Design of a Primary Fly-By-Light Control System

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Abstract

This paper presents the design of a quadruplex Fly-By-Light flight control system, designed for an Eurocopter EC135 helicopter, dedicated for the German research and technology program ACT/FHS.
This purpose implies a dual pilot concept with a safety and evaluation pilot ensuring interaction priority to the safety pilot.
A mechanical emergency backup for the safety pilot has still been kept.

The FBL flight control system consists of a fully digital signal processing computer (COS) connected by optical datal inks to one tandem actuator in each axis. The pilot's stick position inceptors are linked to the COS to generate position comands for the smart actuators.
This quadruplex core system provides the basic functions for controlling the helicopter.
A fault tolerant equipment design combined with a number of system monitoring functions keeps the system protected against internal failures and disturbances imported from outside.

An optional Flight Control Computer can be attached modifying the comand signal flow to the actuators.
In this configuration comprehensive signal processing capability is applied in order to allow experimental test and simulation features.

Most benefits of this flight control system are seen in the reduced EMI susceptibility of optical datalinks as well as in the adaption flexibility due to aircraft configuration change requirements.

Notations

ACE	Actuator Control Electronic
ACT/FHS	Active Control Technology Flying Helicopter Simulator
COS	Cockpit Signal Processing Computer
DLR	German Aerospace Center
EMI	Electro magnetic Interference
EMP	Electro magnetic Pulse
EP	Evaluation pilot
FBL	Fly-By-Light
FCS	Flight Control System
FCC	Flight Control Computer
HC	Helicopter
HW	electronic Hardware
LVDT	Linear Variable Differential Transducer
MCV	Main Control Valve
SOV	Hydraulic Switch Over Units
SP	Safety pilot
SW	Software

Introduction

This helicopter provides a highly sophisticated platform for key technology for future helicopter applications which include:

- In-flight simulation of present or future helicopter types
- system development/integration with emphasis on new active control technology
- demonstration of functionality and operational benefit of new technologies

The paper will concentrate on the third application item, in order to demonstrate the benefit of FBL technology and smart actuation units in hostile environments.

Although the ACT/FHS is designed for use as a test platform for in-flight simulation, the design itself must demonstrate the feasibility of certification of 100% authority FBL control systems, without any mechanical backup systems.

During the use and testing phase of ACT/FHS, the experience of FBL primary FCS gained will lead to technical confidence for future development in series helicopter applications.

ACT/FHS Fly-By-Light System Architecture

The FBL flight control system is divided in two parts (Fig.1).

The first part is the safety critical Core System which contains the Control Signal Processing Computer (COS), the smart actuators as well as the control inceptors for the Safety and Evaluation Pilots. Depending on the actual flight mode, control stick positions of either the safety pilot or the evaluation pilot are converted into actuator position commands by the COS. These comands are transmitted to the smart actuator of each axis, via optical data link.

Additional Hydraulic Switch Over Units (SOV) enable emergency transition into the mechanical backup mode. In the mechanical backup mode, the safety pilot has a direct mechanical link to the control valves of actuator.
This is only for safe mission completion and is not reversible in flight.

The Control and Display Unit (CDU) contains all switch and display logic for flight control mode selection and its indication in the cockpit.

The other section is called Experimental Section, which is equipped with a Flight Control Computer (FCC). Within the Experimental Section, depending on the experimental purpose, different FCC configurations are applicable.

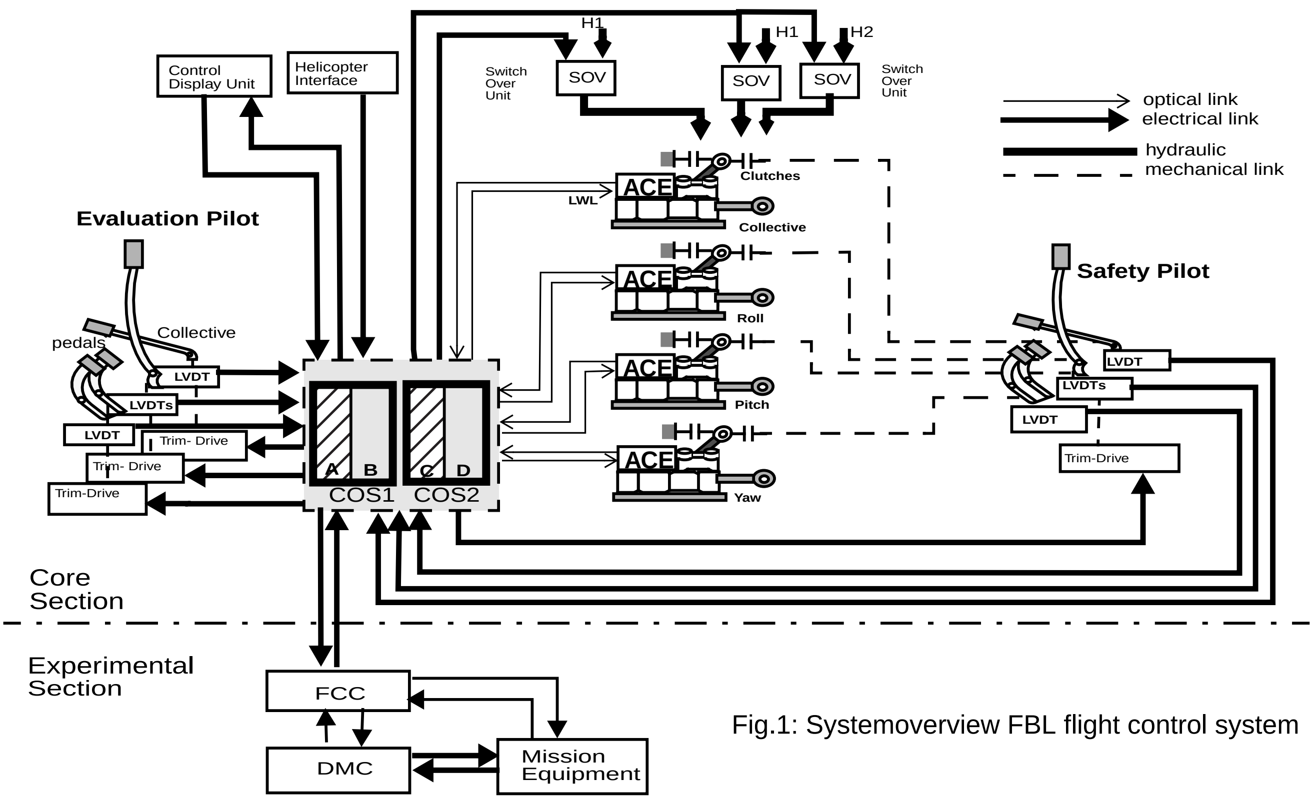

Fig.1: Systemoverview FBL flight control system

In the experimental flight control mode, actuation commands of the evaluation pilot‘s stick positions are computed and fed back to the COS for transmission to the smart actuators.
Highly complex inflight simulations or control law validations may be implemented in the safety uncritical Experimental Section. This is made possible by the fact, that in the event of an emergency, it is possible to revert back to the highly reliable Core System.

System Safety Requirements-System Realisation

The Experimental Section of the ACT/FHS Flight Control System is the platform for various experimental applications. The extension stage of controllers and other equipment installed in this section may vary depending on the experimental purpose.

There are no safety requirements raised for the Experimental Section. The back-bone system of the Experimental Section is based on the very reliable direct link control path of the Core Section.
In order to provide very reliable experimental applications with redundant FCCs installed in the Experimental Section, the Core Section is designed to provide the catastrophic failure probability of less than 1×10^{-9} per flight hour.

An additional independant mechanical backup mode with the predicted failure rate of 1×10^{-7} per flight hour can be selectable by the safety pilot in the event of a total loss of the Core Section.

To reach the safety requirements, a full quadruplex redundant system design has been selected. The complete signal path including the stick LVDTs of both pilots, the Control Signal Processing Computer (COS) and the Actuator Control Unit is designed in quadruplex redundant architecture.

The control signals of safety and evaluation pilot are picked up via 6-wire LVDTs by the COS lanes. Each COS lane is connected to one independent and isolated LVDT for each axis and pilot. The stick positions are computed and the relevant actuator command is calculated by passing position adaption, PIO Filters and rate limitation, as described later on.
For the Safety Pilot direct link mode, the relevant flight control mode must be selected to set the software switch (SW2) to position 1. (Fig.2)

Safety Pilot	direct mechanical link	*Mechanical Backup Mode*
Safety Pilot	SP direkt opto-electronical link	*Fly-By-Light Control Mode*
Evaluation Pilot	EP direkt opto-electronical link	
Evaluation Pilot via FCC	Experimental Mode; opto-electronical link via FCC	

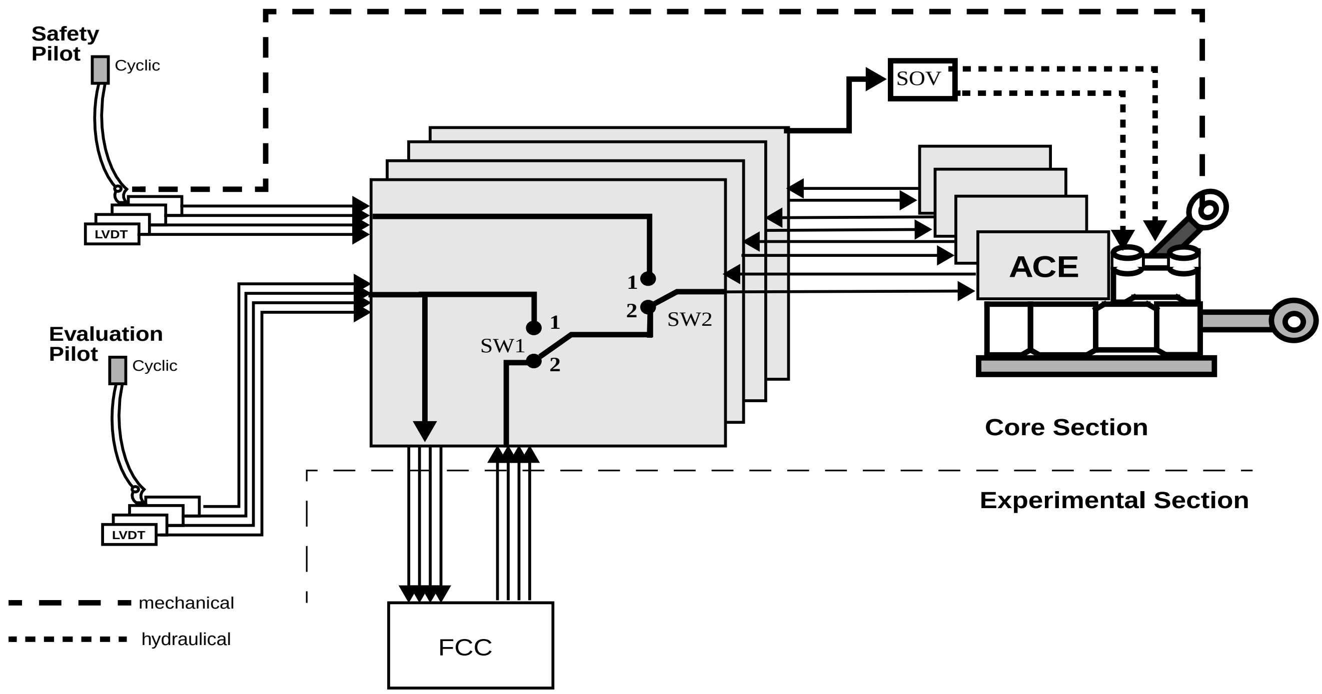

Fig.2: Control Comand signal flow

In this mode, the actuator commands are converted into a serial data format for transmission via optical fiber to the corresponding ACE lane. The current actuator position is fed back to the corresponding COS lanes by an additional optical link.

For selection of the EP direct link mode, the software switch (SW1) must be set to position 1 to enable direct access of EP commands to the actuation system.

In order to include the FCC capabilities into the control path of the flight control system the software switch (SW1) must be set to position 2.

During the Experimental Mode, 100% authority of the FBL Control is given to the FCC. FCC command generation is either derived from the EP stick commands or from the FCC itself, depending on the experiment being performed. The number of data links between COS on FCC depends on the experimental application and the applicable FCC extension stage.

Incoming actuator position commands of all ACE lanes are consolidated via interlane cross-communication. The actuator control loop is asynchronously computed by each ACE lane which controls corresponding coil of a quadruplex torque motor mounted on the shaft of the hydraulic control valve of the actuator.

The mechanical backup mode is realized in the form of a direct mechanical link from the SP stick/pedals to the hydraulic control valves of the actuators.
In the event of an emercency, a cut-off switch initiates electrical deenergizing of the COS, all ACEs and the SOV. The deenergized SOV results in the closure of a clutch within the actuator which connects the mechanical link between the control valves and the SP stick/pedals.
The activation of the emergency backup is not reversible in flight. It is only for safe mission completion in the event of total loss of FBL control. There is also a separate SOV that supplies hydraulic pressure to a centering clutch within the actuator, which sets the mechanical link of the SP control inceptors directly to the actual actuator ram position (only when FBL control is attached to the Evaluation Pilot). This ensures the synchronized position of the SP inceptors to that of the actual posiitons of the actuators in order to prevent major transients whenever FBL control is taken over by the Safety Pilot.

This feature also allows the Safety Pilot to monitor the actuator positions in the EP or Experimental Mode.

<u>COS Design</u>

<u>COS Quadruplex Architecture</u> The quadruplex redundancy of the electronic control path of the core system is designed to use two dissimilar HW variants.
A generic HW failure of one HW variant would cause the loss of only two channels. Even in two channel operation mode, the flight control system still provides level A performance.
For safety reasons the quadruplex control electronic of the COS is mechanical segregated in two identical housings including a fire wall between the two channels.

The choosen system control architecture meets the qualitative safety requirement to survive one software failure.
All control and monitor SW tasks of the COS and the ACE are classified as level A functions according DO/178B and ARP 4754.

The software diversity of the COS is realized to duplex dissimilarity.
The similar system requirements are transferred in duplex dissimilar SW requirements. Based on one requirement document, the following the SW design and verification process is performed by two different teams leading to two dissimilar sets of software.

To avoid a catastrophic event of a 2 versus 2 channel conflict due to a SW failure in one SW variant, a corresponding monitoring between two dissimilar channels is performed.
If a functional divergence is detected, an automatic switching to backup mode is initialized.

<u>COS Partitioning</u> Both HW architectures provide SW partitioning capability which allows execution of two application software packages of different software criticality classifications, running on one hardware.
At the COS application, the uncritical trim system control task as well as the failure storage task, classified as level C, are seperated from the critical level A partition.

<u>COS Signal Processing</u> The safety and evaluation pilot's LVDT command signals are demodulated and converted from analog to digital. LVDT component monitoring is performed prior to any further signal processing. Direct link modes of EP or SP pass through the PIO Filter to avoid pilot induced oscillations in the roll axis.
At the end of the control path, a constant rate limiter ensures actuator command rates within the maximum possible actuator speed in relation to the maximum hydraulic performance of the helicopter.

For the FCC supported Experimental Mode, control commands of the FCCs are monitored with respect to validity, parity and update. Although the incoming FCC data protocol may not show any bus protocol failures, the Experimental Section might produce runaways, which could cause major damage to the helicopter under certain conditions. This runaway limiter cuts off actuator commands exceeding combinations of control rates and time of duration.

The mode selection logic, determines the control signal path according to mode selection inputs of the Control and Display Unit (CDU). Faders are attached to the software switches SW1 and SW2, to provide a smooth transition between the control command sources considered. Different fader algorithms are defined according to the kind of fader and the direction of the transition.

A HW based optical converter is installed at the interface to the ACEs.

Besides direct actuation control the system provides different trim control functions of the EP sticks/pedals.
The conventional ‘beep trim-function‘ controls the trim drives of all axis according to the activation of corresponding beep toggle switches.
Furthermore a synchronization trim mode is implemented, that synchronizes the EP sticks/ pedals with the actual actuator positions.
This synchronization is necessary to assure a transient free switching from SP direct link to EP direct link mode.

COS Monitoring and Built-InTests The electronic includes several selfmonitoring and bulit-in-test functions such as
- ARINC input data monitoring
- Trim System monitoring
- Stick LVDT monitoring

To ensure the availability of the whole system redundancy prior take off, a automatic self check of the control electronics is performed.
During automatic self check, the I/O interface, the watchdog circuit, the processor kernel memory and the partitioning circuits of the electronics are tested to detect all dormant HW failures before transition in normal mode operation.
In case of failure, the fail safe mode is entered.
If the failure is of transient nature, the safety pilot can reconfigure the corresponding channel by pushing the Reset button.

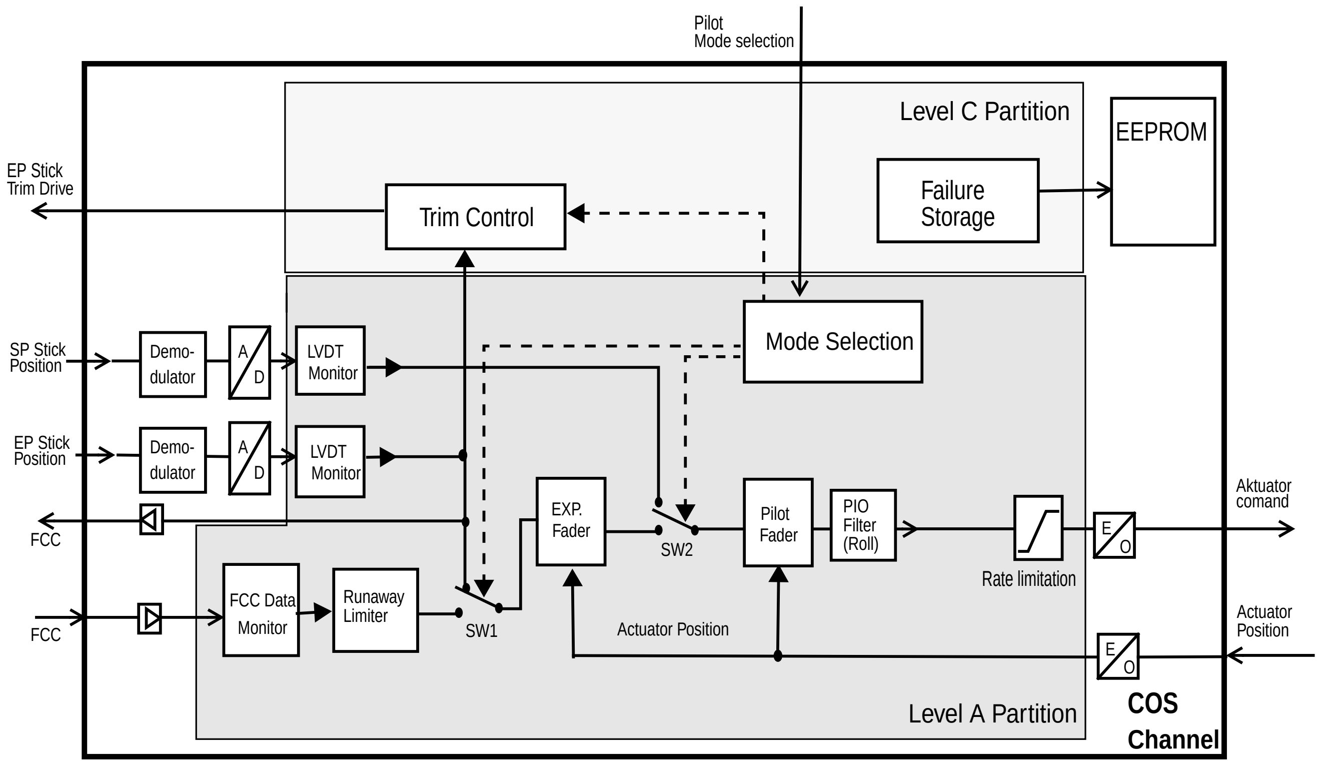

Fig.3: COS Signal Processing

COS Hardware Design For one hardware variant, the 25 MHz microcontroller type Motorola 68332 is used and for the other, the signal processor SMQ320C32 (40 MHz) from Texas Instruments. The internal HW- and SW based watchdog circuits passivates all COS interface in the event of an encountered inlane HW fault or SW runtime fault. Both HW variants provide a 2 ms program cycle time, however program execution is performed asynchronously. An optical crosscommunication between the COS lanes ensures a synchronized flight control mode selection by CDU inputs.

Each COS is powered separately from one of the two helicopter essential 28 VDC power busses. Each power bus is buffered by two additonal batteries to keep the FBL control active in the event of power interruption or failure.

The COS HW provides a stabilized 40 VDC Power Supply to the ACEs.

Each COS lane provides a RS 422 link for on-board SW installation, trouble shooting reasons and executing maintenance SW-packages.

Each COS lane comprises interfaces with the following functions:

Interface Type	**COS Functionality**
Discrete in-/outputs	Mode control and indication
Analog input	LVDT position generation
Optical 100 kbit data interface	ACE data communication COS cross communication
Optical 2 Mbit data interface	FCC data communication
Electrical 100 kbit ARINC 429 interface	FCC data communication
40 VDC Power Output	ACE Power Supply (stabilized)
28 VDC Power Output	SOV Power Drive

Fig.4: COS housing

ACE Design

ACE Quadruplex Architecture The four ACE lanes are functionally equivalent but are realized in duplex dissimilar hardware. All ACE lanes are installed in one housing.
Two lanes of one HW variant are segregated by an internal fire wall.

In contradiction to the COS the ACE software is developed quadruplex dissimilar.
The selected control algorithm is able to guarantee a satisfctory systembehaviour in case of a software error in one channel.

ACE Signal Processing The quadruplex actuator control electronics (ACE) are directly located on the hydraulic actuator.

Each ACE lane receives the applicable actuator command for one COS lane. The actuator control loop is asynchronously computed by each ACE lane. Each ACE lane drives one coil of the quadruplex torque motor mounted on the shaft of the DDV control valve of the actuator.(Fig.5)
Even in two-lane operation of the ACE, nominal actuation performance is ensured.

Stabilization of actuator is maintained by a two level cascade loop control. At the outer control loop the actuator position is fed back to the control loop to compute the DDV set value.

A consolidation of DDV set values of all ACE channels is performed at the consecutive voter to avoid force fighting on the shaft of the control valve. The outer control loop is performed with the program cycle time of 2 ms.

The DDV position passes a voter algorithm to consolidate the DDV read value with the values obtained to the other lanes. Adjustment tolerances of the DDV LVDTs of all ACE lanes are eliminated to achieve equal control inputs of the DDV control loop. The set value of the DDV current is computed by the inner loop with a program cycle time of 400 µs and is passed to the consecutive HW based DDV current control loop. The resulting DDV and actuator positions are fed back to the inner and outer control loops.

ACE Monitoring and Built-InTests The electronic includes several selfmonitoring and bulit-in-test functions such as
- ARINC input data monitoring
- Ram /MCV LVDT monitoring
- Output current monitoring

The Power up self check, the Fail Safe failure reaction and the ability of channel reconfiguration is comparable to the COS features.

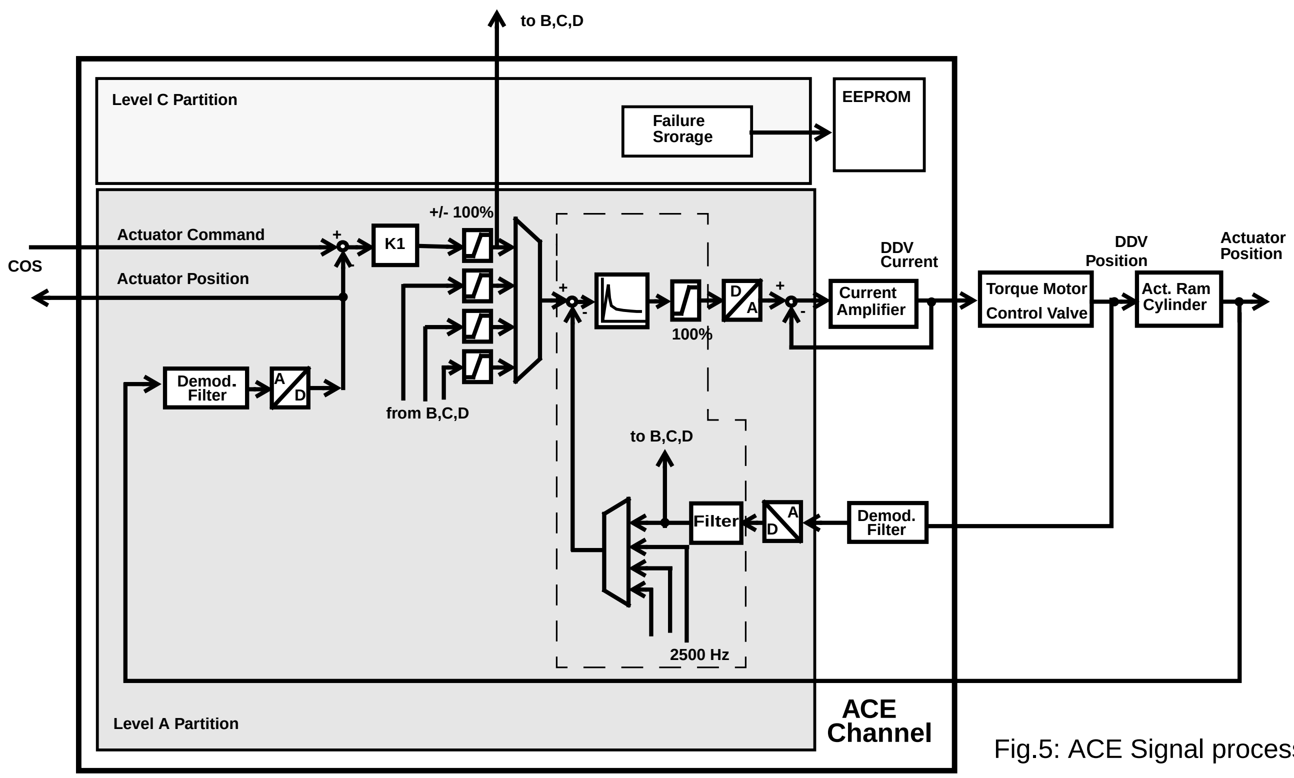

Fig.5: ACE Signal processing

ACE HW Design The quadruplex actuator control electronics (ACE) are directly located on the hydraulic actuator,giving all necessary actuator interface e.g. LVDTs, torque motor coils from the bottom of the ACE, via one sealed connector for each lane. (Fig.6)
At the top of the ACE, the four main connectors are of the electrical/optical hybrid type. They establish a very compact interface in order to provide the optical data communication between ACE and COS lanes and the stabilized 40 VDC power supply of the ACE lanes.

The same CPU types already described at the COS HW design are used for ACE application including the SW partitioning and watchdog function features.

The additional two connectors allow RS422 access to the CPU for onboard SW loading or other shop mode features. (executing maintenance SW-packages)

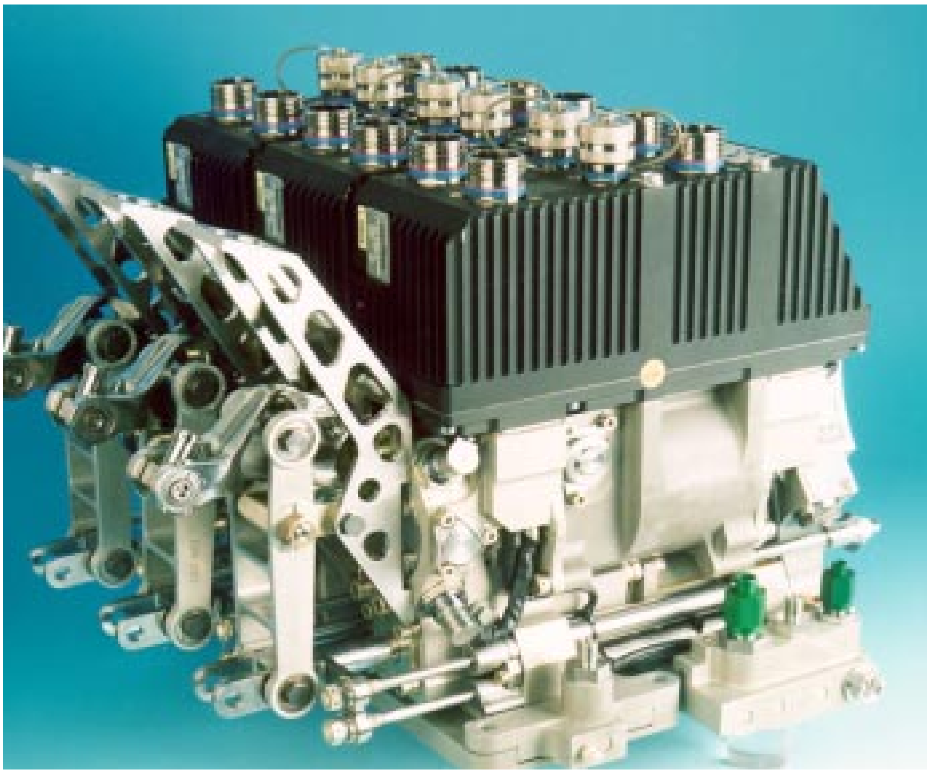

Fig.6:
Smart Main Rotor Actuator

Hydraulic Actuation Design

The ACT/FHS actuator design consists of a tandem cylinder assembly controlled by a quadruplex Direct Drive Valve (DDV) assembly. By design, the two hydraulic systems are completely segregated.

The DDV assembly contains two rotary control valves commanded by a quadruplex electrical rotary torque motor. The torque motor design makes provision for four 90 degree sections containing electrically segregated coils on the circumference of the stator.

The rotor of the torque motor is mounted on the common control valve shaft of both control valves. Both rotary control valves are of a double rotary selector valve type to ensure anti jamming function.

The ACE inner loop controls the rotary valve position. Each valve position is fed back by two LVDTs which are mechanically connected to the rotary spool by a lever.

The ACE outer loop controls the actuator ram position. Four individual LVDTs, connected to the piston rod, and arranged around the cylinder, provide the feedback signal.

The highest possible level of electrical segregation is considered in the actuator design. The wires of all LVDTs and torque motor coils terminate at four segregated electrical connectors, one per lane.

Switching into mechanical backup mode is achieved by deenergizing the SOV. This causes the loss of hydraulic pressure at the motor clutch of the actuator and the control access of the control shaft reverts back to the mechanical input lever.

The ACT/FHS Main Rotor Actuation for cycle and collective axes comprises of three identical smart actuators which differ only in the manner of operational stroke. (Fig.6)
Another single smart actuator drives the tail rotor actuation.

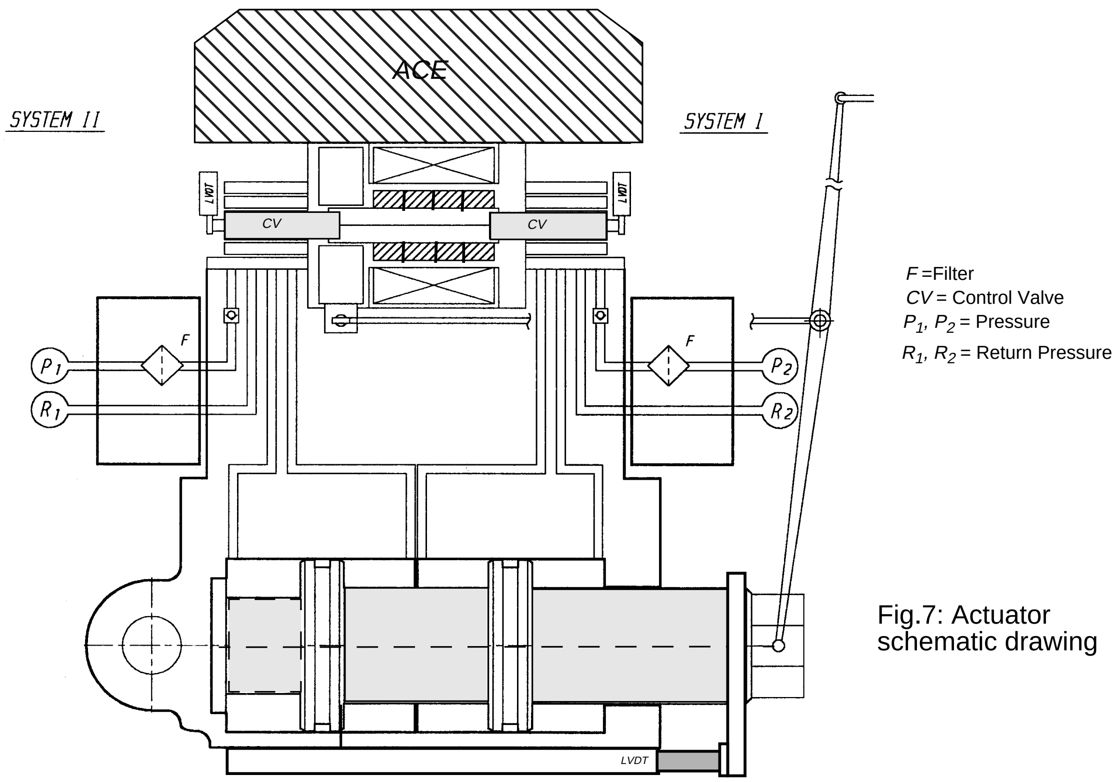

Fig.7: Actuator schematic drawing

Benefits of Fly-By-Light Technology

After twenty years experience in Fly-By-Wire (FBW) technology the conviction in its reliability is well established.
The first civil aircraft with full FBW technology was the Airbus A320. Nowadays even small business jets use this technology. The Fly-By-Light technology has already been examined in several research programs, e.g. LECOS (Light Electronic Control Systems), FOCSI (Fiber Optic Control System Integration), FLASH (Fly-By-Light Advance System Hardware), ATTHeS (Advanced Technology Testing Helicopter Simulator), ADOCS (Advanced Digital Optical Flight Control System) and OPST (optische Steuerung).

The Boeing 777 aircraft was the first commercial aircraft to use a fiber optic network ring architecture based on the ANSI Fiber Distributed Data Interface (FDDI) standard.

The fiber optic control system integration (FOCSI) program has performed in flight testing of fiber optic sensors for flight and engine control system in a F18 aircraft in 1993 at the NASA Dryden test facilities.

The feasibility of fly-by-light technology for actuation applications in helicopters was already demonstrated in the year 1988 by the German research program ATTHeS.[3]

The major benefit of fiber optic systems is the very high bandwidth, unachieveable with conventional electrical wires. For avionics application, due to protection circuits at each controller interface, data rates are limited up to 1-2 Mbit/s. Higher data rates are required from data transmission tasks of navigations and autopilot systems to other subsystems corresponding the interface between Core and Experimental Section for ACT/FHS. Transmission easily achieves data rates >> 10 Mbit, restricted only by the availability of applicable interface hardware of considered bus systems.

An additional key argument for the use of optical data links is the EMI/EMP immunity without the need for additional shielding.
Present HIRF requirements ask for resistance against field strength up to 6000 V/m especially for helicopter avionic application, which usually operates in altitude levels close to broadcasting systems. Reliable data communication was confirmed during qualification testing of ACT/FHS components up to field strength of 5200 V/m.[1]

Another benefit for application of optical data link is the reduction of weight. Comparable high speed data links with conventional wires including sufficient shielding causes approximately five to eight times more weight than a fiber optic linkage. The weight of the fiber optic cable used for ACT/FHS is less than 4 kg per km providing sufficient mechanical strength as well as excellent chemical and oil resistance for use in aircraft environment.

Last but not least, optical data links provide corrosive resistance and eliminates spark induced fire hazards in explosive areas.

Even with the projected benefits, the application of optical technology in aircraft has been affected by technical and economic risk factors.
Fibre optic hardware is much more expensive than the electrical counterparts on a piece-part comparison and there is still a risk in the point of view of certification.
Fibre optic connectors are perceived as difficult to install, maintain and repair.

One aim of ACT/FHS is to confirm the technical and operational benefit by using new optical components in order to demonstrate feasibility of optical links at actuation units, even in series application.

ACT/FHS optical Data Communication

The undirectional optical data links of the COS cross communication and the COS/ACE communication provide a data of 100 kbits/s to fulfill system performance requirements. The interface between Experimental and Core Section requires a 2 Mbit/s optical data link.

The ARINC data protocol is used for the optical data transfer. The ARINC 429 RZ (Return to Zero) output data are passed to a converter to generate light pulses of different duration for High/Low determination on the fiber optic.

The fiber itself is a 200/240 um, glass step index type for 850 mm wavelength, developed by Avioptics. This cable provides sufficient mechanical strength (bending radius 10 mm, break strength 890 N) and chemical resistance to withstand exposure to jet fuel, solvents and hydrolytic liquids often encountered in avionics.[1]

Optical transmitters and receivers are used from Honeywell. The Schmitt Trigger function of the receiver diode is implemented in the diode‘s housing. The diodes are integrated into optical pins which are directly mounted in the connector housing.

A connector housing type of Mil38999 series with different sizes is used. For ACE application a hybrid connector type is used, providing 40 VDC power supply as well as two fiber optics for data communication.

Conclusion

The research and test programm ACT/FHS demonstrates the feasibility and the safe operation of two key technologies:
'Fly By light' and 'Smart Actuators'

The ACT/FHS hierarchical system architecture provides a highly reliable back bone system (Core Section) and an uncritical high level Experimental Section.
This architecture offers flexibility by implementation of automatic flight control functions within the uncritical section without any impact on the certification for series helicopters.

The FBL technology as well as the smart actuation design demonstrates remarkable EMI/EMP immunity an increased survivabilty in hostile environment.

The adaption flexibility and the configurable system architecture leads to an increase of reliability in of air vehicle systems.

First flight took place in January 2002 and the offical entry-into-service at the DLR was in november 2002.

So finally the programm ACT/FHS demonstrates the technical readiness for application of complex electronic computerized flight control systems.

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