THE DEVELOPMENT OF A FIBRE OPTIC DATA BUS FOR HELICOPTERS

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Abstract

There is considerable interest in the application of fibre optics to helicopters. The primary advantages to be obtained from using fibre optics are improved EMC, cost and weight reduction, reduced spark hazards and a greater bandwidth capacity.

The paper will describe the design and development of a fibre optic data bus system which is compatible with the MIL-STD-1553B data transmission standard. A major problem to be overcome with multi-terminal fibre optic data transmission systems is the large amount of optical power lost at couplers and connector interfaces. The design trade-offs involving system optical power budgets, interconnect harness layout options, and optical transmitter and receiver requirements will be discussed, together with the optical system test procedures. The resulting system architecture features a full 31 terminal interconnect capability using a totally passive bus with no signal regeneration.

The paper is based on the results of a thirty month, UK Ministry of Defence funded, programme to develop a prototype system. In this programme Westland Helicopters was prime contractor, with Smiths Industries and Standard Telecommunications Laboratories (STL) acting as subcontractors. Smiths Industries were contracted to supply various items of hardware which are interfaced to optical transmitters and receivers designed and manufactured by Standard Telecommunications Laboratories, and interconnected over a fibre optic data bus harness manufactured at Westland.

The paper will describe the results of the development programme and outline future avionic applications of optical data transmission, such as high-speed data bus and video data transmission.

1. Introduction

The potential benefits offered by fibre optics to data transmission systems have long been recognised. In some areas of communication they have already been proven, and are being exploited increasingly with time, (eg. telecommunications). However, whilst recognising the benefits, the aerospace community has been more cautious in adopting the technology, wishing first to fully understand the implications and drawbacks involved in using fibre optics.

The main benefits to be gained from replacing copper signal conductors with fibre optics are immunity to electromagnetic interference, lack of electromagnetic emission and increased bandwidth. Due to the high density of electrical systems within modern aircraft, significant problems are encountered with electromagnetic interference between systems, signal lines and power lines. The potential application areas in the aircraft are varied, ranging from audio intercomms, through digital data bus to video distribution networks.

This paper describes a 30 month programme of work funded by UK MoD, through the Royal Aircraft Establishment at Farnborough. Westland Helicopters Limited (WHL) was prime contractor for the work with Smiths Industries and Standard Telecommunication Laboratories as the two main subcontractors. The aim of the programme was to design, construct, demonstrate and evaluate a fibre optic implementation of the MIL-STD-1553B [1] digital data bus, equivalent to DEF STAN 00-18 (Part 2) [2].

2. Background

WHL has been actively involved in developing the potential benefits offered by fibre optics as applied to helicopters for some years. The integration of increasingly complex avionic systems poses many problems for the airframe manufacturer, most of which focus around the question of Electromagnetic Compatibility (EMC). Although systems may function quite adequately in isolation, once they are integrated in close proximity electromagnetic emissions from, and susceptibility of, power and signal lines require the designer to give careful consideration to the location of all interconnecting wiring within the airframe. Signal lines must be marked with their EMC category and routed accordingly, relative to the rest of the aircraft wiring. Any subsequent systems retrofit will be prone to similar problems, made worse by the fact that it is generally not feasible to resite the original equipments and therefore additional systems must be integrated with the current aircraft fit. With the move towards composite airframes, these problems are likely to get worse.

The use of fibre optics for data transmission will, however, provide the designer with a solution to many of his problems, as fibre optics are neither susceptible to interference, nor do they radiate. As well as offering greater systems integrity, fibre optics allow the designer much more freedom with the installation of the cable assemblies, resulting in a consequent reduction in the design and development effort required.

MIL-STD-1553B, a military standard for a 1 Mbit/s serial data bus, is gaining acceptance in the military aerospace community, and much effort has been put in to gain experience and confidence in systems based on the Standard. It is very likely that systems based on the Standard will see service well into the next century.

It is for these reasons that WHL have developed a fibre optic implementation of MIL-STD-1553B.

3. The Current Status of Fibre Optic Technology

In an attempt to unify the UK approach towards fibre optics, a working group of the Avionics Systems Standardisation Committee (ASSC) is currently drafting a number of Defence Standards relating to the use of fibre optics. One of these, DEF STAN 00-18 (Part 7), defines a fibre optic implementation of Part 2 of the same standard (which is equivalent to MIL-STD-1553B). Likewise, the US are drafting a fibre optic version of the data bus standard, called MIL-STD-1773. There is, however, a certain amount of disparity between the two fibre optic draft standards, relating to the choice of optical modulation technique.

Prior to this fibre optic data bus study, a number of fibre optic components were undergoing development for RAE, under DCVD funding. These components included fibre optic cable, transmissive star couplers, fibre optic connectors and high radiance LEDs. The development of these components was to take them to Stage A (engineering samples). It was felt that although further development was necessary, the component technology was mature enough to make the fibre optic data bus study feasible.

4. Overview of the MIL-STD-1553B Electrical Data Bus

MIL-STD-1553B provides a standard for a digital command/response time division multiplexed serial data bus. The Standard provides for a means of allowing up to 31 terminal equipments to communicate to one another over a serial 1 Mbit/s digital data bus. All inter-terminal communication is conducted under the control of a dedicated data bus controller, which initiates all data transfers and monitors their success or failure. The Standard provides for system survivability after equipment failures by allowing replication of data bus cables, equipment interfaces and control. Data may be transmitted between terminals in blocks of up to 32 data words, each word comprising 16 data bits, plus parity and sync. The order in which transactions are to take place must be decided and programmed into the bus controllers (generally before use) when constructing the system. The data bus comprises a twisted shielded copper pair. Terminals are a.c. coupled onto the bus, via transformers and stubs.

5. Detail Requirements of the Fibre Optic Data Bus

The fibre optic data bus is required to function in a similar manner to its electrical counterpart. It must therefore interconnect up to 31 active terminals and some undefined number of passive monitor terminals (this is a requirement of the Standard). An electrical data bus is based on a linear T-coupled bus topology (see Figure 1) and by careful routeing of the bus cables can use the near minimum amount of cable to interconnect the terminals, reducing cost and weight. A fibre optic implementation should do likewise.

It was considered important that the optical data bus be based on a passive distribution network, ie. that no optical signal regeneration should be employed. Any signal regeneration would detract from the transmission system all those benefits that made the adoption of fibre optics attractive in the first place.

Considering the distribution of avionic equipment in the airframe, it soon became apparent that in helicopters, avionic Line Replaceable Units (LRUs), which will become the terminal equipments or terminals to be interconnected by the bus, are physically grouped in zones or avionic equipment bays and not evenly distributed throughout the airframe. This was to dictate the configuration of the bus architecture, as the bus is required to physically interconnect the equipments within zones and between zones, using the near minimum of fibre cable.

It was decided that Light Emitting Diodes (LEDs) should be used as the active optical components in the fibre optic transmitter units in preference to laser diodes, as they were more readily available with the required military temperature range. Laser diodes would, however, have the benefit of producing more optical power.

It was also considered important that multiway demountable connectors should be used in preference to fusion splicing for connecting the fibre. The reasons for this were ease of manufacture, test, installation, and repair of cable assemblies, and that multiway connectors are compatible with electrical systems. However, these connectors are used at the expense of optical attenuation and cost.

6. Interconnect Harness Manufacture Considerations

Of prime concern to the designer was the problem of minimising the impact of applying fibre optics in a well established copper based production arena whilst not compromising the technology itself. This required, wherever possible, the adoption of existing electrical loom manufacturing practices. Consequently, multiway demountable circular connectors (Pattern 602) were used in preference both to single way connectors and to non-demountable splices.

Electrical looms are generally manufactured (cable ends terminated and cables loomed together) on the bench before installation. This technique was adopted in the manufacture of the optical looms. Copper conductors are generally terminated with crimp contacts. The optical contacts used in the study were of the epoxy/polish type. The bare fibre end is held within a precision bore with epoxy adhesive, the protruding fibre end is polished optically flat once the adhesive has cured. Although the optical termination procedure is considerably more difficult than the simple 'crimp on' electrical contact, there is much less difference between the complexity of the optical technique and that of the triax electrical data bus connectors.

The techniques for looming and installing electrical and optical cable assemblies are very similar, the only exception being that of the allowed minimum bend radius of fibre cables. Two minimum bend radii figures must be considered: short term and long term. The short term minimised bend radius limit is that which if infringed will cause the fibre to suffer immediate damage. The long term bend radius is that which should not be infringed if the fibre is not to suffer fatigue damage during its operational life (of the order of 30 years in avionic applications). To ensure that the fibre cable is not bent tighter than its long term minimum bend radius, with a subsequent reduction in the fibre's life, 'T' pieces are fixed to the loom at each breakout. This ensures that the fibre cables are not overbent after the looms are installed into the airframe. Cable assemblies built in compliance with the long term minimum bend radius are compatible with existing electrical loom installation procedures, and the long term minimum bend radius is not a problem.

The short term minimum bend radius is very much tighter than its long term counterpart, but as long as care is taken when installing the cable assembly into the aircraft, especially when passing the assembly through holes and cutouts in bulkheads and panels, it presents no serious problem to the manufacturer.

7. Fibre Optic 'Bus' Topologies

A number of prime options exist for optical bus architectures, namely linear or ring T-coupled bus, centralised transmissive star coupled network, and localised transmissive star coupled network, each of which are best suited to interconnect a particular distribution and quantity of equipments. Accordingly they place differing requirements on the transmitter/receiver units to be used.

Of these options, the central transmissive star coupled system is not favoured as it does not match the equipment distribution in the aircraft, and would result in a most inelegant solution using many times more cable than is necessary (see Figure 2). However, in terms of the optical power budget, a central star coupled system imposes the least stringent requirements, providing the minimum inter-terminal loss, and a negligible Intermessage Dynamic Range (IDR).

The T-coupled system initially appears to provide an effective means of connecting the terminal equipments, when considering cable length and equipment distribution, just as it does for the electrical data bus. However, a more important factor in the choice of bus topology was that of minimising the performance required from the transmitter/receiver pair. If 31 terminal equipments were to be serviced, each from one of 31 T-couplers, connected in series with demountable connectors at both input and output, then assuming a loss of only 1 dB per connector, and 1 dB per coupler, the maximum inter-terminal loss will be of the order of 90 dB. This power budget is not currently achievable using LED technology. Problems are encountered if a T-coupled system is to be expanded, as the additional terminals will receive a successively attenuated signal, placing more and more stringent requirements on the receivers' sensitivity.

The local star configuration was the one considered most appropriate for this application. In this configuration a transmissive star coupler is located in each equipment bay. The LRUs in that bay can be interconnected by that coupler via short cable runs. Equipment bays are then connected together via a pair of fibre cables, which connect their respective couplers (see Figure 3). Such an architecture imposes a fairly stringent requirement on the transmitter/receiver pair, with a maximum terminal to terminal loss of the order of 50 dB (this allows for system degradation during the operational life), and a minimum terminal to terminal loss of less than 20 dB. Preliminary research by STL indicated that the required performance was feasible from a transmitter/receiver pair based on existing state-of-the-art components, and consequently such a design was considered worth exploring.

8. Optical Loss Power Budget

In the local star configuration considered here, three star couplers are connected together, one in each of three equipment bays or zones. Around each coupler are a number of terminal equipments connected to that coupler. Therefore any communicating terminals transmit either via one star coupler, if the equipments are in the same equipment bay, or via two couplers if they are in different equipment bays (see Figure 3).

There are three factors of prime importance when considering the loss between communicating terminals, these are:

(i) the maximum loss between terminals, which determines the Path Loss Capability (PLC) of the transmitter/receiver pair, ie. the difference between the transmitter output and the receiver sensitivity for a specified bit error rate performance.

(ii) the difference between the maximum and minimum loss between terminals, which determines the receiver's operating range.

(iii) the maximum difference in optical amplitude between subsequent messages that a terminal may be expected to decode within a predetermined intermessage gap time, in this case 2 µs. This determines the receiver's response rate and time, and constitutes the Intermessage Dynamic Range (IDR) requirement of the receiver.

Consideration is given to each component that contributes to the attenuation of the optical signal as transmitted between terminals. Maximum and minimum loss between terminals is considered, as in this case, the difference between these two figures gives the Intermessage Dynamic Range requirement.

Maximum inter-terminal loss, taking worst case values,

2 x Coupler loss (16 port transmissive star, includes connectors)	2 x 20	= 40.0 dB
Inter-terminal Fibre Loss		= 0.5 dB
2 x LRU connector	2 x 1.5	= 3.0 dB
1 x Bulkhead connector		= 1.5 dB
Path loss		= 45.0 dB
Margin		= 5.0 dB
Required Path Loss Capability (PLC)		= 50.0 dB

Minimum inter-terminal loss, taking best case values,

1 x Coupler loss		= 16.0 dB
Inter-terminal Fibre loss		= 0.1 dB
2 x LRU connector	2 x 0.5	= 1.0 dB
Minimum path loss		= 17.1 dB

Difference between maximum and minimum path loss,

Maximum inter-terminal loss	= 50.0 dB
Minimum inter-terminal loss	= 17.1 dB
Intermessage Dynamic Range	= 32.9 dB

9. Transmitter/Receiver Design

The transmitter and receiver are required to optically encode and decode the tri-level Manchester biphase electrical data bus signal. Electrically the data is transmitted using +ve and -ve voltages, and between messages there is no voltage on the bus. Difficulties arise when trying to encode this bipolar, tri-level, data on a unipolar light source.

The transmitter/receiver pair is required to have a performance as follows:

(i) 50 dB Optical Signal Range (Path Loss Capability)
(ii) 35 dB Intermessage Dynamic Range (intermessage gap time = 2 μs).

As LED technology was to be used in preference to laser diodes, the maximum launch power was constrained to:

1 mW (0 dBm)

consequently the receiver was required to have a sensitivity of:

-50 dBm

Previous studies undertaken had indicated that such a performance was achievable with existing technology, but that the modulation technique would have to be carefully chosen and implemented, especially if the system is to operate over the military temperature range (-55 °C to +125 °C), and be immune to the various second order effects present within the optical data bus, such as short term optical power variations, optical echoes and multipath effects, etc.

Frequency Shift Keying (FSK) was chosen as the optical modulation technique in preference to baseband modulation as it offers, in theory at least, better immunity to the various second order effects. It also allowed the simple coding and decoding of the tri-level Manchester data bus signal. The +ve electrical data bus signals are coded as one frequency, the -ve electrical data bus signals are coded as a second frequency, and when the electrical bus would be quiet the optical bus is also quiet.

The interface between the terminal equipment and the transmitter and receiver units is similar to the interface with the electrical line driver /receiver, ie. it features data in(out) and its (quasi) complement, $\overline{\text{data in(out)}}$. When these two logic lines are complementary the data is transmitted as indicated, but when the two logic lines cease to be complementary and take the same state the bus is quiet and no data is transmitted.

The prototype implementation of the transmitter was based around a high power (1 mW), 850 nm LED. The prototype implementation of the receiver featured a hybrid front end receiver, a non linear first stage amplifier, and digital decoding circuitry.

10. The Laboratory Based Evaluation System

Once the fibre optic transmitter/receiver units and the interconnect harness had been built, and their basic operation validated, it was necessary to interconnect a number of real data bus equipments. These equipments were required in order to fully evaluate the system. However, as it was not the aim of the study to build a full MIL-STD-1553B data bus system, the number of terminals connected onto the bus was limited to six, comprising:

2 x Bus Control Units,
2 x Control/Display Units,
1 x Systems Emulation Computer,
1 x Serial Bus Analyser (Conic SBA 100).

The Bus Controllers' task is to sequence all message transactions over the bus and to monitor the correct transmission/reception of these messages. The Control/Display Units provide a visual display of the system's operation and allow the input of data to the system. The Systems Emulation Computer emulates a number of aircraft systems and functions, and provides a source of realistic data on the bus. The Serial Bus Analyser monitors the bus activity and is capable of detecting numerous error conditions, and also of emulating any number of terminal equipments on the bus. It is also used to inject errors into the system.

Figure 4 shows the rig, set up in the laboratory, including both the terminal equipments and the fibre optic interconnect harness.

11. Results from the Programme

The programme culminated in the construction and evaluation of a dual redundant fibre optic data bus system, capable of connecting 32 terminal equipments, and compatible with DEF STAN 00-18 (Part 2), (MIL-STD-1553B). For evaluation purposes, only 6 terminal equipments were connected onto the bus, together with a number of test equipments. Once the correct operation of the system had been validated against the Standard, a number of system level tests were carried out, concentrating on potential fault conditions and failure modes.

The results from these tests were very encouraging, with the fibre optic receiver units exhibiting a high degree of fault tolerance when subjected to optical echoes, multipath effects and other second order effects. The system is also very tolerant to failed terminals transmitting a constant level of light on the bus. Where terminal equipments fail and transmit legal, but unrequested, data words, either in isolation or contiguously, system operation reverts to, and continues successfully on, the secondary (redundant) bus.

12. Future Applications of Fibre Optics in Avionics

The components used in this study were military style development samples, developed for RAE, Farnborough with DCVD funding. Estimates, based on development sample costs, indicate that the cost of a fibre optic implementation of the data bus would be comparable to that of an electrical version and this does not take account of the reduction in EMC design and development costs that such a system would offer.

The study described in this paper relates to the development of a fibre optic implementation of a 1 Mbit/s, time division multiplexed, serial digital data bus. This system benefits from the use of fibre optics as it provides a transmission medium that is immune to electromagnetic radiation, does not emit electromagnetic interference, does not present a potential fire or spark hazard and, when considering the reduction in design and development effort required, represents a very cost effective solution.

However, this application does not exploit the enormous bandwidth capability offered by fibre optics. Other applications of fibre optic data transmission systems, such as high speed data transmission and video distribution, would of course start to utilise some of the bandwidth on offer. The possibility of upgrading a MIL-STD-1553B data bus to incorporate the transfer of blocks of high speed data between selected terminals has been suggested by other workers in this field [3]. Such a system, using a single wavelength optical source, would benefit from the bandwidth advantage and act as an interim measure between MIL-STD-1553B and high speed data transmission systems. Alternatively, Optical Wavelength Division Multiplexing (WDM), or colour multiplexing, techniques offer the designer a means of transmitting many different channels of data simultaneously over a single optical fibre with negligible crosstalk. This is ideally suited to a video distribution system, where several different formats of display data are required at the same terminal equipment, (eg. primary flight display, mission display).

Looking to the future one can conceive of an optical highway installed in the aircraft that is used to carry a multiplicity of signals, ranging from general avionics data through video data to high speed digital data. It would also be possible and advantageous to transmit audio intercomms signals by the same means. Such a highway would be analogous to ducting installed in office complexes and underground in streets, where additional cables, or in this case signals, can be incorporated at a later date, during the service life of the aircraft.

13. Conclusions

The aircraft system designer faces a number of very real problems associated with EMC when integrating avionic equipments into an aircraft, and these problems will increase in severity as aircraft become more complex, and the use of composite structures becomes commonplace.

Fibre optics provide a potentially cost effective solution to many of these EMC related problems. The programme described in this paper made use of military qualifiable development components and there is considerable effort in the UK to further develop and qualify these components.

Of the numerous applications of fibre optics the MIL-STD-1553B 1 Mbit/s serial data bus has been selected for fibre optic implementation and development. The study described in this paper has shown that fibre optic technology is mature enough to allow a 31 terminal interconnect data bus to be built and demonstrated in the laboratory, that does not employ any optical signal regeneration and is fully compatible with MIL-STD-1553B.

It is important to note, however, that this application does not utilise the enormous bandwidth potential offered by fibre optics; future applications, such as high speed data transmission systems, surely will!

14. Acknowledgements

The author gratefully acknowledges the support of the Royal Aircraft Establishment, Farnborough, and the collaboration of Smiths Industries, Cheltenham and Standard Telecommunication Laboratories Ltd., Harlow.

15. References

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3. C.R. Husbands, R. Katz, The Application of Multiple Speed Data Rate Transmission to a MIL-STD-1773 Data Bus Structure, IEEE/AIAA 5th Digital Avionic Systems Conference, October/November 1983.

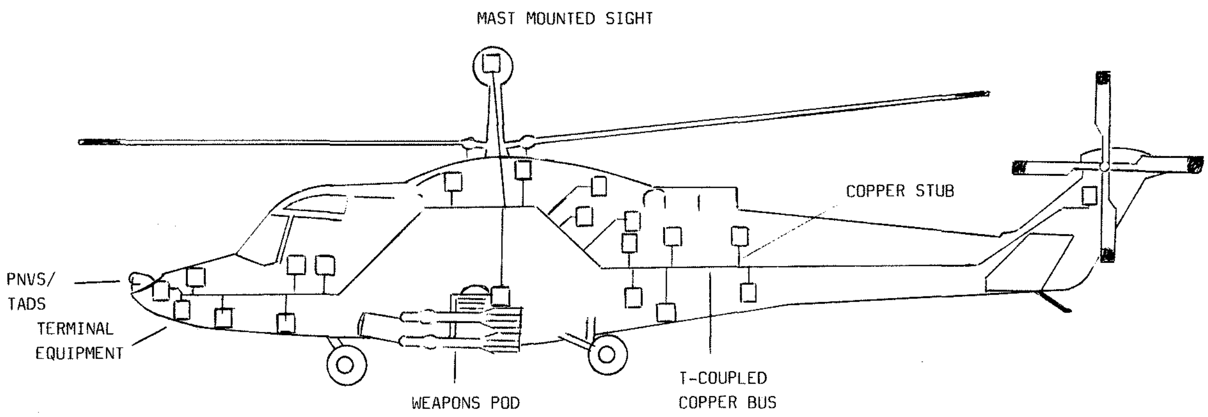

FIGURE 1 LINEAR T-COUPLED ELECTRICAL DATA BUS SCHEMATIC

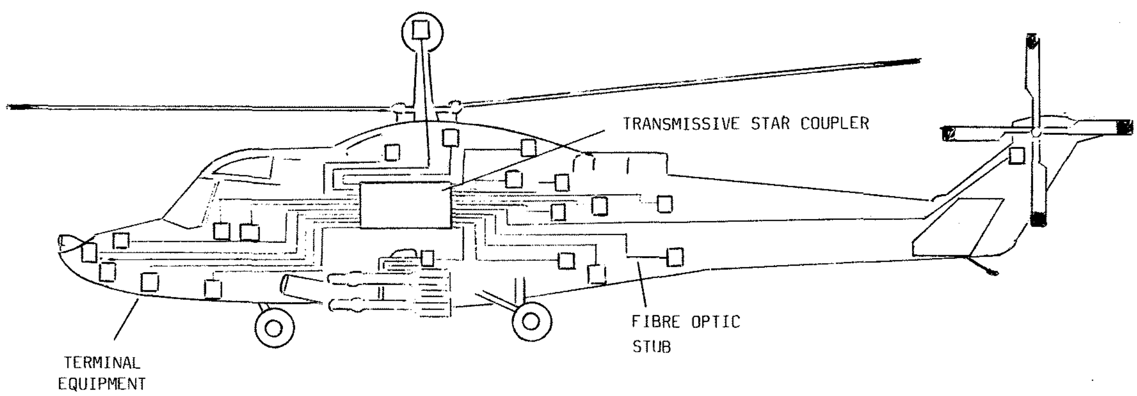

FIGURE 2 CENTRALISED TRANSMISSIVE STAR COUPLED FIBRE OPTIC DATA BUS SCHEMATIC

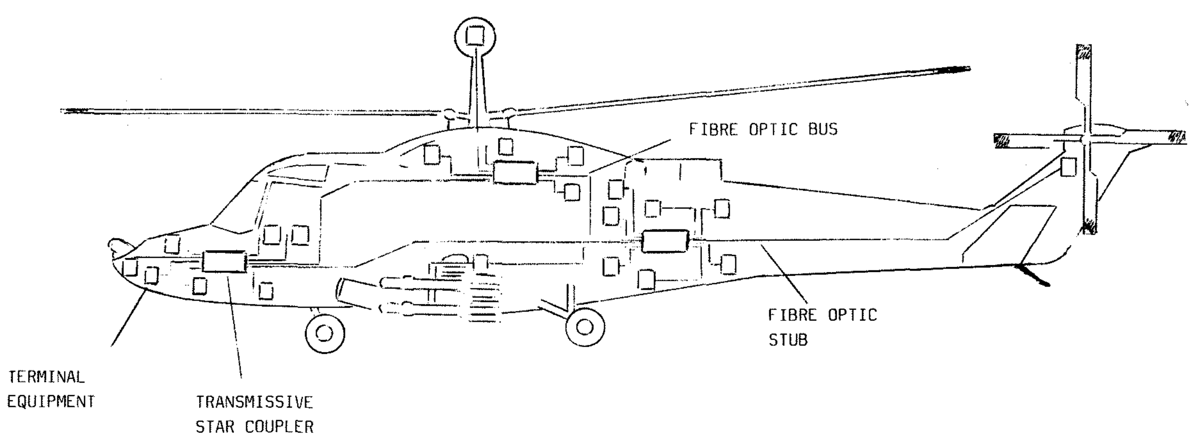

FIGURE 3 LOCAL TRANSMISSIVE STAR COUPLED FIBRE OPTIC DATA BUS SCHEMATIC

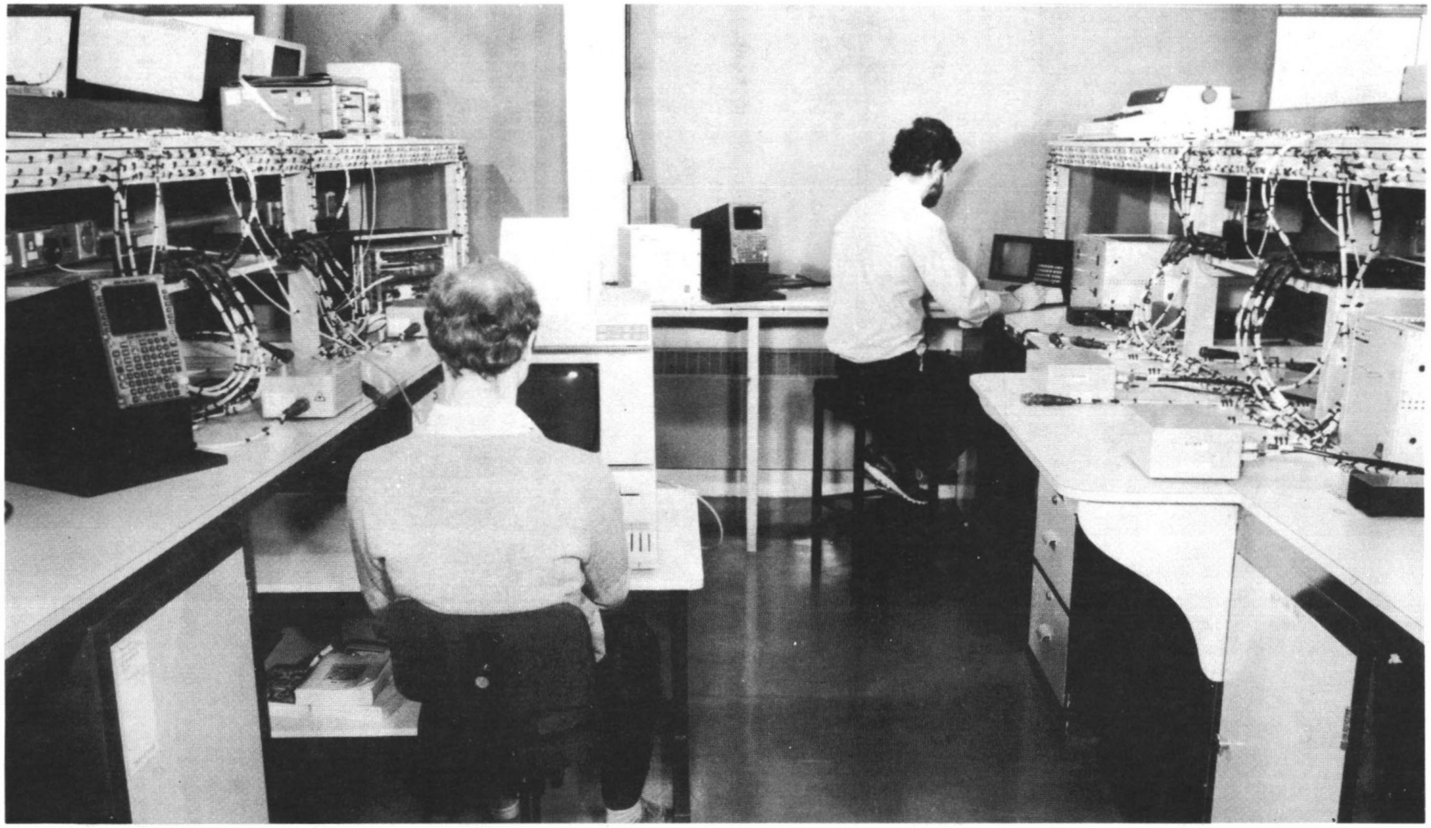

FIGURE 4 THE LABORATORY BASED FIBRE OPTIC DATA BUS SYSTEM

Showing Control/Display Units, Systems Emulation Computer, Data Bus Analyser, Bus Control Units and the Fibre Optic Transceiver Units interconnected by a dual redundant, 32 port fibre optic data highway.