INTEGRATION OF ACTIVE INCEPTORS SYSTEMS IN FLY-BY-WIRE ROTORCRAFT: CHALLENGES AND OPPORTUNITIES

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Abstract

The paper presents the activities performed by LHD to design and integrate Active Inceptors technology in its Fly-by-Wire tilt-rotor product line. LHD started with the definition of the most suitable control laws algorithms for a tilt-rotor aircraft in order to identify what would be the optimal Active Inceptors System configuration. The NGCTR-TD program has then be used as test bed to gain practical experience in both the system architecture definition and the operation of the Active Inceptors by integrating an off-the-shelf product in the aircraft Flight Control System. The outcome of those activities has been used to drive the definition of system requirements for a new generation Active Inceptors System suitable for production aircraft, both single and dual pilot. The three activities highlighted the importance of the Active Inceptors technology for tilt-rotors and, in general, for non-conventional aircraft, and provided a deep insight in the architectural, safety and integration aspects.

1. NOTATION

Symbols:

V_{CON}	Conversion Speed
V_{MIN}	Minimum Speed
V_{MO}	Maximum Operating Speed
V_S	Stall Speed

Acronyms:

ACS	Active Control Stick
AOA	Angle Of Attack
CAT	Catastrophic
CLAWs	Control Laws
COTS	Component Off-The-Shelf
DMU	Digital Mock Up
DoF	Degrees of Freedom
(e)VTOL	(electric) Vertical Take-Off and Landing
FBW	Fly-By-Wire
FCS	Flight Control System
HQ	Handling Qualities
LHD	Leonardo Helicopters Division
NGCTR	Next Generation Civil Tilt Rotor
RVDT	Rotary Variable Displacement Transducer
SAIS	Smart Active Inceptor System
TD	Technology Demonstrator

2. INTRODUCTION

The research into the field of advanced inceptors started in the late 70s with passive inceptors, and evolved through different steps until the mid-2000s with the first units flying on military fixed-wing aircraft (Ref. 1). The introduction of non-conventional aircraft configurations, such as tilt rotors, or multiple rotors (e.g.: eVTOL), and the increasing diffusion of Fly-By-Wire (FBW) technology, lead the engineers to explore non-conventional inceptor designs. In this framework active inceptors become an integral part of strategies aimed at lowering pilot effort and increasing the safety of the operations.

Leonardo Helicopters launched three main initiatives in the past few years to gain experience in the field of Active Inceptors.

The first step has been in the exploration of advanced control laws that can be suitable for tilt rotors aircraft. Experience demonstrated that, to leverage on the full potential of this technology, a full suite of Active Inceptor can be developed only to some extent independently from the intended control strategy. Not all the inceptor solutions are fully compatible with each and every possible control algorithm, also, some configurations might work satisfactorily for the nominal situation while performing poorly in case of failure scenarios where reversionary control laws are used to mitigate the effects of malfunctions.

To complement the information gathered in the first activity, the company proceeded with the installation of an active inceptor unit in a technology demonstrator aircraft. BAE Systems Active Control Stick (ACS) has been chosen as the first operational active inceptor in a LHD aircraft to have a hands-on experience of the capabilities of active inceptors in a tilt rotor. The integration of the ACS in the Nextgen Tilt Rotor highlighted a large number of architectural, safety and system design aspects that needs to be taken into account to ensure safe operations and the integrity of the system once it is deployed on a commercial aircraft.

The study on advanced control law algorithms and the ACS integration effort provided useful information that have been used in the third phase of the activity. This latest stage included the selection of an active inceptor system configuration and the definition of design requirements for such system. The selection has been performed within the framework of the EU Funded CleanSky2 SMAR-TeR Project and saw multiple combination of conventional and un-conventional inceptors being scored against a set of criteria such as Ergonomics, Workload, Innovation and others (Ref. 2). The identified configuration uses a right hand sidestick with three DoF paired with a linear throttle for the left hand side and a provision for conventional pedals. The SMAR-TeR initiative evolved then in the SAIS project, where the concept selected was developed into an actual system design for a dual seat aircraft.

3. FLIGHT CONTROL LAWS INTEGRATION

Active sidestick technology offers wide flexibility for implementation of tilt rotor CLAWs, entailing various operating conditions and Flight Control System configurations, ranging from fully augmented control modes to basic and degraded CLAWs (direct mode), demanding increasing pilots' workload and human dynamic intervention. Sidearm controller configuration, either with classical passive or modern active technology, is nowadays exploited in an increasing number of military and civilian aircraft applications. Based on dedicated ergonomic and functional studies carried out in the framework of Clean-Sky2 funded SMAR-TeR project (Ref. 2) this "right-hand" configuration has been judged beneficial and suitable also for tilt rotor application. Despite of the inherent complexity of active stick hardware (power electronics, redundant processing boards, etc.) and software (monitoring, model following loop closures, etc.), which makes this unit a kind of "smart" equipment, the airframe FCS software must be designed to fully exploit the capabilities offered by such a complex device. Indeed, Flight CLAWs must be designed to properly manage the Active Inceptors in each configuration and during the transitions across all different operational modes. Also, the basic stick force-feel about pitch and roll axis is an important design characteristic with heavy influence on closed-loop aircraft Handling Qualities, and possibly hazardous biomechanical couplings. Many studies have been conducted to assess the impact of controller force-displacement characteristics on the handling qualities of fixed wing Fly-By-Wire aircraft, primarily directed towards minimizing pilot induced oscillations (Ref. 3) and roll ratcheting. The impact of side-stick design characteristics onto rotorcrafts handling qualities has also been studied during the last years (Ref. 3, 4, 5). In the following the proposed implementation of adaptive force-feel characteristics and tactile cues on tilt rotor application, based on selected control strategy, aircraft configuration and flight condition, will be provided.

3.1. Sidestick operational states and Control Laws

From Flight Control System perspective, the active stick encompasses three main operational states: Active, Passive and Jam states. Transition through these states is managed according to stick health management status, FCS condition and Control Laws operative mode (Enhanced / Normal or Direct Mode), see Figure 1.

In most augmented modes (i.e. enhanced and normal modes, Ref. 6), the active inceptor can be profitably operated as *unique-trim* controller, i.e. with Flight Control System (FCS) commanding the active stick electronics to retain a centered anchor position. The aim is to offer optimized ergonomics and improved situational awareness through active cues related to specific flight parameters (e.g. airspeed), or to the remaining control authority. This approach is coherent with highly augmented *command-to-maneuver* control augmentation strategies, such as Rate Command Attitude Hold (standard VTOL Normal Mode strategy) or C* (hybrid load factor – pitch rate demand, attitude hold or flight-path hold, enforced in wing borne flight conditions, Ref. 6, 7, 8).

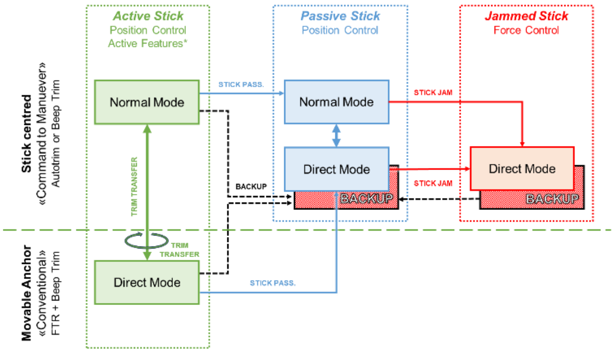

Figure 1 – Active stick operational states and FCS CLAWs

3.2. Active State

Generally, the fully augmented control strategies associated to Enhanced or Normal Mode entail two logic sub-states:

a. Active Stick is out-of-detent in a specific axis (pitch or roll). The pilot is moving the stick from the center detent position, by applying the required force on the grip. The Control Laws can detect such condition by monitoring the read RVDT displacement or by blending position and force information. When this condition occurs, the corresponding axis outer loop (e.g. attitude hold) is open and the position input is processed to achieve the desired *command-to-maneuver* response (e.g. pitch or roll rate response, load factor response, etc.). During this phase, the outer loop reference (pitch or bank attitude, flight path angle, etc.) is synchronized with associated measurement or estimated state to ensure *auto-trim* capability when the stick is released.

b. Active Stick is in detent in a specific axis. The outer loop is closed, and the aircraft is closed-loop retaining the synchronized reference (generally attitude). Because the stick force is nulled in the detent position, the pilot is not required to provide any force input to trim the aircraft. This behavior is consistent with a classical trim device, but it does not require the stick detent position to change. During this phase the pilot has still the capability to provide fine adjustments to aircraft attitudes (or designated outer loop reference) by acting on the 2-axis grip beep trimmer.

It is worth noting that implementation of sub-modes (a) and (b) does not require the availability of active stick. In fact, these control strategies have been successfully deployed on many commercial jet liners and military fighters equipped with passive sidesticks for instance. However, some drawbacks are associated to the described command-to-maneuver control strategies, which active stick technology can help to handle:

Loss of speed stability about longitudinal axis. This issue is related to rate command response, which attempts to ensure steady null pitch rate error with available control authority (e.g. by implementing suitable high-gain follow-up integrators). Conventional control responses shape the closed-loop aircraft short period modes but not the long term (phugoid) modes (e.g. Ref. 9). Therefore conventional control responses provide a classical *return-to-trim* feature to comply with longitudinal static stability requirements. When the bare aircraft phugoid mode is heavily altered by Control Laws, artificial return-to-speed functions can be implemented (see for example C*U scheme used on many fixed wing aircraft, Ref. 7). Alternative software mitigations exist, such as Angle of Attack envelope protection and overspeed protection, which allow to relax longitudinal static stability requirement during certification process. Unfortunately, all these additional features and envelope protection functions add significant complexity to FCS software and might introduce further weakness in the system design. As illustrative example let's consider the critical aspect represented by suboptimal tuning of envelope protection functions which may erroneously limit pilot commands during development flight program.

Loss of control margin awareness (e.g. FAR TR38(e)). When the FCS design relies on auto-trim capability, the relationship between stick displacement and commanded flight effector position is lost. On tilt rotor and generally on multiple redundant flight controls aircraft (such as many modern eVTOL configurations), the FCS gearing and load limiting laws are in charge of properly scheduling and mixing the various flight control effectors (airplane surfaces, rotors swashplate controls, etc.) based on aircraft configuration (e.g. mast tilt angle) and flight conditions (airspeed, pressure altitude, etc.). Therefore the Control Laws inner stabilization and command augmentation loops around the four conventional aircraft axes (longitudinal, lateral, directional and thrust) can operate in a more general framework, by processing "total" cockpit commands which in turn are translated into appropriate flight effectors position demands by gearing laws (Ref. 6). In this context, the control margin is more naturally referred to “total” stick (or pedal) commands, rather than to elevator or cyclic available authority. Additionally, not only Fly-By-Wire vehicles but also those equipped with limited authority AFCS have a certain portion of “total” cockpit command which is allocated to automatic stabilization or dynamic compensation functions. As a consequence, even when the cockpit inceptors (either traditional fixed flight controls or modern active controls) are operated in a conventional way to achieve trim condition and force relief, the grip position is never fully reflecting the available control residual authority. With sidearm controller, additional issues in ensuring adequate control margin awareness are added: the stick is by definition installed away from pilot’s front line of sight, and short-pole inceptors are characterized by small grip displacements (typically less than 50% of equivalent long-pole center stick installations, Ref. 10).

Handling penalties. VTOL aircraft and convertiplanes design must comply with different cockpit control force requirements. Even assuming prescribed limit force values are irrespective of vehicle configuration (which is not necessarily true), acceptable breakout forces and force gradients are indeed peculiar of flight condition. Several research studies on Handling Qualities of both fixed and rotary wing aircraft have proofed the relationship existing between stick control force characteristics and achieved HQ ratings (Ref. 1, 5). In rotor borne VTOL HELO flight the expected right hand forces are obviously smaller than in the high speed airplane conditions. In the second case, these are mainly dictated by “pounds-per-g” requirements (Ref. 11). On tilt rotor vehicles equipped with conventional cyclic fixed flight controls, the center stick pitch and roll force gradient can be automatically adjusted by FCS as a function of nacelle angle through dedicated trim actuation interface and complex mechanical arrangements. Passive stick technology is evidently not suited for this kind of aerospace applications. For conventional fixed or rotary wing vehicles, the mechanical spring gradient can be designed to provide an adequate compromise between low and high speed conditions. If required, Control Laws command sensitivity can be adjusted to improve handling qualities. However, tilt rotor aircraft must be designed to cope with such a wide spectrum of flight conditions that passive stick can be hardly used to achieve satisfactory handling quality ratings.

Crew coordination (cockpit situational awareness). Although NGCTR-TD is a single-pilot Test Demonstrator prototype, it is exploited by Leonardo Helicopters to assess the effectiveness of various innovative flight technologies for future rotorcraft products. One of the most critical limitation of passive stick technology is represented by poor cockpit situational awareness and more difficult multi-crew coordination (Ref. 12). Complex Pilot-In-Command logics must be implemented to mitigate this issue. Majority of rotorcrafts and many commercial jet liners are in fact still relying on traditional, mechanically inter-connected, cockpit flight controls (cyclic sticks, column wheels) to prevent control fights in emergency scenarios. Active sticks with electrical link capability can be profitably used to overcome this issue.

Active stick technology is a valuable complement for Flight Control System to achieve the required level of safety and handling characteristics. The force gradient is easily modified in run-time based on read mast tilt angle, as for legacy tilt rotor application but without the associated mechanical complexity beneath cockpit floor. Pitch rate (and normal load factor) command is scheduled with TAS to achieve constant incremental load factor for a given stick displacement at high-speed conversion and airplane mode. Therefore, pitch gradient must be generally independent from airspeed (differently from a conventional, not control power boosted, fixed-wing aircraft). For this reason, within conversion corridor the stick force gradient is kept constant. Conversely, the force-feel is increased as airflow dynamic pressure (quadratic law) above the conversion speed (V_{CON}) or maximum operating speed (V_{MO}) determined by conversion corridor (Figure 2). This feature is improving pilot’s situational awareness and preventing undesired overspeed conditions while operating the stick against the force-feel.

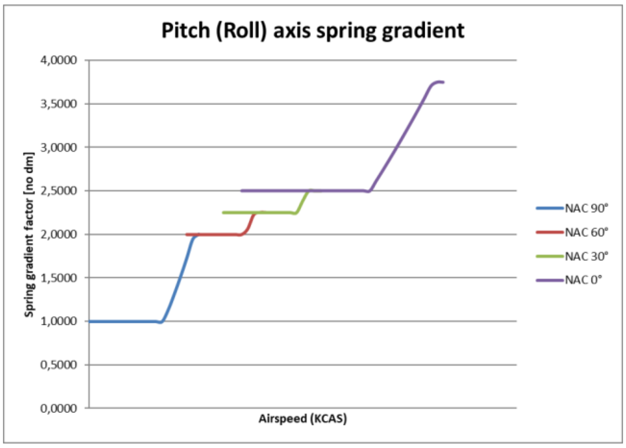

Figure 2 - NGCTR-TD active stick force gradient law

Through the capabilities offered by active stick technology, the pilot situational awareness related to available control margin can be further improved by complementing standard Crew Alerting System messages (aural and visual). Instead of continuously modulating the pitch end-stop position (electrical hard-stop), which could lead temporarily to unacceptable pilot command restrictions as effect of active stick lag, the proposed approach for NGCTR-TD still relies on spring gradient law shaping. The available stick control margin is computed by evaluating the difference between channel authority and auto-trim command. When the integral control margin is increasing a lead-lag filter processes it with the aim of anticipating the effect of auto-trim discharge. The available control margin is compared with the filtered stick displacement to determine whether a residual stick margin exists. When the residual stick control margin is zeroed (or becomes negative), and the system is in Normal Mode, the pitch control gradient depicted in Figure 2 is amplified by a pre-defined factor to clearly advise the pilot of the channel authority limit. It is worth noting that the same mechanism can be calibrated to provide a low control margin caution (e.g. by computing the available integral margin with respect to 90% authority). Furthermore, in Normal mode, the Control Laws command the active stick unit to activate an adaptive soft-stop (i.e. with no pre-defined position as for typical passive sidestick implementation) whenever any of the following event listed in Table 1 occurs.

Based on LHD engineering simulator sessions, it has been decided to implement NGCTR-TD stall force cueing via soft-stop rather than relying on classical stick shaker function, which BAES stick is anyway supporting as well. During maneuver phase (previous bullet (a)), the outer loops reference is suitably limited to enforce envelope protection when the stick is released and hence the pilot is not in control. Pitch attitude reference limiting can be used to enforce speed stability, whereas bank attitude limits can be exploited to implement artificial spiral stability at the edge of Operational Flight Envelope. When the stick is returned to null detent, the Control Laws engage the appropriate outer loops to maintain established trim condition, either set by the pilot or by the envelope protection logic.

Table 1 – NGCTR-TD soft-stop activation logic

Soft-Stop	**Event**
Pitch, Aft	• Incremental load factor is exceeding +1.0 g • Impending/existing AOA stall condition present (from Stall Warning System) • Calibrated airspeed is less than 5 knots above V_S/V_{MIN}
Pitch, Fore	• Incremental load factor exceeding -0.5 g • Calibrated airspeed becomes less than 5 knots below V_{CON}/V_{MO}
Roll, Left (Right)	• Negative (positive) bank angle exceeds 30 deg in VTOL mode • In airplane mode, negative (positive) bank attitude exceeds pre-defined cueing limit defined as function of density altitude and airspeed, with 48.2 deg maximum value (corresponding to 1.5 g coordinated turn)

NGCTR-TD Direct Mode provides basic aircraft stabilization around three body axis, although it retains full Thrust and Power Management System capability. Degradation to Direct Mode, besides being automatically selected following specific core system failures (such as air data or inertial attitude loss), can be manually requested by NGCTR-TD experimental Test Pilot to override Normal Mode erroneous commands or to handle disorientation possibly caused by innovative HMI features. Bearing this in mind, Direct Mode features conventional like (i.e. trim actuator) behavior, with a software movable anchor position enabled by active stick motors. The stick input is smoothly transitioned during the *trim transfer* (Figure 3) process, leading to no change in aircraft state while auto-trim integrators are discharged. While in Direct Mode, the pilot can change the trim anchor position either by pushing Force Trim Release (FTR) button and moving the stick, or at pre-defined trim rate through beep trimmer. The trim transfer process is continuously working to washout the limited authority Direct Mode integral commands (necessary to improve long-term aircraft stabilization). During hands-on operation, basic force-feel capability is provided, with pre-defined breakout values, nacelle-angle scheduled force gradient and without any additional tactile feature.

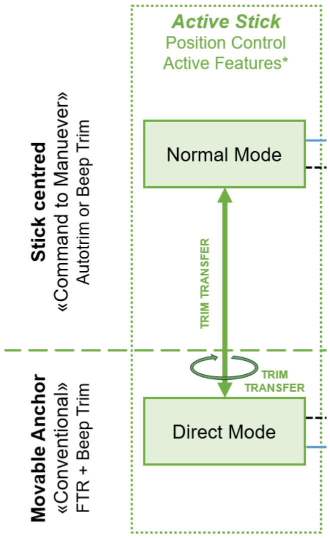

Figure 3 – Stick operated in Active State

3.3. Passive State

The stick could be passivated automatically or manually upon detection of specific active stick unit system failures which prevent the active functions to work properly. When passivated, the NGCTR-TD sidearm inceptor provides standard sprung-centered force characteristics (reversionary force-feel mechanical device), with gradient optimized for wing borne regime and still acceptable for time-limited VTOL HELO operation. Because anchor position cannot be changed, in Direct Mode (missing auto-trim feature) an alternative mean to manually trim the aircraft must be defined.

The NGCTR-TD Control Laws provides two manual trim features, which can be used also in Jam state:

a. Software trim adjustment (longitudinal and lateral axis follow-up integrators), driven by grip beep trimmer. As for Normal Mode auto-trim, the pitch and roll trim commands are automatically reset (with a suitable fadeout time constant) when the aircraft Weight-On-Wheels status is detected.
b. Manual trim sync logic. The pilot is requested to trim the aircraft by moving the stick against the force-feel. When the trim condition is reached, he can press FTR pushbutton and release the stick. The desired trim condition would be automatically memorized by longitudinal and lateral trim integrators.

If the stick becomes passive while Control Laws are operated in Normal Mode, the pilot can still rely on auto-trim capability and augmented response types. However, "hands-on" envelope protection functions (such as soft-stop and variable force gradients) would be unavailable. Fight envelope would be restricted, and additional attention required to not exceed envelope limits.

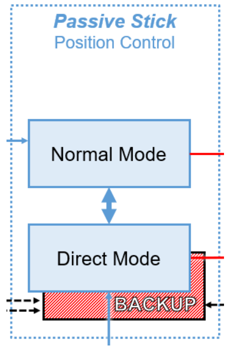

Figure 4 - Stick operated in Passive State

3.4. Jam State

The ACS can be operated in a state where the grip is locked in position (Jam mode) following a failure that jeopardizes the ability of the unit to properly position the stick. From FCS perspective, FCS SW Redundancy Management translates measured stick forces into equivalent stick positions based on CLAWs specifications (sensitivity and dead-band).

Due to a lack of force control guidelines and specifications publicly available (most of aircraft applications using this reversionary mode are military), the roll and pitch force inputs shaping laws have been tuned at NGCTR-TD engineering simulator facility by using a commercial sidearm control loading system and by properly emulating stick jam scenario. Because jam state represents an important system degradation, with large implications in terms of pilot's workload and reduced system safety, the NGCTR-TD Control Laws are automatically reverted into Direct Mode to minimize exposure to Control Laws design immaturity (Figure 5). Manual trim process is made possible with same strategies described for Passive state.

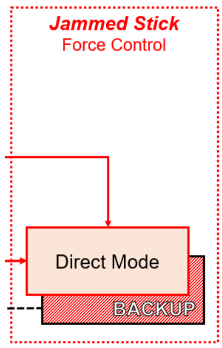

Figure 5 - Stick operated in Jam State

4. INTEGRATION WITH FCS

4.1. Safety objectives and considerations

An Active Inceptor system design must prioritize achieving extremely improbable susceptibility to catastrophic events caused by individual hardware or software component failures, ensuring no single element leads to such a condition. Generally speaking, the active inceptors shall ensure a reliability level adequate to the system that integrates it, remaining fully functional following any single non-extremely improbable failure, while retaining its most critical functionalities even after a second such failure.

To achieve these objectives, redundancy, hardware/software dissimilarity, and physical segregation may be employed in the design, as necessary. Compliance with the Single Pilot Operation scenario may also be requested, meaning relying solely on the single Active Inceptor without additional inceptors as a mitigation strategy for failure cases.

4.2. System architecture to achieve safety objectives

The aforementioned safety considerations have been thoroughly addressed in both the selection of the Active Inceptor for integration into NGCTR-TD and in the design of the Flight Control System that interfaces with it.

The BAE Systems Active Inceptor is an active off-the-shelf side-stick, serving as the pilot's primary interface for pitch and roll control. Equipped with dual actuators and motor drives per axis, it translates pilot force inputs into physical stick movement and generates feel cues as commanded by the FCS. The grip design is tailored to Leonardo Helicopters' specifications, incorporating specific envelope limitations and pushbutton controls. The ACS offers redundancy in position sensing for both pitch and roll axes; it further provides built-in fault detection and cross-checking algorithms to proactively identify potential safety issues and relay its status and fault updates to the FCS through its redundant ARINC 429 interfaces.

NGCTR-TD FCS interfaces with the Active Inceptor redundancy in position sensing and actuation through three distinct channels, one dissimilar to the others. This triplex redundancy ensures that even if two channels fail, the third, dissimilar channel can maintain control functions, thus mitigating the risk of common-mode failures and enhancing overall system robustness. Together with the Active Inceptor built-in fault detection, the FCS monitors its interfaces (ARINC 429, analog and discrete) relaying their health status to displays for pilot awareness and reconfiguring its architecture and algorithms accordingly. In accordance with fail-safe design requirements, the FCS retains direct stick position access in the event of complete power loss, ensuring continued safe flight.

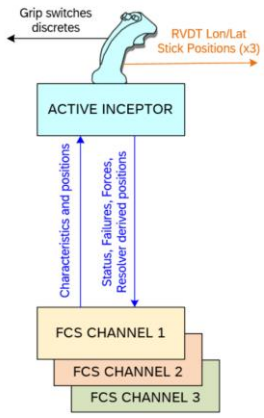

Figure 6 – ACS / FCS general architecture

Concerning ARINC 429 communication, the command lane of each FCS channel has two identical sources of transmissions, which are fed back to the monitoring lane for validation. Both Active Inceptor channels use a single transmitter that splits its transmissions to each FCS channel, enabling the FCS to perform redundancy checks.

Each ACS channel has two receiver pairs (RX1 and RX2), connected to two different FCS channels. Normally, data received on RX1 pair is used unless a failure is detected, then data received on RX2 pair is used in preference. If data on RX2 subsequently fails, control is passed to the other channel. According to failure criticality, an ACS channel may directly pass control to the other bypassing its RX2 couple. If neither channel is able to provide active capabilities, the ACS reverts to passive state.

As shown in Figure 7, FCS Channel 1 transmits data to both ACS channels' RX1 couples, while FCS Channel 2 and 3 are connected to RX2 pair in Channel A and B, respectively. Since legacy equipment used for FCS Channel 3 is unable to keep up with the high transmission rates required by BAE Systems Active Inceptor, ACS Channel B recognizes its RX2 couple as always failed. All things considered, this configuration has been selected to ensure data continuity in case control is handed from one ACS channel to the other, being the same FCS channel connected to both RX1 couples.

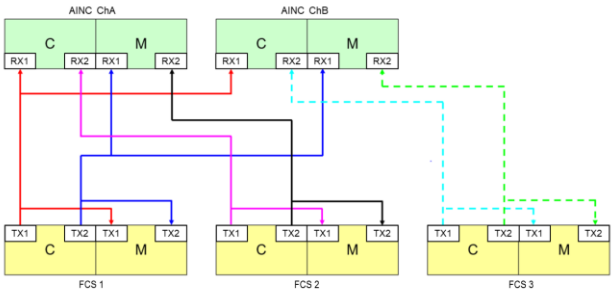

Figure 7 – ARINC 429 connections

4.3. Position transducers common mode failure

Particular attention has been dedicated to the connections between the three FCS channels and the ACS Rotary Variable Displacement Transducers (RVDTs), which are organized into two duplex pairs. Various failure scenarios have been considered, such as the loss or the erroneous of a single RVDT, and a common mode failure of two RVDTs of the same pair. To understand the impact of this latter failure case, two distinct configurations have been examined for connecting the RVDTs to the FCS channels.

1. In the first configuration, RVDTs of the same pair (i.e. couple 1) are connected to both FCS 1 and FCS 2. Assuming a common mode failure of the two RVDTs in the first couple: when Channel A is in control on its RX1 pair, the ACS identifies a fault by comparing the position data received from FCS 1 with its motor resolver's derived position. Once the fault is detected, Channel B takes over. However, since Channel B is connected to the same FCS channel, it also experiences the same failure. Consequently, the ACS reverts to a passive state, halting active control to prevent erroneous operation. Similarly, when Channel A RX2 is in control, the ACS detects a fault comparing the position data received from FCS 2 with its motor resolver's derived position. Channel B attempts to take over, but since the RVDT acquired by FCS 1 is also affected by the same failure, the ACS again reverts to a passive state.

2. The second configuration involves connecting RVDTs of different pairs to FCS 1 and FCS 2. This setup aims to provide better fault tolerance by distributing the RVDTs. In this scenario, with ACS Channel A in control on its RX1 pair, if RVDT couple 1 fails the ACS reverts to a passive state as before. However, if RVDT couple 2 fails, Channel A RX1 continues to function normally; the system recognizes the failure of Channel A RX2 couple, but active features are maintained. When the ACS Channel A is in control on its RX2 pair, if Couple 1 fails Channel A RX 2 operates without issue and the ACS stays active, while Channel B enters passive state. Should Couple 2 fail, the ACS detects the fault by comparing position data received from FCS 2 with its motor resolver's position. Channel B then takes control, allowing the ACS to continue in active mode. This configuration provides a more resilient response to failures, enhancing system reliability.

In normal operation with Channel A RX 1 in control, a failed RVDT 1 results in the FCS receiving an invalidation notice after the ACS detects the fault through its internal RVDT versus resolver comparison. By connecting FCS 3 to the second RVDT in couple 1, a single RVDT failure and a common mode failure can be distinguished using cross-channel monitoring. If the RVDT in couple 2 fails, the standard triple selection algorithm comes into play, protecting the system by identifying the failed RVDT as the outlier among three values. Connecting FCS 3 to the second RVDT of couple 2 is less beneficial because, in nominal conditions, position data from FCS 2 isn't compared against the resolver-derived position. Consequently, a common mode failure in couple 2 might go undetected, as the system would see two incorrect equal values out of three and select their averaged value.

The analysis reveals that the second hypothesis, where RVDTs of different pairs are connected to FCS 1 and FCS 2, generally offers better resilience, allowing the ACS to maintain active control in more failure scenarios compared to the first hypothesis. Moreover, failure messages received from the ACS have been combined with FCS detected failures in a more sophisticated algorithm to minimize the probability of erroneous position data impacting on CLAWs commands to the actuators.

4.4. Jam mode

Due to NGCTR-TD single pilot configuration, stick jam condition cannot be excluded by the safety case. When BAE Systems stick becomes totally or partially jammed, its performance monitors first trigger the activation of passive state (irreversible, IBIT or power request needed). If jam condition is then detected, the stick enters into jam mode. In this condition both axes will be locked and the pilot commands are acquired in the form of force input applied to the grip. Once Jam Mode is entered, the ACS will try to slowly recenter stick, since force controller is ergonomically more efficient when centered.

The force values are transmitted over ARINC 429 bus to the FCS computers and, as mentioned above, are translated into equivalent position inputs to the be used by the CLAWs.

5. FUTURE WORK: SMART ACTIVE INCEPTORS

5.1. Selection of future inceptors configuration

The selection of the most-promising inceptors configuration for a Tilt Rotor aircraft followed the strategy agreed between the Consortium responsible for the EU Funded CleanSky2 SMAR-TeR Initiative and LHD as its Topic Manager.

The Consortium, based on its previous experience and available literature, proposed fifteen basic elements that were intended as building blocks to create different Active Inceptors System configurations.

The basic elements presented included both inceptors well known in the rotorcraft world, like central column, sidestick, pedals, and solutions typically found in the fixed wing realm, e.g. the central column with wheel that characterizes some general aviation aircraft and airliners. Most of the inceptors in this category are dedicated to a single side, the only exception being the sidestick that can be adapted to both left and right hand.

In addition to that, the proposal included some less conventional solutions aimed at providing more advanced functionalities and seamless transition between the Tilt Rotors flying modes (helicopter vs airplane mode). An example of such solution is the *Rotating bar with sidestick*, where a 1-DoF sliding stick is mounted on a bar that can rotate up and down, thus providing the pilot with a movement that can mimic either a conventional linear throttle or a collective lever (see 7 in Figure 8).

The fifteen basic elements have been combined into eighteen cockpit configurations. These have then been scored against a set of eleven criteria to determine three candidate solutions to be produced as lab prototypes for pilot-in-the-loop assessment.

The criteria selected cover various aspects of the usability and installability of a given inceptor system in an aircraft cockpit.

The first four criteria are *General Ergonomics, Handling Qualities, Cognitive Compatibility and Workload.* These criteria fall under the broad category of Human Machine Interface since they evaluate how a pilot is able to easily interact with the system. Aspects like the expected motion of the aircraft following a certain type of inceptors displacement (e.g.: right bank if a right-hand stick is tilted to the right) are analyzed, but also arm positions and extension needed to reach an inceptor full stroke, or need of additional armrest supports is considered.

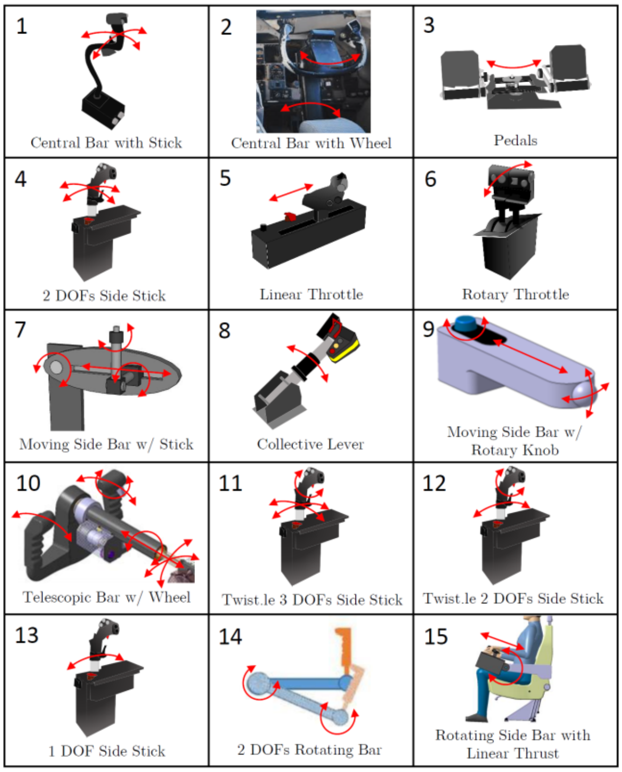

Figure 8 – Possible inceptor building blocks which are combined into cockpit configurations (Ref. 2)

The usability of the active inceptors in off-nominal scenario has also been evaluated with the criteria *Failure Recovery* and *Nacelle Control.* The former aims at covering how the pilot would be able to fly the aircraft in case a degraded mode is engaged following a failure of a non-critical sensor on the aircraft. The FBW technology allows to map to a controller a reference to virtually any physical quantity relevant for the flight (e.g.: ground speed, altitude, rate of climb…), if all the needed sensors are available. Typically, sensors suites with a probability of loss that is extremely improbable are limited to some critical parameters, accepting the degradation of the CLAWs to simpler modes in case some failures are detected. One or more reversionary mode, depending on the failure considered, are available; in this case, the Active Inceptors System must provide to the pilot a means to govern the aircraft also when the most basic mode is active. *Nacelle Control* can be considered as a special case of what is explained above. The adjustment of the tilt angle of the nacelles in a tilt-rotor can be included in a control algorithm so that the pilot does not have to actively monitor and control it, thus avoiding exceedance of defined flight envelopes. On the other hand, if failure occurs, the pilot must be able to regain control over that parameter to govern the aircraft safely. The Active Inceptors System must then include a dedicated controller (e.g. switch or knob) to directly adjust the nacelles in case the automatic algorithm is no longer effective.

Two further criteria consider the ability to install the Active Inceptor System on the aircraft. *Range of motion* must be taken into account to ensure that the controller itself does not have clashes with other equipment, structure or cockpit elements. This criterion falls in between the installability and the usability considerations because the range of motion is also part of the ergonomic considerations. *Ingress and egress* evaluates how the installed Active Inceptors System allow for a comfortable access to the cockpit, considering also emergency egress scenarios (e.g. with an ejection seat).

In the framework of a longer-term strategy, *Innovation* and *Training* have also been considered to assess how a new Active Inceptor System could be effectively deployed on a product without negatively affecting the work of the current aircraft operators. *Scalability* is a key aspect to port the equipment to platforms other than a 9 tons tilt-rotor. Active Inceptors can be beneficial also to conventional aircraft or smaller vehicles like eVTOLs that might not be allow for the same space and weight of a mid-weight tilt-rotor. The ability to identify a configuration of Active Inceptors able to be installed also on different platforms provides a good advantage for a future entry into production.

Taking into account all the considerations above, the configuration selected for further studies is based on a left-hand linear throttle, a right-hand stick with 3 DoF, and conventional pedals.

5.2. New Active Inceptor Systems requirements definition

The requirements for a new Active Inceptors System have been developed in the framework of the EU Funded CleanSky2 SAIS Initiative, with LHD as its Topic Manager, in collaboration with Università di Pisa, Umbria Aerospace Systems and MARE Engineering.

5.2.1. Physical requirements

The requirements concerning physical characteristics of each single component of the Active Inceptors System derive from both ergonomic evaluations and DMU installation studies. The aim was to demonstrate the feasibility of the integration of the Active Inceptors System in the cockpit of a tilt-rotor of similar size of the Nextgen-TD. The size and weight constraints influenced the choice of whether to use a single control box with simpler inceptors units connected to it, or to distribute the computational capabilities into each inceptor.

Also, typical stick/throttle strokes, passive force feel characteristics and loads are defined. Previous studies and available literature provide a basis for defining these characteristics; regulations such as the CS 25 and CS29, and the ARP 5764 guideline have also been taken into account to validate design choices and to ensure that the product could be actually used in a certified aircraft in the future.

5.2.2. Interface requirements

The choice of the interfaces implemented in the Active Inceptors System reflects the scalability and modularity objectives. Common and well-known digital data busses have been chosen to ensure that the system could be integrated into both new and legacy FCS, thus providing a wider use case for the equipment. Safety considerations played also an important role in the definition of the interfaces to ensure adequate dissimilarity and segregation where needed.

5.2.3. Functional requirements

A list of system level functions covering all the expected functionalities performed by the Active Inceptors System has been defined and considered as a reference throughout the entire system design and safety assessment process.

The functions identified are listed and briefly described in Table 2. Not all the functions are available on all axes (degrees of freedom) for all inceptors. For instance, the Active Capabilities are not foreseen for the torsional DoF of the right-hand stick. A suitable compromise have been defined in order to avoid adding further complexity in the system without gaining an equivalent benefit from the functionality introduced.

As per the physical requirements, the ARP 5764 guideline was the main source for performance requirements related tot he Active Capabilities, defining adequate ranges of parameters for force gradients, residual force, damping and so forth.

A key characteristic included in the functional requirements related to the Active Capabilities is the possibility to adjust in real-time the force feel characteristics of the Active Inceptors. This could either happen by switching between pre-defined parameters sets or by constantly updating the definition of the required force feel curve.

Table 2 – Active Inceptors System functions

Function	**Description**
Basic Capabilities	All the core functions critical to retain control of the aircraft Include: • Controls position measurement • Passive force feel • Neutral position hold
Active Capabilities	Functions that provide the pilot with advanced haptic cueing and possibility of trimming the stick to mimic the autopilot commands
Inceptors linkage	Function that provide a virtual link between the pilot and co-pilot inceptors
Hands-On detection	Function that recognizes and communicate if the pilot is actively acting on the Active Inceptors

5.2.4. Safety requirements

In order to match the strict safety objectives that characterize any Fly By Wire Flight Control System, the Active Inceptors System must be able to provide an integrity and availability compatible with catastrophic events. This means that any failure leading to loss or erroneous unprotected operation must be extremely improbable.

If all the functions seen in Table 2 were designed to meet such stringent target, the complexity and weight/size of the Active Inceptors System would have likely exceeded reasonable values.

To optimize the design, the decision has been made to target a *fail-op, fail-safe* safety objective for the Active Inceptors System.

The *fail-op, fail-safe* concept summarizes the robustness of the system to at least two non-extremely improbable failures and provides details on how the system should react to a sequence of two of such failures. After the first failure, the system must maintain its normal operational capabilities; i.e. no function should be lost or suffer a severe degradation. After a second failure, the system should still be able to provide a minimum sub-set of functions identified to ensure a safe control of the aircraft.

With reference to the list provided in Table 2, the *Basic Capabilities* are considered the group of functions that need to have the highest availability and to meet the requirements for CAT events.

6. CONCLUSIONS

The Active Inceptors technology is a key enabler for providing pilots with low workload, enhanced safety and advanced control capabilities on tilt-rotors and other non-conventional aircraft configuration.

The integration of an Active Inceptor suite in a Flight Control System forces the engineers to consider a multitude of aspects that are usually not taken into account in order to design a system that is both safe and functional. The activities presented in this paper allowed LHD to get hands-on experience in the field of the Active Inceptors System and the key outcome can be summarized as follow.

1. The selection of the control strategy should be the first step before defining the Active Inceptors suite configuration. As illustrated above, advanced CLAWs can benefit from cockpit solutions different from the classic cyclic-collective-pedals, however, not all the possible combinations are adequate for every control strategy.
2. Change in aircraft configuration, either due to failure or change in flight phase (e.g., Helicopter mode vs airplane mode for tilt-rotors) must be taken into account in the design of the Active Inceptor suite. If the FCS must be reconfigured after a failure in a way that a particular physical quantity is no longer automatically adjusted, the Active Inceptor must provide to the pilot a means to retain control over that. The most straightforward example is the nacelle angle, that can be automatically managed by an advanced control strategy or directly controlled by the pilot if a degraded mode is engaged. Another example is the thrust control that intuitively is opposite in helicopter (pull to increase thrust) versus airplane mode (push to increase thrust).
3. The safety level provided by the Active Inceptors System must be coherent with the overall FCS

safety objective. This apparently obvious statement leads to a series of requirements influencing the architecture of the Active Inceptors System and the way it is integrated with the rest of the FCS that can greatly increase its complexity. For instance, the decision could be made to design an Active Inceptor System that alone can meet strict CAT requirements or to relax the safety target on the Active Inceptor System and assign part of its functions to a different unit in the FCS. The right balance depends on the target aircraft and other common design constraints (e.g. COTS availability, budget, size, weight).

4. Suitable strategies should be identified to cope with the contrasting pilots input scenario (dual pilots configuration) and single point of failure scenario (single pilot configuration).
5. Installability criteria should be taken into account since the very first stages of design of a new Active Inceptor System. Some cockpits might not be large enough to host two full sets of Active Inceptors, thus configuration where an inceptor is shared between the pilots might be needed. Some inceptor might also be more suitable for aircraft equipped with ejection seats or can pose an obstacle for the access to the cockpit. A study on a 3D mockup is of paramount importance to identify possible issues that would be hard to solve later on in the design process.

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