DESIGN VALIDATION OF A NEW GENERIC FLY-BY-X FLIGHT CONTROL SYSTEM FOR HELICOPTERS

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OVERVIEW

A new design approach using a generic platform model has been validated in the development of a laboratory prototype of a redundant fly-by-X flight control system for helicopters. This concept offers more flexibility in scalability, cost-effective system upgrades and adaptation to different helicopter types. The resulting prototype is characterized by a high modular architecture with segregated modules for input/ output, central processing and actuation control. Scalability is supported by application of modern bi-directional data bus communication. The redundancy management algorithms result as an encapsulated middleware layer from the generic platform instantiation process. For flight control modes the ADS33 response types have been implemented. System verification has been successfully performed in a closed-loop verification environment by normal and failure mode robustness testing.

INTRODUCTION

In the last two decades fly-by-x (FBX) [X=wire/light] flight control systems (FCS) became more and more attractive for helicopter application. This technology has paved its way over various technology demonstrators such as the EC135 ACT/FHS fly-by-light helicopter [1] up to its series implementation on bigger helicopters as NH90 [2] and S92 [3]. The interested reader can find an excellent description of the history about the beginnings and progress of the FBX development up to today's technology in the paper of L. R. Stiles et al [4]. A big advantage of the FBX technology is the exploitation of a full electronic control path up to the hydraulic actuator lacking any mechanical connection between the pilots' controls and the actuator. This allows the implementation of new command models specially designed for the pilot's needs with excellent handling qualities and without any interference with the helicopter's native control behavior such as axes coupling which is cancelled out by (advanced) control laws. Pilots' workload reduction and comfort can be further enhanced by use of active side sticks which are predestined for the combination with the FBX flight control system due to the electronic nature of both systems. The tactile cueing properties of an active side stick give the pilot a dynamic "force-feeling" with certain cue capabilities into his hand, e. g. such as essential first limit indications, allowing a more intuitive helicopter control.

However, there are also some drawbacks of the FBX technology. Rigorous safety requirements request in consequence the complex development of an adequate (redundant) system design. In the current state of the FBX technology the system developments or adaptations of commercial-off-the-shelf (COTS) products concentrate more on a specific helicopter type which result in a big challenge to achieve cost efficiency in development and life cycle. Some potential to master this challenge is seen in a modified approach to create a FBX system design which is applicable to a broader band of helicopter types from the beginning. Such a design will be supported by some kind of "generic bricks" used in the system development process as well as by exploitation of system modularity and scalability features.

A more advanced "generic" FBX system design shall introduce a kind of standardization of the redundancy management layer based on a deterministic rule set implemented on a platform model. A specialization process applicable to the generic platform model shall configure the redundancy management layer for specified target system hardware. This design characteristic shall include a strict segregation between redundancy management and control law software layers as well as further features such as modularity and scalability.

This paper reports on the new FBX design approach and its laboratory prototype implementation for technology validation. It presents also results of closed loop testing within a laboratory verification environment. The work has been performed within research cooperation with the main contributors EUROCOPTER, LIEBHERR, LITEF, UNIVERSITY OF STUTTGART and DLR.

OBJECTIVES OF THE NEW GENERIC FBX FLIGHT CONTROL SYSTEM

The new "generic" FBX flight control system shall achieve the following objectives:

- Excellent handling qualities shall be provided by application of advanced control laws for pilots' workload reduction and safety enhancement.

- No essential reduction of handling qualities shall occur in case of occurrence of failure modes; abort of missions and pilots' training costs for emergency procedures shall be avoided.

- The control laws which are helicopter specific shall be built on top of the separated redundancy management layer generated by the generic platform process. The control laws shall be "simplex-minded" which means they shall "see" one virtual signal of each sensor type and shall be no longer affected by the complexity of the management of redundant sensor signals. This concept shall allow cost-efficient adaptation to different helicopter types and share of development costs.

A modular target system design shall drive the following features: Chosen basic FCS system architecture shall be configurable to an operator's needs from cost-efficient minimum configuration being compliant with certification requirements up to maximum configuration providing dispatch capability in failure cases. Hardware interfacing to sensors and helicopter avionics shall be restricted to special input/ output modules (IOMs) and shall not affect the central processing modules (CPMs) core flight control computer hardware. A "smart actuator" concept shall be available with the electronic actuator control modules (ACMs) integrated in the hydraulic actuator and saving bigger amounts of analog wiring across the helicopter. The use of a modern bi-directional data bus system shall generally reduce the wiring overhead.

CERTIFICATION REQUIREMENTS

The design of an electronic FBX FCS as a complex system has to be compliant with the following CS 29 airworthiness requirements:

- (a) “No single failure shall result in a catastrophic failure condition”.
- (b) “Each catastrophic failure condition is extremely improbable”.
- (c) Common mode errors have to be regarded during the safety assessment process.

The consequence of requirement (a) is that the FCS must at least exhibit a fail/operative – fail/X behavior. In case of an even more demanding requirement with dispatch capability in an electronic failure case the system shall be able to follow at least a fail/ operative – fail/operative – fail/X approach. Based on requirement (b) the occurrence probability Q for catastrophic failures must not exceed 10^{-9} (per flight hour). As the failure probability Q_i of single electronic modules is in the range of $10^{-5} < Q_i < 10^{-3}$, the requirement of the failure probability $Q<10^{-9}$ for the total FCS system can be only achieved by a redundant implementation of modules performing the same function. Focusing on requirement (c) one has to consider that development errors in hardware and/ or software could lead to a failure of all redundant modules performing the same function when those modules are implemented by the same hardware and software (“similar” design). Dissimilar design of redundant components performing the same function is a common approach to mitigate common mode errors. Using this approach two kinds of dissimilarity have to be considered: “Integrity” dissimilarity for detection and isolation of common mode failures and “availability” dissimilarity for continuation of the required function.

Remark: A design compliant with dissimilarity requirements have to be implemented in a series development, however, it has not been regarded in the set-up of the laboratory prototype described here in this paper because of its priority on the functional design validation.

DESIGN CHARACTERISTICS OF THE NEW FBX FLIGHT CONTROL SYSTEM

The definition of the new FBX design was driven by the boundary condition to fulfill on one hand the requirements in terms of safety, functionality, availability, scalability, dissimilarity as well as dispatch capability in electronic failure cases and on the other hand to limit the system’s weight and recurring costs.

Before fixing of the final system architecture an assessment of several candidate architectures being compliant with the requirements has been performed. The selected architecture is described in the following.

As mentioned initially, the new FBX FCS shall be capable to be combined with different types of pilots’ controls in the range from conventional sticks/ pedals up to the technology-demanding active side stick units. The side stick units belong to a separate development which is seen decoupled from the FCS development, so the FBX FCS laboratory prototype has been equipped with conventional controls. As trim functions can be taken over by the modern control laws the cyclic stick and pedals utilise a pure spring-centred layout without any electro-mechanical trim actuation system. This design corresponds fully to the “command” (stick/ pedal deflected) and “hold” (stick/ pedal released) control law response types. Only the stick for collective axis control is implemented with an electro-mechanical trim system which can move the spring-fixed stick over the whole control range. This supports the pilot to keep the control range limits in view.

The core platform of the finally fixed FBX FCS architecture (see Figure 1) consists of redundant Input/ Output Modules (IOMs), redundant Central Processing Modules (CPMs), redundant Actuator Control Modules (ACMs) and two dual-redundant FCS main data buses. The data buses are of a modern bi-directional type providing the base of module scalability and restriction of wiring overhead. The IOMs acquire sensor and control sticks discrete (switches) data. The CPMs contain “special intelligence” to control the platform (redundancy) management with the platform management software itself being distributed over all modules of the platform. They perform also the control law computation with modern “response types”. The ACMs process the actuator commands issued by the “master” CPM and by driving the electric coils of the Direct Drive Valves (DDV) of the hydraulic actuators in closed loop with the DDV and ram position sensor data.

The data bus system is composed of two FCS buses (“Red” and “Blue”) for high-redundant signal communication among the core FCS platform modules and one avionics bus (“Green”). Each bus comprises two separated transmission channels. The “colour” of the buses (“Red” and “Blue”) and that one of the attached FCS modules denote the exploitation of time-triggered synchronous data communication among system components of the same “colour”. This synchronisation (to one of the data buses) optimises the data transport delay. The system concept itself does not require a time-triggered data bus protocol. In a series application the colours “Red’ and “Blue” could also mark the hardware variants (HW1, HW2) used for realization of the “availability” dissimilarity. The main rotor (MR) and tail rotor (TR) ACMs utilize an additional cross communication bus for exchange and consolidation of the redundant actuator (ram and DDV) position sensor data.

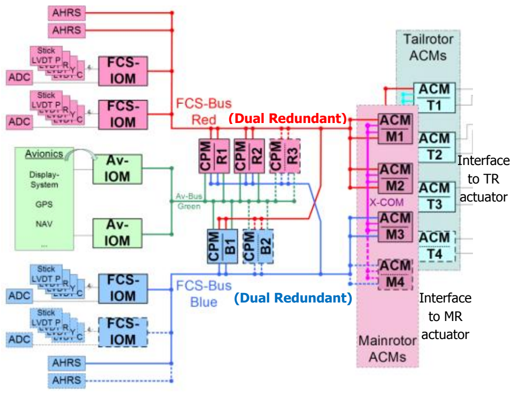

Figure 1: Scheme of the FBX FCS architecture.

As shown by the system configuration in Figure 1 the main data input/ output to and from the FCS bus system is performed by four FCS Input/ Output Modules (FCS IOMs, 2 “Red”, 2 “Blue”) and two avionics IOMs (“Green”). The avionics IOMs establish the interface to the avionics system while the four FCS IOMs process basic FCS relevant data such as pilot control stick/ pedal position sensor data, stick switches data, air data computer signals (Arinc429), etc. The FCS IOM redundancy reflects also the sensor redundancy. Four redundant Attitude and Heading Reference Systems (AHRS) are connected directly with both FCS bus systems. As an advantage, any modification of helicopter signals affects mainly the (less complex) IOMs but not the CPM hardware and in certain cases only its software.

The CPMs (with scalable number) perform the platform redundancy management and the control law computation. They follow a dual-lane design with cross-lane-comparing data exchange resulting in a high degree of self-monitoring and failure passivation capability. This prevents the spread of failures across other system modules. Incoming bus data are checked for validity in each lane and are then cross-lane exchanged and compared for ensuring data consistency between both synchronously running lanes. Any data corruption or bus signal transmission failure must be detected and isolated in order to ensure a consistent FCS platform state. The CPMs are operating in a “master/ slave” configuration meaning that only one CPM as “master” has actuation control while the “slaves” operate in standby mode but ready to take over the master function, if required. A schematic of a dual-lane CPM is presented by Figure 2. Both CPM lanes contain power supply device, CPU and I/O controllers for the FCS and avionics FlexRay buses, for Ethernet used for internal module debugging and maintenance and for discretes established for pin programming. An internal Ethernet link between both CPM lanes is provided for the cross-lane communication. A Freescale MPC

5567 micro-controller containing CPU and I/O controllers is used for the lab prototype as this kind of hardware concept was available from previous research projects and the risk of a complete new development within a short time period could be avoided. This micro-controller and the related module concept were also used for the IOMs and ACMs, however, with modifications mainly affecting the interfaces.

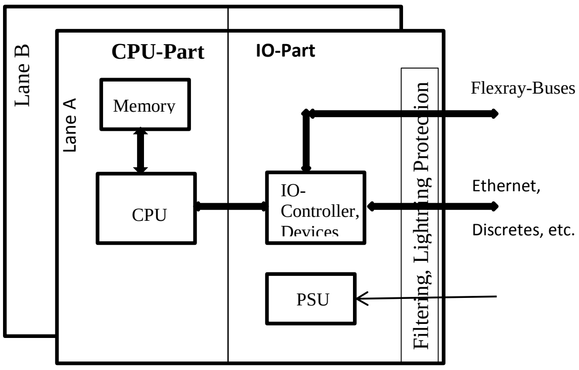

Figure 2: Schematic of a dual-lane CPM.

A photo of an opened prototype CPM module is given by Figure 3. The IOM and ACM housings are of the same type and size, but differ in the number of configured interface connectors.

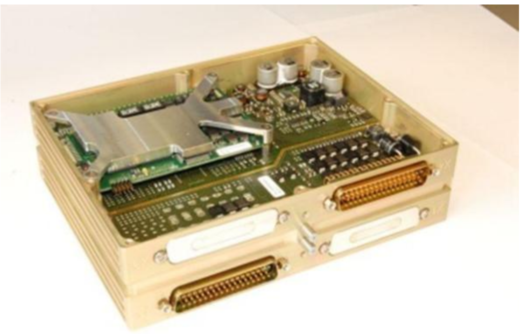

Figure 3: Opened module box of a CPM (manufacturer: SET GmbH, Wangen, Germany).

Four ACMs operate the MR actuation (pitch, roll, collective), four others the TR actuator, all ACMs being “active/ active” at the same time and running time-synchronously within the TR-/MR-ACM group. The four MR/TR ACMs follow, like the CPMs, a dual-lane synchronous design with cross-lane data exchange resulting in a failure self-passivation capability. Each MR/TR ACM drives one DDV coil of the hydraulic actuator and is fed by signal values of one ram and DDV LVDT position sensor per helicopter axis which are cross-exchanged and consolidated with the other ACMs. Within the lab environment the hydraulic actuators have been substituted by electronic simulation devices. The combination and interfacing of the TR ACM group with the hydraulic actuator (simulation) is shown in Figure 4.

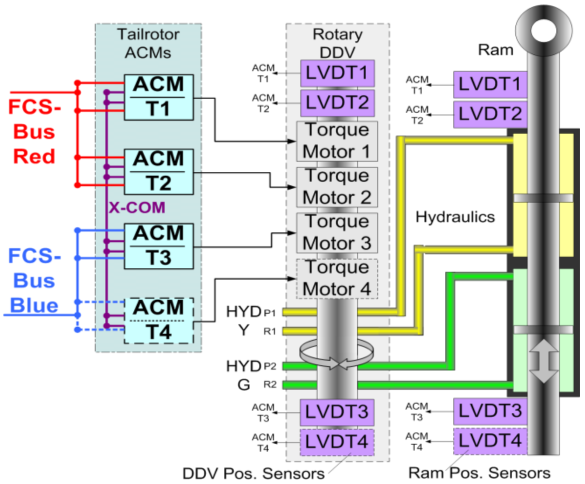

Figure 4: Redundant “active/ active” operating ACM dual-lane modules interfaced to the hydraulic actuator, here substituted by an electronic simulation device. Each ACM drives one DDV motor (coil). Redundant RAM and DDV sensor position data are cross-exchanged among the ACMs via cross-communication bus (violet) and consolidated within the ACMs.

The ACM cross communication (see violet line in Figure 4) for actuator sensor signal consolidation and ACM time-synchronization is also implemented by a single (dual-channel) FlexRay bus in the lab prototype, although its safety figure is not compliant with the “catastrophic” failure criticality. Hence, for a future series application the FlexRay ACM cross communication bus will be replaced by e. g. single Ethernet point-to-point links. The resulting wiring overhead will be limited to the local ACM installation space.

A schematic of a dual-lane ACM is shown by Figure 5. Both ACM lanes contain power supply devices, CPU and I/O controllers for the FCS

FlexRay buses, for Ethernet used for internal module debugging and maintenance and for discretes established for pin programming. Following the CPM concept an internal Ethernet link between both ACM lanes provides the cross-lane communication. The Freescale MPC 5567 micro-controller in each lane containing CPU and I/O controllers is used for actuator RAM and DDV position sensor signal cross-exchange and consolidation as well as for outer loop RAM position control. An additional digital signal processor (DSP) in each lane performs the inner loop DDV position control and the DDV current loop processing. One ACM lane acts as command lane driving the associated DDV motor by a pulse width modulation (PWM) controlled current while the other lane acts as pure monitor lane re-reading the DDV current and checking its value. In case of a mismatch between both lanes each lane of the ACM is able to passivate the module.

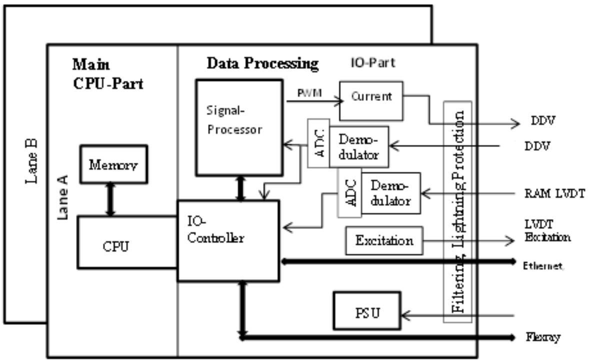

Figure 5: Schematic of a dual-lane ACM (Design: Liebherr).

PLATFORM REDUNDANCY MANAGEMENT AND RECONFIGURATION

The CPMs operate in a master/ slave configuration. Only one CPM can be master at a specific instant of time and only the master has actuation control. Each CPM is connected with the two FCS buses and the avionics bus. In case of failure of one FCS bus the FCS system is still fully operational by continuing its function with the remaining valid FCS bus. These principles assure reliable broadcast characteristics between the CPMs and perform the baseline for consensus-generation between the correctly operating CPMs even under FCS failure conditions. This scheme ensures that the correctly working CPMs have the same “view” of the platform essential state and enables a “platform consistent data base” (PCDB) within those CPMs.

The internal design of a CPM and its connections with the two FCS buses “Red” and “Blue” is illustrated in the next Figure 6.

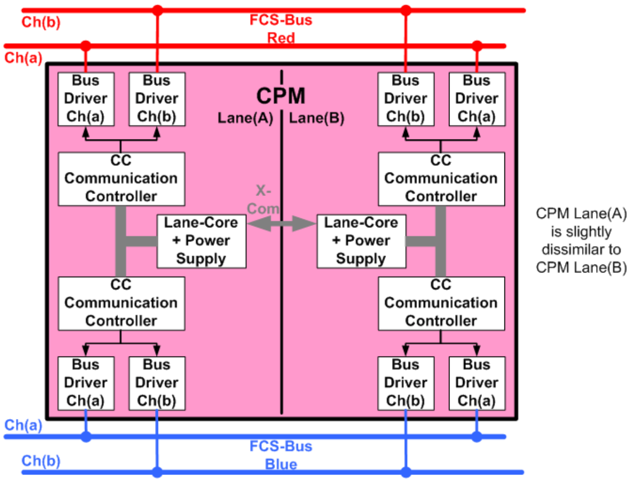

Figure 6: Internal (redundant) CPM design with both Lanes L(A) and L(B) interfaced to the FlexRay FCS buses “Red” and “Blue” each with the transmission channels ch(a) and ch(b).

Each of the two CPM lanes L(A) and L(B) is connected with both channels ch(a) and ch(b) of the two FCS buses. The same is true for the avionics bus “Green”, not shown explicitly here. The two transmission channels ch(a) and ch(b) of one bus are operated by two independent bus drivers but controlled by one common communication controller per CPM lane. The communication controllers of one CPM lane exchange the data with the Lane-CPU-core. A CPM module internal cross-lane Ethernet link provides the data exchange and allows cross-comparison between the synchronously running lanes with a high failure detection capability. Except for the microcontroller used here, a separated CPU core which would be applied in series equipment has no direct access to the bus configuration data which are stored in the communication controllers. The effect of a failure of a bus controller or bus driver is confined only to that bus concerned by this event. This design assures that no single failure will adversely affect both FCS buses. This scheme of data processing described for the CPMs is also used for the ACMs.

A dissimilar design approach for a series implementation would look like as follows: "Integrity" dissimilarity of a CPM (and ACM) will be implemented by dissimilar software variants of the two CPM (ACM) lanes for generic fault detection. Hardware diversity e. g. between the CPM (ACM) modules of the "Red" and "Blue" side shall provide "availability" dissimilarity of the CPM (ACM) function. A diverse design between the communication controllers of the "Red" and "Blue" side shall ensure "availability" dissimilarity of the bus systems.

Central system parameters are determined upon the platform consistent data base (PCDB) according to a well-defined principle. Following this principle the same functions in the correctly operating CPMs determine respectively the same results for the central system parameters such as:

- Health level as the maximum possible execution degree of the control law function in the different CPMs.

- The actual master/ slave status.

Each CPM generates its own health level and compares it with those of the other CPMs within the PCDB. If the master determines that his own health level falls below that one of a slave then the master status is given up and the slave with the highest health level takes over the master function. The health level of a CPM is evaluated by the single health levels of the registered devices such as redundant sensors, actuator DDV motors, etc. If e. g. the redundancy of an AHRS signal seen by a certain CPM degrades, the health level of this CPM is degraded due to the lack of monitoring capability of that AHRS signal. The CPM master function is "transparent" for the ACMs meaning the ACMs do not know which CPM is the master.

The redundancy management software layer – the so-called middleware layer – is generated by a generic platform environment developed by the Institute of Aircraft Systems of the University of Stuttgart [5]. This platform is based on a multi-layer meta-model with related tool chain. A successive detailing parameterisation of the platform model is performed during a specialisation process with respect to envisaged target system architecture. The final output of this process results in the middleware software layer which executes the redundancy management function of the flight control system according to a deterministic and transparent rule set. As illustrated by Figure 7 below, this middleware layer is part of all FCS modules and contains the functions for system ("SysMa") and platform management ("PlaMa"). The middleware layer is set up upon the low-level driver layer of the FCS modules while the application layer as the top layer is set up upon the middleware. This allows the "simplex-minded" implementation of the application ("App", especially control laws in CPMs and ACMs) which means that the application is no longer concerned with redundant sensor signal processing but "sees" only one consolidated sensor signal. The signal consolidation process is confined by the middleware layer.

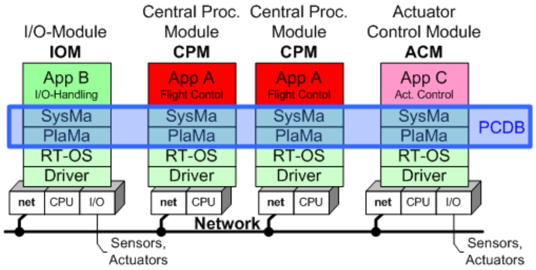

Figure 7: From generic platform process generated and in target system implemented middleware layer with system management ("SysMa") and platform management ("PlaMa"). Source: University of Stuttgart.

RESPONSE TYPES CONTROL LAW IMPLEMENTATION

The application of a highly redundant designed electronic flight control system (“Fly-by-X”) allows the removal of the direct mechanic link between the pilot’s controls and the mechanic-hydraulic actuators. This fact supports the strategy, to incorporate a completely new flight control behavior onto the helicopter which is much more pilot-orientated and reduces the pilot’s workload in contrast to a conventional flight control. This is mainly true for the “Primary Flight Control System” (PFCS) modes where the pilot still controls the helicopter by manual interactions, whereas the automatic helicopter flight is performed by the “Automatic Flight Control System” (AFCS) modes.

Classical autopilot systems already used for AFCS modes on conventional helicopters are set upon the mechanic-hydraulic control system; however, they exhibit a limited availability figure. In case of loss of the autopilot system the pilot is concerned by an abrupt workload increase caused by the fall back on conventional manual control or a SAS (stability augmentation system) mode at the best.

Functional degradations under failure conditions resulting in a manual control mode with high workload will no longer be possible by application of the fly-by-X flight control system. This results in a safe and comfortable flight control and is also valid for the PFCS mode. If the pilot takes his/her hand/foot from the control the currently reached flight state will be stabilized and held by the system until the next pilot’s command.

The PFCS mode is realized by advanced control laws according to the ADS-33 standard [6] response types which utilize “command/ hold” control functions. Pushing or pulling the pilot’s control results in a “command” and therefore changes the flight state. At release of the pilot’s control the “hold” function is activated and keeps the actually achieved flight state. For most response types the “hold” signal (e.g. speed) corresponds to the integrated value of the “command” signal (e.g. acceleration). In contrast to a conventional helicopter the pilot can fly hands-off anytime in the basic (manual) PFCS mode.

The response types implemented in the PFCS nominal mode are as follows:

- Pitch axis: “Acceleration Command/ Airspeed Hold” (AcC/AsH):
  The stick elongation generates acceleration whereas the achieved airspeed is held at stick release.
- Pitch axis: “Acceleration Command/ Ground Speed Hold” (AcC/ GsH):
  The stick elongation generates acceleration whereas the achieved ground speed is held at stick release.
- Roll axis: “Attitude Command/ Attitude Leveling” (AC/AL):
  This control law is designed for forward flight. The stick elongation generates a roll attitude whereas attitude leveling is re-established at stick release.
- Pitch/ roll axis: “Translational Rate Command/ Position Hold” (TRC/ PH):
  The stick elongation generates a longitudinal or lateral ground speed command whereas the achieved ground position is held at stick release. This response type is decoupled from the yaw axis.
- Yaw axis: ”Rate Command/ Direction Hold” (RC/DH):
  The pedal input generates a yaw angular rate whereas the achieved heading is held at pedal release.
- Yaw axis: “Turn Coordination” (TC):
  Above a certain air speed the yaw control law switches to TC at which roll stick inputs keeps the ball of the side-slip indicator centered.
- Collective axis: “Vertical Speed Command/ Height (Altitude) Hold” VsC/HH:
  Elongation of the collective stick generates a vertical speed command. The achieved GPS height or barometric alti-

tude is held at stick release. The collective trim actuator ensures the fixed ratio between stick and rotor blade position.

Within an environment of good visual cue ratings, the pilot feels comfortable with the natural response type of a conventional helicopter, which equals a “Rate Command” (RC). However, with increasing degradation of the visual environment the aircraft positioning task, for instance, becomes more cumbersome and handling quality rating will decrease. Application of the adequate response types by a fly-by-X FCS simplifies the aircraft positioning task and raises the handling quality level.

A practical combination of response types with “automatic” speed dependent activation and transient-free transition fading has been already investigated and successfully flight tested in the previously performed ACT-IME research project [7]. The functional control mode scheme described there has been also used in this research project for implementation on the FCS functional prototype.

The specified response behavior on pilots’ command inputs will be produced by a command model which generates the desired helicopter states (angular rates [p, q, r], attitudes [Theta, Phi, Psi], etc.) as output. The axes coupling usually present at a conventional “physical” helicopter is not wanted here and is therefore not regarded in the command model. In order to achieve a helicopter control behavior equivalent to the command model it is necessary to cancel out the original helicopter dynamics by application of an appropriate feedback or/ and feed forward controller. The feed forward control is here realized for the first time by an inverse (plant) helicopter dynamics model [8]. The design procedure [9] has been developed to application maturity by DLR in the past years. The feed forward controller with the helicopter in sequence establishes theoretically the transfer function TF=**1**, so the total control behavior is finally determined by the command model alone (see Figure 8). In order to compensate disturbances (e. g. wind) and model inaccuracies an additional feedback controller is introduced which corrects the differences between references and acquired state values.

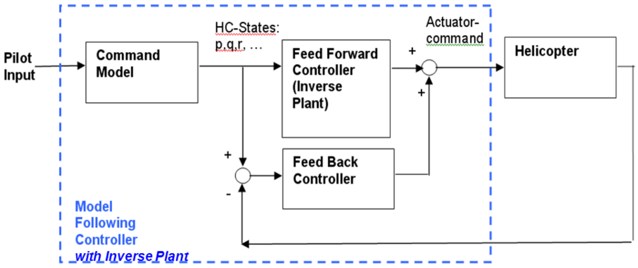

Figure 8: Control structure with command model, inverse plant feed forward controller and feedback controller.

The helicopter, a 3 tons class agile type, is replaced by a non-linear helicopter dynamics model in the closed-loop verification environment. For implementation of the (inverse plant) feed forward control a special system identification procedure with frequency sweeps have been performed on the helicopter model. This leads to parameter estimations of a defined model structure according to the maximum likelihood algorithm ([9], [10]). Due to the speed dependent helicopter dynamics several linear state space models for different speed values have been identified. The inverse plant model is received by combination of the inverted state space models with speed dependent fading function.

The single response types as well as the basic “Rate Command/ Attitude Hold” (RC/AH) type have been designed according to the ADS-33 standard [6]. Handling qualities of level 1 have been defined as goal for the highly dynamic flight with target acquisition and tracking. Level 1 means that the task can be easily performed by the pilot. Level 2 means that the task can be performed but with increased work load. Level 3 means that the task cannot be performed with a tolerable pilot workload.

During practical experience it turned out that it does not make always sense to take over this “dynamic flight” response behavior. Often it has shown that it is more reasonable in terms of flight controllability to reduce the performance to level 2 or even level 3. This reduces the risk of overdriven command inputs. This approach is founded on the fact that the chosen criteria for a highly dynamic flight require also a well-trained pilot. The problem can be counteracted by care-free handling function; however, this has been not regarded here.

Some essential ADS-33 criteria for the analysis of the control behavior in the frequency domain are the bandwidth [rad/s] and the phase delay [s] (see [6]). The bandwidth is the minimum of phase and amplitude bandwidth with respect to the bode plot. The phase bandwidth is the frequency at which the phase goes below -135°. The amplitude bandwidth is the frequency 6 dB above the amplitude of the -180° phase crossover. The higher the bandwidth the better is the helicopter reaction to high frequency command inputs.

The next Figure 9 shows the ADS-33 bandwidth and phase delay diagrams for the pitch/roll/yaw axis with the areas of handling quality ratings (HQR) for the target acquisition and tracking task. With respect to the RC/AH response type in pitch/ yaw and AC/AH in roll the bandwidths and phase delays designed for the pure command model are marked as triangles and those gained by frequency sweeps for the complete system (controller + helicopter) are marked as quadrates. The evaluation has been performed with the tool CONDUIT at DLR. As illustrated by Figure 9 the bandwidth of the total system is slightly worse than that of the command model. This is caused by the striking effect of dead time. The dead time is composed of the dead time in the helicopter system (model with FCS and bus systems) and that of the testing equipment in the closed-loop verification environment. Latter would not be present at a real helicopter. The pitch axis exhibits a stronger increase of the phase delay. However, evaluation of the coherence resulted in low values in the frequency range used for extraction of the ADS-33 phase delay parameter.

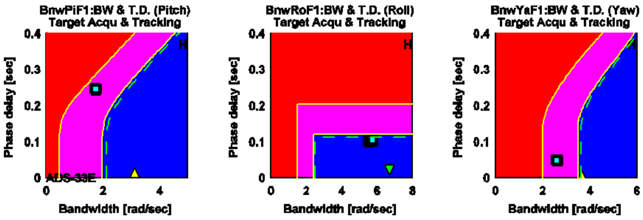

Figure 9: Comparison of band widths (and phase delays) of the pure command model (triangles) with those of the total system with controller and helicopter (quadrates) for RC/AH (pitch), AC/AH (roll) and RC/DH (yaw). Colors: Blue: HQR level 1; Violet: HQR level 2; Red: HQR level 3.

For cross-checking a dead time measurement has been performed in time domain by step command inputs and recorded rate (r) response on the yaw axis; only this axis is fully equipped by a hardware simulation device of the hydraulic actuator. After subtraction of asynchronous dead time of the testing equipment, a dead time value of maximum 87 ms results which is considered to be realistic also for the other axes and therefore compatible with HQR level 1.

As a summary it can be stated that the performance of the total system lies in some points below that of the command model which is caused by the additional dead time of the verification environment. The model following performance shows good results but is slightly decreased in the upper frequency range caused by the falling response phase.

Beyond all these theoretical considerations it could be demonstrated that the helicopter model can be easily controlled even by non-pilots with the implemented FCS prototype in loop.

SYSTEM VERIFICATION AND VALIDATION

The design validation of the FCS prototype has been supported by a real-time closed loop verification and testing environment. The core of this environment (see Figure 10) consists of two main rigs, a pilot station and additional separate computers.

Figure 10: “Core” systems of the verification environment: The middle picture shows the rig (Eurocopter) with FCS modules such as CPMs, IOMs and MR-ACMs as well as real-time test control computer, break-out panels and power supplies. The left picture exhibits the rig (Liebherr) comprising the TR-ACMs and electronic TR-actuator simulation device with break-out facilities. The cockpit station (Eurocopter) with controls and display simulation is shown on the right.

The rigs comprise the FCS modules with breakout facilities on signal and power lines, furthermore, they contain the test control computer and the actuator hardware simulation device representing a hydraulic actuator on yaw axis with DDV control and provision of the RAM/ DDV position sensor signals for ACM processing. A non-linear helicopter model implemented on a separate computer is running in closed-loop with the FCS which is commanded by a cockpit station equipped with quadruple redundant LVDT position sensors on the pilots’ controls of the four axes. A vision system provides the cockpit view of the flight simulation. The closed-loop signal transmission is managed by a test control computer which is generally used for the set-up of the normal and failure mode verification cases as well as their execution and result evaluation. In contrast to the yaw actuator simulation the redundant AHRS function is simulated by the test control computer software.

Beside normal mode testing the system verification activities comprised test scenarios demonstrating robustness in case of sensor failures, CPM-CPM reconfigurations, ACM and actuator component failures. One main concern of the test cases is to demonstrate that multiple subsequent failure events are adequately intercepted by the degree of system redundancy and that a single failure (except that of generic kind) will not cause the loss of more than one redundancy.

An example of a multiple failure sequence of AHRS sensor signals is illustrated by Figure 11.

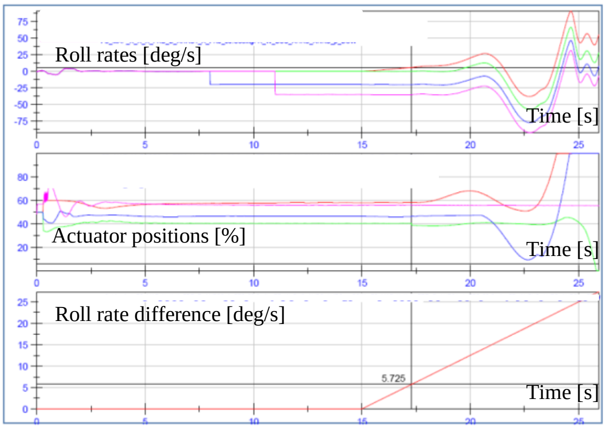

Figure 11: Time dependent roll rate runaways of three of the four redundant AHRS signals (upper diagram). Actuator positions (middle diagram) and difference of the last two in the voting remaining roll rate signals (lower diagram) as the difference between the red and green rate signal curves of the upper diagram.

It can be seen in Figure 11 that a trimmed flight state with a roll rate at 0 deg/s and nearly constant actuator positions results approximately 5 s after system start (see middle diagram). As shown in the upper diagram the failure stimulation creates a high offset value on the “blue” angular rate of the first AHRS after 8 s. This leads to the exceeding of the redundant signals’ monitor threshold and in consequence to the exclusion of the “blue” rate signal from sensor voting. After 11 s the same happens with the “violet” angular rate of the second AHRS. At this time only the “red” and “green” angular rate remain active for the (duplex) voting. After 15 s a “disturbing” ramp signal is added on the “red” angular rate of the third AHRS leading to an increasing discrepancy between the “red” and “green” rate (see also roll rate difference signal in the lower diagram). With proceeding time some uncontrolled actuator travelling occurs in all four axes after 17 s which is visible in the middle diagram. This is the point of time at which the monitor threshold of 5.0 deg/s of the remaining duplex voting has been exceeded preventing the system from determination of a consolidated valid sensor signal.

This test scenario of a stimulated failure sequence, also performed for all other sensor signals, has demonstrated that the system can survive two sensor signal drift/ runaway failures adequate to its quadruple sensor redundancy design and that the flight control function is preserved until occurrence of the third sensor signal drift failure. In a similar way multiple failure sequences have been also tested and verified on the CPMs and ACMs including their interfaces to the electronic actuator simulation device.

For design validation of the new FCS system an assessment of the prototype has been performed using the results from the verification activities and from qualitative analyses. A summary of the most interesting validation parameters is given as follows:

- CPU/ bus controller: For project risk reduction an integrated micro-controller concept (CPU, bus and I/O controller on one chip) has been applied to the FCS prototype for which experience could be gained in a previous research project. However, considering a possible future series development, the hardware concept has to be revised.

- Data bus: The FlexRay protocol originally destined for automotive applications has been used for the FCS prototype because of its cost-effective availability and the exploitation of the time-triggered characteristics. Although FlexRay offers all safety features being conform to the aerospace application, qualification data have to be updated/ completed if a certification is envisaged. However, the new FCS design does not depend on FlexRay; another bus system such as e. g. AFDX is also possible.

- Physical data bus transmission layer: The standard electrical transmission of the FlexRay data bus has been kept for the prototype implementation. For series development the electro-magnetic compatibility (EMC) has to be assured by (partly) expensive shielding and lightning protection devices. An alternative is the optical data transmission. For this a more accurate trade-off analysis between electrical and optical data transmission in terms of weight, size, and costs has to be performed.

- Similar/ dissimilar design: The main objective of the prototype is seen in the validation of the system functions related to redundancy management algorithms and control laws; therefore, the prototype design has been confined to a similar implementation. A series development requires a dissimilar design where redundant units perform the same function but are implemented in diverse design variants for protection against common mode failures.

CONCLUSION SUMMARY AND PERSPECTIVE

The new generic FBX flight control system approach could be successfully validated by an “instantiation” of a laboratory prototype and by performing closed-loop normal and failure mode robustness testing. It has been demonstrated that the flight control function and handling quality level is preserved under various simulated “in-flight” failure conditions. No noticeable transients could be observed during resulting system reconfigurations such as CPM master/ slave transitions within different flight states.

The generic platform feature shall enhance the FCS system portability to different helicopter types which is further supported by modular system architecture. The generally increasing wiring effort associated with modular systems has been compensated here by application of a modern bi-directional bus system. Although the FlexRay protocol is used originating from automotive industry it is compliant with the safety standards adequate for airworthiness applications. This is seen apart from the fact that qualification life cycle data are not in the proper format and not exhaustive enough for achievement of a formal certification. As already said the new FBX flight control system does not purely rely on the FlexRay bus standard, other protocols with comparable safety standards and deterministic transmission capability can be applied as for example AFDX , TTP or TTEthernet. However, each of the choices has its drop of bitterness mainly when regarding the criteria of cost efficiency, maturity, availability of diverse variants and qualification/ certification records. At the current situation no candidate fulfills all criteria so additional cost or development overhead has to be taken into account for application in an operative system.

For an operative system the modular system approach encourages the integration of the ACMs into the hydraulic actuators resulting in a “smart” actuator concept when the compatibility with environmental requirements of the installation zones is given. This has been realized at the ACT/FHS demonstrator (see reference [1]). The idea of a “smart” flight control system with distributed modules is further driven by the proceeding minimization of electronic components which encourages for further investigations towards size and weight optimized series “packaging” concepts.

On the software side the generic platform approach is fully in line with the “smart” flight control system concept as it allows the generation of the “encapsulated” middleware layer for system redundancy management destined for distributed systems. Beyond that further standardization activities and tool support development on the generic platform approach will increase the possibility for application to a broader spectrum of new flight control systems with the chance to reduce the development costs in spite of the increasing system complexity.

NOTATIONS

ACT/FHS	Active Control Technology/ Flying Helicopter Simulator
ACM	Actuator Control Module
ADC	Air Data Computer
AFCS	Automatic Flight Control System
AFDX	Avionics Full Duplex Switched(X) Ethernet
AHRS	Attitude and Heading Reference System
App	Application (control law)
COTS	Commercial-Off-The-Shelf
CPM	Central Processing Module
CPU	Central Processing Unit
DDV	Direct Drive Valve
DLR	German Aerospace Center
EMC	Electro-Magnetic Compatibility
FBX	Fly-By-X
FCS	Flight Control System
GPS	Global Positioning System
HQR	Handling Qualities Rating
HW	Hardware
IMU	Inertial Measurement Unit
I/O	Input/ Output
IOM	Input/Output Module
LVDT	Linear Variable Differential Transformer
MR	Main Rotor
PCDB	Platform Consistent Data Base
PFCS	Primary Flight Control System
PlaMa	Platform Management
PSU	Power Supply Unit
RAM	(Actuator) Ram
SAS	Stability Augmentation System
SysMa	System Management
TR	Tail Rotor
TT	Time-Triggered
TTP	Time-Triggered Protocol

RESPONSE TYPE NOTATIONS

AC	Attitude Command
AcC	Acceleration Command
AH	Attitude Hold
AL	Attitude Levelling
AsH	Air Speed Hold
DH	Direction Hold
GsH	Ground Speed Hold
HH	Height Hold
PH	Position Hold
RC	Rate Command
TC	Turn Coordination
TRC	Translational Rate Command
VsC	Vertical Speed Command

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