I'M ALL "LIGHT" JACK

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Abstract

This paper presents the case for using optical data transmission for helicopter flight control systems FBL, concluding that the technology is mature for the introduction into future helicopters. Though FBW is able to meet current specification needs, FBL may be a more cost effective solution in the future owing to the increasing EMI requirements. The experience gained during the development and experimental flight test programme (OPST) is presented and discussed. Details of the computing technology and hardware installation, the use of "smart" sensors and "smart" actuators is given together with the current activities since completion of flight testing. The results of new developments in micro-components to replace existing accelerometers, rate gyros and position sensors are shown.

The work performed during the OPST programme was in close collaboration between MBB, DLR and LAT under sponsorship of BMVg.

Introduction

The helicopter has established its self as a permanent part of both the civil and military inventories. Because of its unique characteristics of vertical take-off, hover and flight at below tree top height, the helicopter is often employed in extreme weather situations at night or in poor visibility and at very low altitudes where other vehicles are prevented from operating. The nature of medivac, SAR, environmental disasters and military stealth missions dictate complete pilot concentration on the "flying" task thus reducing his "free observation time" for his primary mission. Studies have shown that if the pilot's normal "flying" work load can be reduced then the he is able to carry out his primary task more effectively and indeed perform missions which up till now have resulted in a too high safety risk. Modern computing technology permits the simplification of cockpit displays, automating monitoring functions (engine limitations, fuel, electrical and hydraulic power) and the application of full authority automatic flight control systems, thus ensuring more effective and clearer control response characteristics to the pilot than the classical limited authority autopilot. The application of electrical signalling technology (FBW) has an additional safety benefit owing to the multiple redundant signalling paths which can be routed via different paths throughout the structure.

A Short FBW History

(or Life before Light)

When preparing a paper such as this, the presenter often reviews the historical background which triggered the current study and justified the new developments. It is not our intention to follow this mode of presentation here, as there are far better papers available on the subject. But for the uninitiated, who may believe FBW to be a relatively new '80s technology it is worth listing a few milestones in FBW development, and particularly MBB's involvement, if only to demonstrate that FBW has been around for a long time.

The Early Experimental FBW Days

MBB became involved in FBW technology in the late '50s when experimental systems were built and laboratory tested. When the era of VSTOL emerged in the early '60s full authority FBW systems became the only choice for the VAK and VJ101 prototype aircraft because of there complex handling. These installations were of course fully analogue, triplex or quadruplex redundant, without mechanical backup, rather heavy; ≅50kg for the VJ101, not counting the cabling and actuators.

The First Production FBW Aircraft

When the Panavia Tornado entered service in '70s, it was the first European military production aircraft to be equipped with a FBW primary control system. Again analogue, and based on the experience gained during the VSTOL experiments of the '60s, the Tornado, which is currently in service, is equipped with triplex redundant computing lanes plus a mechanical backup which synchronises to the pilot's control positions and locks should a second identical failure of the FBW system occur. The decision to incorporate a mechanical backup for the Tornado was probably made to simplify the certification exercise rather than for technical misgivings and proved latter to provide considerable technical "headaches" due to the compromises that had to be entered into to provide smooth transition from FBW to mechanical control. A mechanical backup has never been incorporated in any subsequent design.

Looking to the more recent past, FBW CCV F104(4D), FBW Jaguar (4D), F16, Rafale (3D+2A), EAP/EFA (4D), Lavi (4D+2A), F15E (3D), Grippen all use FBW in one form or another for flight safety critical primary flight control surfaces.

The FBW Helicopter Comes to Life

The early '70s also saw the first application of FBW technology to helicopters at MBB. It is worth noting that the only other company seriously investigating FBW for helicopters, at that time, was Boeing Vertol in the TAGS programme for the HLH [1][2] and subsequently bid a FBW option for the Boeing UH-61A UTTAS. MBB's helicopter work concentrated on the potential handling qualities improvements which could be achieved by full authority control systems rather than the implementation of FBW its self. After all the technology could be imported from the fixed wing fraternity. This work was necessary as the reasons for implementing FBW in a fixed wing machine are not the same as those for a helicopter. It was not clear at that stage what improvements could be achieved, and if the effort involved would be justified.

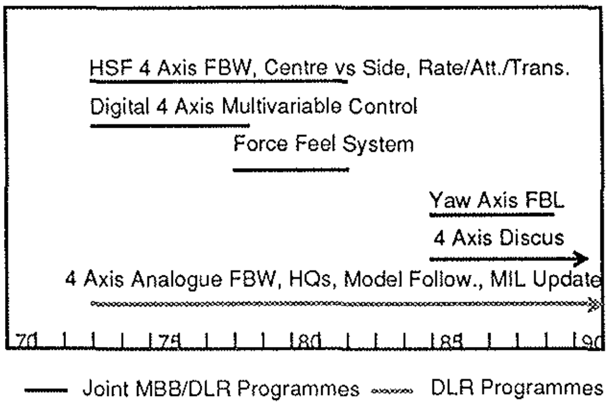

Figure 1: MBB FBW/L Helicopter Research Programmes.

MBB entered into a number of FBW programmes (Figure 1) in which a Bo105 was modified to take 4-axis, full authority, electro-hydraulic actuators in parallel with the existing primary flight control system. Since the objective of these tests was flying qualities improvements and in-flight simulation, fail-operational was not at the forefront of the investigations and the original mechanical controls were retained for the safety pilot. Hence, the FBW architecture could be purely simplex. The initial systems used analogue computing, though a "hardened" commercial computer (PDP11) was later installed for investigation of multivariable control concepts.

It can be seen that FBW has been around for the past 30 years(i) and there is evidence to suggest that experiments started a lot earlier. It can be concluded therefore, that FBW is an established technology.

So What's Wrong With Wire?

(or Wire Rules OK?)

Nothing. FBW systems can be designed to fulfil present-day specifications *(full stop)*.

Like with so many technologies (the thermic valve, the mechanical piston engine distributor...) FBW technology performs it's task adequately but has inherent limitations. Table 1 compares wire and light data transmission technologies with respect to 3 key parameters.

Characteristic	FBW	FBL
Data Transfer (effective) [Mbit/s]	1-2	>20
Transmission Line Mass [gm/m]	27 (STP)	4
Economic EMI/EMC Spec. [v/m]	≅200	>>200

Table 1: Key Parameter Comparison, Wire vs. Light Data Transmission.

Data Transfer Rate

(at Light Speed?)

Data transfer electrically is limited to 1-2Mbit/s at best. The military standard data bus, MIL-STD-1553B, operates at 1MHz. The widely used civil serial bus for point-to-point connection, ARINC429, in it's high speed mode is limited to 100kbit/s, which will permit around 30 different signals of 32bit words to be updated every 10msec. Whilst adequate for transmission of navigation and autopilot signals to a Flight Control Computer, there is no available space for exchanging data for monitoring, status signals or computer synchronisation. Arguably these specifications originate from a time when other computer considerations limited signal transfer rates and could be revised. However, strict electrical segregation of computing lanes in flight safety critical functions dictates coupling between transmitter and

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(i) About the same time as the first domestic transistor radio and the wide spread introduction of digital computers commercially.

receiver by transformer which will in any case limit the signal transfer rates to 1Mbit/s. The conclusion is that there is no growth potential in electrical signalling.

Cable Mass
(Feather Light?)

Thought not the single largest item in a FBW/L primary flight control system, the interconnecting signal lines do contribute a significant factor. Recent studies into an electrical flight control system for a medium class (15 tonne) convertible rotor helicopter concluded a mass of 98,26kg for the interconnecting cables and fittings (excluding power supply cables) based on state-of-the-art FBW technology. This was despite taking into account data transmission from flight state sensors to the FCCs using an ARINC429 data bus consisting of a simple screened twisted pair. An equivalent optical data transfer system requires only 3kg of fibre optic cable. Taking into account connectors, additional power supply lines and data conversion within the FCCs the total mass amounts to 41,16kg, still 57,1kg saving over the baseline FBW solution.

Studies into other vehicles indicate similar results. It is estimated that around 14,5kg could be saved off the 55,7kg estimated for the interconnecting cable mass of a FBW solution for a medium (9000kg) transport helicopter by applying FBL technology instead.

FBW systems for helicopters, which have up till now come out mass neutral when compared with conventional mechanical controls, now show positive mass savings when implementing FBL technology.

EMI/EMC
(or Electro-Light)

The last decades have seen a steady increase in the requirements for both radiation and susceptibility of electrical equipment in aircraft to electromagnetic influences. This is justifiable in part due to the world wide increase in radio and radar transmitter powers and due to the criticality of the aircraft equipments them selves. Saarlouis a LW transmitter has a 2MW output, Heusweiler a MW has 1,2MW power and there are a number of SW transmitters in the 500kW power range. Despite a trend towards satellite communication, radio transmission will continue to be wide spread for domestic entertainment well into the next century. The tendency will be for more and higher power transmitters in the future and not less.

For civil applications, the minimum EMI test requirements of [3] have proven insufficient in operation for application to AFCS equipment. For this reason MBB has always specified it's own internal EMI test standards of at least 70v/m in the critical 2 to 30Mhz frequency band when installing electrical flight control equipment in helicopters. It is not surprising that the FAA recently revised it's policy on EMI testing and is due to publish a Notice of Proposed Rule Making in October, 1990. It is expected that this discussion paper will recommend testing under field strengths of 80v/m up to 2Mhz, 200v/m between 2 and 30MHz, and 33v/m at frequencies above 30MHz. Military specifications have always been more critical owing to the environment on ships and military airfields. STANAG 4234 or MIL-STD-1385A, for example, requires 200v/m up to 30MHz. It is expected that the EMI equipment test specifications will generally become more stringent and it is likely that 200v/m will become the minimum acceptable standard in the future.

Entry of EMI into a Flight Control Computer [4] is either through the mechanical housing, via upsets on the power supply cables, or via pick-up on the signal lines. An hermetically sealed aluminium housing provides a good basis if the electrical resistance of the joints is kept low. For reasons of mechanical robustness, the walls have to be a minimum thickness and requirements for the exclusion of dust and foreign particles precludes the use of cooling slots. Gaskets and seals need to have a good electrical continuity (less than 2,5 mOhms) and the effects of oxidation due to aging have to be prevented. This can be achieved using conductive rubbers and conductive adhesive which can be replaced during a repair operation.

Power supplies to a computer need special attention to filter out generation spikes, short power interrupts and supply fluctuations. EMI protection can be combined within this design, which can be a low pass filter, as a high signal band width is not required. To prevent re-radiation within the computer housing, the filtering and protection elements are usually kept within a separate "dirty chamber" (Figure 2), before passing the supplies through feed through filters to the internal power stabilisation module.

Signal lines are more difficult to treat. The first difficulty is that there are many more signal lines which are normally transferred by multiple pin connectors. The second is the low voltage levels usually associated with signal lines which make them more prone to corruption. Filter pin inserts are available but have a high cut-off frequency (>1 MHz) and go into saturation quite early due to the small size of the reactors. Filter pins do not provide adequate protection. A more effective method is an all round screened shield, which if installed correctly will provide protection to 200v/m. More expensive all round shielded plugs and sockets are to be

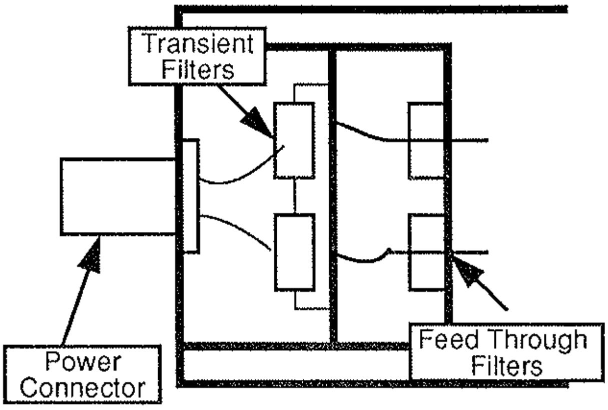

Figure 2: Filter Chamber for DC Power Supply Lines.

recommended. At levels above 200v/m even screening, filters and all round shielded plugs are unable to provide adequate protection and a double braided shielding or conductive pipe is necessary, thus adding to the cable mass. Furthermore, the performance of this type of shielding is dependent on the quality of workmanship and can well deteriorate with age. Regular inspection and/or testing, which can add to maintenance costs, is therefore mandatory and preflight testing of the filters must be performed to ensure their functionality

Designers of digital computers are forced to carefully consider the EMI aspect. The result of a 70v/m test on a poorly protected analogue circuit, as shown in Figure 3, is spasmodic and unpredictable movement of the actuator with partial recovery and breakdown. EMI entering a digital computer will probably cause complete loss of the function. A self recovery procedure and exception handling must be part of any digital computer design and the MC680xx family of processors have hardware features that are particularly suited to airborne equipment. However, all means must be taken to minimise such an event.

The optical data transmission is completely EMI free and shielding and filtering are unnecessary. Figure 4 shows the results of EMI testing of an optical data transmission system; the actuator position remains undisturbed. In the frequency range shown in Figure 4, 175v/m represented the limitation of the test installation and not the limitation of the equipment. In other frequency ranges, tests were successfully completed in excess of 220v/m.

LEMP

(or Flash Lights)

LEMP presents a slightly different problem to EMI. A lightning flash attaches itself to an extreme top corner (tail fin, rotor blade etc.) of the helicopter and attempts to find the easiest path through the aircraft, usually exiting from a skid or the lading gear. Modern helicopters with composite blades and fuselage have additional lightening conductors to provide a controlled passage of the flash. High currents are induced in the electrical wiring and the primary form of protection is to provide local all round shielding of the individual cables. The rise time of the LEMP is around 1 microsecond, equivalent to a frequency range of 1 to 100 kHz. At the equipment level, gas filled arrestors which have short ignition times of around 0,2 microseconds and varistor combinations can be used to protect power lines. On signal lines, 150v can be induced in a 3m length of good double screened cables, hence zener diodes are needed as protection to limit the induced voltages. Fast reacting circuits are needed to direct the energy to earth and thus prevent permanent damage to the components.

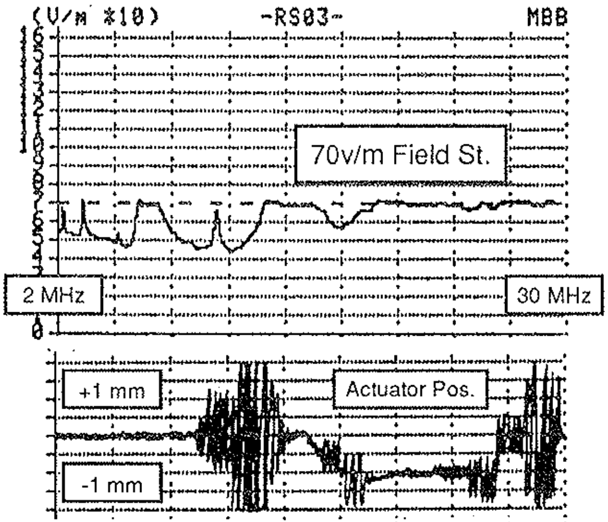

Figure 3: EMI on a Poorly Screened Actuator Servo- Loop.

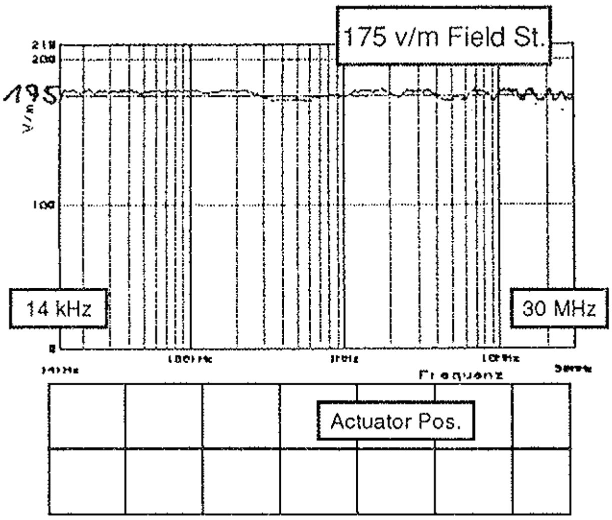

Figure 4: No EMI when Employing Optical Data Transmission.

The optical data transmission is completely LEMP immune and only the power supply lines have to be protected.

Is the Technology Mature?

(or Light 'n Easy?)

Having been convinced of the limitations of FBW and the inherent advantages of FBL, MBB endeavoured to estimate the technology status of FBL in the early 80's. Questions arose as to the integrity of FBL; the status of optical connectors; type of fibre optic cable most suited to helicopters and it's the robustness; the existence of electro-optic components able to withstand the vibration and temperature environment of the helicopter. Whilst some of the answers could be found from existing programmes and from component manufacturers it soon became evident that a flight demonstrator was necessary and the outcome was the OPST programme. The only other known work being carried out in the application of optical technology to helicopter flight controls was that of the ADOCS programme on the Sikorsky UH-60A Black Hawk, thought there were some significant differences in the OPST and ADOCS programme objectives.

Since completion of the OPST programme there have been some significant technology advancements. What then is the current and near term projected status?

Computing Technology

(Processed Light)

In preparing this paper the authors cam across a "not so old" report [5] surveying the suitability of a range of microprocessors for aircraft engine control systems. We doubt whether any of the 46 components analysed would be used in any new equipment today!

It is difficult to predict the component technology of 10 years hence, and even 3 years is a problem, but there is one certainty that component prices fall at around 100% per year until they become a virtual negligible cost. A 16bit Motorola 68000, 8Mhz processor which cost 3000DM as an industrial sample only 5 years ago, is now available for 12,50DM in the local "radio shop". The 4bit microprocessor technology marvel of the late '70s has long been forgotten. State-of-the-art is now a 64bit i860 RISC processor board running at 40MHz and claiming 120 MIPS all for a price of 10000DM. The 1Mbit RAM costs little more than the 64kbit variant, the 4Mbit is in the shops, and the 64Mbit is on the drawing board. There is no sign that this trend is slowing. Table 2, extracted from [6], shows the historical increase in performance, and the downward cost, and size trends of digital processing and memory. The data for 1990 has been added based on currently advertised prices in technical journals. In short, the developments in computing power and levels of integration are currently out pacing our ability to make use of them and the processing aspect in no longer a limiting factor in the complexity of flight control systems as was the case in the '70s and early '80s.

Optical Fibre

(or Finding the 'light Line)

Airborne systems are short distance systems. Signal attenuation and dispersion in the fibre are not the limiting parameters. Instead, ease of transmitter-fibre and fibre-fibre coupling is essential in view of ramified systems and system costs. Therefore, a thick core fibre with a 200μm core diameter optimal for the short distances to be considered. It is important that the tolerances of fibre core, cladding and numerical aperture are small because these qualities directly effect the connector performance. Furthermore, robustness, reliability, and survival in a severe environment are of greatest importance. The best compromise is the 200/280μm step index, multimode fibre (product example DO200/280-68-3 from Reinshagen).

	Computer Hardware			Memory	
	Cost ECU/MIPS	size m^3/MIPS	MTBF [hrs.]	Cost ECU/MByte	Size m^3/MByte
1965	3000000	90	40	2000000	3
1975	80000	0,9	800	100000	0,009
1985	2000	0,006	10000	1000	0,0002
1990	50	0,00002	?	80	0,000002

Table 2: Historical Trends in Declining Costs and Increasing Performance of Computers.

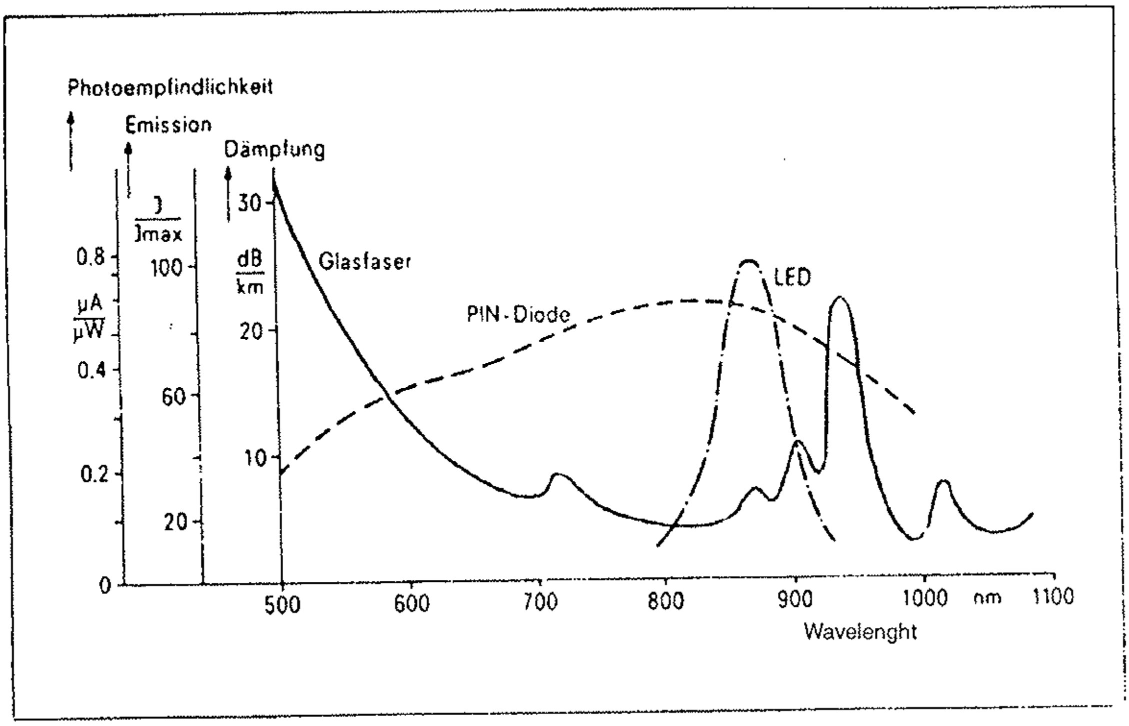

Figure 5: Optical Transmission Frequency Range.

Transmitter and Receiver Modules

Since the transmission lengths for aircraft do not exceed 100m, LEDs and PIN-diodes operating in the 850nm wavelength (Figure 5) are acceptable and cheaper than lasers and avalanche diodes. Complete hybrid transmitter and receiver modules qualified to aircraft specifications (-55°C to +100°C, humidity, vibration) are now available.

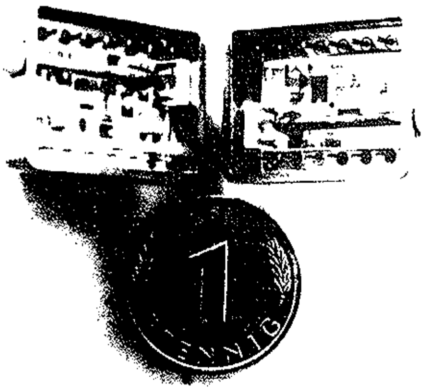

Figure 6: Hybrid Optical Transmitter and Receiver Modules.

Figure 6 shows two such hermetically sealed modules with fibre pigtails for direct mounting on PCBs. The LED transmitter operates in the 850nm wavelength, is TTL compatible and requires a +5V power supply. The receiver module uses a PIN-diode, is TTL compatible, and has a minimum input signal strength of -27dB. Capable of 10Mbit/sec transfer rate, a de-rated 1Mbit/sec is adequate for current applications.

Connectors

Experience has shown that up to 17dB signal strength loss is acceptable between transmitter and receiver. Since fibre loss can be neglected over these short distances, nearly all the 17dB can be used by connectors and couplers. Typically 3dB is lost per connection. Hence, a maximum of 4 connections should be made. A beam-splitter would loose 1,5dB and 3dB per branch. If a greater fan out than 2 is required it is probably more economic to install an additional transmitter.

MIL-C-38999, Series IV multi-way connectors are available which can be equipped with standard electrical contacts as well as fibre optics contacts, thus minimising connector count (sources Soureau, G&H Technology). These require a some what tedious process of stripping the fibre end, and crimping a supporting end fitting. The optical connection is made by precision end-to-end contact of the crimped fitting in both the plug and socket. Other connectors use a lens method of transfer so that precision axial line-up is not so critical. Since connectors are often a source of corrosion or suffer from the influx of dirt (it has been known for a pin from an electrical connector to puncture the rubber insulation and short to it's neighbour) a new method being investigated is to completely cover the plug with a glass "window" so that mechanical contact is eliminated.

The Case for Distributed Intelligence

(or Bright Lights)

The original analogue FBW systems had a centralised computing architecture; the only one possible. In this architecture, position sensors, of either potentiometers or LVDT type, are energised by the central FCC which then demodulates, filters and votes on the returned signals. Actuator position servo-loops are also closed by the FCC. This puts a heavy mass penalty on the analogue FBW and makes it less attractive for helicopters than for aeroplanes.

Early digital FBW systems followed the analogue centralised architecture, as processing power was then expensive and heavy. As we have seen, this is not the case now. The introduction of the microprocessor and associated components has eliminated these two problems. The dramatic fall in processing cost, volume, and equally dramatic rise in processing power now allows us to apply the most suitable architecture to the FBL system. Owing to the flight safety criticality, one of the biggest tasks is the continuous signal monitoring, consolidation, filtering, validation, and failure management. This is best performed at the local sensor or actuator unit level and not at the central Flight Control Computer.

The maximum advantage is obtained from applying "smart" principles to actuators. By installing microprocessors directly inside the hydraulic actuator, the servo-loop can be closed without having to return to the FCC, and complex self monitoring can be included in the actuator without loading the central FCC processor. With current technology, optical interfacing and duo-duplex processing (2x2 microprocessors) for a duplex hydraulic actuator can be housed within a 100ccm module and mounted on the back of the actuator.

Who gains from of "smart" sensors and actuators? Just about everyone.

The aircraft manufacturer and subcontractor gain because the interface specification is much simpler. Actuator servo closure and performance is all under the control of the actuator manufacturer and he no longer has to liaise with the FCC manufacturer. Product improvement is easier because the simplified interface means that old components can be exchanged as new products evolve.

The customer benefits because the intelligence in each unit can be used to perform more comprehensive BIT and more accurately isolate a defect. The failure codes can be stored in a nonvolatile EEPROM so that when the unit is returned to the manufacturer the reasons for the failure can be identified without having to rely on a terse customer failure report. Indeed the complete history (serial number, operational hours, repair log, software release) can be held within the EEPROM. Correct configuration can also be checked by the FCC calling up the part numbers electrically stored within each unit during the power up BIT. Incorrectly installed equipment will result in a "NO GO" and a clear maintenance instruction.

Experimental Helicopter Programme OPST

(or Verti' light)(i)

The object of the OPST programme [7. was to gain practical flying experience of optical control system technologies at minimum cost and risk; technical as well as flight safety risk. Under a BMVg sponsored programme, MBB collaborated with the DLR and the actuator manufacturer LAT to design, build and flight test a triplex redundant optical control system for installation in the Bo105-S3 research helicopter operated by the DLR at Braunschweig.

Though handling qualities improvements could be demonstrated during flight testing with the OPST system, this was not the primary objective. Neither were direct optical sensors as investigated in the ADOCS programme; though due to the local processing concept applied in OPST, exchange of the existing sensors for those measuring on a direct optical basis is easily implemented. But the critical key technology ares of optical data transmission, connectors, opto-interfaces, "smart" sensors and actuators all formed part of the demonstrator programme.

The yaw axis was chosen for the work since it: requires the longest signal line runs; is the control axis likely to obtain the most handling qualities benefits due to the axis response de-coupling which can be achieved with 100% control and stabilisation authority; is most challenging technically due to the high flight mechanic bandwidth and structural filtering required (up to 35Hz); can be separated as a single axis (all main rotor axes are inherently coupled); and lower flight criticality (complete passive failure of the yaw axis will not automatically result in loss of the aircraft).

(i) With apologies to AHS

Triplex redundancy was chosen to provide fail-operational, fail-safe characteristics in keeping with the existing S3's FBW flight control system. The S3 is operated with 2 pilots (experimental and safety), the safety pilot retaining full control in the event of an emergency via the parallel mechanical back-up system.

System Description

(The Lightware)

A very straight forward and "clean" architecture was chosen for the OPST demonstrator. The system consisted of triplex "semi-smart"(i) pedal and collective position transducers; triplex "semi-smart" yaw rate gyro unit; triplex FCCs and duo-duplex "smart" electro-hydraulic actuator.

For simplicity, the triplex units were boxed in common housing thought in all other aspects the triplex lanes were kept segregated to meet the integrity requirements.

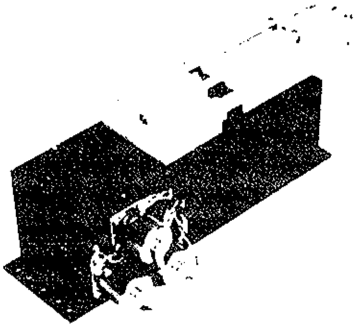

Figure 7: Triplex Motion Transducer Unit.

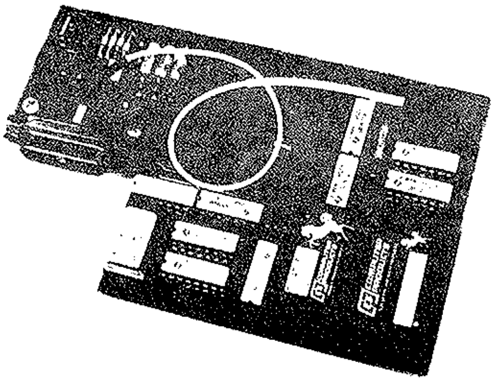

Figure 8: Sensor Data Processing Electronics with Optical Signal Conversion.

A typical position sensor unit with 50mm stroke (Figure 7) contains it's own LVDT excitation, demodulation, 12bit A/D conversion and optical driver unit.

The optical interface module (Figure 8) which provides a more than adequate update rate of 20kwords/sec, was designed using discrete TTL logic components. Current integration technology would permit a dramatic reduction in the component count thus saving considerably on the 2,5kg for the complete sensor unit.

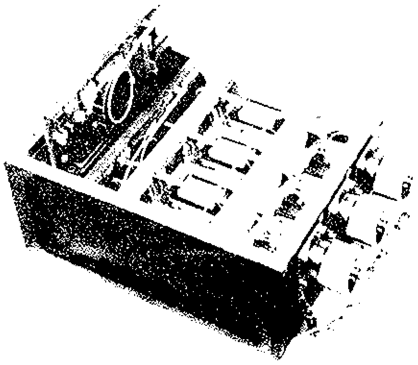

Figure 9: Triplex Rate Gyro Unit.

The rate gyro unit is again a "semi-smart" device (Figure 9) similar to the position sensor. The connectors which pass 26V AC power for the rate gyros and optical signal lines are mounted on the exterior wall of the "dirty chamber" containing the EMI filter circuits. In the centre compartment are the rate gyros and the associated AC/DC power conversion. The rear compartment contains the triplex standard interface modules.

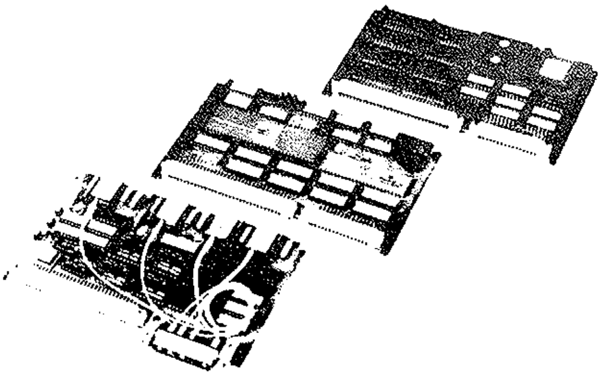

Figure 10: The Three Major Modules of the FCC: RAM and coprocessor; CPU; Optical Interface.

(i) The term "semi-smart" is used here since not all the attributes discussed on the section on Distributed Intelligence above were not included.

The FCC is based on a Motorola 68000 running at 12,5MHz which gives a performance of about 1,5MIPS. The 3 major modules (Figure 10) consist of a memory unit and coprocessor, the central processing unit with the M68000, and the optical interface unit for 2 input and 2 output lines. All 3 computing lanes are hosed in the same 650x170x190mm box (Figure 11).

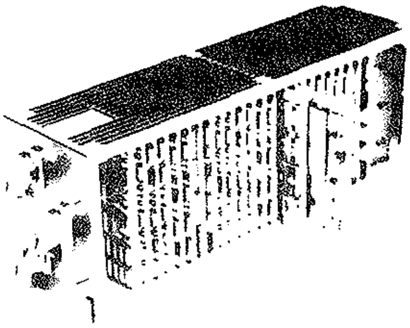

Figure 11: Triplex Flight Control Computer.

A low power consumption of 3x20Watts total requires no forced cooling and permits a totally sealed unit against EMI. At the rear of the box is the "dirty chamber" for the electrical power supplies, the front connectors being used for optical I/O only. All computers are connected together with a 1Mbit/s optical data link for frame synchronisation lines. The FCC software, consisting of control laws, signal voting and redundancy management is written in "C" with run time support in assembler, and executes at 300Hz.

The "smart" actuation unit (seen here installed in the S3, Figure 12) was specially developed by LAT for the programme.

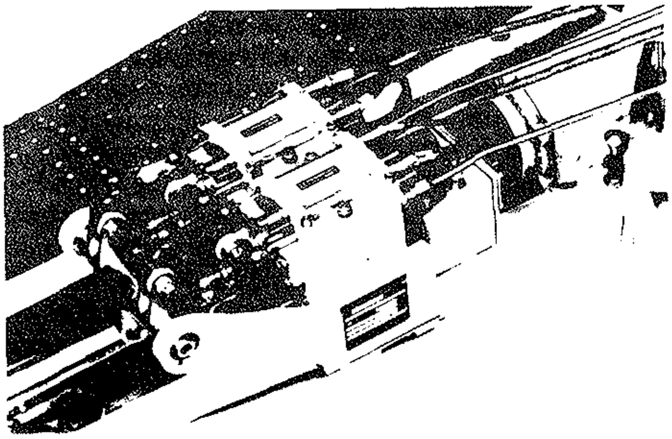

Figure 12: Duo-Duplex "Smart" Actuator Installed in the S3.

The fully duplex hydraulic actuator contains 2 microprocessors per lane for input signal voting, loop closure, and self monitoring. It has a stroke of 25mm and speed of 50mm/sec into a 300N load. Failure of one lane sends that half of the actuator into bypass mode to achieve fail-operational, fail-safe characteristics.

Experience Gained during OPST Development

(or Making Light Work....of it?)

Preceding the helicopter integration, the control system was subjected to EMC testing (Figure 13) to evaluate EMI resistance.

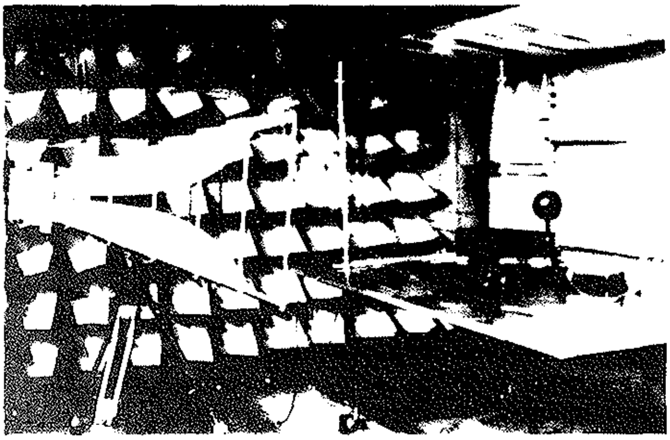

Figure 13: EMC/EMI Testing of the OPST System.

For frequencies between the 14kHz to 2GHz tested, no performance impact was noticed at field strengths in excess of 150V/m. Tests were conducted with amplitude modulation and single side band modulated fields to simulate known worst case conditions. At field strengths above 150V/m, power supplies used in the test chamber to simulate aircraft units malfunctioned at certain field frequencies. In the other frequency ranges, field strengths of 220V/m did not create a malfunction.

The FCC unit was installed on a pallet in the rear cargo compartment of the S3 (Figure 14) along with telemetry. The installation is designed for use with the

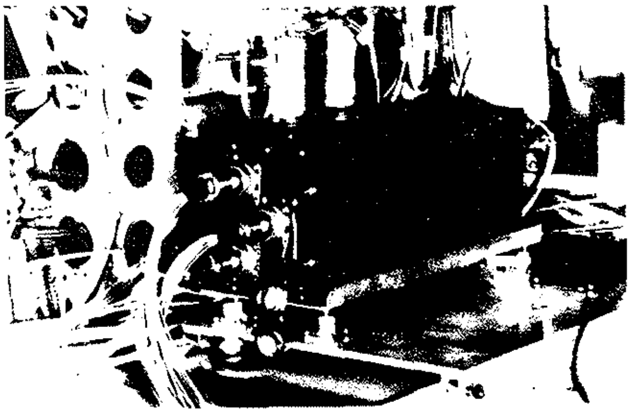

Figure 14: FCC Installation in Rear Cargo Compartment of Bo105-S3.

MBB DFCS or the DISCUS system operated by the DLR. The yaw rate gyro unit was installed on the outside of the tail boom close to the engine floor (Figure 15).

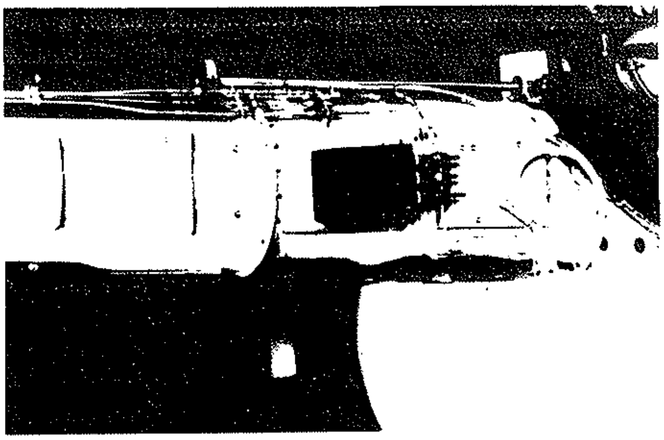

Figure 15: Triplex Yaw Rate Gyro Installed on Tail Boom.

Power supply lines and optic fibres were installed using the same electricians and procedures. Still to be improved is the fibre optic connector technology. It was found that the initial method of cleave/crimp techniques resulted in excessive signal attenuation and had to be abandoned. Epoxy/polish technology performed well but was found too difficult to handle in the helicopter. Finally a successful cleave/epoxy method was developed but due to the large variation in attenuation and contamination problems this can not be accepted as a standard. It is for the connector manufacturers to develop a more suitable method, laboratory standard techniques (Figure 16) can not be used for production.

Figure 16: Precision Assembly of Connectors.

Optical lens contacts previously described above may be a solution, but these were not available for the OPST programme.

A total of 40 hours of flying was completed with the DLR and the DFCS installed without hardware malfunction. Both company test pilots from MBB and the DLR and selected military pilots were invited to participate in the flight trials which received favourable comments.

Will the Customer Accept Light?

(or PPL Pilots' Prefer Light)

Why not? The operator is not concerned with the medium used for the flight control system provided it works, is reliable, and adds positive benefits for a reasonable extra cost. The reasons for requiring 100% FCS authority, or "Fly-by", for the next generation of helicopters were briefly explained in the introduction. The arguments for FBL are inherent EMI immunity, and the more comprehensive BIT possible with "smart" replaceable units. Both these aspects are designed to simplify and minimise maintenance costs for the operator. The OPST programme showed that pilots are willing to accept light.

Future Technology Advancements

(or Is there... After Light?)

Computing Technology

In the short term, the objective is to increase the performance while at the same time reducing the mass, volume and component count of the electronics and opto-electronic interfaces. Reference to the OPST system description will show that the computer performance no longer represents sate-of-the-art. For this reason the specification for OPST II calls for a 32bit M68020 microprocessor with a 68882 arithmetic coprocessor running at 25MHz, 256kByte

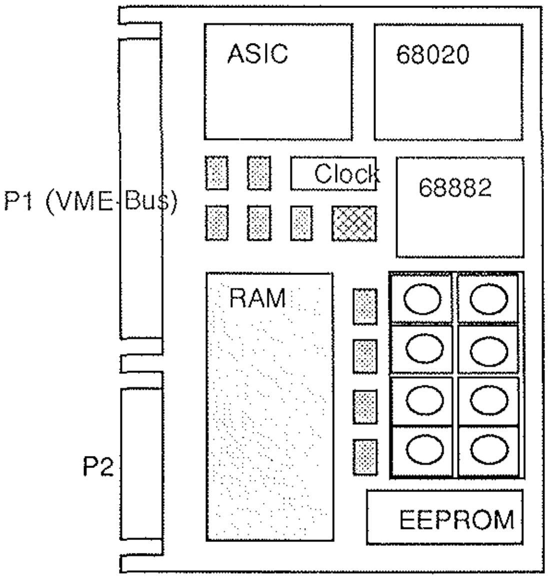

Figure 17: Development CPU/Memory/Bus Interface Card using ASIC Technology.

PROM, 256kByte RAM, and 8kByte EEPROM. In this rather conservative configuration, performance over OPST I will be at least a factor of 5. Mass production by the component manufacturers means that we will always be able to benefit from the latest general purpose processor technology at minimal cost. This is not true for application specific interfacing. Thought performing rudimentary tasks of decoding the incoming optical signals, validating data and performing wrap around checks, the implementation in discrete components requires a number of boards as seen by the OPST I computer. For small production runs, as seen in the aircraft industry, the most cost effective solution is an ASIC. Figure17 shows a processor card with VME bus driver, clock, RS232 and 8bit parallel interfaces. A similar single card could be used for all analogue, ARINC429, RS422, MIL-bus interfaces, so that the original 9 cards required for OPST could be replaced by only 3.

Direct Optical Sensors

In the long term, the objective is to replace the current LVDT position transducers with direct optical sensors to further reduce their mass and volume. Research activities by major manufactures are further looking at the possibility of completely eliminating the power supplies to the sensor (currently required for sensor energisation and interface electronics) and to extract the minimum power required to drive the interface electronics from the optical energy landing on the receiver. Since the conversion efficiency of photo-electric devices is poor, this will require high efficiency LED transmitter devices and large scale integration technology to be applied to the interfaces. It is probable that it will not be possible to eliminate electrical power supplies from hydraulic actuators, especially if direct drive vales are used which under normal operation require 10 Watts but may demand 70 Watts to overcome a valve jam.

Micro-Components

(or Micro-Lights)

Still yet at the experimental research stage, one of the most promising new technologies is the application of micro-machining of silicon to allow the fabrication of a multitude of miniaturised sensors and actuators. Among these, sensors for pressure and acceleration have attained the highest degree of industrial development. Similar principles can be used for load measurement and position sensors.

Most silicon accelerometers published to date use the piezoresistive principle to measure the mechanical strain in a cantilever beam, deflected by a seismic mass under acceleration [8][9]. The resistance changed is converted to a voltage change by the usual bridge configuration. There are disadvantages in this principle as there is a relatively large temperature drift and piezoresistive devices are quite sensitive to mechanical strain during fabrication. In the capacitive accelerometer [10], the seismic mass is simultaneously used as one electrode of a variable capacitance, moving with respect to a counter electrode situated on a second plate. Thus, a capacitive sensor measures a variable distance due to the deflection of the movable plate.

The design principle of the sensor (Figure 18) shows the movable plate is formed by a block connected to a surrounding frame by at least 8 cantilever beams located on both sides of the silicon wafer. A scanning electron micrograph of this seismic element is shown in Figure 19. The air gap between electrodes has a typical dimension of 5µm leading to a zero capacitance of 10pF. A second pair of capacitors of identical size but without the free seismic mass is also included on the same chip for temperature compensation effects. Using hybrid integration, the capacitive sensor is placed next to a custom CMOS signal conditioning and voltage output stage on the same chip base. With a sample and hold circuit clocked at 100kHz, the final signal can be digitised by an A/D converter. The whole unit can be housed in a 20 DIP IC package. Measurements over ±1g range

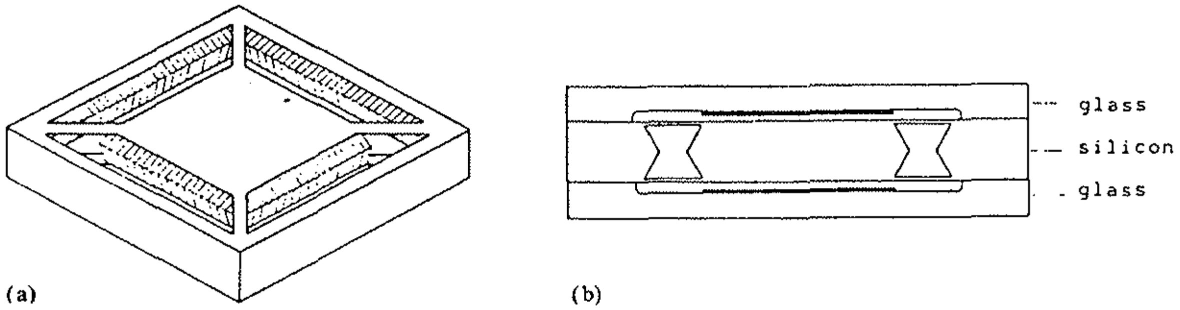

Figure 18: Schematic Diagram of a Capacitive Accelerometer: (a) Cross Section; (b) Top View of Seismic Mass.

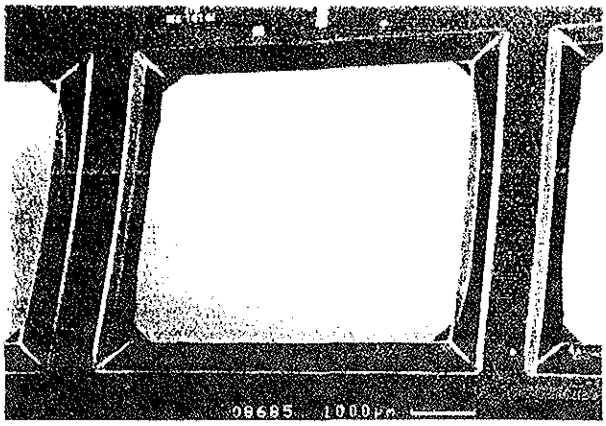

Figure 19: Scanning Electron Micrograph of the Seismic Mass of Accelerometer.

show a good linearity of less than 0,5% and bandwidth to 3,5kHz (Figure 20). Tested from -40°C to +70°C, 20μg/K temperature drift can be achieved using both capacitors.

When fully developed, such sensors will be ideal for flight control systems. There attractiveness lies in the integration of electronics an sensor on the same chip thus reducing mass, power consumption, size and increasing reliability due to a reduction of component count. Combined with the concept of "smart" systems, it should be possible to systematically reduce the size of a typical 3-axis accelerometer and rate gyro package to that dictated only by the physical handling and mounting constraints.

Ancillary Components
(The Side Lights)

Whilst this paper has dwelt on the computing, data transmission and actuation associated with FBL, the pilots' interface, namely the cockpit will see a revolution in the next generation of helicopters. Conventional centre cyclic sticks will disappear to be replaced by side-arm controllers. The are, however, some lessons to be learnt from fixed wing aeroplanes and helicopter research activities. The original concepts of combining all 4 control axes (longitudinal, lateral, directional and vertical) into one side-arm controller have not proved satisfactory to the pilots and required more complex control laws. Current consensus is for retaining separate vertical and directional axes with a combined longitudinal/lateral side-arm controller on the right hand side, or at most combining longitudinal/lateral/directional in the right hand controller to eliminate the pedals. In contrast to many fixed wing solutions, a trimmable displacement stick has found the most favourable comments from pilots during simulation trials (Figure 21) and permits the most flexibility for control law design.

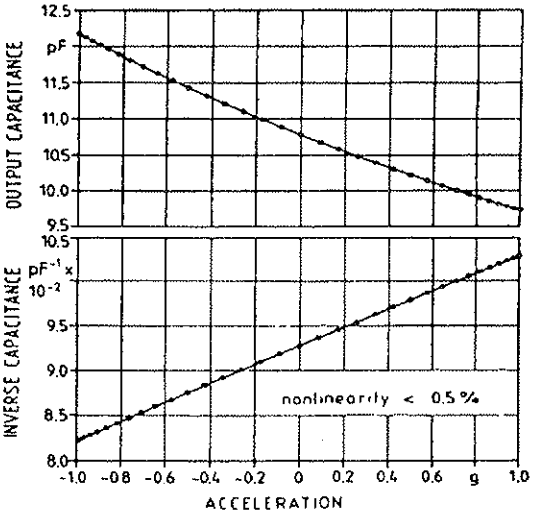

Figure 20: Output Performance of Accelerometer for ±1g.

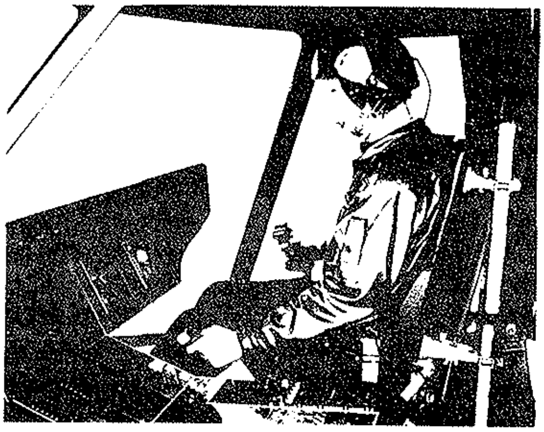

Figure 21: Active Side-Arm Controllers Undergoing Testing in the MBB Simulator.

Since the sick position is no longer coupled directly to the rotor blade angles, it's position and force feel presented to the pilot can be programmed arbitrarily. We call this type of stick an active controller.

Figure 22: Active Side-Arm Controller.

Experiments at MBB have lead to the building of a prototype single axis controller for the left hand side and a dual axis controller for the right hand side (Figure 22). Both controllers have quadruplex redundant sensing of the pilots grip forces which are then processed by the FCCs to compute the stick position demand signal which is transmitted back to the controller. Since it is the pilot's force which is measured, and not stick displacement, no problems exist between synchronisation of both pilot's and copilot's controllers and confusing priority switches can be avoided. Experiments have shown that the pilot's prefer shallower gradients than normally associated with conventional centre sticks, but variation is slope as a function of displacement and the manoeuvre is highly desirable. This is easily achieved in this design since the "spring forces" are produced purely by software (the controller contains only the force sensor unit and servo-actuator, there are no springs) and are fully programmable. In the degraded mode, if the actuation should fail, the controller reverts to a rigid state. Simulation experiments have shown that although the pilot workload increases, this could be acceptable for an emergency. Plans are to install the side-arm controller into the S3 in the near future.

Summary and Conclusions

(The High Lights)

The case for optical data transmission, FBL, has been presented.

The major advantages can be summarised as:

- Inherent immunity to EMI and LEMP and hence in this respect maintenance free;
- Higher data transmission rates and hence "built-in" growth potential;
- Mass savings as no special shielding is required;
- Since no special provisions are necessary, suitable for retro-fitting existing aircraft.

Light is no longer a revolutionary technology, the basic building blocks already exist. FBL is ideally suited to decentralised data processing and "smart" sensors and actuators. This concept applied to new designs will permit the integration of micro-components and all optic transducers as they evolve without requiring major architecture redesigns every time.

The reader is left to make his own conclusions, but the authors are convinced light is here to stay and will establish its self as the leading technology. To summarise in a single phrase, "we 're all Light Jack". What about you?

Notation and Abbreviations

ADOCS	Advanced Digital Optical Control System.
AFCS	Automatic Flight Control System.
ASIC	Application Specific Integrated Circuit.
BIT	Built-in Test.
BMVg	(German Ministry of Defence).
CMOS	Complementary Metal Oxide on Silicon.
DLR	Deutsche Forschungsanstalt für Luft und Raumfahrt e.V.
EEPROM	Electrically Erasable Programmable Read Only Memory.
EMC	Electromagnetic Compatibility.
EMI	Electromagnetic Interference.
FAA	Federal Aviation Administration.
FBL	Fly-by-Light.
FBW	Fly-by-Wire.
FCC	Flight Control Computer.
HLH	Heavy Lift Helicopter.
LAT	Liebherr Aero-Technik.
LED	Light Emitting Diode.
LEMP	Lightning Electromagnetic Pulse.
TTL	Transistor Transistor Logic.
LVDT	Linear Variable Differential Transducer.
LW	Long Wave.
MIPS	Million Instructions per Second.
MW	Medium Wave.
OPST	optischer Steuerung (Optical Control).
PROM	Programmable Read Only Memory.
SAR	Search and Rescue.
STP	Screened Twisted Pair (22SWG).
SW	Short Wave.
TAGS	Tactical Aircraft Guidance System.
VSTOL	Vertical/Short Take-Off and Landing.

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