10 ms	H	AB
MLS Azimuth	2	13	10	10 ms	H	AB
MLS Evaluation 1	2	13	10	10 ms	H	AB
MLS Evaluation 2	2	13	10	10 ms	H	AB
MLS Range	2	13	10	10 ms	H	AB
MLS Data	2	90	0.1	1 sec	M	AB
GPS Receiver	8	32	0.5	10 ms	M	AB
GPS Data	1	1500	.008 (2/min)	N/A	M	AB
GPS Line of Sight Vel In	4	16	50	10 ms	M	AB
Weather Radar Attitude Stab	2	14	50	10 ms	M	Nose
Weather Radar Data	2	1600	512	N/A	M	AB
Navigation Frequency and Mode Control	10	21	5	100 ms	H	AB

TABLE 5

Radio Communications Equipment

Parameter	Quantity	Resolution (BITS)	Samp./Sec	Resp. Time	Criticality	Location
Comm Receiver Frequency and Mode Control	5	21	5	100 ms	H	AB
Transponder Control	2	18	5	100 ms	H	AB
DABS Data Link	4	88	1600 16	100 μs* 250 ms**	H	AB
ARINC Data Link	1	220	.5	1 sec	L	AB
Passenger Service Terminal	1	220	.5	10 sec	L	Cabin

*Non Buffered

**Buffered

target time period. A dedicated buffer is used with the DABS data link so that the data communications system can be relieved from tight timing requirements.

3.5 COCKPIT EQUIPMENT

The tasks performed in the cockpit are involved in almost all aircraft functions. These tasks are divided into five areas: the primary flight controls (wheel, pedals, etc.), the primary flight displays, the aircraft operational control and display (flight path commands, autopilot mode selection and display, system status, etc.), aircraft systems control and display, and terminals for communicating with the avionics system. The estimated parameter list is given in Table 6.

During the target time period, the mechanical linkage will presumably be removed. The primary flight control thus becomes flight crucial. This task will place the highest reliability requirement on the communication system from the cockpit.

The primary flight displays and the great majority of aircraft system displays will be multifunctional, using CRTs or some newer technology. These displays will normally be generated in electronic units mounted in the primary electronics bays. The communication between the display generators and display indicators are very high frequency video signals which remain dedicated and do not affect the communication systems. The basic data input into the display generators will be included in the communication requirements. The other cockpit data requirements are more moderate and are at the levels listed in Table 6.

3.6 ENGINE AND AIRCRAFT SYSTEM MONITORING, CONTROL, AND SUPPORT

The communications necessary to support the monitoring, control, display, and maintenance aides for the engines and all of the assorted aircraft systems, are primarily distinguished by the large number of different signals scattered throughout the aircraft. Table 7 gives a rough estimate of parameters that can be presently identified for each of the major systems. Most likely, several more signals will be added, particularly for maintenance support purposes. To account for these additional parameters, the total load on the communication system doubles that shown in Table 7.

TABLE 6

Cockpit Controls and Displays

Parameter	Quantity	Resolution (BITS)	Samp./Sec	Resp. Time	Criticality	Location
Cockpit Primary Controls						
Control Wheel	6	12	50	10 ms	VH	Cockpit (CP)
Pedals (Rudder & Brakes)	6	12	50	10 ms	VH	CP
Trim	9	1	10	50 ms	H	CP
Flaps	3	8	10	50 ms	H	CP
Speed Brakes	3	1	10	50 ms	H	CP
Nose Wheel Steering	3	8	10	50 ms	M	CP
Primary Flight Displays						
Display Indicators	4		Dedicated (> 10 MHz)			CP
Flight Display Generator	2	576	50	10 ms	H	AB
Systems Display Generator	2	528	10	50 ms	H	AB
Flight Operational Control and Display	1	288	10	50 ms	H	CP
Systems Control and Display	1	50	10	50 ms	H	CP
Avionics System Terminal	2	80	10	50 ms	M	CP
Cockpit Printer	1	640	1	N/A	M	CP

TABLE 7

Engines and Aircraft Systems

Parameter	Quantity	Resolution (BITS)	Samp./Sec	Resp. Time	Criticality	Location
Aircraft Engine	4	96	10	50 ms	M	Wings
Hydraulic	1	96	1	100 ms	M	Mid Fuselage(MF)
Fuel	1	156	1	100 ms	M	MF
Electrical	1	168	1	100 ms	M	MF
Pressure/Oxygen	1	180	1	100 ms	M	MF
APU	1	102	10	100 ms	M	Tail
Airconditioning	1	180	1	100 ms	M	MF
Bleed Air/Anti-Ice	1	24	1	100 ms	M	Wings
Flight Data Recorder	1	768	1	N/A	M	Tail

3.7 MISCELLANEOUS EQUIPMENT

Listed in Table 8 are two other pieces of equipment most likely used in support of several functions: One is a flight data storage unit which stores data for use in flight management and navigation, and can also store flight manual and maintenance manual type data for display in the cockpit. Provision must be made to update this data periodically, with some operational data to be updated every flight. Navigation reference data must be updated at established times, such as every 60 days. The update may actually replace the memory medium, e.g., tape or by data link.

The other device listed is an audio generator. This device would be commanded by the system to generate the inputs into the audio system for the warning functions, as well as be used for some of the ATC and company data link messages.

3.8 SUMMARY OF DATA REQUIREMENTS

The data requirements for the various types of equipment are summarized in Table 9. Almost all parameters are transmitted as 16 bit words, and discretes are packed into 16 bit words. The flight data storage system rates are not included because this transfer should occur during a non-critical time, probably on the ground. Flutter control is included, while weather radar data is not because of the high data rates.

Table 10 gives the data requirements by approximate location in the aircraft, assuming both that the servo electronics are in the avionics bay and alternatively located with the servos. The numbers in parentheses are for a system with flutter control parameters removed.

TABLE 8

Miscellaneous Equipment

Parameter	Quantity	Resolution (BITS)	Samp./Sec	Resp. Time	Criticality	Location
Flight Data Storage Unit	1	8000	1	N/A	M	AB
Audio Generator (Tone and Voice Synthesis	2	80	1	100 ms	H	AB

TABLE 9

Summary of Communication Requirement

Equipment Class	Words/sec
Flight Data Sensors	1744
Flight Control Actuators	3500
Navigation	641
Communications	130
Cockpit	3191
Aircraft Systems	446
Miscellaneous	10
	9662
Bits/sec	155K

TABLE 10

Communication Requirements by Area

Location	Central Servo Electronics	Dispersed Servo Electronics
Avionic Equipment Bays	131.5k(98.5k)	60k
Nose & Nose Gear	2k	3.5k
Wing	1k	57.5k(24.5k)
Tail	2k	15.5k
Cockpit	17k	17k
Fuselage/Cabin/Main Gear	1.5k	1.5k

Chapter 4

ALTERNATE SYSTEM CONFIGURATIONS

This chapter discusses configurations of total systems that might be used to organize the basic hardware elements described in the preceding chapter. First, several factors are discussed that will influence the system design. Next, a broad range of potential system configurations is created. This range is then narrowed down to three alternative system designs that are representative of the configurations expected to develop through the target time period.

4.1 SYSTEM DESIGN CHARACTERISTICS INFLUENCING THE COMMUNICATION SYSTEM

Some characteristics of the potential avionics system configurations are discussed that influence the communication system. These include: the degree of functional integration, the physical location of the equipment, and the configuration of the central fault-tolerant computer system.

4.1.1 Extent of Functional Integration

One design characteristic which will have significant influence on communications is the degree to which individual functions are kept separate or integrated into the system. The degree of integration can influence the load on the communication system in either direction, as illustrated in the following examples:

The first example, the flutter control function, illustrates how greater integration can increase the amount of data handled. The flutter control function, previously described, requires a very high data rate. If the control function is integrated into a central processor, high sensor and command signal data rates must be handled by the primary communication system. If this control loop is closed locally, there is essentially no load on the communication system due to this function. The second example, the air data function, is one in which a greater degree of integration reduces the amount of data communicated. In current systems, a Digital Air Data System (DADS) processes measurements from the total and static pressure sensors, a total temperature probe, and angle of attack sensors, to produce a set of parameters that can be derived from these measurements. The DADS produces as many as 16 output parameters, including: barometric corrected and uncorrected altitude, altitude rate, computed airspeed, Mach number, true airspeed, etc. In a system where other functions using air data are also not integrated, these parameters must be distributed to many different locations. In the current system, the DADS output may go to as many as 19 other systems, such as: redundant flight control, flight augmentation, flight management, and warning computers, as well as the flight instruments, transponder, and cabin pressure controller. In a more integrated system, only the basic sensor measurements are communicated. Also, assuming most other user functions are integrated, this data does not have to be distributed to many different places.

4.1.2 Physical Location

Another system characteristic which will have an important influence on the communication system is the physical location of the electronics, or the degree the hardware is centralized or dispersed. Factors that influence the physical location of electronics are:

1. Environment
2. Maintainability
3. Wiring costs
4. Damage tolerance

Environment and maintenance considerations will require that the equipment be concentrated in central locations with good environmental control and easy access. Wire length and damage tolerance considerations will require that equipment be dispersed and placed closer to the equipment being serviced. The balance between these conflicting trends is determined by the pace of technological development. As electronic devices become available to provide very high reliability in severe environments, the balance will shift to more dispersed systems.

For the next generation of aircraft to start development at the beginning of the target time period, the most important factor is the environment, followed closely by maintenance. Aircraft operators, especially airlines, want to improve the failure rate of electronics and thus reduce maintenance costs. One of the major causes of failures is environmental stress, particularly temperature. New installation concepts are being developed particularly by the AEEC for the airline industry. The first phase of the work of the New Installations Concepts (NIC) Subcommittee of AEEC has resulted in ARINC Characteristic 600[8], which will be used for the generation of aircraft currently being developed, including the Boeing 767 and 757. The new ARINC characteristics allow electronic modules to be smaller, and to be more protected from the environment. Of particular interest is self-contained cooling, which operates when the aircraft is on the ground and the primary aircraft environmental control system is not operating. Following phases of the NIC activity have already been identified which further improve the environment for electronics. This trend will encourage the electronics to become more concentrated as long as suitable precautions can be taken to avoid common mode failures due, for example, to physical damage or fire. If this trend prevails, a majority of the electronics in an aircraft may be relatively close to each other in a substantially protected and controlled environment. The nature of the communication system that is most effective in this situation may significantly vary from one which supports equipment distributed throughout the aircraft in an arbitrarily poor environment.

In the near term, the dominant factors will most likely draw the equipment together. Electronic equipment is thus most likely to be in centrally located equipment bays that can be environmentally controlled and conveniently maintained. Some equipment previously dispersed in the aircraft may now be brought into central locations where the environment can be more easily controlled.

A competing trend arises from the advantages of embedding electronics within many aircraft subsystems. This trend is motivated not only because these subsystems are getting more complex, and thus more difficult to control, but also because the development of electronic technology is making available high capability at low cost. Manufacturers of various pieces of equipment will probably use embedded electronics to improve the performance and/or reduce the cost of their equipment. The explosion in electronic technology can give significant opportunities to greatly improve the effectiveness of many existing devices, and make possible the use of completely new techniques. For example, simple digital processors are embedded inside pressure transducers. The electronics provide functions, such as temperature compensation and output signal linearization, to make it possible to use new types of highly accurate sensing devices.

Another example is high technology engines, which have become too complex to be controlled by hydromechanical controllers alone. Production military engines and the engines now being developed for commercial aircraft already have integrally mounted electronic controllers.

Another situation which may have even greater impact on the communication structure is flight control surface actuators. At least one manufacturer is interested in including the servo control electronics integrally with the servo. The moving of the servo electronics from the electronics bay to the actuators will probably be most influential in changing the nature of the communication system from one primarily concentrated in avionics bays to one distributed throughout the airplane.

The communication technology itself can influence the spread of electronics. If fiber optic links can solve problems such as lightning interference, active electronics will most probably be employed on the remote end of these links to convert the signals to a usable form. Once active electronics are established at remote locations, they can support both the local equipment and the communication system.

For many devices, electronic technology cannot provide the necessary reliablilty in the severe environments associated with the devices. However, as more advanced technology becomes available, electronics are likely to be dispersed throughout the aircraft, independent of any explicit decision by those responsible for the design of the total system. When this occurs, a more effective total system design can be produced by recognizing the existence of this dispersed electronic capability and by including it in the design concepts. For example, this dispersed electronics can support a more global communication structure. An assumption made here is that a majority of the electronics will be in centralized electronic bays at the beginning of the target time period, but that a greater percentage will be distributed in the aircraft by the end of the time period.

4.1.2.1 Physical Location Alternatives

These trends can now be used to identify a range of physical locations that might be used during the target time period. A trade-off analysis is performed to distinguish the relative characteristics of these locations. This information is used to narrow the alternatives down to the three that become the basis for the system configurations used in the remainder of this study. The system defined at one end of the range will have almost all electronics in one location. This choice of location represents some retreat from current practice. Now, a majority of the electronics are located in a primary avionics area, usually near the nose of the aircraft under the cockpit. Much equipment is in other locations, however, such as in the wing root area, tail, and various other locations. This more concentrated configuration could result from equipment being drawn into a common location to take advantage of special environmental control equipment that may be incorporated in future aircraft. Nonetheless, this configuration is included in this study to provide a baseline and a logical extreme for the requirements of the communication structure.

Electronics may be dispersed from this one location option for at least two reasons: One reason is to put the electronics closer to the equipment being serviced. This move could substantially reduce wiring and installation costs and possibly improve performance. The other reason is to reduce the probability that a common event, such as damage, could cause complete failure of a critical function.

The next location alternative defined for this study is to separate the single location into two or three compartments in generally the same area of the aircraft. These compartments will be sufficiently separated or protected so that the probability of a single survivable event damaging equipment in more than one location will be extremely small. These locations may or may not be related to the logical organization. For example, a dual-dual system may be put in two locations, and a triplex system in three, or a triplex system can be placed in two locations as long as probable damage at one location will not cause loss of a critical function. If a correspondence exists between the logical and physical organization, the redundancy within a compartment may be relaxed for items like power supplies or communication buses.

The next extension in location alternatives is to move the electronics closer to the equipment being serviced. The primary driver in this process is the flight control servo electronics which may require as many as 13 wires for each channel. Flight critical fly-by-wire and active control functions require significantly larger numbers of actuator channels than at present both for redundancy and additional aerodynamic surfaces. These actuators are almost all located in the wings or tail. By creating electronics areas in the wing root area and aft fuselage, considerable wire can be saved. Within these three general areas, nose, wing root, and tail, the electronics can be located together or again separated into two or three compartments at each general location.

Until now, there has been no significant disadvantage from environmental or maintenance considerations. All locations have essentially the same opportunity for environmental control and maintenance access. The only significant cost may be that special environmental equipment may have to be duplicated and maintenance personnel may have to visit more than one area to make repairs.

The next step in dispersing electronics involves moving outside the environmentally controlled fuselage, thus considerably increasing the environmental and maintenance disadvantages. The final two options for this study create additional areas for electronics both outside the fuselage in the wings and tail and embedded in the using equipment.

The embedded alternative is most easily defined. Here, the electronics are included in the equipment being serviced. Much of the electronic equipment, such as central computers, navigation sensors, and communication equipment, will be located in central equipment compartments. Electronics associated with other aircraft equipment, such as actuators, engines, and environmental control systems, will be embedded directly in the equipment being serviced. This embedded electronics will be recognized in the total system design and must be serviced by the communication structure.

Finally, a physical location option is defined that is a compromise between the embedded system and those systems with all the equipment in the fuselage; this option is called a multilocation system. Though incentives exist to move the electronics as close as possible to the equipment being serviced, it may not be desirable for environmental, space, or maintenance reasons to embed the electronics in the equipment. The multilocation system would thus establish remote electronics areas in locations such as: the wing trailing edge, engine pylon, and tail, where the environment is less severe than it might be on some of the equipment, and where maintenance access is reasonable.

The range of possible locations studied is summarized in Table 11. The following section compares these locations and narrows down to three the number to be used in the subsequent analysis of communication structures.

4.1.2.2 Comparison of Physical Locations

A comparison of these physical location options is made in four areas: wire lengths, damage tolerance, environmental penalties, and maintainability. Rough quantitative comparisons are made of the wiring differences, while the other comparisons are qualitative.

To estimate relative wire lengths, assumptions are made about the number of wires involved in servicing the various pieces of aircraft equipment. These assumptions are listed in Table 12. The presumed size of the aircraft and the

TABLE 11

Location Options Considered

1.	One location:	One compartment
2.		Two compartments
3.		Three compartments
4.	Three locations:	One compartment each
5.		Two compartments each
6.		Three compartments each
7.	Multilocation	
8.	Embedded	

equipment locations are shown in Figure 3. The calculation of estimated wire length is given in Table 13. The three alternative configurations in the same general location will have essentially the same wire lengths. For all configurations, except the ones in one location, the wire saved will be offset to some extent by the wire necessary to interconnect the equipment locations. This amount of wire depends on the communication technique used. The amount of wire involved is relatively small compared to the wires necessary to service the equipment and will thus not significantly effect the results. A representative amount is used here.

These results show that the biggest change in the amount of wire occurs when going from the one location systems to the three location system. The percentage reductions for the multilocation and embedded systems are less but still significant.

Damage tolerance is a concern for a system contained in a single compartment in a single location. The results of the damage probability study discussed in Chapter 2 show that the probability of damage to a single location can be as high as 10^{-8} per hour. This probability can be reduced to acceptable levels with some separation or protection between compartments so one event is unlikely to damage all redundant equipment needed to perform any critical function. Care must also be exercised in systems where equipment is placed in three different locations in the aircraft to assure that no particular function is vulnerable to damage. For example, to put all of the pitch control electronics in a single compartment in the tail of the aircraft would be unwise. The damage study indicates that the tail area is more likely to be damaged than an area near the nose. The pitch control function will be protected by placing redundant pitch control electronics either in another location in the aircraft or by separate compartments in the tail. When

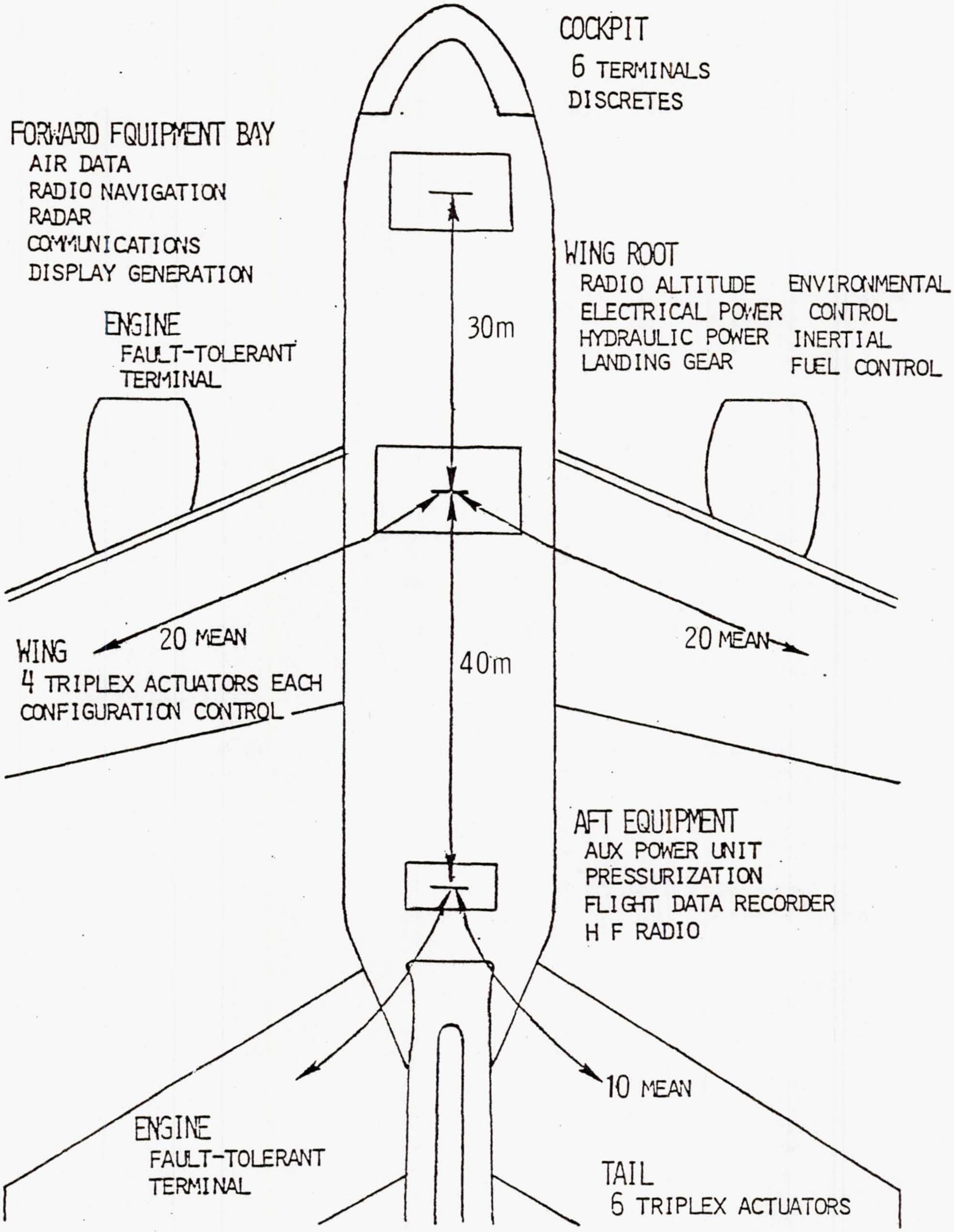


Figure 3: Assumed Wire Run Distances

TABLE 12

Assumptions for Wire Length Comparisons

EACH ACTUATOR CHANNEL:	
COMMAND	2
ENGAGE	3
RATE FEEDBACK	4
POSITION FEEDBACK	4
(PER ARINC 701)[9]	13
MID EQUIPMENT AREA:	
HYDRAULICS	42
FUEL	43
MAIN GEAR	50
ELECTRICAL POWER	50
PRESSURIZATION	16
AIR CONDITIONING	33
	234
WING:	
ENGINE (EACH 75)	150
BLEED/ANTI-ICE	19
	169
AFT COMPARTMENT:	
ENGINE	75
PRESSURIZATION	16
AIR CONDITIONING	14
	105

minimal precautions are made to increase damage tolerance, damage will not be a significant factor in determining location.

Environment and maintenance are discussed only qualitatively. Neither environment nor maintenance is significantly affected as long as the equipment remains in the pressurized fuselage. Only small penalties exist in going from systems located in generally one area to ones located in three areas. Some environmental control equipment may have to be duplicated and maintenance procedures may be slightly less efficient. These two factors become significantly more important when any equipment is located outside the pressurized fuselage. A multilocation system allows some consideration for avoiding the worst environments and provides loca-

TABLE 13

Wire Length Comparison

ONE LOCATION SYSTEM:

WING ACTUATORS	24 ACT X 13 WIRES X 50 M =	15,600
TAIL ACTUATORS	18 ACT X 13 WIRES X 70 M =	16,380
	234 WIRES X 30 M =	7,020
	169 WIRES X 50 M =	8,450
	105 WIRES X 70 M =	7,350
		54,800

THREE LOCATION SYSTEM:

WING ACTUATORS	24 ACT X 13 WIRES X 20 M =	6,240
TAIL ACTUATORS	18 ACT X 13 WIRES X 10 M =	2,340
MID EQUIPMENT	234 WIRES X 3 M =	702
WING EQUIPMENT	169 WIRES X 20 M =	3,380
AFT EQUIPMENT	105 WIRES X 5 M =	525
BAY INTERCONNECT	4 BUSES X 6 WIRES X 30 M =	720
	4 BUSES X 6 WIRES x 70 M =	1,680
		15,587

SAVINGS 39,213 M OR 72%

MULTI LOCATION SYSTEM:

WING ACTUATORS	24 X 13 WIRES X 6 M =	1,872
TAIL ACTUATORS	24 X 13 WIRES X 6 M =	702
MID EQUIPMENT	234 WIRES X 2 M =	468
WING EQUIPMENT	169 WIRES X 3 M =	507
AFT EQUIPMENT	105 WIRES X 3 M =	315
LOCATION INTERCONNECT	4 BUSES X 6 WIRES X 60 =	1,440
	4 BUSES X 6 WIRES X 80 =	1,920
		7,044

SAVING 47,756 OR 87%

EMBEDDED SYSTEM:

TERMINAL INTERCONNECT

ASSUME NETWORK	6 BUSES DEEP THROUGH FUSELAGE AND	
	3 BUSES DEEP OUT EACH WING	
	6 BUSES X 6 WIRES X 80 M =	2,880
	2 X 3 BUSES X 6 WIRES X 30 M =	1,080
		3,960

SAVING 50,840 M OR 93%

(ASSUME 1 TWISTED SHIELDED PAIR = 3 WIRES) tions with reasonable access for maintenance. However, it will not likely be cost effective to provide any special equipment to control the environment at multiple locations. The embedded electronics is completely at the mercy of the equipment in which it is located. The environment may be considerably worse and maintenance may be complicated if the electronics cannot be removed without removing the equipment in which it is embedded.

A summary of the results of the comparison of physical locations is given in Table 14. The environmental and maintenance factors are weighted from 0 to 10 where 10 is taken as ideal and numbers less than 10 correspond roughly to the relative standings of the locations with respect to the ideal.

TABLE 14

Summary of Physical Location Comparisons

	ONE LOCATION	THREE LOCATION	MULTI LOCATION	EMBEDDED LOCATION
DAMAGE TOLERANCE	10^{-8}	$10^{-9}/10^{-11}$	$<10^{-11}$	$<<10^{-11}$
WIRE LENGTH/ COST SAVINGS	0	72%	87%	93%
ENVIRONMENTAL CONDITIONS	9	9	3	1
MAINTAINABILITY	9	8	5	0

The systems placed in three locations in the aircraft can obtain a majority of the potential savings in wire length without significant disadvantages in environment or maintenance. A multilocation system can save an additional 15% in wire. This additional wire savings may not compensate, however, for the disadvantages in environment and maintenance. The embedded system can save an additonal 21% in wire but has greater disadvantages in other categories. An embedded system will not be chosen on the basis of wire savings alone. As technology develops toward the end of the target time period to provide components with a high reliability in a severe environment, electronics are likely to be embedded to increase the effectiveness of the remote equipment itself, as previously discussed.

The location alternatives can now be reduced to a representative set for the communication study. As far as the communication requirements are concerned, little distinction exists among configuration alternatives where the equipment is found in one or more compartments in the same general location. When communication structures are studied to the level of detail where this distinction is important, appropriate extensions can be made to account for the separate compartments. The communication structures can be adequately studied using the smaller subset of configurations obtained by merging the options where equipment is located in essentially the same places.

The multilocation system has also been eliminated since it is not significantly different from the embedded system as far as communication requirements are concerned, and thus does not significantly contribute to the study. Nor does it appear to offer sufficient advantages to the total system design for extensive use in future systems.

The three basic system configurations chosen for this study are thus: a one location system, a three location system, and an embedded system. The one location system provides a logical extreme in the range and forms a good baseline most representative of current systems. The three location system is chosen as the one that appears most efficient for near term systems. The embedded system provides the other logical extreme and may be used at the end of the target time period.

4.1.3 Computer Configuration

The central fault-tolerant computer system could also have a significant impact on the communication structure. Traditionally, computers have been large, relatively expensive, and placed in some central location. However, with the explosion of microprocessor technology and the need for multiple interconnected computers, the central computer complex will most likely be dispersed in the aircraft. For example, in the three location system, a part of the computer could be in each location.

A dispersed central computer could have an obvious impact on the nature of the communication structure. Depending on the particular design of the computer system, external equipment may be connected to the computer at each location. The various parts of the computer system will be interconnected by its own data transfer technique. In these cases, the central computer will create a common data base. The location-to-location communication thus implicitly occurs within the computer system. The need for a communication structure to handle a large amount of data over long distances in the aircraft is reduced. Thus, the optimum design for the communication structure will probably be different from one responsible for communicating data throughout the aircraft to and from one central location.

Even though a dispersed fault tolerant computer may be attractive for some future systems, it is not considered in this study for the following reasons. First of all, existing fault-tolerant computer designs are not dispersed, largely because it is difficult to do so without enlarging the system's cross section to damage. Second, the internal communications among the elements of a fault-tolerant computer are an integral part of the design of the computer and are beyond the scope of this study. The effective design of a system of this type requires the integration of the design of a particular fault-tolerant computer with the design of the communication with the external equipment. Since this study is not concerned with the design of fault-tolerant computers themselves, it is assumed that the central computer is in one location and the communication system under study must transfer all data from the various locations in the aircraft to this one location. Also, a reasonable amount of care in the design and some protection will reduce the probability that a damage event will cause total failure of the computer system.

The assumption that the computer is in one location also places the highest requirements on the communication system. The results from this study apply to most systems with a distributed central computer if proper adjustments are made. Each of the three alternative system configurations will now be discussed in greater detail to create the environment for the study of communication structures.

4.2 ONE LOCATION SYSTEM

An overall diagram of the one location system is shown in Figure 4. A majority of the electronic equipment is found in one or more compartments at this one location which is in some convenient place, usually under the cockpit near the nose gear and forward of the cargo compartments.

The electronics are packaged in standardized units and housed in environmentally controlled enclosures. These units contain: the fault-tolerant computer, all the electronics necessary to provide sensor inputs, effector outputs from the system, and the equipment necessary to support the system, such as power supplies and environmental control equipment. To create a realistic environment for the communication structure, some electronics must be outside this

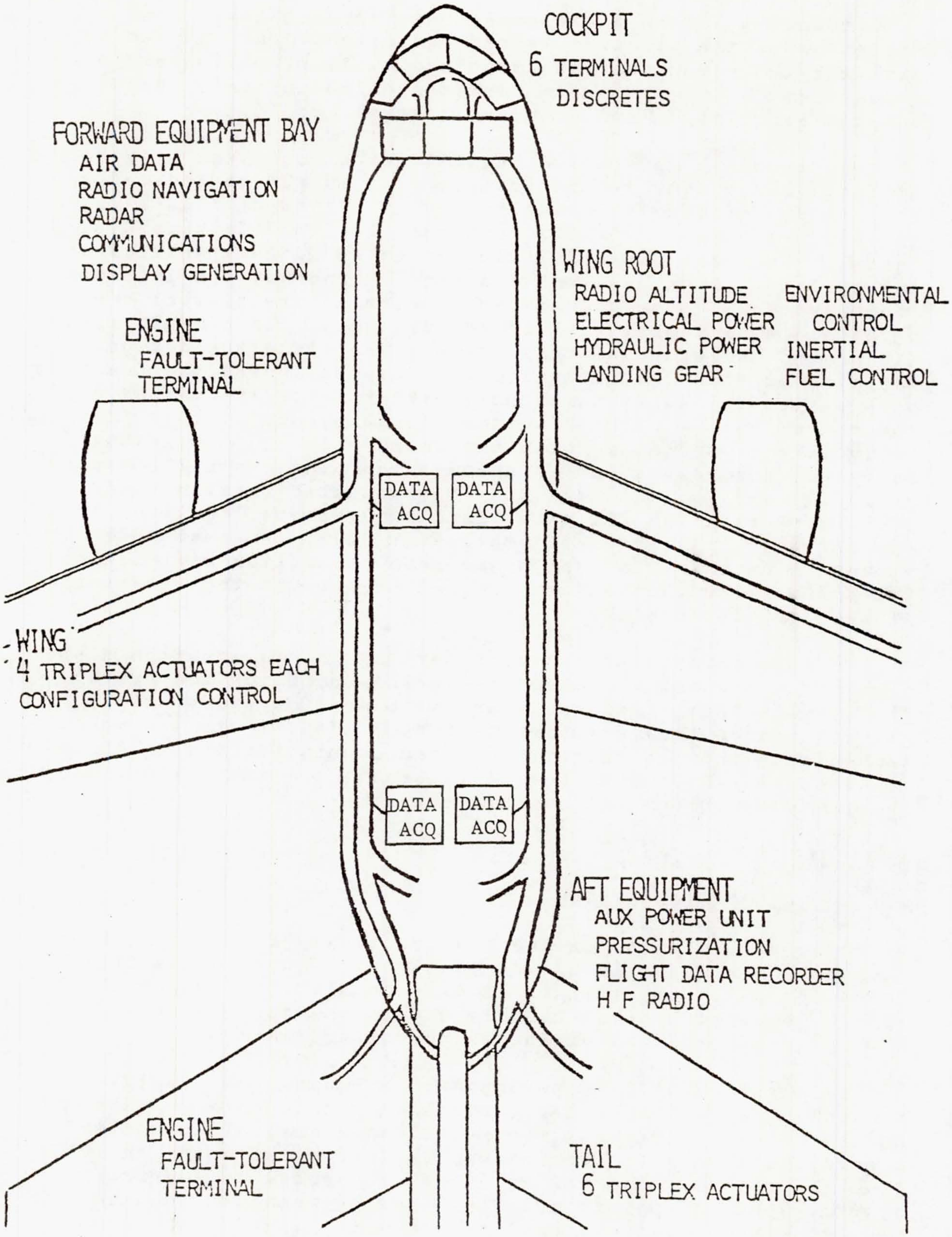


Figure 4: One Location System

primary location. Of course, electronics will be in the cockpit to support the pilot controls and diplays. Electronic controls are already on the engines and will certainly continue to be in future aircraft. A significant number of input signals in the wing root and tail areas of the aircraft require remote data acquisition equipment, and this system description will thus include these remote electronics.

The following paragraphs describe a set of equipment designed to meet the system requirements by providing the organization of the sensors and effectors described in Chapter 3. The physical packaging of the equipment is first described briefly. Next, the units involved in the most flight critical functions are described. The remaining modules are then briefly identified. The function and communication requirements of the remote electronic units are described, and finally, a list is compiled of all equipment, along with the communication requirements for each unit.

4.2.1 Mechanical Packaging

The equipment in the primary avionics location should conform to a later phase of the NIC packaging now introduced in the commercial avionics industry. The form factors and connectors should remain the same as described in ARINC Characteristic 600. The only significant change expected is a more closely controlled environment.

The ARINC Characteristic 600 provides for the electronic modules to have a common height and depth with incremental widths. The sizes of the units, called Modular Concept Units (MCU), are listed in Table 15. A typical installation is shown in Figure 5. Three types of low insertion force connectors are available. The smallest will handle 120 signal pins and several power and special purpose pins. The largest will handle 600 signal pins and more special purpose connections. The connectors permit wire wrap techniques to be used to provide interconnection between units and with other connectors for the cables that interface with the rest of the aircraft. In some installations, the interconnect backboard may be removable from the aircraft to reduce the initial costs of aircraft wiring and to greatly simplify modifications. The modules comprising the system for this study will probably require five to six shelves, approximately four feet long.

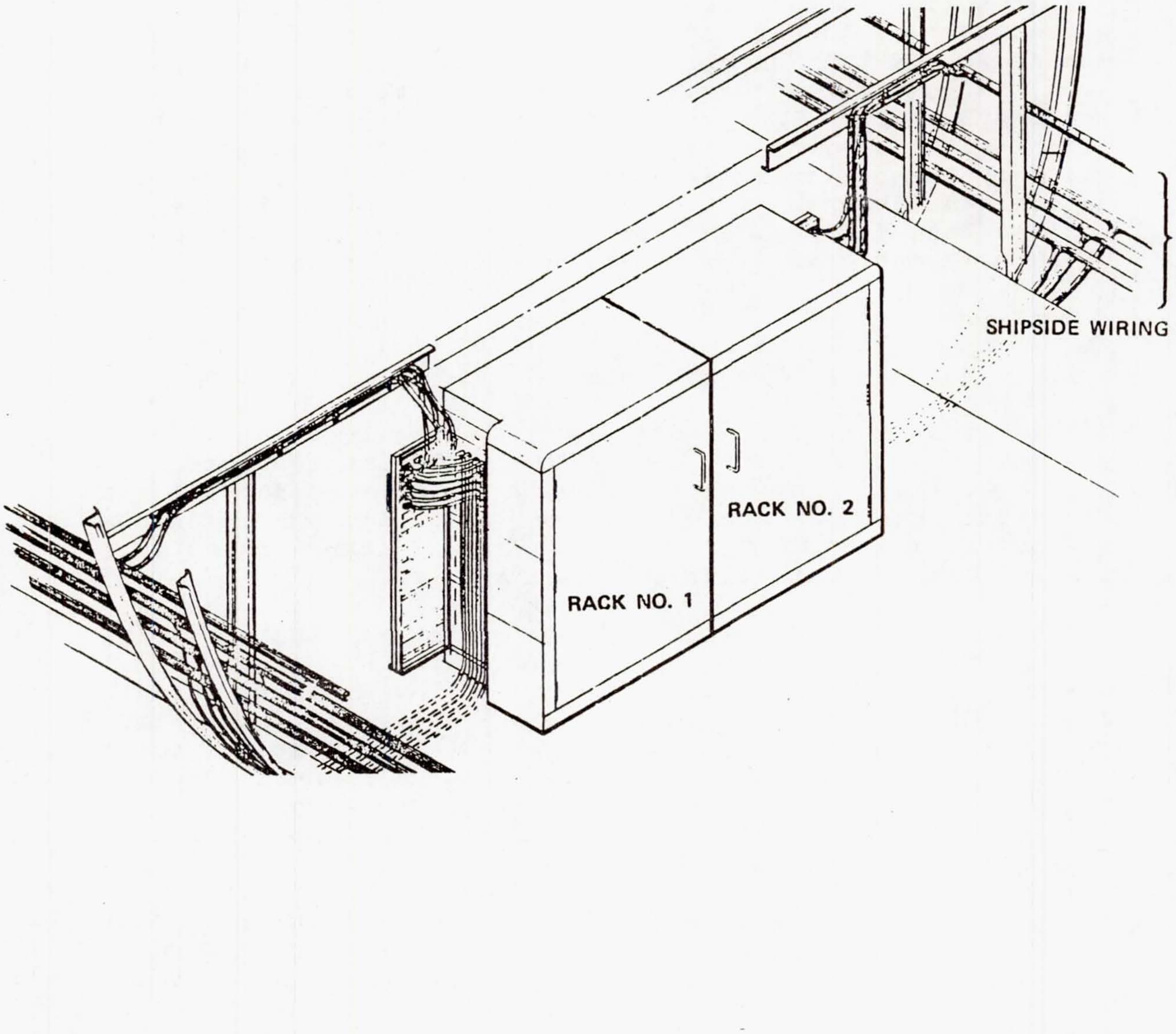


Figure 5: Avionic Rack Installation

TABLE 15

Modular Concept Unit (MCU) Sizes

MCU	WIDTH (MM)	LENGTH (MM)	HEIGHT (MM)
1	25.1 (1.0 IN)	318 (12.5 IN)	194 (7.64 IN)
2	57.2	"	"
3	90.4	"	"
4	124.0	"	"
5	157.2	"	"
6	190.5	"	"
7	223.3	"	"
8	256.3	"	"
9	289.3	"	"
10	322.3	"	"
11	355.3	"	"
12	388.4	"	"

4.2.2 Module Descriptions

4.2.2.1 Fault-Tolerant Computer System

The fault tolerant central computer is housed in some number of units depending on the design of the particular system. The assumption is made that the computer will have provision for a variable number of interface ports necessary to support the communication system. The central computer also is assumed to have the primary responsibility for the control, monitoring, and redundancy management of the communication system.

4.2.2.2 Servo Electronics Module

These modules are a key part of the flight control function. They provide the interface between the communication structure and the actuators and will normally contain: digital-to-analog (d/a) converters, the servo positioning control electronics, and, possibly, actuator monitoring and equialization circuits.

A diagram of what may be contained in a servo electronics module is shown in Figure 6. The basic elements of the design include: the interface with the digital communication system to accept commands from the central computer, a d/a converter to put the command in the proper form for the servo electronics, and the servo electronics themselves, which command the actuator to the desired position using position and possibly rate feedback signals. The module may also contain: the drives for the engage discretes to the actuators, equalization circuits that receive delta pressure signals from other channels of a force-voted redundant actuator to prevent force fights, and monitoring circuits that use information such as the cross wired delta pressures to detect actuator failures. Most likely, a servo electronic module will be designed to control more than one actuator, either by duplicating the circuits within the unit or by demultiplexing the outputs of the d/a converter using sample-and-hold circuits. Redundant electronics in two different servo modules may also control a single actuator channel. This redundancy would achieve a more balanced design between the relative costs and reliabilities of the actuator versus the electronics. A single actuator channel can have a mean time before failure (MTBF) as high as 100,000 hours, where the electronics may have an MTBF around 10,000 hours but be considerably less expensive. Thus, the total design may be more balanced if an actuator continues service after a failure of the servo electronics channel by the utilization of redundant electronics and some technique like dual windings in the electro hydraulic valve. This redundancy can have a significant impact on the communication load by requiring two commands to be communicated for each actuator channel.

Most likely, a basic design principle of future systems will be the complete monitoring of all units so any failure will be detected and the failed unit will be positively identified. In some cases, this may be performed by built-in test equipment. In other system designs, however, a higher level of failure coverage and a more effective total design can be achieved if the monitoring capability is provided by other equipment and that the monitoring process be controlled by the central system. In the system design assumed for this study, the servo electronics modules are monitored by feeding the output signals back into the system

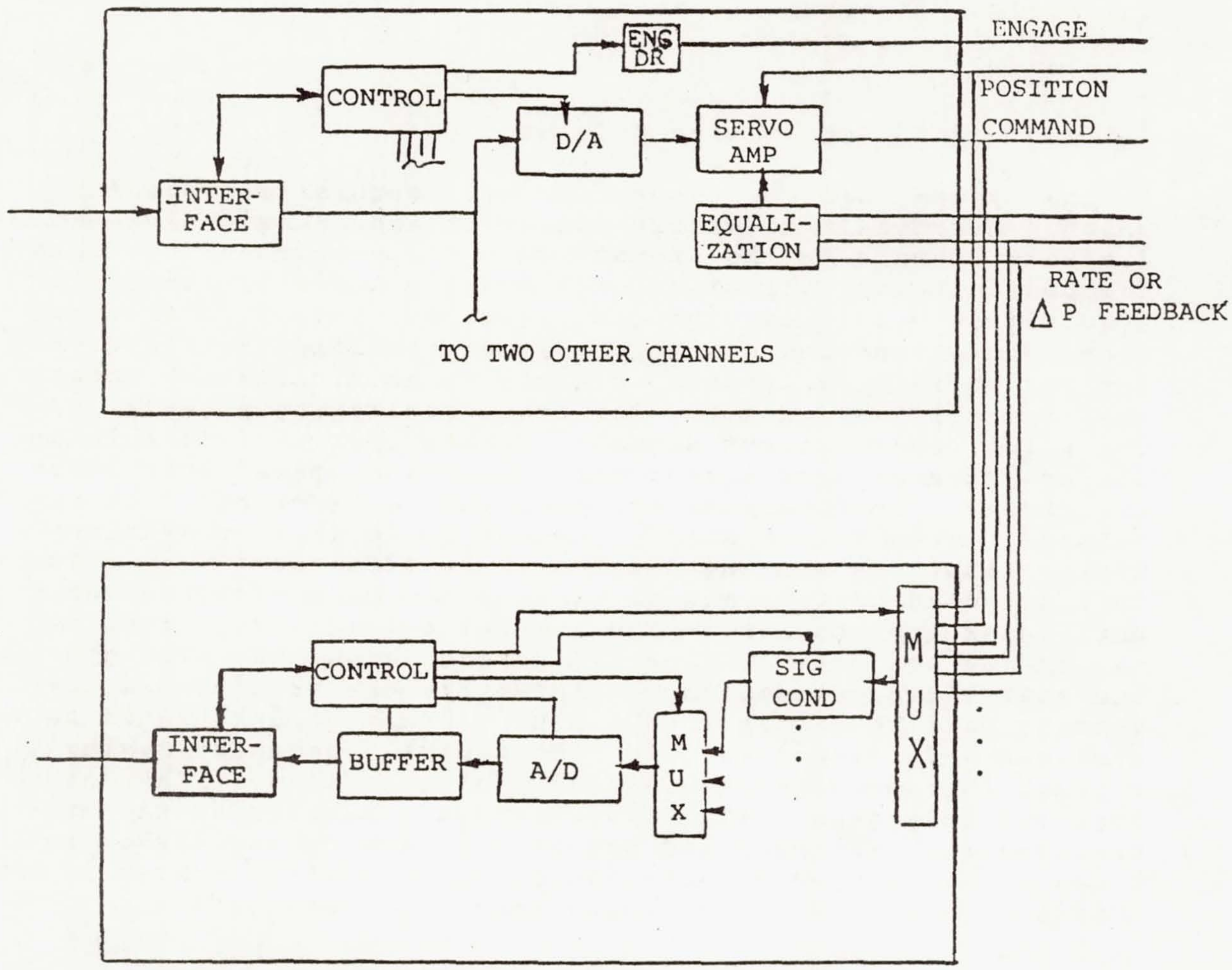


Figure 6: Typical Servo Electronics and Data Acquisition Units

using the data acquisition modules described next. The servo modules are then monitored by comparing the measured output with the intended command sent to the module. For the most critical channels, it may be necessary to feed the output commands into two different data acquistion modules for positive identification of the failure. Again, these additional signals can have a significant impact on the total load on the communication system.

4.2.2.3 Data Acquisition Modules

The system will use several data acquisition modules which convert all necessary analog ac and dc signals and discrete signals to the proper form and interface them into the communication structure. A diagram of a typical data acquisition module is given in Figure 6. Each data acquisition module contains a set of signal conditioning circuits for the variety of typical signals on an aircraft. Among the most critical will be the servo monitoring signals and the pilot control input signals. These will include both dc and ac, such as from linear variable differential transformers (LVDT). Some form of standard unit will probably be developed, such as the Analog and Discrete Data Conversion System (ADDCS) now being defined by an AEEC committee. In this standard unit, a mix of signals can be programmed for a particular application. The signal conditioning circuits may or may not be multiplexed, depending on what will give the most efficient design. Presumably one or more a/d converters will be multiplexed. The resulting data would be buffered and transferred to the central computer system through the communication system when requested. The data acquisition process will be controlled primarily by the module itself. The sampling sequence and rate may either be fixed or programmed by commands from the central system as a function of flight phase or equipment failure status.

4.2.2.4 Power Supply Module

The electrical power conditioning and control module also has an important role in critical functions. A diagram of the module is shown in Figure 7. The module receives power from the auxiliary or ground power unit, and from the aircraft batteries. This module removes all power spikes, over-voltages, under-voltages, and interruptions caused by the raw supply sources. Since advancing technology reduces the size of the digital circuits, this design avoids the inefficiencies of a power supply in each module which would otherwise require a large percentage of a typical unit volume. Separate power supply modules also allow more flexi-

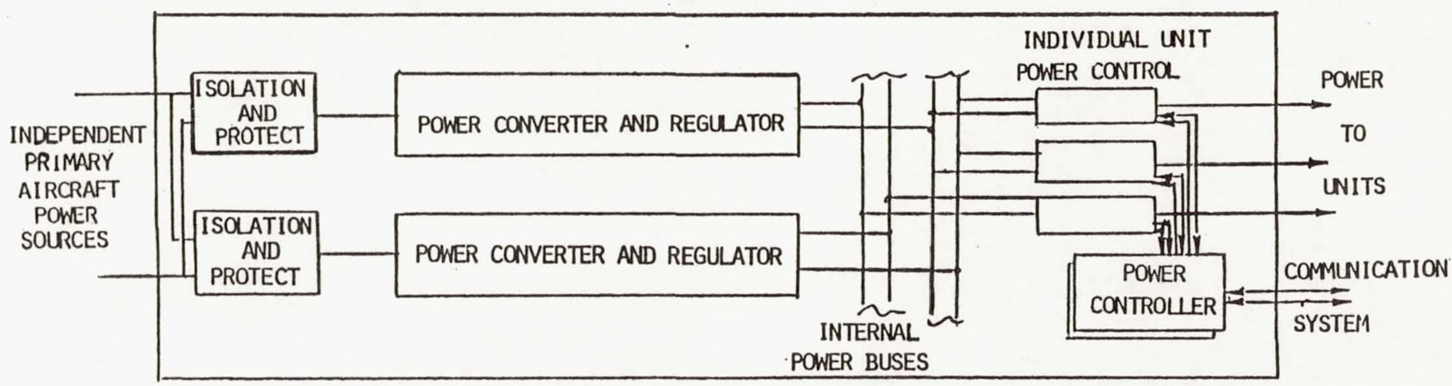


Figure 7: Typical Power Conditioning and Control Unit

bility in the reconfiguration of a system after failures. The module receives power from the aircraft primary generator buses,

Power from a power supply module is supplied to each of the other system modules through individual current regulator/circuit breaker circuits. The power supply module connects to the communication structure to allow the integrated system control of the power to the other modules. This ability has several advantages: First, the number of circuit breakers necessary in the cockpit is reduced. Next, and probably most important, this ability can be used in the overall redundancy management of the system. Power can be removed from a failed module, greatly reducing the probability that it will have any adverse effect on any good module. Finally, power control can remove power from a module not in opeation, particularly when the aircraft is on the ground and the engines and environmental control systems are not running. This feature could significantly improve the environmental control problem.

4.2.2.5 Other Modules

Other types of modules will be in the avionics compartments, as well. Many of these modules will contain the sensors needed by the aircraft systems. The inertial sensors will probably be most flight critical and have a high data rate. These sensors include both qyros and accelerometers and provide data for the inter-loop flight control functions, as well as the altitude and inertial heading data for outer-loop functions. The inertial data may also be utilized for inertial navigation or inertial smoothing of radio navigation data. In some unique situations, inertial sensors may have to be put at remote locations in the aircraft either because of structural mode interaction or to directly sense a structural mode being controlled, such as a wing bending mode or flutter. In the above instances, the sensors would either be wired to electronics in the avionics compartments or to a remote data acquisition unit. Another important sensor module will be for air data. The primary pressure sensors will most likely be in this module. Other sensors, such as angle-of-attack vanes, will be remote and hard wired to the electronics module.

Several modules will be devoted to radio navigation sensors, such as: VOR, DME, ILS, MLS, and Omega. Several radio communication modules will also be included: VHF, HF, DABS, and digital data link. Some modules will generate the symbology for the CRT type display in the cockpit, as well as the weather radar which will feed the radar data into the display generators. Finally, modules outside the central computer will perform the data format conversion necessary to interface with the communication structure to serve the remote electronic units.

4.2.3 Remote Electronics

4.2.3.1 Cockpit Electronics

The primary flight and aircraft system displays are serviced by display generation electronics in the primary avionics area, which are connected to the cockpit by dedicated wires. However, numerous controls and dedicated displays in the cockpit must be serviced by active electronics to eliminate an excessive number of wires. The most critical electronics in the cockpit service the flight operational control and display unit. This unit, sometimes called the autopilot controller or glare shield controller, is the primary means for the pilots to control the operation of the automatic flight control system. These controls include: the selection and display of the commanded flight parameters, such as desired heading, altitude, and speed; the commanded flight mode, such as control wheel steering; the automatic coupled modes, such as cruise, approach, and landing. In addition, this unit will provide the primary display status of the control system including the warning of degraded functional capabilty due to equipment failure. Because of the critical nature of this unit, redundant electronics will be involved. For this study, the unit will be serviced by two communication terminals for interface to the central system. Thus, the entire system will continue to function after any failure and have a functional reliability goal of 10^{-6} per hour. The controller is not fully flight crucial, however, since all critical functions can be performed either by other control units or by dedicated wires.

Another essentially equivalent unit controls the electrical, hydraulic, fuel, and environmental control systems, and may also be involved in the control of the engines. Because of the critical nature of these controls, this unit will also contain redundant electronics with two communication system terminals.

At least two terminals in the cockpit will allow the crew to communicate with the avionics system. These terminals will service a general purpose display and keyboard and operate like a conventional computer terminal. The unit will enter and review flight planning information, determine system status, allow manual involvement in the system reconfiguration process, and operate as a backup to the other controllers. This now gives a total of at least six terminals in the cockpit that must be serviced by the communication structure.

4.2.3.2 Remote Data Acquisition Units

The system design for this primarily one location system includes at least four remote data acquisition units wherever a concentration of signals exist: Two will be in the wing root area to service equipment there, such as: the environmental control, electrical, and hydraulic systems, as well as signals coming in from the wings. Two other units will also be in the tail area to service the auxillary power unit (APU) and possibly auxillary engine functions if the aircraft has engines in the tail.

These units will contain signal conditioners for a variety of different types of signals, including: ac, dc, synchro, and various kinds of discrete signals. The outputs of these signal conditioners would be multiplexed into one or more a/d converters. The resulting data will be buffered for subsequent transmission to the central system over the communication system. Non-critical signals would be used for status and maintenance monitoring and would be wired into one unit. More critical signals would be wired into both units in that area, thus increasing the load on the communication system. Most likely, any flight critical signals would be wired directly to the primary electronics area.

4.2.3.3 Engine Electronics

For this study, the engines will use full authority electronic control. The engine manufacturer will provide the electronic fuel controls; these will be mounted directly on the engine. The electronics will have sufficient redundancy to give a total electronic reliability significantly better than the engine itself. The primary thrust command will reach the engine through the communication structure. Thus, each engine will have two terminals to provide the necessary reliability. The engine electronics are not directly involved in gathering data that is not needed for the control of the engine itself and is thus not the responsibility of the engine manufacturer. These include: data needed for engine monitoring and maintenance trend analysis, the control and monitoring of engine accessories, such as generators, hydraulics, and engine bleed air. These signals will be wired into the wing root data acquisition units.

4.2.4 Summary of Terminals

The total number of terminals that must be supported by the communication system for the one location configuration is summarized in Table 16. A total of 66 terminals are in the primary electronics area, with a requirement to communicate 16K 16 bit words per second. In addition, a total of 16 remote terminals are distributed throughout the aircraft: 6 in the cockpit, 2 on each of 3 engines, and 4 remote data acquisition modules which require another 2K words per second for communication. Thus, a total of 80 terminals requires the communication of almost 18K words.

4.3 THREE LOCATION SYSTEM

The three location system will be similar to the one location system. The compliment of electronic modules will be essentially the same, only with different locations. The assumed set of modules for each location is shown in Table 17. The primary change will be the movement of the servo electronics modules to the wing root and tail areas closest to the actuators in service. The functions of the remote data acquisition units will be absorbed by data acquisition modules within the electronics areas. If advantageous, other sensor units may be moved to different areas. For example, the inertial sensor modules may be brought to the wing root area if closeness to the aircraft's center of gravity were an advantage.

The significant impact on the communication structure is that a great amount of critical data must be moved over longer distances between electronics areas. Thus, the nature of the long distance communication system may significantly vary from the one location system.

4.4 EMBEDDED SYSTEM

The equipment to be serviced by the communication system in the embedded system configuration remains essentially the same as the previous two system configurations. The only significant difference is the placement of much of the electronics. By the end of the target time period it is assumed that technology will have progressed far enough that electronics can be placed in almost any location without significant reliability, maintainability, size, or cost penalties. With this capability available, electronics will most likely be placed in almost every piece of equipment. The most crucial function, in terms of the communication structure, is the support of electronics attached to the flight control

TABLE 16

Sensor/Effector Units in the One Location System

UNIT	NUMBER	SIZE (MCU)	DATA (WORDS/RATE)	DATA RATE (WORDS/SEC)
SERVO ELECTRONICS	12	3	5/20 MS	3000
DATA ACQUISITION	8	4	4@ 16/20 MS & 48/SEC 4@ 64/SEC	7296
INTERIAL SENSORS	6	8	8/20 MS 8/100 MS	1920
AIR DATA	3	4	5/100 MS	150
VOR	2	2	2/100 MS	40
ILS	2	2	5/100 MS	100
MLS	2	2	4/100 MS 10/10 SEC	82
RADIO ALT	2	2	1/20 MS	100
TACAN	2	3	3/100 MS	60
ADF	2	2	1/100 MS	20
GPS	1	6	4/20 MS 16/2 SEC 100/2 MIN	209
TRANSPONDER	2	3	2/4 SEC	2
DABS	2	2	MAX 320/4 SEC NORM 4/4 SEC	2
VHF COMM	3	2	1/SEC	3
ARINC DATA LINK	1	1	14/2 SEC	7
HF COMM	1	6	1/SEC	1
VOICE/TONE SYNTH	2	1	20/SEC	20

TABLE 16

Sensor/Effector Units (Cont.)

UNIT	NUMBER	SIZE (MCU)	DATA (WORDS/RATE)	DATA RATE (WORDS/SEC)
WX RADAR	2	8	2/20 MS	200
FLIGHT DISPLAY GENERATOR	3	6	6/20 MS 30/100 MS	1800
SYSTEMS DISPLAY GENERATOR	2	6	33/100 MS	660
FLUTTER CONTROL	2	6	4/20 MS	400
POWER COND/CONT	3	8	1/SEC	4
TOTALS IN PRIMARY LOCATION	66			16076

REMOTE AVIONICS UNITS	NUMBER	DATA (WORDS/RATE)	DATA RATE (WORDS/SEC)
WING ROOT DATA ACQ.	2	128/SEC	256
TAIL DATA ACQ.	2	32/SEC	64
ENGINE CONTROL	6	2/20 MS 10/SEC	660
FLIGHT CONTROLLER	2	10/100 MS	
SYSTEM CONTROLLER	2	10/100 MS	200
CONTROL AND DISPLAY	2	150/SEC	300
TOTALS UNITS REMOTE	16		1680
TOTAL TERMINALS	80		17756

actuators. Electronics are also likely to be directly associated with most of the aircraft systems, such as: electrical power, hydraulic power, environmental control, and the APU. Electronics involved with the engine, and particu-

TABLE 17

Sensor/Effector Units in Three Location System

UNIT	NUMBER (NOSE-MID-TAIL)			SIZE (MCU)	DATA (WORDS/RATE)	DATA RATE (WORDS/SEC) (NOSE-MID-TAIL)		
SERVO ELECTRONICS	-	10	8	3	5/20 MS	-	1666	1333
DATA ACQUISITION	2	6	4	4	4@ 16/20 MS & 48/SEC 4@ 64/SEC	1333	4000	2666
INTERIAL SENSORS	-	6	-	8	8/20 MS 8/100 MS		1920	
AIR DATA	3	-	-	4	5/100 MS	150		
VOR	2	-	-	2	2/100 MS	40		
ILS	2	-	-	2	5/100 MS	100		
MLS	2	-	-	2	4/100 MS 10/10 SEC	82		
RADIO ALT	-	2	-	2	1/20 MS		100	
TACAN	2	-	-	3	3/100 MS	60		
ADF	2	-	-	2	1/100 MS	20		
GPS	2	-	-	6	4/20 MS 16/2 SEC 100/2 MIN	209		
TRANSPONDER	2	-	-	3	2/4 SEC	2		
DABS	2	-	-	2	MAX 320/4 SEC NORM 4/4 SEC	2		
VHF COMM	3	-	-	2	1/SEC	3		
ARINC DATA LINK	1	-	-	1	14/2 SEC	7		
HF COMM	-	-	1	6	1/SEC			1
VOICE/TONE SYNTH	2	-	-	1	20/SEC	20		

TABLE 17

Sensor/Effector Units in Three Location System (Cont.)

UNITS	NUMBER (NOSE-MID-TAIL)			SIZE (MCU)	DATA (WORDS/RATE)	DATA RATE (WORDS/SEC) (NOSE-MID-TAIL)		
WX RADAR	2	-	-	8	2/20 MS	200		
FLIGHT DISPLAY GENERATOR	3	-	-	6	6/20 MS 30/100 MS	1800		
SYSTEMS DISPLAY GENERATOR	2	-	-	6	33/100 MS	660		
FLUTTER CONTROL	-	2	-	6	4/20 MS		400	
POWER COND/CONT	2	2	2	8	1/SEC	3	3	3
TOTALS IN EACH LOCATION	36	28	16			4691	8089	4003
TOTAL:		80					16783	
REMOTE AVIONICS UNITS								
ENGINE CONTROL				6	2/20 MS 10/SEC		660	
FLIGHT CONTROLLER				2	10/100 MS		200	
SYSTEM CONTROLLER				2	10/100 MS		200	
CONTROL AND DISPLAY				2	150/SEC		300	
TOTALS REMOTE UNITS				12			1360	
TOTAL TERMINALS				92			18143	

larly with the engine accessories, will probably significantly expand.

However, electronics will not be scattered in the aircraft just for the sake of being scattered. Presumably, much of the electronics, such as: the basic central computer system, navigation equipment, and communication equipment located in equipment bays in the one and three location system configurations, will remain in bays. The bays will be retained for this equipment for maintenance convenience, and other logistics and installation reasons.

A significant amount of other electronics will be embedded in their respective equipments, particularly in the cockpit, around the engines, and in the primary aircraft equipment areas. The actual specifics of a candidate system configuration of an embedded system must necessarily be more speculative since it is in the distant future. However, to define a representative system as a baseline is crucial for analyzing the communication structure. In particular, the determination of how many communication terminals (nodes) must be serviced and what the data rates is vital for this analysis.

The equipment used as a baseline for the embedded system studies is described in Tables 18 to 24. These tables generally follow the equipment requirements given in Chapter 3. The number of nodes and the communication rate necessary to support the system are shown in the tables. The number of nodes is established by a trade-off between reliability and costs. For example, more than one sensor is serviced by a common node to reduce costs where there is no compromise in reliability. In other cases, a node is dedicated to a particular sensor or piece of equipment because of reliability or physical location considerations. A summary of the baseline system configuration is given in Table 25.

TABLE 18

Flight Data Sensor

PARAMETER	NODES	DATA RATE (WORDS/SEC)
ANGULAR RATE AND ACCELERATION	6	1250
FLUTTER SENSOR	6	1000
STATIC PRESSURE		160
TOTAL PRESSURE	3	140
TOTAL TEMPERATURE		20
ANGLE OF ATTACK	3	550
MAGNETIC FIELD SENSOR	2	600
TOTALS	20	3720

TABLE 19

Cockpit Controls and Displays

PARAMETER	NODES	DATA RATE (WORDS/SEC)
CONTROLS		
CONTROL WHEEL AND TRIM	4	600
PEDALS	4	600
THROTTLES		10
FLAPS	4	80
SPEED BRAKES		10
NOSE WHEEL STEERING		80
DISPLAYS		
FLIGHT DISPLAY GENERATOR	4	2,880
SYSTEM DISPLAY GENERATOR		5,280
FLIGHT OPERATIONAL CONTROL		
CONTROL AND DISPLAY	4	2,880
SYSTEMS CONTROL AND DISPLAY	2	500
AVIONICS SYSTEM TERMINAL	2	800
COCKPIT PRINTER	1	640
TOTALS	25	14,360

TABLE 20

Flight Control Acutator Signals

PARAMETER	NODES	DATA RATE (WORDS/SEC)
WING DYNAMIC CONTROL AND CONFIGURATION CONTROL	18	3720
TAIL DYNAMIC CONTROL SURFACES	18	1200
LANDING GEAR OPERATION	9	111
STEERING	1	100
BRAKES	6	80
TOTALS	52	5211

TABLE 21

Navigation Sensors

PARAMETER	NODES	DATA RATE (WORDS/SEC)
VOR ANGLE	2	192
DME DIST	2	256
ADF BEARING	2	192
ILS LOCALIZER	2	208
ILS GLIDE SLOPE		208
MARKER BEACON	2	1
RADIO ALTITUDE	2	340
MLS AZIMUTH		130
MLS EVALUATION 1	2	130
MLS EVALUATION 2		130
MLS RANGE	2	130
MLS DATA		9
GPS RECEIVER		16
GPS DATA	1	12
GPS LINE OF SIGHT VEL		800
WEATHER RADAR ATTITUDE STAB	1	700
NAVIGATION FREQUENCY AND MODE CONTROL	3	105
TOTALS	21	3559

TABLE 22

Radio Communication Equipment

PARAMETER	NODES	DATA RATE (WORDS/SEC)
COMM RECEIVER FREQUENCY AND MODE CONTROL	3	105
TRANSPONDER CONTROL	2	120
ARINC DATA LINK	1	110
PASSENGER SERVICE TERMINAL	1	110
TOTALS	7	445

TABLE 23

Engines and Aircraft Systems

PARAMETER	NODES	DATA RATE (WORDS/SEC)
AIRCRAFT ENGINE	9	960
HYDRAULIC	3	96
FUEL	5	156
ELECTRICAL	3	168
PRESSURE/OXYGEN	3	180
APU	2	1020
AIR CONDITIONING	3	180
BLEED AIR/ANTI-ICE	6	24
FLIGHT DATA RECORDER	1	768
TOTALS	35	3552

TABLE 24

Miscellaneous Equipment

PARAMETER	NODES	DATA RATE (WORDS/SEC)
FLIGHT DATA STORAGE UNIT	1	-
AUDIO GENERATOR (TONE AND VOICE SYNTHESIS)	2	80
TOTALS	3	80

TABLE 25

Summary

EQUIPMENT CLASS	WORDS/SEC	NODES
FLIGHT DATA SENSORS	3720	20
COCKPIT	14360	25
FLIGHT CONTROL ACTUATORS	5211	52
NAVIGATION	3559	21
COMMUNICATIONS	445	7
ENGINES AND AIRCRAFT SYSTEMS	3552	35
MISCELLANEOUS	80	3
	26923	163
BITS/SEC (16 bit word)	431K	

Chapter 5

CANDIDATE COMMUNICATIONS SYSTEMS STRUCTURES

Candidate communication system structures are now proposed for each of the three system configurations. The basic communication techniques used to construct these candidate communication systems consist of the following: (1) dedicated serial links from each device to the central computer (or intermediate communication controller), (2) a multiplexed serial bus with several devices connected to the same wires, (3) a point-to-point communication network where devices are connected to each other and the central computer with multiple dedicated links, and (4) a local bus appropriate for communication within an avionics compartment and using parallel wires for address, data, and control much like the internal bus in any computer system. Candidate communication structures are composed of one or more of these basic techniques.

This chapter first discusses some of the basic design choices made in constructing a communication system and how these options may be implemented in a broad range of candidate designs. The candidates are then narrowed to those determined to be most promising and are then described in greater detail. The comparative analysis of these primary candidates is discussed in the following chapter.

Broadcast data buses are not considered in this study. Broadcast buses are the basic philosophy of the current generation of commercial avionic systems. This technique is compatible with a federated system design philosophy. Each subsystem in a federated system either performs some function or provides a particular type of data in an essentially autonomous way. The subsystems provide their data to the rest of the system using one or more broadcast buses. Multiple bus drivers are sometimes used for critical data to prevent one receiver from failing in a way that would prevent data from being obtained by a receiver in a flight critical unit. Each subsystem that needs data from another subsystem has a dedicated receiver for the bus coming from that system. (In some cases, data may be passed through an intermediate third unit which already has the desired data to avoid the necessity of additional interface hardware.)

This broadcast technique is not particularly appropriate for a highly integrated design with a central computer. Almost all data transfer is to and from the central computer system and the sensor and effector units. A broadcast bus from each peripheral unit normally has only one receiver at the central computer system and thus degenerates to a dedicated link system. A broadcast bus may be plausible for communication from the central computer to the remote units where addresses indicate which unit receives the data. This is a hybrid between dedicated lines and multiplex buses and is not specifically considered in this study. However, the characteristics of this combination can be inferred from the characteristics of the other combinations studied.

5.1 BASIC DESIGN CONSIDERATIONS AND INITIAL COMMUNICATION STRUCTURE CANDIDATES

The existence of hierarchical levels in the structure will have a significant influence on the nature of the communication system. Will the communication system provide a direct link from each device to the central computer, or will devices be placed in subgroupings with their own intercommunication and connected to a higher level communication structure through some intermediate communication control device? A multilevel structure could be used for both logical and physical reasons: A multi-level system might be used with a system design that grouped related equipment into functional subsystems, such as flight control, navigation, display, etc. This type of system design is inconsistent with the highly integrated design assumed for this study and is thus not considered. A multilevel system could also be incorporated into the logical design of the fault tolerant concept, where any failure within a sub-grouping would be prevented from propagating to other areas. A multilevel system could also be used either because of capacity considerations or limitations in device addressing capability of the particular technique. Some techniques, such as the local bus, cannot communicate over long distances; consequently, the physical requirements imply a second level for communications to remote units.

In this study, we limit ourselves to one or two level systems. The local bus cannot be used for long distances thus can only be used as one level of a two level system. The other techniques can theoretically be utilized in a one level system or interchangeably on either level of a two level system. Therefore, three possibilities exist for a one level system, three possibilities for the upper level of a two level system, and four possibilities for the lower level, making a total of 15 system structures. Some of these combinations are impractical and can be eliminated. The relative characteristics of the remaining possibilities are discussed and narrowed down to those most promising.

In the one location system, if a local bus operates within the primary avionics location, a two level system must provide communications to the six remote terminals. Little physical justification would be possible for a two level system within the primary equipment location itself. However, there may be logical reasons, such as fault containment or address space limitations. These factors are not considered in this study. Thus, for the one location system, three alternative single level communication structures are considered, two level systems are considered with the local bus for in the primary avionics location, and three alternatives for the communications to the 16 remote terminals.

The three location configuration will most likely be able to effectively use a two level system. A communication structure will be established within each location. An upper level system will then provide communications between the avionics locations, the other remote terminals, and the central computer. If local buses are utilized in the avionic areas, a two level system will be necessary. The other techniques can still be used as a single level system or as two levels with various combinations for the upper and lower level. A two level system with dedicated links will have obvious advantages over a single level dedicated system. Significant wire is saved by having a terminal in each area that distributes the messages to the individual units in that area. The advantages of a two level multiplex or network system are less obvious but feasible.

In the embedded system, many of the units to be serviced by the communication system are dispersed about the aircraft and offer little advantage for a two level system. In the early stages of the evolution toward an embedded system, much of the electronics will still probably be located in central areas. Within these areas there may still be an advantage in using a lower level communication system. However, for the purposes of this study, the embedded system has been assumed to be the logical limit of a dispersed system, offering little advantage for a two level system. Therefore, only single level systems are considered in this study for the embedded system.

The different communication structures considered are shown in Table 26. Only single level communication systems are considered for both the one location and the embedded systems, except for the servicing of the remote units when a local bus is used in the one location system. A full set of alternatives are considered for the three location configuration. The results of the tradeoffs for the three location apply, at least in part, to cases where a two level system may be used with the other system configurations.

TABLE 26

Initial Communication Structure Candidates

ONE LOCATION SYSTEM:		
ONE LEVEL	TWO LEVEL	
	WITHIN LOCATION	TO REMOTE TERMINALS
DEDICATED BUS	LOCAL BUS	DEDICATED BUS
MULTIPLEX BUS		MULTIPLEX BUS
MESH NETWORK		MESH NETWORK
THREE LOCATION SYSTEM:		
ONE LEVEL	TWO LEVEL (ALL COMBINATIONS)	
	WITHIN LOCATION	AMONG LOCATIONS AND REMOTE TERMINALS
DEDICATED BUS	DEDICATED BUS	DEDICATED BUS
MULTIPLEX BUS	MULTIPLEX BUS	MULTIPLEX BUS
MESH NETWORK	MESH NETWORK	MESH NETWORK
	LOCAL BUS	
EMBEDDED SYSTEM:		
ONE LEVEL		
DEDICATED BUS		
MULTIPLEX BUS		
MESH NETWORK		

5.2 COMMUNICATION STRUCTURE FOR THE ONE LOCATION SYSTEM

5.2.1 Dedicated Bus

The first communication structure considered for the one location system utilizes dedicated lines from the computer to each peripheral device. This option requires a minimum of hardware and complexity for the interface at the peripheral unit, with only one channel in and one out. The remote units do not have to distinguish the address of messages since they are all for that unit. The timing constraints are also likely to be tight. The multiplicity of interface electronics is on the computer end. A dedicated interface is required for each external device. Although any practical design presumably shares as much of the electronics as possible, the design is still cumbersome.

Some of the primary advantages of a dedicated bus system are:

* simple interface at the using equipment

* simple communications protocol

* high throughput capacity

* high degree of fault isolation

The interface at the using equipment and the protocol will be simple because the units do not have to read and decode addresses to determine if they will respond to the messages. The timing constraints can also be relaxed. A dedicated link will have high throughput since each link serves only one device. The communication channel does not have to be time multiplexed among a number of devices. A dedicated link system simplifies the task of assuring fault tolerance. Each link is independent and cannot fail in a way that affects other channels.

The primary disadvantages of a dedicated bus system are:

* interface on the computer end is cumbersome

* a very large number of wires is required

* the system will not be flexible or expandable

A dedicated interface is mandatory for each piece of external equipment. Numerous wires are required to focus at the computer and make the installation difficult and heavy. More interface hardware must be added to the computer every time a new device is added, or additional spare interfaces must be included in the original system. Even with spare interfaces, more wire must be added. A more quantitative measure of the relative advantages and disadvantages is included in the next chapter.

5.2.2 Multiplex Bus

The next communication structure considered for the one location system is a multiplex bus system. The multiplex bus provides communication to a number of units using the same wires. Messages include an address which must be recognized and decoded by each unit to see if the message is intended for it. More than one multiplex bus is used. The number of buses is determined by requirements for total system communication capacity, by the physical and logical limitations on the number of devices on a single bus, and by the need to isolate failures which could prevent the use of the bus for any of the devices connected to it. Since all devices on a single bus must share the time available, a number of buses is essential to provide the necessary communications capacity. There is also a limit to the number of devices that can be put on one bus, as well as limits to the electrical loading that can be accommodated, and the number of unique addresses available in the address space. The MIL-STD-1553B bus is limited to 30 terminals. The system designed for this study uses six buses.

The basic configuration of the communication system using multiplex buses is shown in Figure 8. Each of the six buses has a primary and a backup controller to prevent most of the single point controller failures from causing the loss of all the units on that bus. The critical units are distributed on the six buses so that all critical functions can still be performed after multiple bus failures. The most important units in this category are the actuator control modules. The analysis of a particular arrangement of these units is included in the reliability analysis in the following chapter. Each multiplex bus extends out of the primary electronics area to provide communication with the 12 external units. The assumed routing of these buses is shown in Figure 9.

Some advantages of the multiplex bus are:

* reduced interface equipment at the computer

* reduced interconnecting wiring

* flexible to system growth and modification.

A multiplex bus system significantly reduces the number of interface circuits needed at the computer compared to a dedicated bus system. The communications with a number of different units can share the same channel using time multiplex techniques without the necessity of duplicating the interface for each unit. A similar advantage also applies to the amount of wire necessary to support these communications. In particular, the concentration of wire terminating at the central computer system is essentially eliminated. The system is also more flexible for system modification and expansion. More units can be added by attaching them to the bus at some point and adding them to the communication control software without any change in hardware at the computer and with minimal change in the wiring.

Some of the disadvantages of a multiplex system are:

* the interface at the units is complex

* the communications protocol is complex

* the system throughput is limited

* the system is vulnerable to a class of faults that

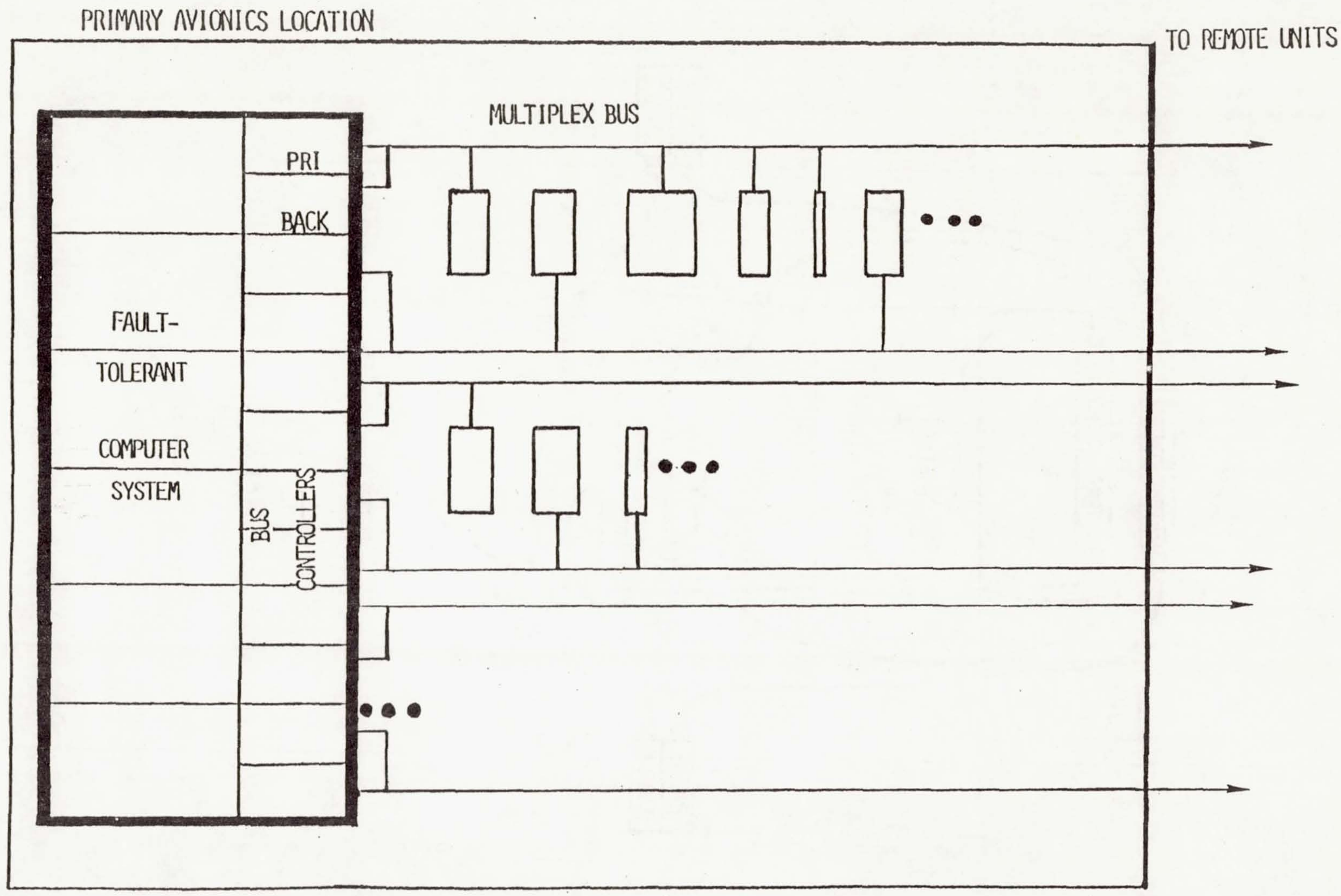


Figure 8: One Location Multiplex Bus System

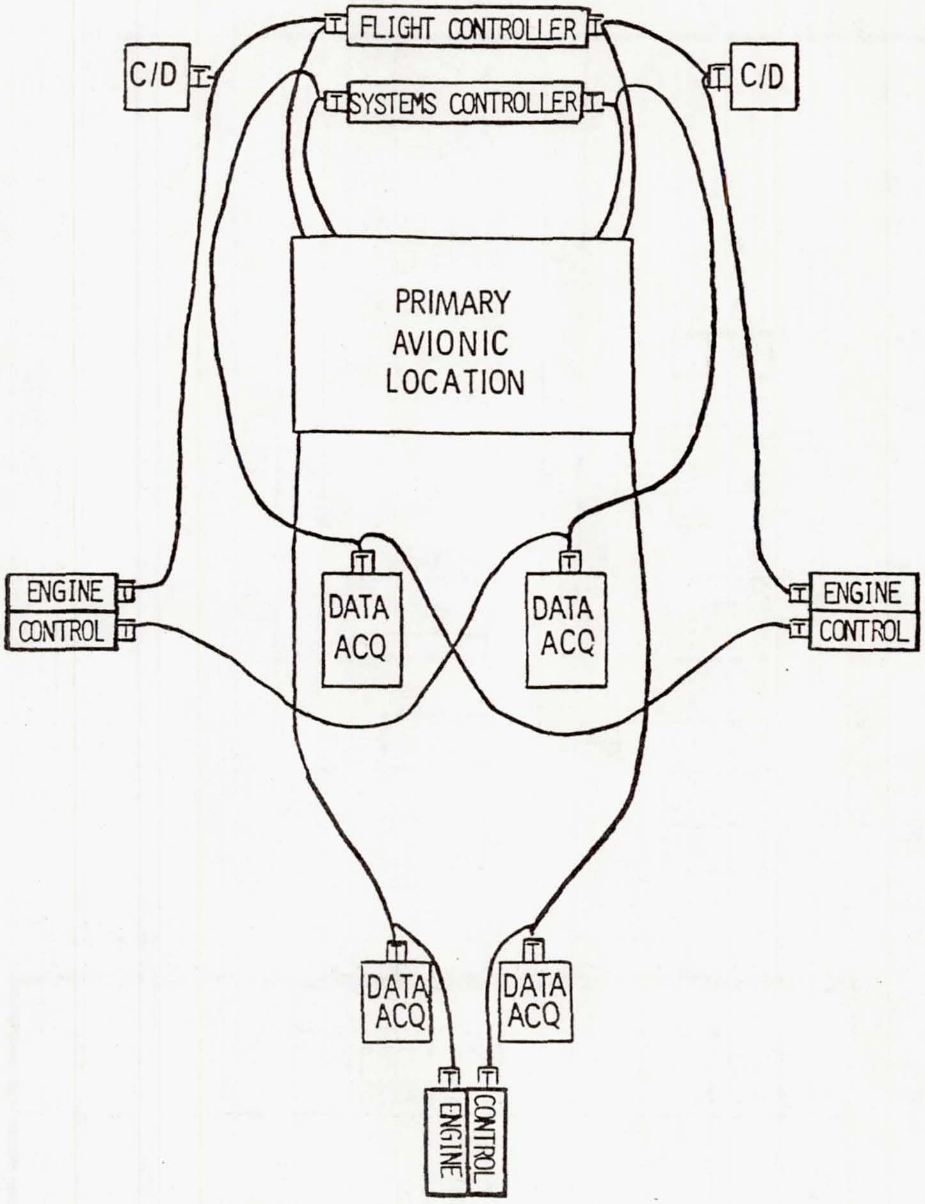


Figure 9: Multiplex Buses to Remote Terminals

can deny communications to a significant percentage of the total system

The interface at the remote units and the protocol is more complex than necessary for a dedicated link system. Additional circuits must be included to receive and decode both the unit address and the control messages, in addition to providing the proper messages in the required time interval. The throughput is less than a dedicated link since the channels must be time shared among a number units. The throughput is also reduced because of the greater overhead necessary to support the communication protocol. The sharing of the communication channel among several different units also significantly increases the vulnerability of the system to common mode faults that can cause the loss of all of the units on that bus. These include: failures in the bus controller that are not detected and prevent the backup controller from taking over, physical brakes in the wire, some terminal failures, such as spurious transmissions that cannot be stopped, and a terminal responding to the wrong address. These failures cause all units connected to this bus to be lost. Some of the more important units may have terminals on more than one bus; however these duplicate terminals increase the hardware requirements.

5.2.3 Network

The next communication system defined for the one location system is a point-to-point network. Each unit is connected to a node in this network; each node has dedicated links to three other nodes, or a port into the central computer system. Communication is established to each unit by 'growing' a bus; the bus is 'grown' by sending messages from the computer to the individual nodes starting with those connected to the computer. These messages close electronic switches that establish a path to all operating nodes. Once the nodes are interconnected, communication is carried out as in a multiplex bus system. The communication links are 'grown' at system initiation, or any time a failure occurs in either a node or a link that disrupts communication to any otherwise good device. (See Volume 1, Chapter 3 for a more detailed description of how a network is 'grown'.)

For the system designed for this study, the network is connected into the central computer through six ports. The nodes are connected together in a regular pattern, with the remote terminals included within the pattern of the network, as shown by the labelled nodes in Figure 10. The arrangement of these links in the aircraft is shown in Figure 11.

Some of the advantages of a network system are:

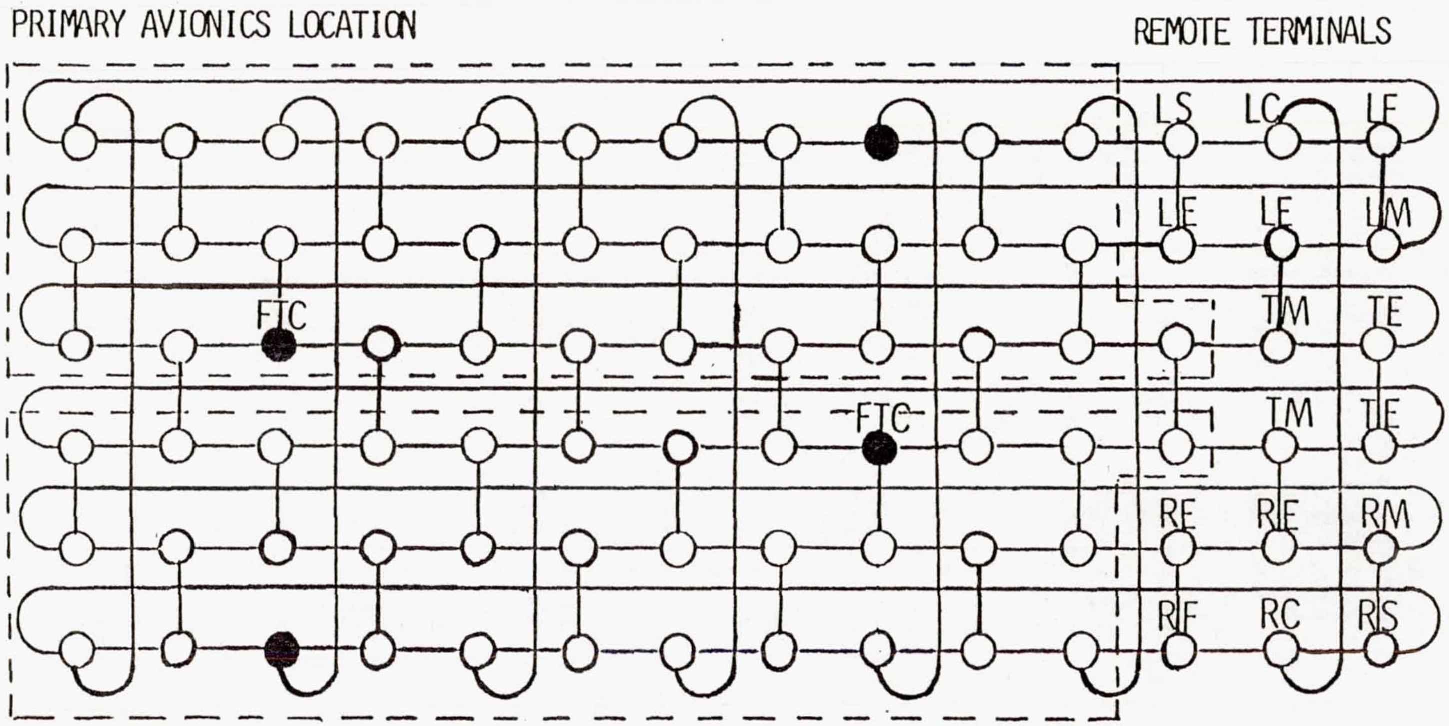


Figure 10: Mesh Network for One Location System

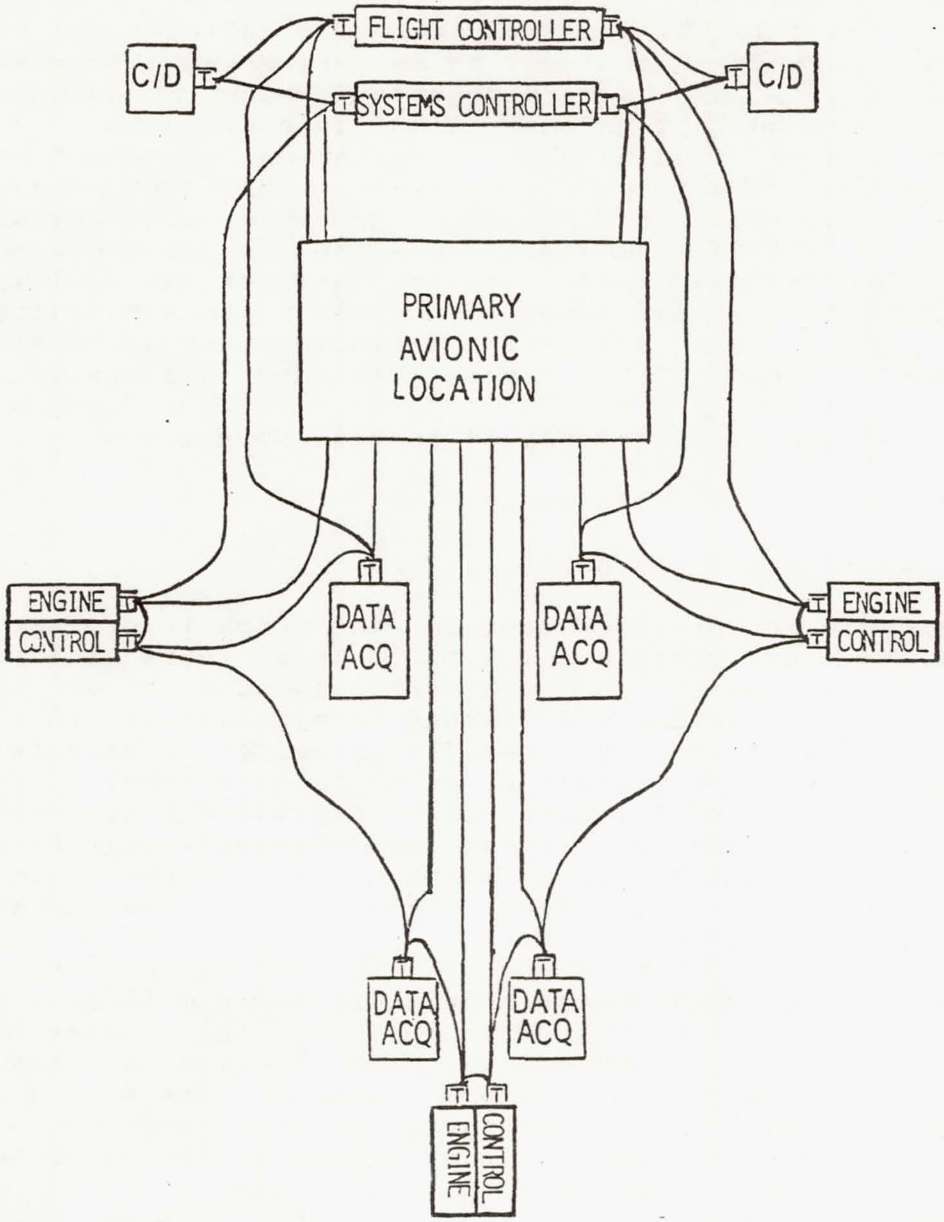


Figure 11: Mesh Network to Remote Terminals

* very high degree of protection against failure and damage events

* uniform availability of communication to units throughout the system in the presence of failures.

A network system offers a very high degree of protection against virtually all types of equipment failures and damage events. A system has almost no failure modes that prevent communication with an otherwise good terminal. Communication can only be lost because of multiple failures. A mesh network is also invulnerable to the types of common mode failures that simultaneously cause a significant percentage of the total system to be lost. In any system that uses buses, a class of faults can cause the loss of every device on a particular bus. These faults restrict the ability of the system to use all resources to effectively reconfigure itself. With a mesh network, information from all functioning units is uniformly available throughout the system.

Some of the disadvantages of network system are:

* complex node interfaces

* restricted throughput

The hardware in the interfaces in the nodes is greater than any of the other techniques, with at least three link interfaces in each node. The node must also have the ability to simultaneously receive and respond to messages on all of the links. This ability is needed to receive reconfiguration messages to provide protection from certain types of failures, which means that some of the control electronics must be duplicated. The disadvantage of complexity will diminish in time, particularly if a majority of the node functions are implemented in LSI circuits that are produced in relatively large numbers.

The throughput of a mesh network system may be less relative to multiple bus configurations. If the network system is configured as one logical bus, the capacity will obviously be less than the bus system, assuming the same data rates. A network can be configured as more than one logical bus to increase the capacity, or dedicated links can be established between nodes where the data rate is high. These multiple links may not be supported after failures, however, thus reducing throughput. The system, of course, will be designed to maintain all critical communications after these failures.

5.2.4 Local Bus

The final candidate communication structures defined for the one location system are based on the use of local buses within the primary electronics location. This system is logically similar to the multiplex bus system, with six buses, each controlled by a primary and backup controller.

Since this local bus is inappropriate for long distances, another level of communication is necessary for the remote terminals. These remote terminals can be serviced by dedicated links, multiplex buses, or a network.

Dedicated serial buses are a leading candidate for communication to the remote terminals. At least some of the data will be very critical, particularly the operational control data to the cockpit and the engine thrust control data. To support this critical data, at least four multiplex buses are required, or a network with at least four ports into the fault tolerant computer. Therefore, the small number of terminals is not likely to justify the complexity of a multiplex bus or network. A multiplex bus would have only three or four terminals. Although some of the signals are critical, they are not crucial enough to justify the fault- and damage-tolerance characteristics of a network.

Some advantages of a local bus system include:

* simple interface at both the central computer and the peripheral unit

* high throughput

The primary advantage of using a local bus within an avionics compartment is the simplicity of the interface equipment and protocol. A local bus can be designed to closely relate to the internal bus structure normally found not only in the central computer system, but also in the microcomputers that are likely to be a part of almost every module. Consequently, considerably fewer data format conversions and less hardware lie between the existing internal buses and the communication structure. Also, the throughput can be considerably greater than other techniques for two reasons: First, the data can be transmitted in parallel as opposed to the serial transmission used for all the other techniques studied. Second, the communication overhead and conversion delays can be considerably reduced.

Potential disadvantages of a local bus communication structure are:

* cannot be used over long distances

* numbers of wires, connectors, and associated failure

rates can be large.

A local bus is impractical over long distances for several reasons: The primary problem is the large number of wires involved, particularly if data and address are transmitted on separate and parallel lines. The number of lines can be reduced at the cost of greater complexity if data and address are multiplexed on the same lines or if one or both are transmitted with a serial technique. Separate control and clock lines will still exist, otherwise the advantage of simplicity will be lost and the technique will degenerate into the multiplex bus technique. These large numbers of wires have the obvious disadvantages of high installation weight, complexity, and cost. The signal levels for a local bus may also be inappropriate for long distances. The immunity to interference may be degraded and problems may arise due to time skew between signals on parallel lines. The primary disadvantage of the inability to use the local bus over long distances is that a two level communication structure must be used. Extra hardware must translate from the local bus to the communication technique used for the remote terminals. The commonality and uniformity of the communication structure will thus be lost.

The large number of wires and associated connectors lead to another disadvantage. Several failure modes, such as: broken or shorted wires, bad connections, and faults in line drivers and receivers, are generally directly proportional to the number of lines involved. This number is significantly greater for the local bus than the other techniques. Also, a large number of line buffer circuits are needed and may require a special design to reduce the possibility of failures that cause the loss of the entire bus.

5.3 <u>THREE LOCATION SYSTEM</u>

The three location system configuration creates a potential for more communication structure candidates. All of the single level configurations are still potential candidates for the three location configuration. Also, potential justifications exist for two level structures, one level within a location and the other among these primary locations and remote terminals. Many of the communication candidates will be similar to the one location configuration, while others will vary due to the change in the basic system configuration.

The one level candidates using dedicated, multiplex bus, and network communication techniques, will be almost identical. The logical organization and the interface hardware will be the same. The nature of the communication system remains unchanged by the added distance between the central computer system and the peripheral terminals. The only significant difference will be the lengths of the interconnecting wires. The length of the wire has virtually no effect on the dedicated and network candidates, except for the cost and weight of the installation, which is more than offset by the significant reduction in the length of dedicated signal wire between the electronics and the equipment served, as shown in Chapter 3. The length of wire may have some effect on the multiplex bus system. Care must be exercised in routing the buses to assure that they do not become too long as far as loading is concerned. The routing must also assure that the system is not vulnerable to single point damage events. These problems should be surmountable, however, and the one level multiplex bus system will then have essentially the same characteristics as it did for the one location configuration.

The three location configuration makes many different communications structures theoretically possible if two hierarchical levels are used. A candidate structure could be formed from all combinations of techniques on the two levels except that the local bus would be unused on the upper level. This would have the potential for the full 12 different two level structures. Several of these can be eliminated as implausible alternatives.

First, consider the combinations with the multiplex bus at the lower level. One possible justification for this candidate would be the need for increased throughput. As discussed for the one location system, at least six buses are needed to provide the redundancy necessary to meet the reliability requirements. These six buses would have ample capacity to meet the throughput requirements projected for the system. Thus, if each of the peripheral units has the capability to communicate on a multiplex bus, little logic exists in interposing any kind of intermediate communication controller between that unit and the central computer. This additional unit would only contribute to complexity, cost, and reduced reliability without making any compensating positive contribution. From these arguments, all candidates involving the multiplex bus on the lower level offer no advantages and can be eliminated.

Similar arguments can be made for structural candidates with a network on the lower level. A network logically operating as a single bus may have difficulty meeting the throughput requirements of some systems. However, these problems can best be solved by providing dedicated links between communication nodes where high data rates are required. Much of the fault tolerance of the network system would be lost if the system were divided into two levels. A much higher degree of fault tolerance can be achieved by maintaining a globally homogeneous organization, where the network controller makes any combination of connections necessary with any node in the system. Again, by these arguments, all two level structures where the lower level is a network are eliminated from consideration.

An advantage for a two level system may exist when dedicated links are used on the lower level. Considerable wire could be saved over a one level dedicated system if communication terminals in each location could receive messages from the central computer and distribute them to the units at that location. The upper level communication technique could be one of three alternatives; however, only a limited number of terminals must be interconnected on the upper level. Also, many of these terminals must handle a relatively high data rate and are critical to the reliability of the system. Thus, each of these terminals should have its own dedicated link to the central computer system. A multiplex bus or network system would be unjustified for these few important terminals. The candidate selected thus has dedicated links on both levels. This configuration has the disadvantage of significantly increasing the effect of single point failures within these communication terminals. Some form of redundancy and the associated redundancy management would be needed, such as redundant circuits within the terminals or the use of multiple terminals within each location.

The final set of candidate structures has the local bus on the lower level. The candidate structure using local buses will thus be similar to the one location candidate. In this case, two of the six local buses are placed in each location. For some central computer designs, support of these remote locations is possible without creating an additional level in the communication structure. The interface between the central computer and the local bus will be designed with the ability to communicate over the greater distances involved. The logical design and the great majority of the hardware will be the same as for the one location configuration. The communications to the remote units would also be simplified. Now fewer terminals exist since the remote signal multiplex units have been absorbed into the two additional locations. Also, the interface units for the links to the remote terminals can be placed in the nearest locations. For example, the links for the engines in the wings would originate in the wing root electronic location.

Thus, the candidate structures for the three location configuration are essentially reduced to those for the one location configuration. The only new candidate is the two level dedicated link system. The advantages and disadvantages are also virtually the same for similar candidates. The two level dedicated link system will have the previously discussed advantage of significant wire savings over a one level dedicated system, but have the disadvantage of added failure modes.

5.4 EMBEDDED SYSTEM

The embedded configuration in this study represents the limiting extreme of systems likely to emerge by the end of the target time period. These systems are assumed to be fully dispersed, with electronics embedded within sensors, actuators, and other pieces of aircraft equipment, as defined in the previous chapter. Although any pratical system will still probably have electronics in equipment compartments, for the purposes of this study the electronics are assumed to be fully dispersed. This configuration thus establishes a logical extreme in the environment it creates for the communication requirements. Consequently, this limiting configuration will have significant implications on the appropriate candidate communication structures.

Several combinations of structures can be eliminated as impractical or impossible: The local bus cannot be used since it is not usable over a significant distance in an unprotected environment. Thus, any candidate configuration with a local bus can be eliminated. A system using dedicated links connecting a central computer system to 150 plus terminals would be so awkward that it also does not need to be considered. Therefore, the only candidates considered are those that use multiplex buses or mesh network.

Two level communication candidates are also not considered. The same arguments can again be made to eliminate the two level multiplex bus or network candidates in the three location configuration. Thus, the candidates are reduced to two: a one level multiplex bus system and mesh network.

5.4.1 Multiplex Bus for the Embedded System

The multiplex bus retains the same characteristics of the current MIL-STD-1553B. Therefore, each bus is limited to 30 terminals. At least six buses must be used with essentially the same logical configuration used for the one and three location configurations. The problems of arranging viable paths for the buses are more severe, however. In the one and three location configurations, a majority of the terminals are relatively close together, with only a few remote terminals. These remote terminals can be serviced with reasonable bus connection designs, as shown in Figure 9. The loss of communications to any of these remote terminals is not immediately catastrophic and so physical damage to the bus is not an overriding consideration. The embedded configuration considerably complicates the situation by imposing conflicting requirements. Highly flight critical functions must be performed throughout the aircraft. The most critical tasks for the communication system is to provide commands to the flight control surface actuators in the wings and tail. Thus, redundant buses are essential for each of these critical locations. Significant problems are likely, however, if all redundant buses are routed to all locations. First, to design a bus that is consistently reliable over the long distances involved may be difficult. The A version of MIL-STD-1553 limited total length to 91 meters (300 feet). This limitation is removed in the current B version so no formal restraint exists from attempting longer bus lengths. This does not mean all problems would be trivial, however. A single bus designed to support all areas of the aircraft could be as long as 200 meters. A bus run out into a wing must return before going to the the other wing or tail. A bus this long is likely to be vulnerable and difficult to design. Also, much wire, and thus an increase in the installation cost and weight is required.

Probably the most important consideration for the design of a multiplex bus system is vulnerability to physical damage. If it is necessary to route all redundant buses to all parts of the aircraft for reliability reasons, the cross section of the system to damage is made very large. If any part of the aircraft is substantially damaged, a large percentage of the total communication capability of the system could be lost with the unacceptable probability of catastrophic system failure.

The solution to the problems of excessive bus length, wire weight, and damage vulnerability is a significant increase in the number of buses. This design requires a complete set of redundant buses for each major location, such as each wing and tail. The design thus becomes increasingly awkward. A large number of ports will be required at the central computer system. The system is susceptible to failure modes that cause the loss of a bus, and thus loss of all devices on that bus.

5.4.2 Network for the Embedded System

Because of these problems with a multiplex system, this study is primarily concerned with a mesh network system. A mesh network provides a homogenous, highly damage tolerant technique for providing communication to all devices throughout the aircraft and has no failure modes to cause simultaneous loss of multiple resources.

Once a decision is made to use the point-to-point network technique for the embedded system, the network must be carefully implemented to develop a total stucture that effectively meets all requirements. The network can be laid out in the aircraft in several ways; these will be discussed, analyzed, and compared.

The most straightfoward design for the network is a uniform, logical, rectangular layout. The design is shown in Figure 12. The pattern is one of regularly connected hexagons or bricks. The rectangle is laid out to conform to the fuselage to minimize the wire length as much as possible, with the edges connected to complete the pattern. Of course, some areas have concentrations of communication nodes, particularly in the cockpit and wings. Figures 13 and 14 show possible detail in the cockpit and wing, respectively. Note that nodes physically adjacent tend to be connected. In particular, redundant nodes on the same LRU are connected. For example, a triply redundant hydraulic actuator is attached, as shown in Figure 15.

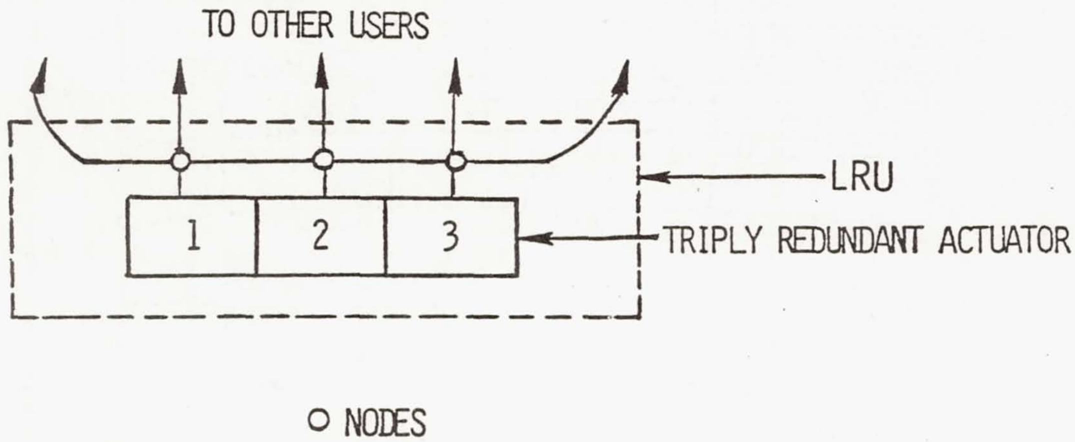


Figure 15: Network Connection to a Triplex Actuator

Somewhat higher reliability can be achieved by logically separating these nodes in the network. However, such separation increases the complexity and wire length without any significant increase in the total system reliability. As seen in Figure 15, the actuator, as a unit, has five links in the rest of the network to provide greater reliability than the actuator itself.

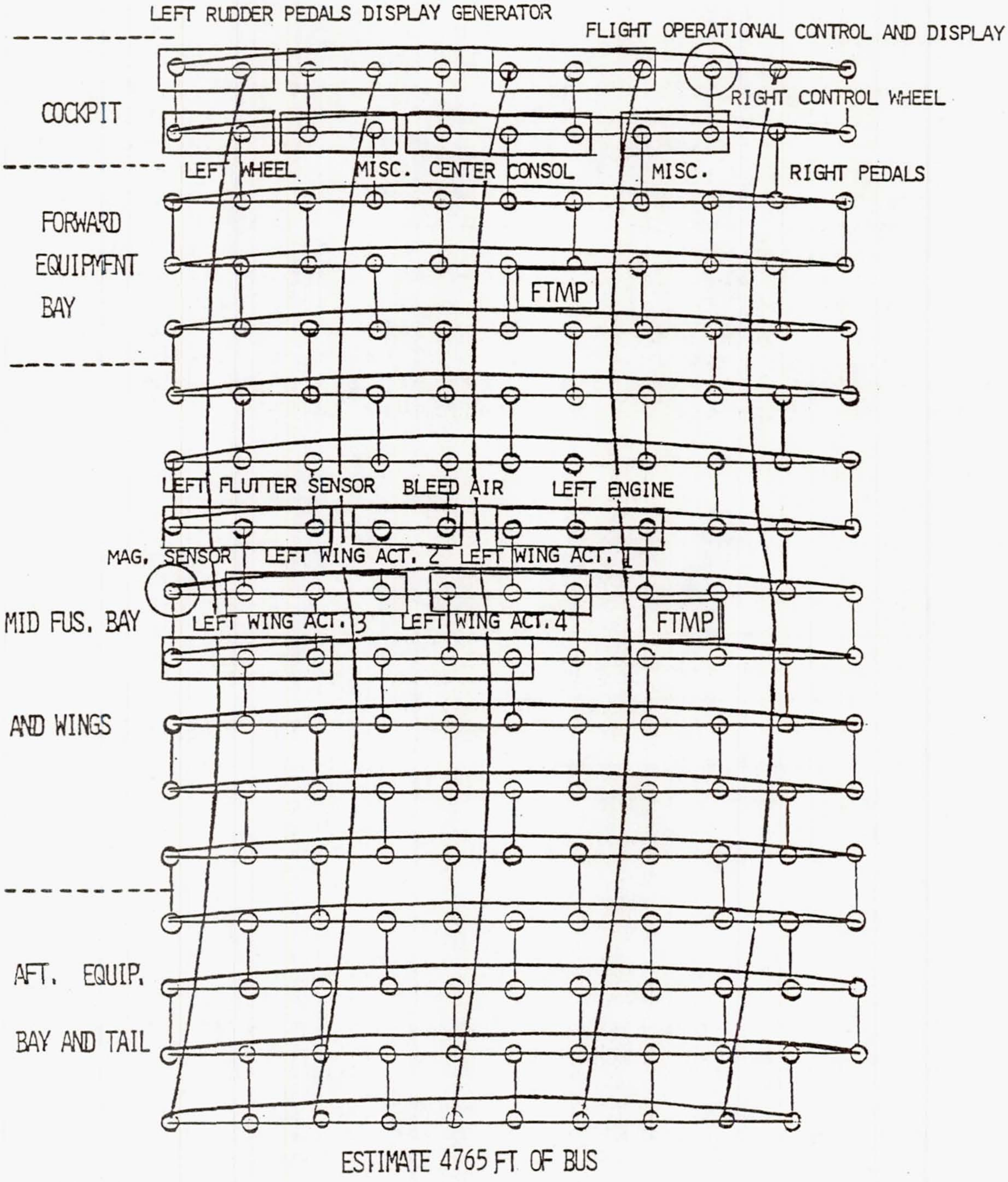


Figure 12: Mesh Network for Embedded System

Examination of Figures 13 and 14 show that the regular arrangement of node interconnections leads to an excessive number of links connecting various parts of the aircraft; for example, 14 links go into the wing. The amount of wire can be significantly reduced without compromising safety, by establishing regular networks in various places in the aircraft where concentrations of nodes exist. These subnetworks are then interconnected by a sufficient number of links to give the required reliability. One possible configuration is shown in Figure 16.

A specialized network could be designed with each node having only enough interconnection to provide adequate reliability and dispatchability, taking into consideration what type of unit is attached to the node. Also, the interconnection between nodes could be specialized. The result would be some wire saving, but the design problem is greatly complicated by the necessity of assuring no way exists for the isolation of a crucial set of nodes after a small number of failures. This problem is worsened by the possibility that the aircraft must be dispatched with one or two existing node failures.

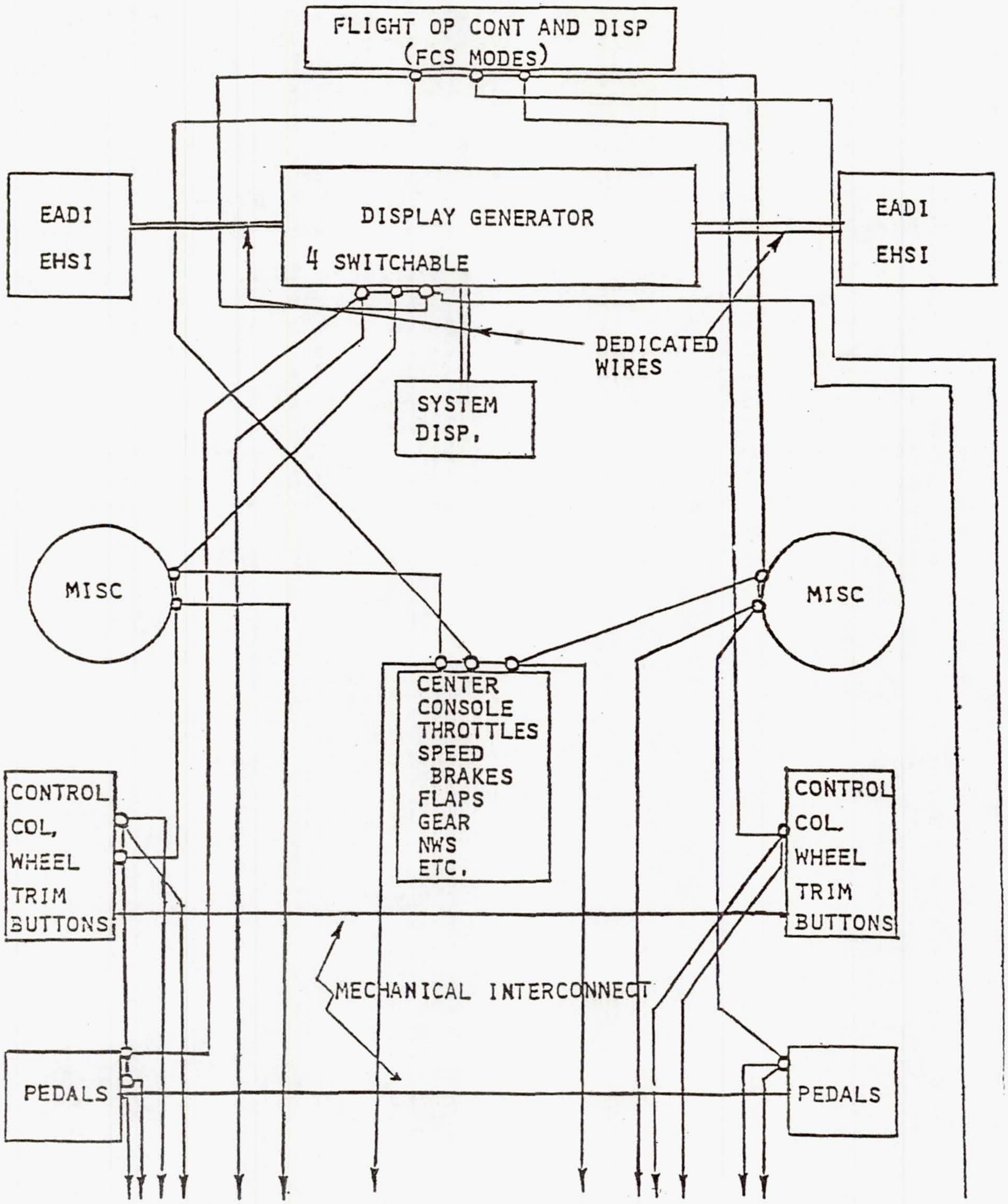


Figure 13: Mesh Network in Cockpit

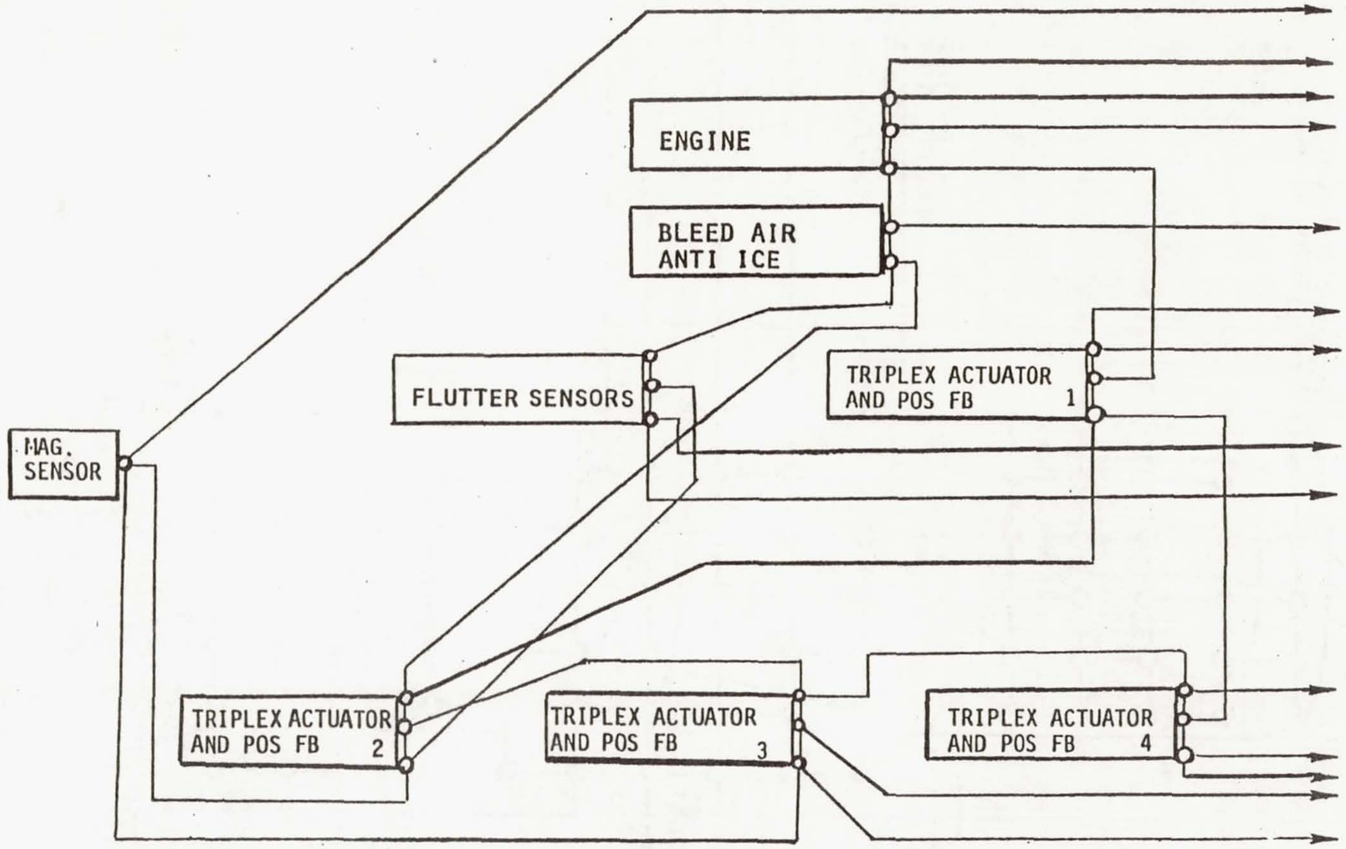


Figure 14: Mesh Network in Wing

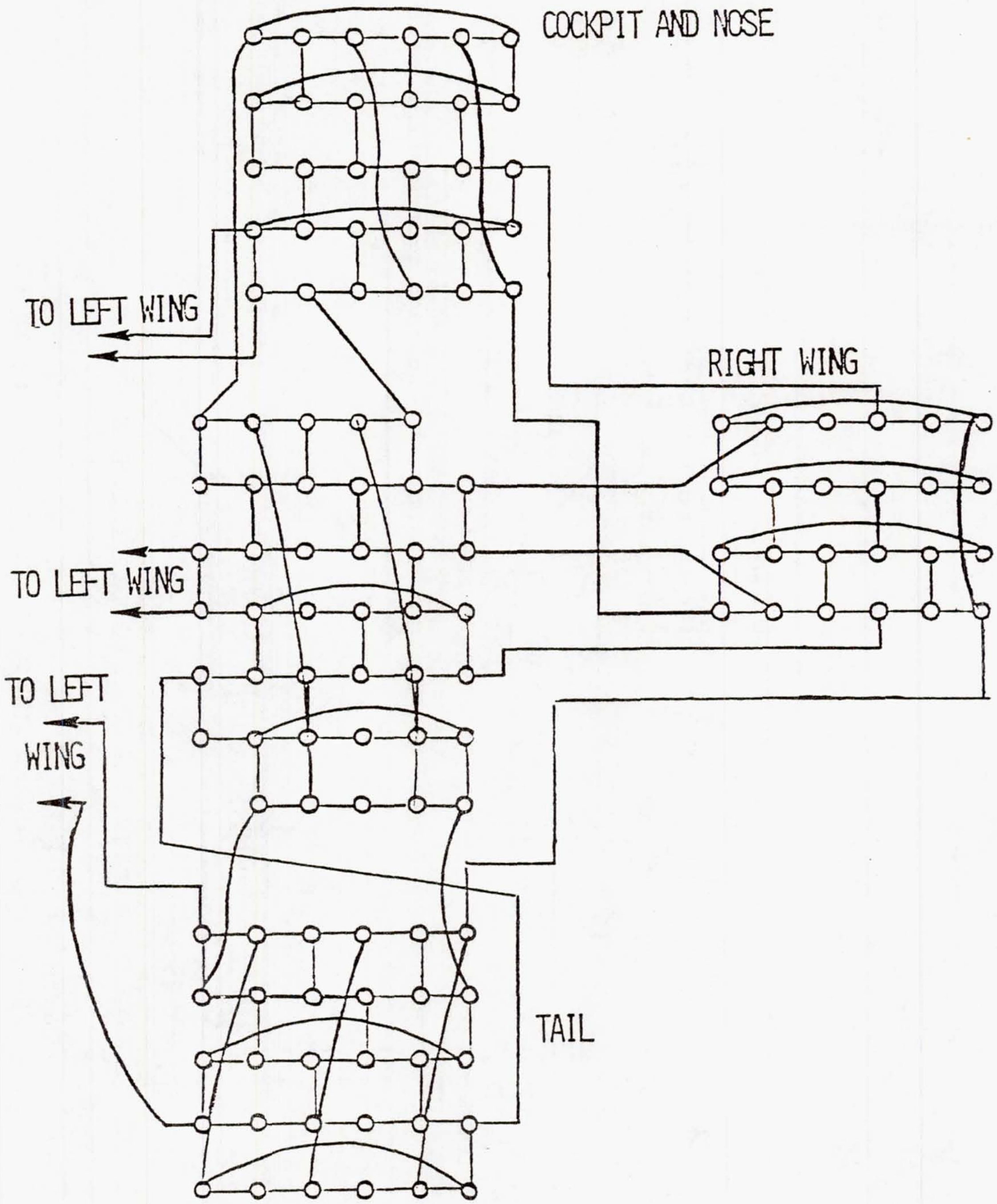


Figure 16: Interconnected Meshes

Chapter 6

TRADE-OFF ANALYSIS

Several communication structures were described in the preceding chapter. In this chapter, an analysis of the differences between these alternatives is made to determine their effectiveness in avionic system applications. Several factors can be used to measure the relative worth of different alternatives. To determine the desirability of the different alternatives, consideration must be given to the overall performance and cost effectiveness of the system. Measures of the system's performance include: capacity, reliability, and availability. Cost effectiveness is determined primarily upon the cost needed to support the system, which includes maintainability and adaptability, in addition to the original cost of development and production.

For a system which must support life critical functions, reliability itself cannot be considered a trade-off factor in the sense that one system is chosen over another because it is more reliable. All systems must be able to meet the stringent reliability requirements before they can be certified. Little advantage is gained by significantly exceeding the reliability requirements. Rather, the effectiveness of the total aircraft would be enhanced if efforts were made in other areas where the unreliability is greater.

However, the reliability analysis of the communication structure does become an important indirect factor in the trade-off among alternative designs. The basic characteristics of the system are dominated by how effectively the design can meet the reliability requirements. A system with characteristics that enhance reliability can meet the requirements at a lower total cost. The reliability advantages are thus reflected in other areas, such as increased performance or especially lower life cycle costs. Therefore, a reliability analysis establishes a basis for all other comparisons, and thus forms a major part of this study.

Capacity characteristics have much the same role as reliability characteristics in that all communication systems must provide the required capacity. Systems with inherent characteristics that provide more efficient capacity will have advantages in other areas, such as life cycle costs.

This chapter first discusses the reliability analysis technique used in this study. (A more complete description of the technique is given in Volume I, Chapter 6). The reliabilities of the candidate systems are then analyzed and compared. Next, the capacities of the various candidates are discussed. This reliability and capacity analysis provides the basis for many of the basic design decisions made in forming the candidate structures described in the preceding chapter. With the reliability and capacity requirements established, the other characteristics of the candidate systems are discussed to help determine the best candidates for particular applications.

6.1 BASIS FOR THE RELIABILITY ANALYSIS

The purpose of the reliability analysis in this chapter is to determine the contribution made by the various candidate communication structures to the probability of failure of the critical functions performed by the total system. In Volume I of this study, general measures of the reliability of communication techniques were discussed, such as the connectivity of mesh networks. In the final analysis, however, the reliability of a communication structure cannot be fully resolved in isolation from the particular critical functions it is supporting. Therefore, the analysis in this chapter measures the reliability of the communication function in the context of the critical avionic functions.

To perform a reliability analysis on a complete system, much less several alternate systems, would be too big a task and not within the scope of this study. However, the reliability of the communication system can be effectively evaluated by analyzing a subset of the total system, representing the most critical communication tasks. The task chosen for this particular study is the pitch control function, often the most critical function in a fly-by-wire flight control system.

To create a realistic environment for the communication system, a representative actuator configuration is used. This configuration is necessary to define how communication failures contribute to failure of the function. Failure of the function will depend on various combinations of failures of actuator channels. Certainly, no one communication channel to a particular piece of equipment will be critical. A certain level of redundancy will be used both in the actuator and the surfaces. A critical communication failure will occur if communications are lost to the minimum set of actuator channels. Furthermore, the significance of a communication failure must be judged in relation to failures of the actuators and other system elements. Combinations of failures must also be considered. If actuator channels have failed, communication failures will be significant if they cause loss of communication to the remaining good channels.

A typical configuration for the primary equipment involved in providing the pitch control function has been chosen for this study, which realistically exercises the communication function. Presumably, the aircraft is built with reduced static stability and fly-by-wire linkage, thus completely dependent on the pitch control electronic function. If the electronic system fails, the aircraft is immediately lost so that a high degree of reliability and thus redundancy is required. Consequently, four pitch control aerodynamic surfaces are used, each surface controlled by a triplex force voting actuator.

Each actuator channel has two failure modes: a passive mode and an active mode. A triplex actuator can sustain one active failure or two passive failures. The aircraft itself can sustain the loss of two surfaces. Therefore, the minimum set of equipment that must be operating is two surfaces, each controlled by a redundant actuator with a minimum of two channels operating if one channel has failed actively, or one channel operating if two have failed passively.

The central computer system is not included in the reliability analysis since the computer has a very high level of reliability. In addition, failure modes of the computer do not interact with failure modes of the communication system. Hence, if the computer has not failed, then it can completely support the communication system. Since unique interface circuits in the central computer system are included with the communication link, the total reliability of the function can be determined by adding the failure rate of the computer to the failure rate of the rest of the system.

Representative numbers for the probability of failure in the actuator channels provide a consistent basis to compare the contribution of the communication structure. The servo electronics are included with the hydraulic channel since one cannot operate without the other. The numbers chosen for the combined hourly failure rates are:

3.0×10^{-3} for a passive failure
3.0×10^{-4} for an active failure

Conservative rates are chosen to create a realistically complex environment for the communication system.

The baseline reliability requirement for the pitch control function assumed for this study is a failure rate of 10^{-9} per hour at the end of a 10 hour flight. A flight time is given because the failure rate for a highly redundant system will be a strong function of time. The failure rate will increase due the failure of redundant resources. It is thus required that the instantaneous failure rate at the end of the expected operational time of the aircraft be within the required value. The probability of functional failure of the system during a short period of time at the end of the flight will thus be approximately this maximum failure rate times the time period. A nominal maximum operational time for a commercial aircraft is assumed to be 10 hours.

In addition, this reliability requirement must be met with any component failed at the beginning of the flight. This requirement is necessary, otherwise all equipment must work at dispatch. The levels of redundancy necessary to meet the reliability requirements will involve a large number of elements. The probability that all of these are working at dispatch may be too low to be acceptable for commercial operations. A fault-tolerant system can reconfigure available resources to assure that the most critical functions are performed. Thus, any practical design will include more resources than the minimum required for operational reliability. These additional resources will allow dispatch with one or more elements failed. The end result will be a significant increase in dispatchability over current experience. This philosophy is used in the communication systems considered in this study.

6.2 RELIABILITY ANALYSIS OF CANDIDATE ARCHITECTURES

A reliability analysis for the critical elements involved in the pitch control function will be made for each candidate architecture. The analysis technique used is the reliability equation method, described in Volume I, Section 6.7.

6.2.1 One Location Configuration

6.2.1.1 Dedicated Links

The dedicated link system is simple enough that a direct computation of reliability is practical. The other system configurations cannot be analyzed as easily, however. Therefore, the equation diagram method is used for the dedicated link system, both to maintain consistency with the analyses of the other systems and to begin the explanation of the reliability analysis with a less complex system.

The reliability analysis will be discussed in terms of the steps described for this technique in Volume I. These steps are summarized here, along with their application to this system.

Step 1: Partition the System into Basic Elements.

First, the system must be partitioned into elements. A diagram of the critical parts of the system using dedicated links is shown in Figure 17. The partitioning of this system is straight foward. Since a dedicated link exists for each actuator channel, the communication channel can be combined with the servo electronics and the hydraulic actuator channel. If any of these components fail, the others in the serial chain cannot be used. Consequently, this system can be described using only one type of element, which includes all of these components, including the dedicated parts of the link interface within the central computer system. The entire system is modeled by 12 of these elements.

Step 2: Identify Events that Define the State of Each Element

The condition of this one type of element can be defined by three states: (1) the good state, (2) the failed state with the actuator failed passively, and (3) the failed state with the actutor failed actively. The probability rate of entering a failed state is the failure rate of the link, assumed here to be 1.0×10^{-4}, added to the appropriate rate for the actuator channels.

Step 3: Select an Order for the Application of the Equations

An order must be selected to incorporate the elements into the reliability analysis. Dependency primarily determines the order in the analysis of most systems, i.e., how one element depends on others for proper operation. In the dedicated link system, none of the elements depend on another; thus the order can be somewhat arbitrary. To simplify the diagram, a minimum sequence of elements is chosen to accomplish system success. The sequence chosen here is first link/actuator channels 1 and 2. If both are good, the operation of one surface is assured independent of the state of channel 3. For symmetry, channels 10 and 11 are chosen next. If these two channels are good, a second surface is operational and thus the pitch function is assured. The sequence for the remainder of the system is determined primarily by how elements are added to replace failed elements, described in Step 4.

Step 4: Construct the Diagram of the Equations

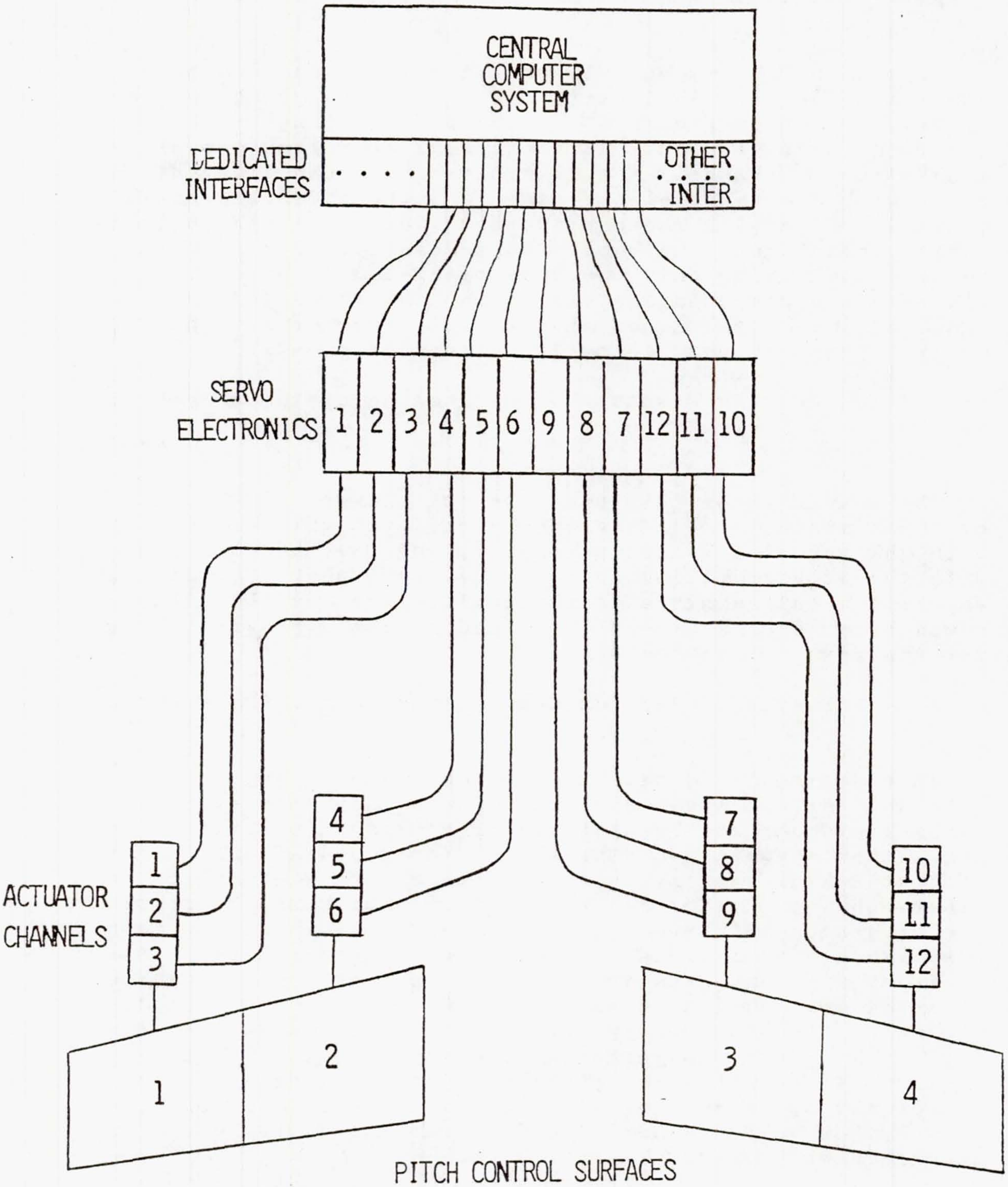


Figure 17: Dedicated Bus System for Pitch Control

The equation diagram is now constructed using the analysis program described in Volume I; the results of this process are shown in Figure 18. The label chosen for the basic system element is "dac" for dedicated link/actuator. A number is attached to distinguish which element is considered. The process of building the equation diagram begins by entering the codes for channels 1, 2, 10, and 11. The first state considered by the program is all of the elements good. If these four elements are good, the pitch function is good independent of the state of any other element. The unreliability of 0 can then be specified by entering "q0". The next system state prompted by the program is channel 11 failed passively, with the other three channels still good. Channel 12 must be added to account for the possibility that is has failed actively. If it has not, the unreliability is still 0; if it has, another channel must be considered. Channels 4 and 5 are now added. If both are good, the unreliability is again 0. If not, channel 6 is again added. If this surface is also not functioning, channels 7, 8, and then 9 are added in the same way as the previous channels. For the states of any successful channels, the system unreliability is again 0. For states of unsuccessful channels, the unreliability of the system is now 1 since three surfaces have failed and no other resources are available.

The process of constructing the equation diagram continues by accounting for the system states as they are prompted by the program. The pattern followed by the program is first to go down the left hand edge of the diagram and then to fill in the branches beginning from the bottom left hand corner and moving up and to the right until the diagram is finished.

Step 5: Compute the System Unreliability

The analysis program automatically computes the unreliability for each branch when all necessary information is available. Thus, when the diagram is complete, the computed unreliability will be available, as shown in Figure 18. In this diagram, the number at the top is the unreliability of the system. Under that number are those components summed to give the top number. These numbers are the result of the analysis of the remainder of the system, given the state of the first element. This state is shown by the code above the number. The analysis that produces each of these numbers is shown by the branch of the diagram. The same process is repeated at each level until the system is determined to be either good or failed. A more complete description of this analysis process is given in Volume I. This diagram gives the unreliability after one hour, assuming all components are good at the beginning. The failure rate of a highly redundant system is a very strong function of time. The present version of the program cannot directly compute the failure rate as a function of time. This failure rate can be estimated, however, by computing the unreliability at two times at the end of the required time period. Figures 19 and 20 give the unreliability at 9 and 10 hours respectively.

The unreliability analysis can now be interpreted to determine the implications for comparison with other system designs. The dramatic growth in the unreliability as a function of time can be seen by comparing Figures 19 and 20. The unreliability increases by almost 6 orders of magnitude between 1 hour and 10 hours. To be conservative in this analysis, the total unreliability after 10 hours will thus be used to determine how well the system meets its requirements.

Even after 10 hours the analysis shows that the system exceeds the requirements by several orders of magnitude under the conditions that all equipment is working at the beginning of the time period. The unreliability for different initial failure conditions can be determined by looking at various branches of the equation diagram.

The unreliability of the system with one channel failed passively can be seen in Figure 20 on the third line, column four to be 9.7×10^{-14}. The unreliability is approximately two orders of magnitude less than the system with no initial failures. The unreliability of the system with one channel failed actively can be seen at location 3,7 to be 1.3×10^{-12}, another order of magnitude larger. The unreliability of the system after one surface is completely lost is 5.6×10^{-11}, as shown at the location 7,4.

This analysis shows that this system exceeds the requirements. The development of a system intended to go into a production aircraft would likely have a finer tuned design that would not exceed the requirements as much, allowing some savings in hardware. However, for the purposes of this comparative analysis, a conservative approach is taken to fully exercise the communication system.

6.2.1.2 Multiplex Bus

A diagram of the critical parts of a multiplex bus system involved in the pitch control function is shown in Figure 6.5. There are six buses, with a primary and backup controller for each. Two actuator channels are serviced by each bus. The assignments are made so that a bus failure will not cause the loss of any one control surface. The reliability analysis procedure is similar to that used for the

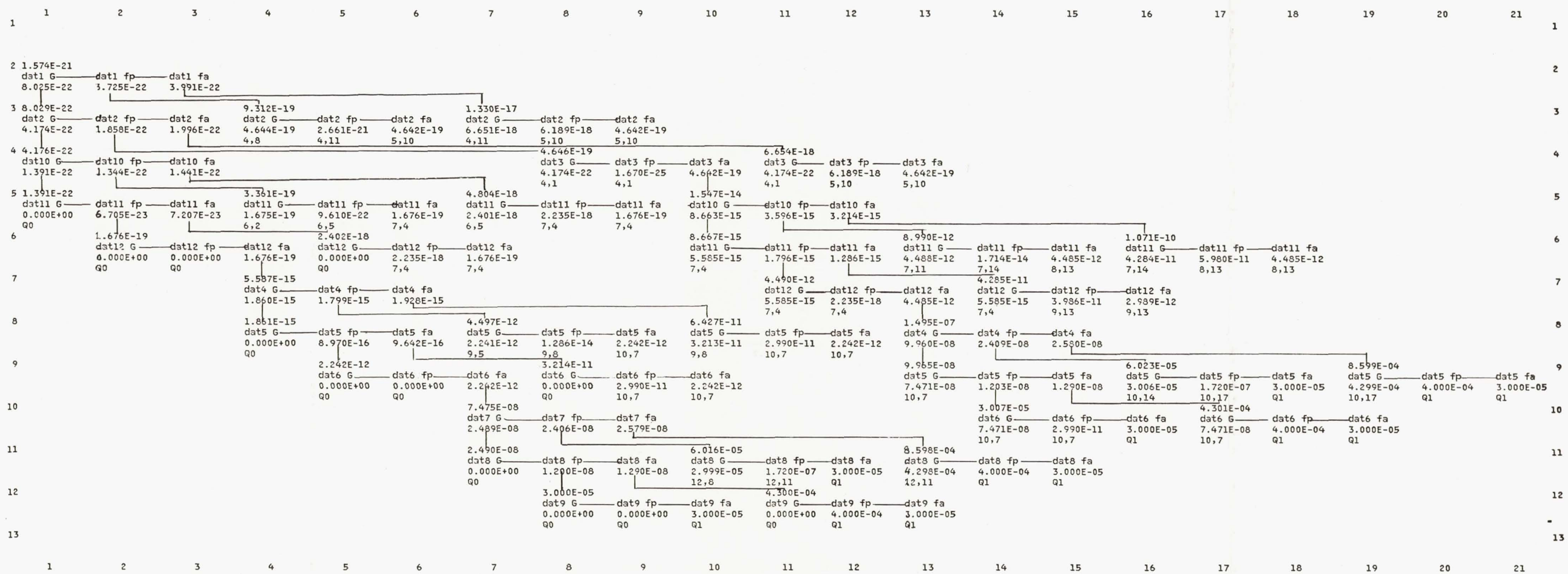


Figure 18: Reliability Equation Diagram for the Dedicated
Link System Time = 1 Hour

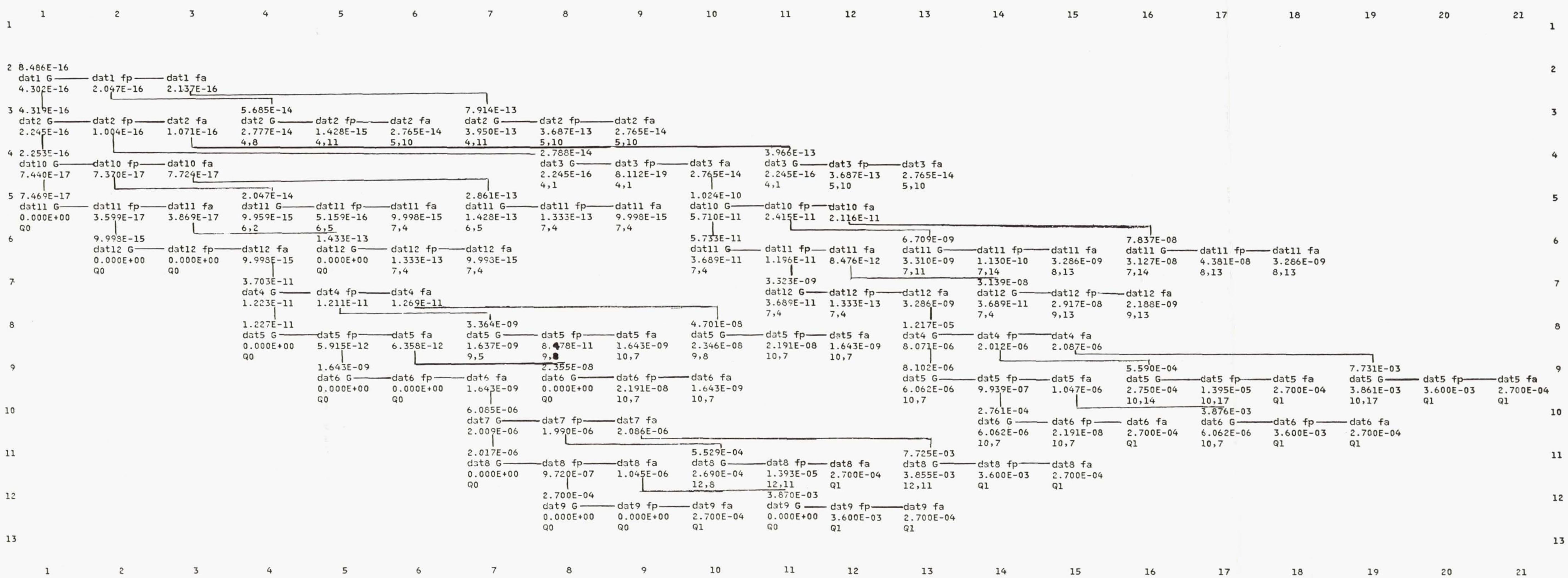


Figure 19: Reliability Equation Diagram for the Dedicated Link System Time = 9 Hours

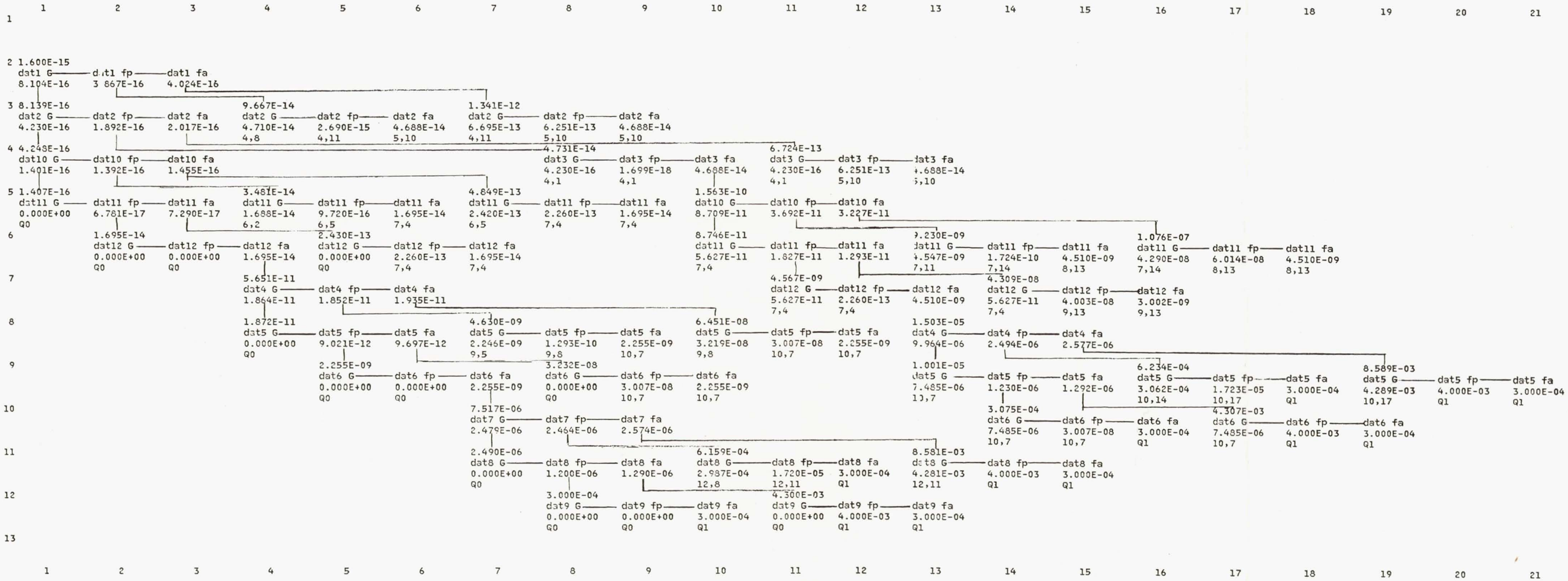


Figure 20: Reliability Equation Diagram for the Dedicated Link System Time = 10 Hours

dedicated link system. The steps taken are briefly discussed, with emphasis on any different aspects.

In the first step, the system is partitioned into two basic elements: One is the actuator channel which includes both the servo elecronics and the hydraulics. The other element encompasses both the controllers and the bus itself. These two types of elements cannot be combined into one since the failure of one actuator channel does not cause the loss of the bus or the other actuator channel on that bus.

The two controllers and the bus itself can be combined into one element for the total system analysis. The communication function is not lost on that bus for most of the failure modes of one controller, although it will fail if both controllers fail or if the bus itself fails. The way the bus fails is not significant as far as any interaction with the failure of other elements. The failure mechanism within the bus element can be separately analyzed and the resulting net failure rate used in the analysis of the total system. This situation significantly simplifies the analysis of the total system.

The actuator element again has active and passive failure modes, as dicussed earlier. The failure rates will also be the same, as previously assumed. The bus element will have only two states: good and failed. The failure rate for the controller is assumed to be 1.0×10^{-4}. The bus can fail either from broken or shorted wires or from any failed units on the bus that prevent its use. These failures not only include grounds or highs on the bus, but also include more complex failure modes, such as responding to the wrong address or transmitting when not commanded. Also, many other units exist on the bus, other than those shown in Figure 21 which directly involve the pitch control function. As many as 20 other units on each bus are not directly involved in the pitch control function but can become indirectly involved since they are attached to the same bus carrying pitch control commands. The bus interfaces in the units will be designed to make these failure modes very unlikely. However, these types of failures are still possible. For this analysis, a conservative failure rate of 1.0×10^{-5} per hour is used. The failure rate for the bus element is thus:

$$\Omega = \Omega(\text{cont})^2 + \Omega(\text{bus})$$

$$= (1.0 \times 10^{-4})^2 + 1.0 \times 10^{-5}$$

$$= 1.001 \times 10^{-5}$$

The failure rate is essentially the rate for the bus itself with almost no contribution from the failure rate of the controllers. The sensitivity of the system unreliability to

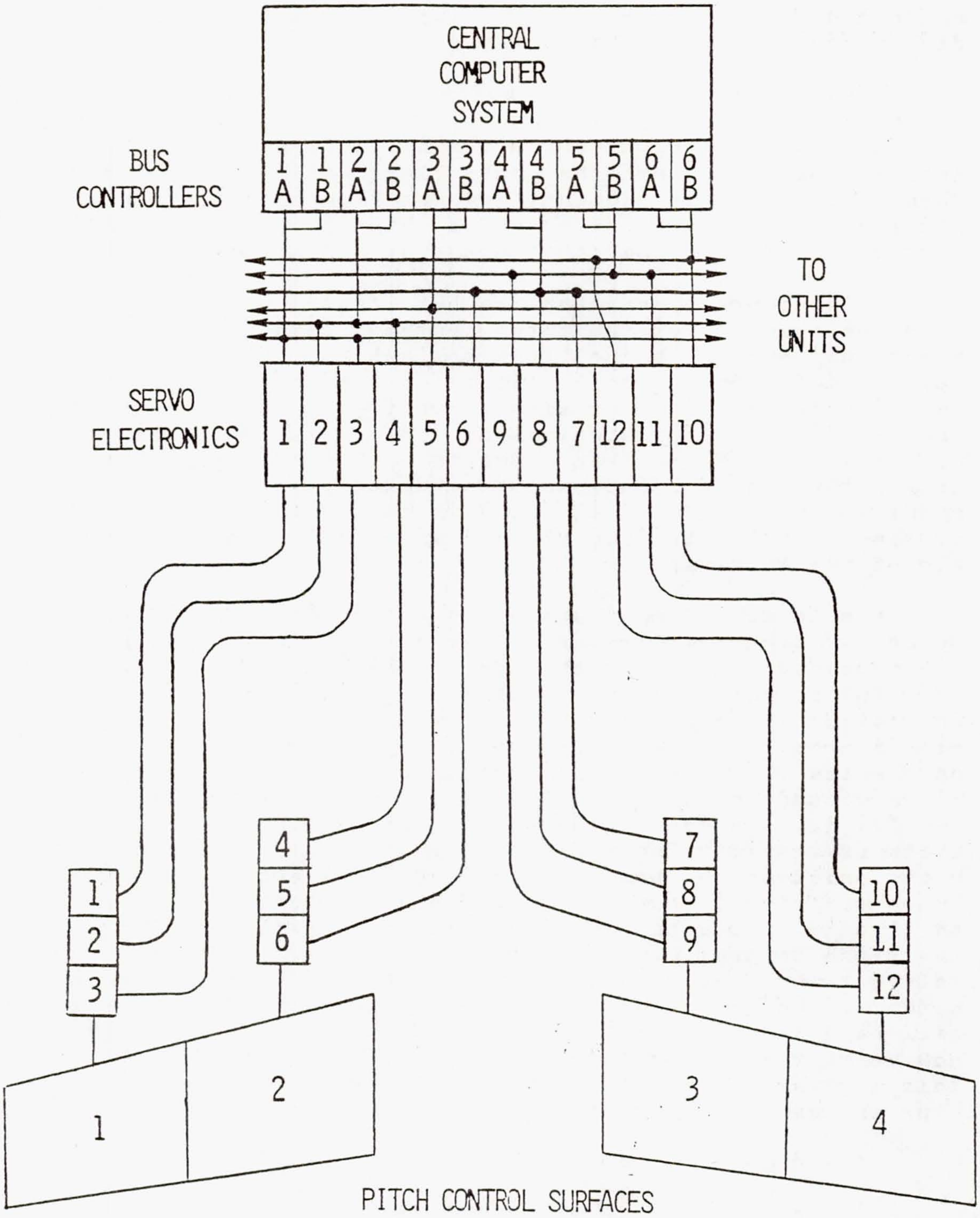


Figure 21: Multiplex Bus System for Pitch Control

this failure rate number and the design decision to use dual controllers is discussed a little later.

The order in which the elements are incorporated into the analysis follows much the same pattern as for the dedicated link system. However, now two different types of elements and dependancy are important. The state of the bus must be determined before any of the elements attached to that bus may be considered. The order chosen for this analysis is bus 1, actuator channels 1 and 3, bus 6, and actuator channels 10 and 12. Other elements are added in a similar sequence until all elements are included, with the appropriate bus accounted for before the attached actuator channel can be considered operational.

The equation diagram and the results of the analysis are shown in Figure 22. The entire diagram is given for completeness. It will only be necessary, however, to review several of the branches in the upper left hand corner to learn the nature of the failure process for this system configuration and assess the results. The diagram is developed by entering the codes for bus 1, then actuators 1 and 3, followed by bus 6 and actuators 10 and 11. At this point, the pitch control function is assured and an unreliability of 0 is entered. The next state considered is actuator channel 12 failed passively with the earlier elements still good. To determine the success of the system, channel 11 must not be failed actively. This channel does not have to be working since channel 10 is already good, thus bus 5 does not have to be considered. However, when channel 12 is failed actively, bus 5 and actuator channel 11 must be added, as shown in the diagram at location 8,6. For a complete failure of surface 4; bus 3, actuator 5, bus 2, and actuator 4 are added, starting at location 9,4. Location 9,4 is the point in the diagram that corresponds to the system state that includes the active failure of actuator channel 12. This same sequence is also used for the other states, which result in the failure of the channels 10-11-12 actuator system. The result of the sequence is transferred to the other places where it is needed, as shown by all of the 9,4's in rows 7, 8, and 9. A similar process is continued until the entire diagram is complete.

The results of the analysis prove that the requirements are comfortably met when all elements are working at the beginning of the 10 hour flight. The reliability drops significantly, but the requirements are still met if a bus is bad at the beginning of the flight. This result is shown at location 3,4, the conditional unreliability of the system, given that bus 1 failed. In fact, the requirements are met when one entire surface is failed, as shown at location 9,4.

Figures 23 and 24 show the sensitivity of the system unreliability to changes in the failure rate for the bus. These figures give only the upper left hand part of the total diagram, which sufficiently shows the results. Figure 23 is for a bus failure rate of 1.0×10^{-6} per hour. The reliability is not signficantly improved. Figure 24 is for a bus failure rate of 1.0×10^{-4}, corresponding to the case where the backup controller is eliminated. The reliability still meets the requirements, but is almost two orders of magnitude worse.

6.2.1.3 Mesh Network System

A diagram of the critical parts of a network system involved in the pitch control function is shown in Figure 25. The analysis of a system that uses a mesh network is significantly more complex than the analysis of the previous systems. Numerous combinations of failures within the network that can be sustained before a communication failure will cause the loss of a critical function. The analysis of a complete system, such as the one shown in Figure 10, would be very complex and beyond the scope of this study. A simplified system can be defined, however, that adequately represents the full system for the purpose of this comparative analysis. The analysis is considerably more involved than it was for the previous two systems although it can be performed.

The system is simplified by including only those elements directly involved in the pitch control function. This simplification is performed by assigning those nodes interfaced to the servo electronics to adjacent positions, that are also adjacent to the ports in the central computer system. The rest of the system is then deleted and the affected links joined together. The resulting system is shown in Figure 26.

This system is a conservative simplification since it will have a lower reliability than the original system for two reasons: First, if the nodes servicing the servo electronics are not placed in adjacent positions, the number of failures required to isolate particular channels will be considerably greater and thus less probable. Second, by eliminating other nodes from the analysis, alternate paths that could have compensated for failed nodes or links are now unavailable. The appropriateness of this simpification can only be judged after the results of the analysis are available. If these results show that communication failures do not significantly contribute to the failure of the critical function, then the simplification is successful.

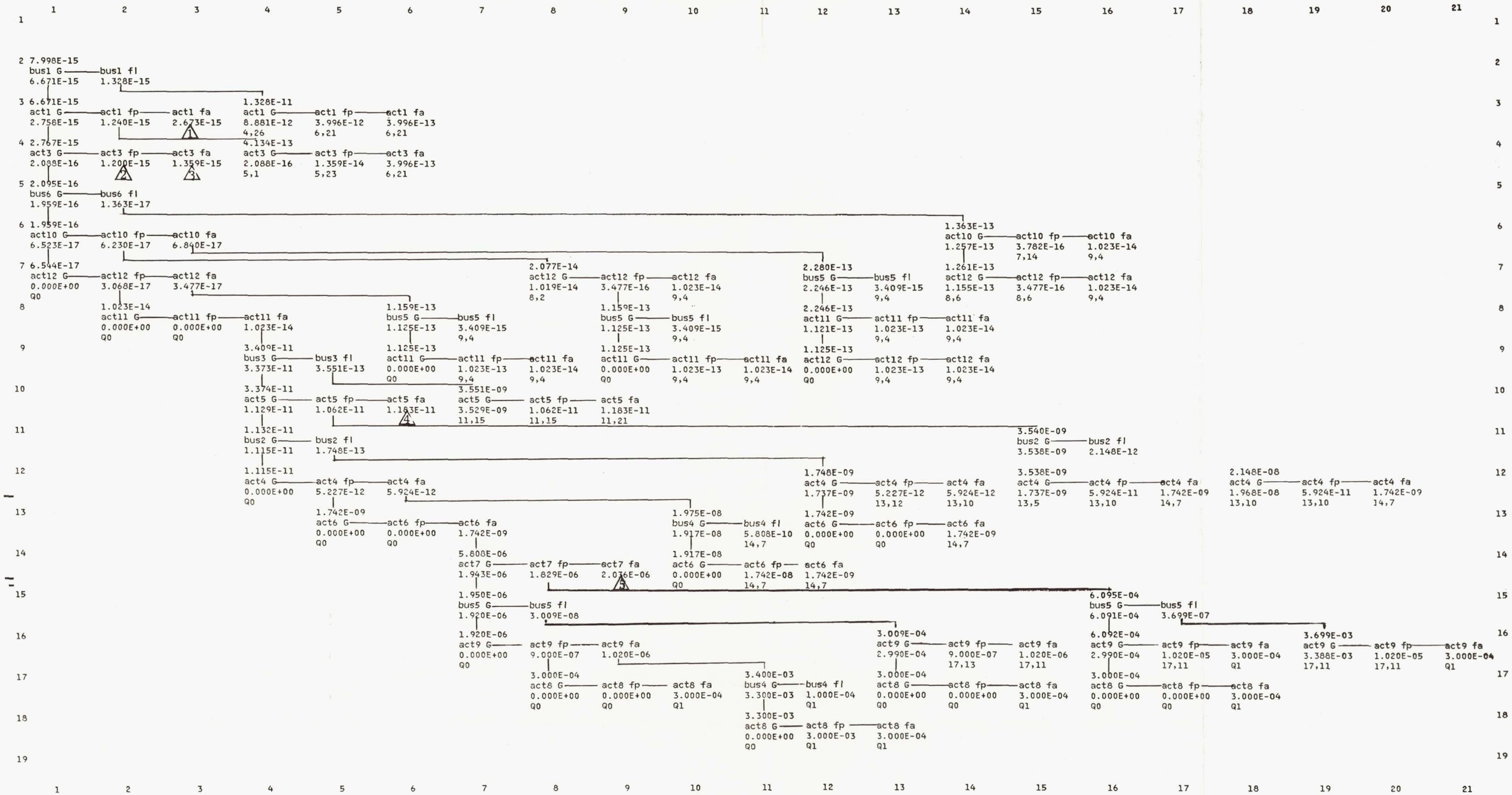


Figure 22: Reliability Equation Diagram for the Multiplex Bus System Time = 10 Hours

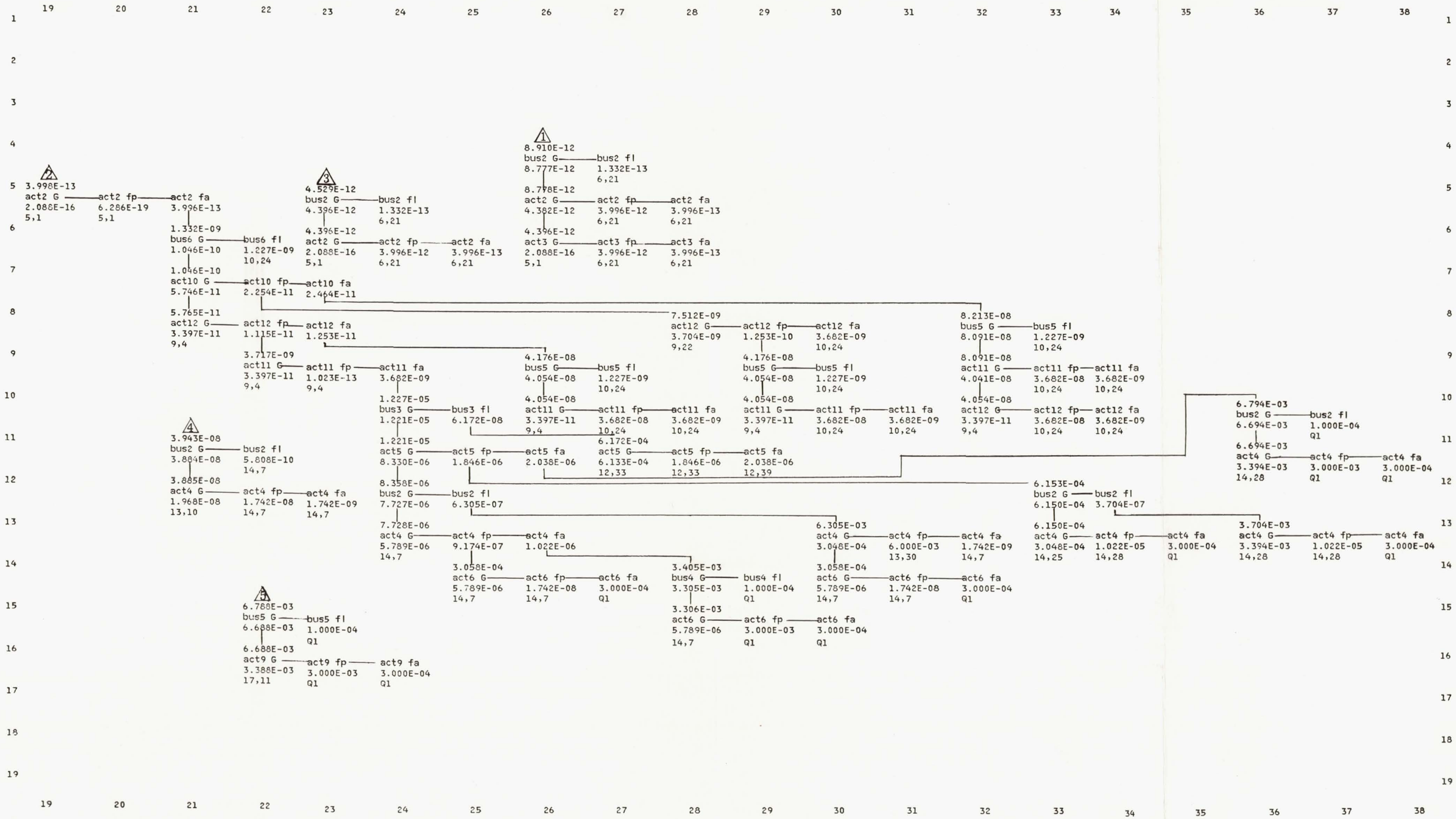


Figure 22: Reliability Equation Diagram for the Multiplex Bus System Time = 10 Hours (Cont.)

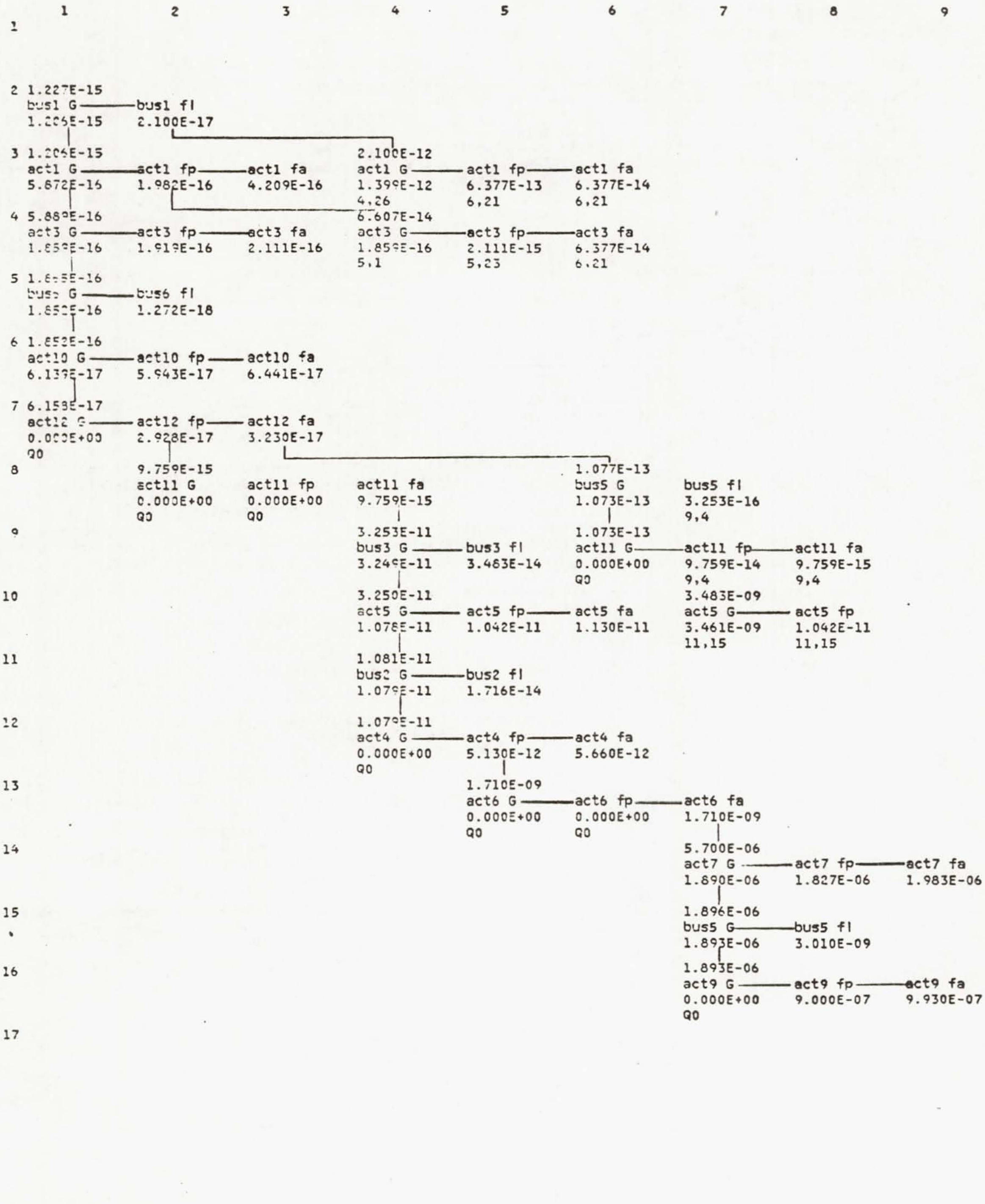


Figure 23: Multiplex Bus System with the Bus Failure Rate Decreased by a Factor of 10

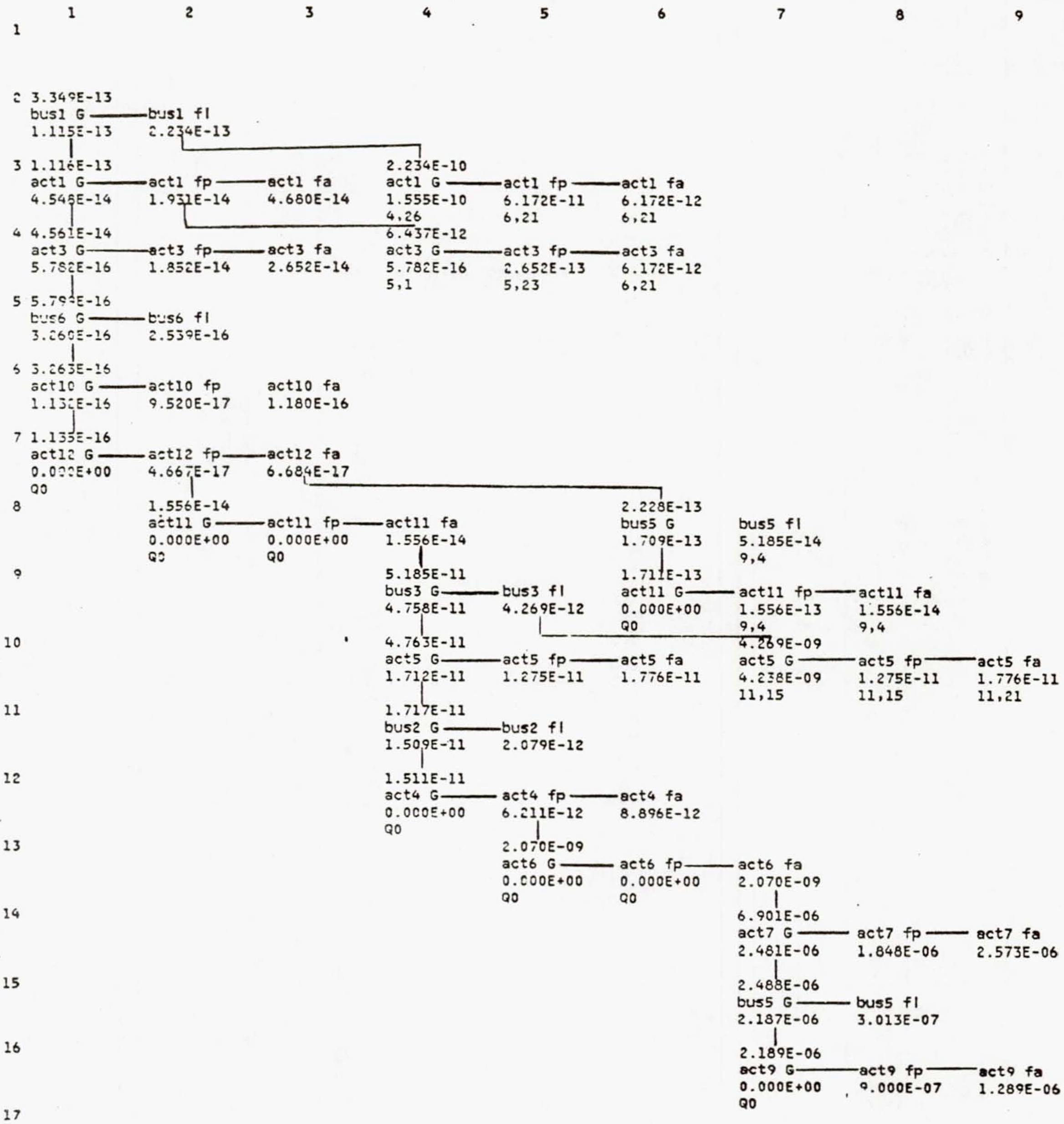


Figure 24: Multiplex Bus System with the Bus Failure Rate Increased by a Factor of 10

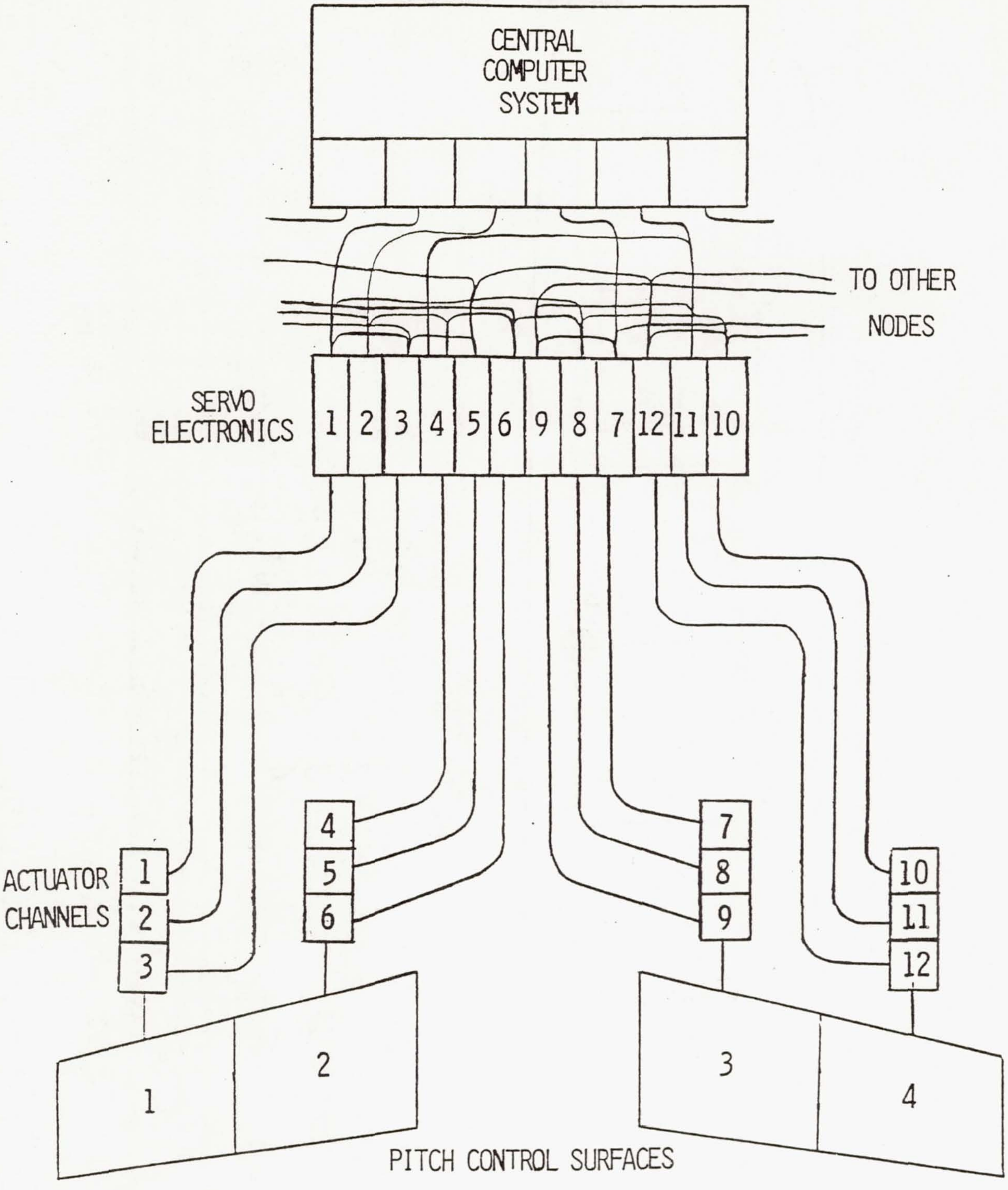
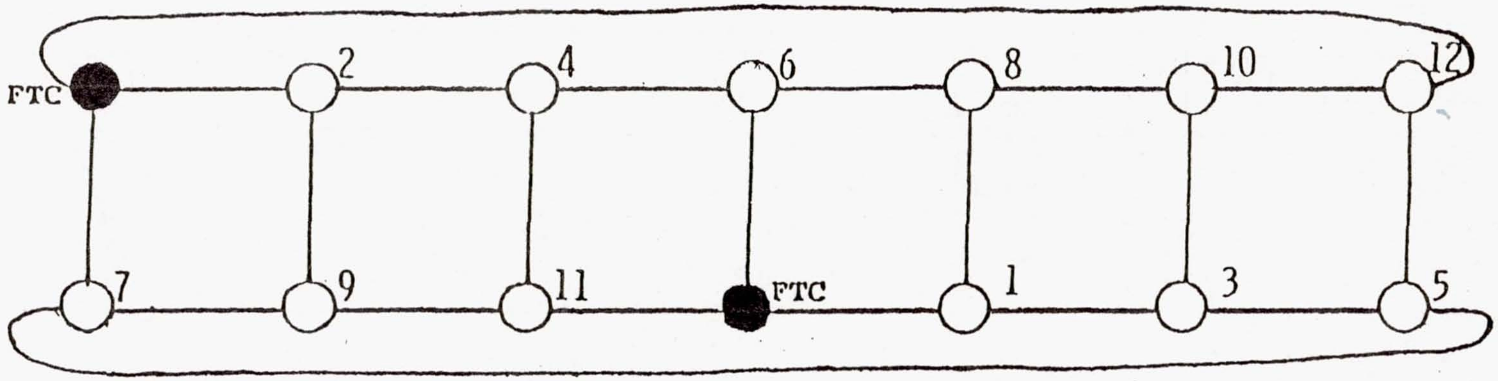


Figure 25: Network System for Pitch Control



ACTUATOR	NODES
1	1 2 3
2	4 5 6
3	7 8 9
4	10 11 12

Figure 26: Simplified Mesh Network System

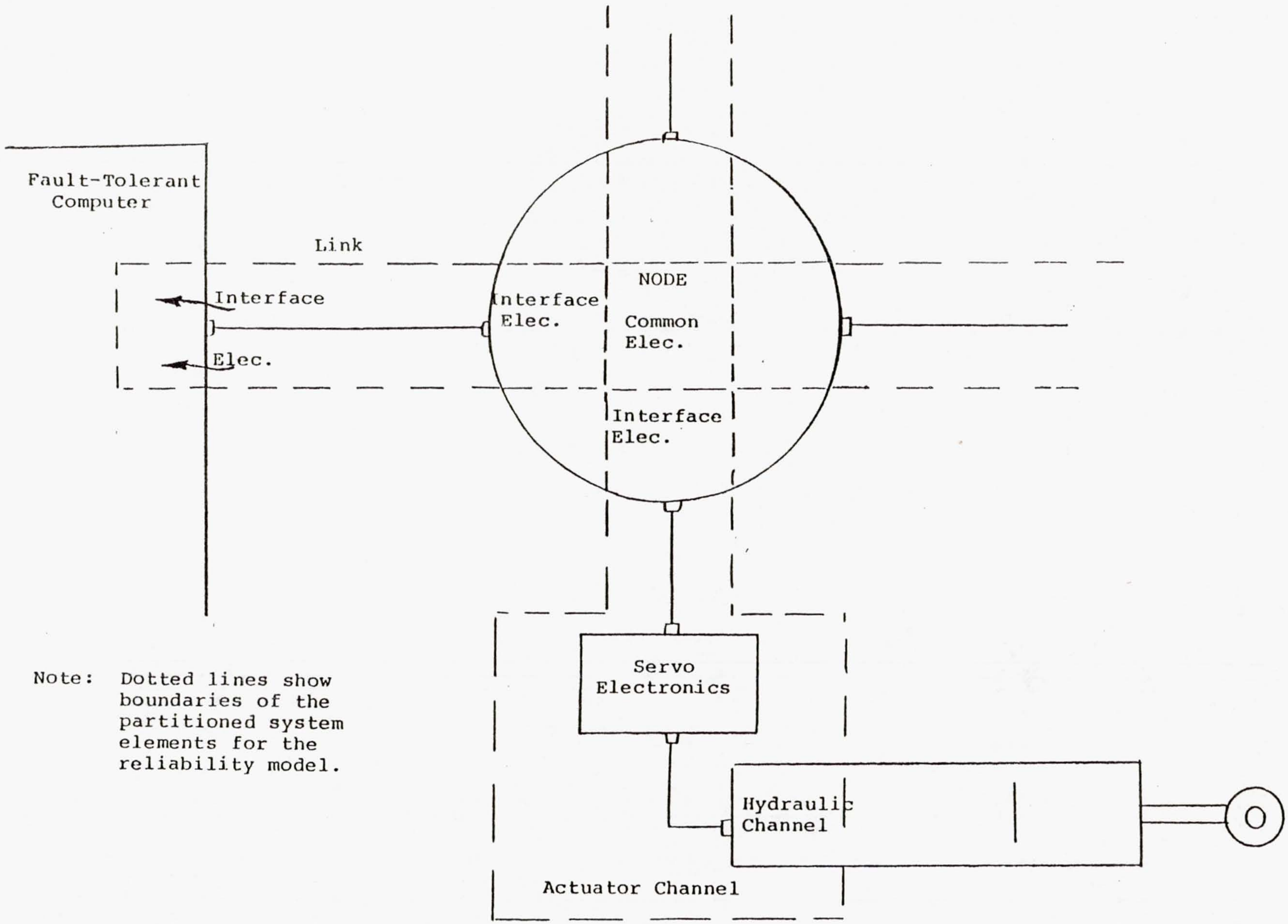
The network system is partitioned into three elements: One of the elements is the actuator channel, as also seen in the previous system configurations. The network itself is divided into two elements: One is the core of the communication node and the other is the link between nodes, or between a node and the computer system. This division is necessary since a node can be used after a link to that node has failed by using an alternate path through other links and nodes still operating. The link element includes all of the interface circuits unique to that link on both ends, plus the wire and connectors in between. The node element includes all of the equipment common to all paths through that node. This partitioning is shown in Figure 27.

The actuator element has the same failure modes and the same probabilities as in the previous system. The node and the link are assumed to have only one failure mode, with a failure rate given by:

node 2.0×10^{-4}
link 1.0×10^{-4}

The order in which the elements are included in the analysis begins with a node that has a potential link to the computer system. The node must be good before any links to that node can be used. Also, a sequence of good elements must be established between the computer and the element in question. The next element after the node is the link from that node to the computer. Then, the actuator channel attached to that node is added. This pattern continues until enough good elements assure the operation of the pitch function. When an actuator channel fails, a similar strategy to the previous analysis is followed. When a link fails, alternate paths are added.

Part of the equation diagram, and the computed unreliability, are shown in Figure 28. The upper left hand corner of this diagram sufficiently illustrates the failure characteristics of the system and provides enough information to compare to other systems. The computer program used to perform this analysis is an older version that does not present the results in as readable a format. Therefore, lines have been added to show how the branches relate. The nodes are represented by the letter N, then by a number to designate which node, followed by a G for good or an F for failed. The links are represented by an L, plus either a C (for computer) and/or numbers to designate what two ports are connected by the link. Again, a G or F show whether the link is good or failed. The actuator is represented by A with a number, plus either G for good, S for passive (soft) failure, and F for active failure.



Note: Dotted lines show boundaries of the partitioned system elements for the reliability model.

Figure 27: Partitioning of Network System Elements

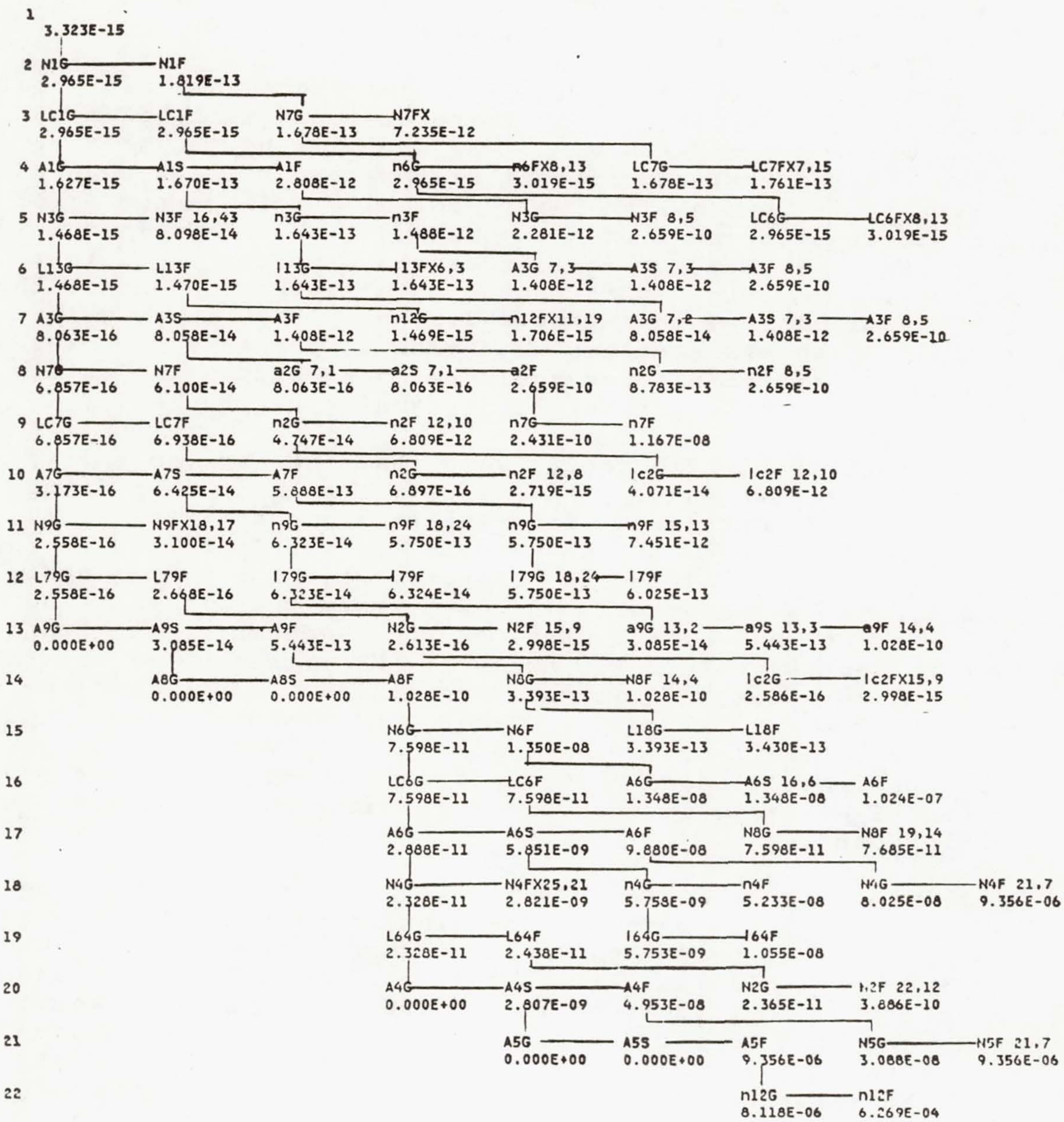


Figure 28: Upper Levels of the Reliability Equation Diagram for the Mesh Network System

The initial sequence can be seen by following down the left hand edge of Figure 28, then relating this to the system diagram in Figure 25. To establish one control surface, this initial sequence is node 1, link from the computer to 1, actuator channel 1, node 3, link for 1 to 3, and actuator channel 3. To establish a second surface, these are followed by node 7, link from C to 7, node 9, link from 7 to 9, and actuator channel 9. If all of these elements are good, the function is assured. If these elements fail, elements are added in a similar way to the analysis of the previous systems. The most significant difference will be when a link fails. When a link fails, normally a large number of alternate routes can bypass the failed link. This factor is the primary reason for the increased complexity of this analysis. Of course, this factor is also the reason for the high reliability of the network system. Experience gained as the diagram was constructed, made it possible to determine where approximations could be made without affecting the results. These points are designated by the letter X.

The results in Figure 28 show that the system easily meets the requirements. The results given in this figure are in a different format from the previous analyses. The number at the top of the diagram is the unreliability of the total system after 10 hours of operation. The number under each symbol is the unreliability, given the state of the system as defined by the state of the elements on the branch down to that symbol. For example, the first number on the second line under N1G is the unrelibility of the system, given that node 1 is good. The second number on that line is the unreliability of the system, given node 1 is failed. The 0 on line 13 means that the system state defined as good by the 12 elements in the first column assures the success of the function.

The results given in this figure also show that the requirements are met when any one element is initially failed. The result on line 2 show the requirement is easily met when one node is failed and likewise for a failed link, as shown on line 3. The results on line 4 indicate that the requirements can also be met when an actuator channel has failed, either passively or actively. The results under A8F show that the requirements can be met after the complete failure of one surface, but only by a narrow margin.

The contribution of the network communication structure to the unreliability of the system can be estimated by observing several of the results shown in the diagram. First, a significant drop in reliability by two orders of magnitude is seen when node 1 fails. This drop in reliability is primarily due to the loss of the use of the actuator channel connected directly to that node, rather than an indication of the reliability of the communication system itself. This fact can be determined by observing the results on line 4. The unreliability of the system, given that actuator channel 1 is failed passively, is almost as large as the unreliability with node 1 failed, confirming that the loss of the actuator channel is the major component in the unreliability with the node failed.

Line 3 shows a more direct measure of the contribution of the communication system to the unreliability of the system. The unreliability of the system with the link from the computer to 1 failed is no greater than with this link good, illustrating that the failure of the link makes no contribution to the unreliability of the system. This same result is observed by comparing the unreliability of the system with a link good to that same link failed for all of the other links shown in Figure 28. These results show that the network communication structure makes an insignificant contribution to the unreliability of the system. This result also confirms that the simplifications made in the system are legitimate. The complete system would have only added more alternate paths to replace a failed link. Since the failure of links makes an insignificant contribution to system unreliability, additional redundancy is unnecessary.

6.2.1.4 Local Bus

The configuration of the system using the local bus is logically identical to the multiplex bus configuration. In both cases, there are two controllers each for six buses. There are also servo electronics for two different actuator channels on each bus. Most probably, the failure rates for the elements will vary, although the direction of the difference is not obvious. The complexity of the local bus controllers and terminals are expected to be simpler. The local bus requires many more wires so that the failures, from such causes as connector failures, will be greater. An extensive analysis of a particular system design is necessary for a definitive comparison.

6.2.2 Other Configurations

The reliability analysis of most of the communication alternatives for the three location configuration and the embedded configuration, have the same form as the corresponding alternative for the one location configuration. The failure rates of the elements may vary, particularly because of the greater distances involved. Again, only a detailed analysis of a particular design could produce any quantitative difference. However, the essential purpose of this study is to compare communication alternatives within a given system configuration. For this purpose, the completed analysis is adequate for most of the necessary comparisons.

The two level dedicated link configuration will have a different form for the analysis since an extra element is present in the system. This extra element is the intermediate terminal in each location. However, this system configuration is not of sufficient interest to justify creating an additional detailed analysis.

6.2.3 Summary of Reliability Results

The reliability of all the candidate communication structures have basically the same level of reliability. This level of reliability is significantly greater than necessary even when any one unit is failed initially. Most likely, a more optimized design for an actual system would reduce the reliability margin somewhat and produce savings in hardware. However, this high level of redundancy may be retained so that maintenance intervals can be extended and/or dispatch reliability increased. Yet, the purpose of this study is not to perform a detailed design of a system, but to create system alternatives with essentially equivalent levels of reliability. With these equivalent levels of reliability established, the alternatives can be compared to see which best achieves the requirements. In fact, the analysis in this chapter is a part of the iterative design process that led to the alternatives described in Chapter 5.

6.3 SYSTEM CAPACITY ANALYSIS

The requirement for the actual data rate capacity is given in Chapter 3. The total requirement is 155K data bits per second. The one location system configuration described in Chapter 4 requires a total throughput of 18K 16 bit words per second to produce the required data. The data throughput required is thus 288K bits per second. The basic transmission rate assumed for the communication links for each candidate is 1 MHz. This rate is based on the soundest technology and is consistent with MIL-STD-1553B. This rate can be supported by twisted shielded wire, avoiding the the problems and expense of broader bandwidth wire, such as coaxial cable.

The dedicated link system can easily meet the capacity requirements. Each link can be used independently (unless constrained by the use of shared equipment in the central computer, which is assumed not to be the case in this study). The data rate capacity is thus judged by how well the requirements are met for the link with the greatest rate. The link with the greatest requirement can thus be easily met. The protocol overhead for a dedicated link is minimum, so the 1 MHz rate is more than adequate and could be reduced if desired.

The multiplex bus system can also easily meet the capacity requirements. With a total of six buses, units are assigned to the buses in a way that balances the communication load. The data rate requirement for each bus is thus approximately a 72K bit rate. The protocol overhead for a multiplex bus is much greater than the dedicated link. In the worst case, the multiplex bus is expected to be 45% efficient. Thus, a 1 MHz bus will easily meet the requirements.

The network can also fulfill the capacity requirements, although the margin may be less depending on the mode of operation of the network. The worst case is that the network operates as a single logical bus. The overhead will be the same as the multiplex bus system, except during network reconfiguration. Presumably, reconfiguration seldom happens and can be accomplished in a short enough time that it has no effect on critical functions. Thus, the capacity requirements can be met in this worst case configuration. Unfortunately, there is little flexibility for growth. This problem can be alleviated either by using dedicated links between nodes with high data rate requirements, or by organizing the network as more than a single logical bus.

6.4 COMPARISON OF CANDIDATES

The previous sections established that the systems employing the candidate communication techniques have equivalent levels of reliability and capacity. The systems can now be compared to see which best meets the requirements. However, to establish firm quantitative distinctions between these alternatives is impossible without the detailed design of each system. Nevertheless, some general observations can be made to aid in making effective choices at the beginning of a system design effort.

Several of the advantages and disadvantages of each candidate have already been discussed in Chapter 5. These comparisons are summarized for the candidate systems for the one location configuration. This comparison will also generally apply to candidate systems for the three location configuration because they have similar characteristics. A trade-off is unnecessary for the embedded system since, in this study, the mesh network is considered to be the only likely candidate for this configuration.

The effectiveness of the candidate systems for the one location configuration can be compared using several different criteria. Some of these criteria are initial development costs, production costs, maintainability, availability, flexibility, and technical risk. Most of these factors can eventually be resolved in terms of the total life cycle costs. The initial development and production costs along with much of the maintainence costs, will primarily depend on the amount and complexity of the hardware. Lack of flexibility will require greater costs when future modifications must be made to the system. Higher technical risk gives the probability of higher costs when technical problems must be solved, or replacement equipment must be utilized.

The comparison of development and production costs based on complexity can be estimated quantitatively, with the other standards compared only qualitatively.

6.4.1 Comparison of System Complexity

The complexity of the communication system can be compared by looking at the equipment required to provide the basic interface at the using terminals. To form a common basis for comparison, each unit connected to the communication system presumably has an embedded digital processor. This assumption is essentially true for most of the units in current avionics systems and will be more common in future systems. The circuits to compare among the alternate communication techniques are those that provide the interface between the internal bus of a typical microprocessor system and the communication system.

The dedicated serial bus is taken as the baseline for the comparison of complexity. The format of the data must be changed using serial-to-parallel and parallel-to-serial converters. Control logic must be included to sequence the data through the conversion process. A clock signal must be provided for transmitting data, and the clock reconstructed for received data. A method must also be implemented to synchronize the receiver to the transimitted data. There must also be differential line drivers and line receivers. Large scale integrated circuits already exist that may be appropriate for this application, making it the least complex interface.

The multiplex bus interface becomes substantially more complex since it has all of the components of the dedicated bus, plus the additional functions required to operate in a multiplex environment. These additional functions include: responding only to a particular address, recognizing commands from the bus controller, and generating the proper status word in response. The timing restraints will be considerably tighter since any delay in response will create a penalty for the entire system. These timing constraints are likely to be too tight to meet without dedicated hardware. Also, data buffering will probably be needed for entire outgoing and incoming messages. The complexity is thus estimated to be 3 times the dedicated bus interface.

The mesh network system will be the most complex, having to service three multiplex links. Some of the control and data buffering can be shared. However, a limited ability to simultaneously monitor all buses will be required for reconfigurations to be made after failures. Additional control logic must be included for the node to respond to the commands that configure the mesh. The resulting equipment is thus expected to be 5 times as complex as the local bus.

The local bus is already in a form that is close to the internal bus in the terminal unit. The bus is not likely to be identical, however. There will thus be some logic circuits necessary to convert the signals into the correct form. Bidirectional three state buffers will be required on most of the lines. The number will be a function of the design of the local bus. For example, the number will be less if data and address are multiplexed on the same lines. Data storage buffers may also be required if the terminal unit cannot respond within the timing requirements of the local bus. Particular care must be taken to assure that the failure modes of the interface that would disrupt communication on the bus have very low probability. Extra hardware may thus be required to reduce the probability that a unit can put a high or a ground on any of the bus lines, primarily because of the circuits required to support the large number of lines, the local bus interface is expected to be 2 times as complex as the dedicated bus interface.

The comparative complexity of the candidate systems can now be estimated by multiplying the number of interfaces by the complexity factor for each case. The interface at the central computer system for the dedicated link system is assumed to be essentially the same as the interface at the remote unit. The total number of interface circuits is thus twice the number of units. The bus controller for the multiplex bus system is assumed to be approximately 50% more complex than the interface in the remote unit. Since there are 12 controllers, one primary and one backup for each bus, there are an equivalent of 18 interfaces. The interface at the computer for the network is assumed to be the equivalent to two nodes since each node has three ports, giving the six ports assumed for this system. The controllers for the local bus system are assumed to be twice as complex as the interface in the remote unit. Since there are 12 controllers, this is equivalent to 24 interfaces. The results are combined to form an index that gives an approximate total measure of the complexity of the alternative systems. These results are summarized in Table 27.

TABLE 27

Summary of Estimated Relative Complexity

SYSTEM	REMOTE TERMINALS (NUMBER)	COMPUTER INTERFACE (EFFECTIVE NO. OF TERM.)	TOTAL	COMPLEXITY FACTOR	COMPLEXITY INDEX
DEDICATED LINKS	92	92	184	1	184
MULTIPLEX BUS	92	18	100	3	300
MESH NETWORK	92	2	94	5	475
LOCAL BUS	92*	24	116	2	232

*NOTE: THIS NUMBER INCLUDES THE REMOTE TERMINALS WHICH CANNOT ACTUALLY BE SERVICED BY THE LOCAL BUS. A DEDICATED LINK IS ASSUMED FOR THESE INTERFACES WITH ESSENTIALLY THE SAME COMPLEXITY.

6.5 SUMMARY COMMENTS ON TRADE-OFF ANALYSIS

The relative complexity will be a major factor in determining which communication structure is best for a particular application but it will not be the only factor. The complexity will be important since it will have a major influence on the initial and support costs. The significance of complexity will decrease with time, however, with the introduction of special purpose VLSI circuits. When these circuits are produced in high quantities, the advantages of a more complex system can be obtained at little additional cost. Other factors, such as flexibility and technical risks, may outweigh strict cost considerations in some cases.

The dedicated bus system is not likely to be the most effective choice for any very large system because of the awkwardness and inflexibilty of the interface at the central computer system. The wiring installation in the aircraft will also require a large amount of wire and be difficult to modify.

The multiplex bus system has the greatest current acceptance. It provides a reasonable amount of flexibility and installation efficiency. The difficulty of designing a reliable and efficient bus will become harder as more units are attached to the bus. The bus will also become more vulnerable to failure and damage when it attempts to support units distributed throughout the aircraft.

The network system is currently more complex than the other alternatives. However, as the technology becomes available to implement the node with VLSI technology, there is likely to be a shift from a multiplex bus to a network system to avoid the problems of designing a very large and flight critical multiplex bus system.

The use of a local bus system will depend largely on what trends develop in the architectural design of large, highly integrated systems. If a modular system emerges and if these modules are packaged as individual line replaceable units within environmentally controlled compartments, the local bus is likely to be the most effective communication structure within those compartments, particularly since it can support a much higher data rate than serial buses can.

Chapter 7

CONCLUSIONS AND RECOMMENDATIONS

This study contributes to the technology base necessary for the development of effective avionic communication systems. A general study such as this cannot recommend a universally preferred communication structure. The best choice for a particular system must be the product of an analysis of the requirements, oppurtunities, and constraints of that particular situation. This study does discuss, however, some of the factors involved in choosing the best communication technique and also provides some of the necessary design and analysis tools.

This report first establishes a realistic environment for the study of communication techniques. The communication structure is highly dependent on the overall configuration of the equipment to be serviced. One of the most important characteristics is the distribution of the equipment in the aircraft. The next generation of aircraft will probably have a significant percentage of the hardware in compartments where the environment is controlled and maintenance is simple. Future generations of aircraft will most likely have electronics distributed throughout the aircraft.

An important factor influencing future system development is the state of electronic technology. Inexpensive devices that operate in severe environments will presumably be available in the next few years. This development will encourage the introduction of electronics within equipment distributed throughtout the aircraft. This same technology will, of course, also support the communication system that services this distributed equipment.

This study concludes that the best choice for near term systems, where a large percentage of the system is contained in centralized compartments, is some form of multiplex bus. This bus would be either a serial two wire system similar to the current MIL-STD-1553B, or a local bus patterned after a conventional minicomputer interface bus. A multiplex bus provides a good compromise between complexity and flexibility. Multiple buses must be used to provide the necessary fault tolerance.

The conclusion for future systems, where equipment is distributed throughout the aircraft, is that a mesh network is most effective. Cost effective, integrated circuit technology is predicted to be available to perform the complex operations required in extreme environments. The network will be an efficient solution for meeting the problems that would be encountered in designing a multiplex bus system that supports critical functions throughout an aircraft. It will be difficult and cumbersome to design a multiplex bus system for these long and exposed distances to meet the reliability requirements for life critical functions in the presence of the inevitable failure and damage hazards. The inherent characteristics of the network provide effective techniques for containing these hazards. The primary disadvantage of complexity will diminish with the development of the new technology.

Extensive research is needed to provide all the technology necessary for developing the communication structure for highly integrated avionic systems. One area of research recommended for the next generation aircraft is further study of the communication techniques within an avionics compartment. Current multiplex buses, such as MIL-STD-1553B, are designed for longer distances and do not have the simplicity and throughput appropriate for communication between modules within a relatively small compartment. On the other hand, the system buses developed in the commercial industry require a large number of connections and may be difficult to make fault tolerant. Some compromise between these two concepts may be appropriate. A thorough study is necessary to arrive at that compromise.

In the longer term, more work is recommended on network communication concepts. Work is needed particularly to develop the technology that will provide the necessary functions cost effectively in a severe environment. Additional work is also needed to develop the design tools and guidelines for effectively constructing the network comfiguration within an aircraft.

APPENDIX A

PHYSICAL DAMAGE HAZARDS TO FLIGHT CRITICAL ELECTRONIC EQUIPMENT

I. Introduction

Advanced electronic flight control equipment is being developed to perform increasingly flight-critical functions. These functions are becoming integral parts of the basic aerodynamic and structural designs of aircraft, thereby creating control-configured vehicles (CCV). Electronic equipment is also providing the basic connection between the pilot controls and the aerodynamic control surfaces, replacing mechanical linkages to give fly-by-wire systems.

In commercial aircraft, these advanced avionic systems must meet the Federal Aviation Regulations, which state that it must be extremely improbable that a system failure cause a catastrophe. Where numerical analysis is appropriate, "extremely improbable" is interpreted as a rate of 10^{-9} per hour or per flight. These systems are becoming so critical to safe flight that a complete failure is almost certain to be catastrophic. Thus the required functional failure rate for the systems is 10^{-9} per hour.

Electronic components inherently have much too high a failure rate to provide the required reliability. This problem has been attacked by building redundant systems that are tolerant to individual electronic failures by using techniques to detect and identify failures and reconfigure the system to allow continued operation. Advanced systems are being developed which give reasonable confidence that they can provide the required functional reliability in the presence of random failures.

The success in solving the problem of random failures has significantly increased the relative importance of other hazards. Other hazards such as damage and design faults have been considered sufficiently unlikely so that they could be realistically ignored in the past. However, dramatic reductions in primary failure rates and lowering failure rate requirements have made it necessary that other types of hazards be carefully considered. They could become the dominant contributors to the total failure rate. The hazard of particular concern in this discussion is physical damage.

Physical damage can result from collision with other aircraft, birds, collision with the ground or other stationary objects, excessive aerodynamic loads due to abrupt maneuver or turbulence, explosion (terrorist or accidental), massive failure of engine or other equipment such as air conditioning turbine including effect of parts thrown out, loose objects such as cargo, and damage due to rapid decompression. Fire can result from many of the same causes plus massive failure of electrical and electronic equipment, cargo fires, accidental trash fire such as a cigarette in a waste container, etc. Physical damage would also include liquid damage due to fuel, hydraulic, galley, and toilet leaks.

Physical damage to the flight control system has been involved in the two worst single aircraft accidents. The Turkish DC-10 ultimately crashed because of lack of pitch control due to damage to the control lines under the floor. Preliminary reports of the American DC-10 indicate that a major contributor to the ultimate loss of control was the retraction of the leading edge flaps due to damage to the hydraulic lines or control lines.

In order to begin to account for the damage hazard, it is necessary to establish some measure of the rate of damage events and estimate the effects they are likely to have on electronic equipment. This paper is intended to be a first step toward estimating these rates and effects.

II. Method of Estimating Damage Hazard Rate

The method used here for estimating damage failure rate is based on a survey of all U.S. air carrier accidents from 1964 through 1977. The initial survey was done using the briefs of accidents in the Annual Reviews of Aircraft Accident Data published by the National Transportation Safety Board (NTSB). For selected accidents, the complete accident file or report was reviewed at the NTSB offices in Washington, D.C.

The electronic system assumed for this study involves electronic units contained primarily in bays within the fuselage with some electronic equipment contained in other areas including the wing, the tail, and on the engines. These electronic units are assumed to be interconnected with a communications system. It is assumed that normal practice has been used in installing this equipment, and that no extraordinary steps were taken to avoid physical damage.

For each accident, a determination was first made on whether damage to the electronic system could have contributed to an accident. Two classes of accidents were eliminated; those where it was judged to be very unlikely that any part of an electronic system would be damaged, and those where the results of the accident would be the same whether the electronic system was damaged or not.

For each of the remaining accidents, rough estimates were made in three categories; the probability that at least one cable containing a communication line or communication terminal was damaged, the probability that more than one line or terminal was damaged, and the probability that one particular area in the forward avionic bay was damaged which could correspond to a system controller.

These estimates were based primarily on the limited amount of information available in the briefs of accidents in the NTSB reports. In a few cases these estimates were reviewed and refined by the complete accident report file which contained pictures of the damage in many cases.

III. Estimates of Damage Hazard Rates

The time period 1964 through 1977 produced 771 accidents for U.S. air carriers including the certificated route carriers and supplemental carriers. This represents a total flying time of approximately 83 million hours.

Of these accidents, 58 were judged to be ones where damage to a flight critical electronic system could have been a factor. For each of these accidents, estimates were made of the probabilities in each category that the electronic system would be damaged. Detailed reports were reviewed for nine accidents (see Table I). These detailed reviews led to revision of the estimates in some cases but in general confirmed the original numbers.

The damage probability estimates are given in Table II. These probabilities are then summed and divided by the total flight hours to give the estimate of the damage hazard rate. The results are:

1. Damage rate to at least one communication line in the system — $2x10^{-7}$/Hr

2. Damage rate to two or more communication lines — $6x10^{-8}$/Hr

3. Damage to one particular unit in the forward avionic bay — $4x10^{-9}$/Hr

IV. Conclusions

The damage hazard rates estimated here are not intended to be definitive. Because of the limited amount of information available for the preliminary study, the rates may be in error by as much as an order of magnitude in either direction. One potentially significant source of damage hazard which was not considered was incidents which might have caused damage but were not severe enough to be reported to the NTSB as an accident.

These preliminary estimates do indicate, however, that physical damage can be a significant failure mode for advanced electronic flight control equipment in a commerical airplane. It is recommended that more work be done to improve the estimates of the damage rates and that damage be included in any failure analysis of any flight critical electronic system.

TABLE I

DETAILED ACCIDENT REPORT REVIEWED

DATE	LOCATION	AIRLINE	AIRCRAFT	ACCIDENT TYPE
Jan. 9, 1979	Newark	American	B-707	Collison, Mid-Air
	Substantial damage to No. 1 engine, nacelle, strut, and leading edge of wing out board of No. 1 engine.			

July 30, 1979	San Franciso	Pan AM	B-747	Collison, Landing Lights
	Fuselage pierced by multiple steel beams. Landing gear forced up into cabin. Damage bulk head. Three of four hydraulic systems lost.			

Nov. 3, 1973	Boston	Pan AM	B-707	Fire
	Chemical fire in cargo producing dense smoke. Little actual damage to aircraft equipment. Factor in accident was loss of yaw damper inadvertently turned off because crew thought fire was from electrical equipment.			

Nov. 3, 1973	New Mexico	National	DC-10	Engine Explosion
	Engine disintegrated probably due to crew experimenting with auto throttle. Numerous punctures in fuselage. Power lines cut. Two of three hydraulic systems damaged. Control cables in tail severed.			

Feb. 4, 1975	Miami	Eastern	B-727	Fire
	Missing clamp caused rubbing between wire and hydraulic line. Power wire arched through hydraulic line causing fire.			

Sept. 8, 1975	San Juan	American	B-747	Structure
	Flap separated. Punctured fuselage, broke windows, dented horizontal stabilizer.			

TABLE I (CONT.)

DATE	LOCATION	AIRLINE	AIRCRAFT	ACCIDENT TYPE
Sept. 20, 1975	JFK	Airlift Inter.	DC-8	Collison, Landing Lights/ILS
	Fuselage punctured, pressurization valve damaged, wheels damaged, anti-skid junction box damaged.			

June 1, 1976	Kansas	TWA	L-1011	Fire
	Small hydraulic leak created mist which was ignited by electrical arc. Fire destroyed all electrical cables and hydraulic lines in compartment.			

Sept. 3, 1977	Tuscon	Continental	B-727	Collison, Power Lines
	Wind shear on take-off. Hit power lines. Damaged wings, wing root, engine cooling.			

TABLE II

ESTIMATES OF POTENTIAL DAMAGE TO ELECTRONIC SYSTEMS

TYPE OF ACCIDENT	ESTIMATED PROBABILITIES		
	ONE LINE DAMAGED	MORE THAN ONE DAMAGED	ONE LOCATION DAMAGED
1964-1969			
Engine	.05	-	-
Fire	.2	.1	.03
Fire	.5	.1	-
Fire	.1	.01	-
Engine	.0	.3	-
Collision, Mid-air	.8	.2	.01
Collision, Mid-air	.8	.2	.01
Engine Fire	.5	.05	-
Engine	.1	-	-
Hail	.05	.01	-
Hail	.05	.01	-
Bird	.05	.01	-
Lightning	.1	.05	-
Bird	.05	.01	-
Collision, Trees	.1	-	-
Engine	.1	-	-
Engine	.1	-	-
Engine	.05	.01	-
Structure	.3	.1	-
Engine	.1	-	-
Fire	.3	.1	.01
Fire, Electrical	.3	.1	.01
Fire	.3	.03	.005
Mid-Air	.5	.1	.005
Collision, TV Tower	.05	-	-
Engine	.3	.1	-
Collision, Mid-Air	.05	-	-
Collision, Mid-Air	.6	.2	.05

TABLE II (CONT.)

TYPE OF ACCIDENT	ESTIMATED PROBABILITIES ONE LINE DAMAGED	MORE THAN ONE DAMAGED	ONE LOCATION DAMAGED
1970-1972			
Engine	.1	-	-
Lightning	.4	.05	-
Engine	.05	-	-
Collision, Mid-Air	.6	.05	.005
Collision, Landing Lights	.9	.6	.05
Fire	.4	.1	.01
Engine	.2	-	-
Bird	.6	.1	.05
Structure, Decompression	.8	.5	-
Engine	.1	-	-
Fire	.1	-	-
Engine	.3	.02	-
1973			
Engine	.9	.5	.01
Fire	.2	.01	-
Engine	.3	.05	-
Fire	.6	.1	.01
1974			
Fire/Engine	.05	-	-
Structure	.1		
Engine Cowl	.3	.1	-
Hail	.1	.03	-
Bomb	.06	.02	.005
1975			
Fire	.4	.05	.005
Engine	.2	.05	-
Control Surface	.1	-	-
Collision, ILS	.2	.05	-

TABLE II (CONT.)

TYPE OF ACCIDENT	ESTIMATED PROBABILITIES ONE LINE DAMAGED	MORE THAN ONE DAMAGED	ONE LOCATION DAMAGED
1976			
Fire	.9	.5	.05
Engine Fire	.1	.01	-
Engine	.5	.1	-
1977			
Collision, Power Lines	.1	.05	-
TOTALS	17.3	4.8	.33
TOTAL FLIGHT HOURS	83.06×10^6		
DAMAGE RATE/HOUR	2.1×10^{-7}	5.8×10^{-8}	4.0×10^{-9}

Appendix B

ACRONYMS

AB	avionics bay
ADDCS	Analog and Discrete Data Conversion System
ADF	automatic direction finding
AEEC	Airline Electronic Engineering Committee
APU	auxilary power unit
ARINC	Aeronautical Radio, Inc.
ATC	Air Traffic Control
CP	cockpit
CRT	cathode ray tube
DABS	Discrete Address Beacon System
DADS	digital air data system
DITS	digital information transfer system
DME	distance measuring equipment
GPS	Global Positioning System
HF	high frequency
ILS	instrument landing system
LRU	line replaceable unit
LSI	large scale integration
LVDT	linear variable differential transformer
MCU	modular concept unit
modem	modulator/demodulator

MTBF	mean time between failures
NIC	New Installations Concept
NTSB	National Transportation Safety Board
VHF	very high frequency
VLSI	very large scale integration
VOR	VHF omni range

REFERENCES

1. Mark 33 Digital information Transfer Systems (DITS). ARINC Specification429, 21 October 1978.

2. Welch, J.D. and P.H. Robeck: Proposed Technical Characteristics for the Discrete Address Beacon System (DATS). Lincoln Laboratory Report ATC-71, (FAA-RD-77-143), 30 September 1977.

3. Environmental Conditions and Test Procedures for Airborne Equipment. Radio Technical Commission for Aeronautics, DO-160A, 25 January 1980.

4. Air Transportation Avionics Equipment Interfaces, (NIC). ARINC Specification 600, 10 October 1978.

5. A Study of U.S. Air Carrier Accidents: 1964-9. National Transportation Safety Board, Washington, D.C., NTSB-AAS-72-5, 10 May 1972.

6. Annual Review of Aircraft Accident Data, U.S. Air Carrier Operations, 1976. National Transportation Safety Board, Washington, D.C., NTSB-ARC-78-1, 5 January 1978.

7. Franklin, A. Fisher; and Plumer, J. Anderson: Lightning Protection of Aircraft. Prepared for Aerospace Safety Research and Data Institute, Nasa Lewis Research Center, 1977.

8. Air Transportation Avionics Equipment Interfaces, (NIC). ARINC Specification 600, 10 October 1978.

9. Flight Central Computer System. ARINC Characteristic 701, 6 November 1978.