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Horizon Europe Project:
Flight control laws and air data monitors Lot 1 (EASA.2021.HVP.28)

Final Report on Project

Deliverable D-7

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1 Introduction on the Project

1.1 Prerequisites and conditions

This project was based on an invitation to tender in Cluster 5 Climate, Energy and Mobility of the Horizon Europe Work Programme 2021-2022. In that Work Programme, the European Commission has entrusted EASA with the management of six research actions with a budget of EUR 14.2 million. The invitation to tender addressed chapter 1 'Response to lessons-learnt from recent accidents / incidents in air transport' under the category of Indirectly managed actions and had been divided into two lots. The project depicted here focused on Lot 1 "Monitoring of flight control laws".

1.2 Technical premise and approach

The objectives and scope had been outlined by the contracting authority as follows:

Flight control laws are becoming increasingly complex, and having dissimilar control laws to compare and address the integrity aspect and detect errors is difficult, and sometimes impossible, to achieve. There are typically several modes of flight control systems designed with different sets of control laws: the 'Normal Mode' with the most complex functions and protections, and lower-level modes with degraded functionalities/protections, also known as 'Direct Mode', with or without any protections. The research project is limited to the monitoring of the Normal Mode control laws.

Today, reliance is mainly based on rigorous development assurance processes which have been developed and applied to establish confidence that the control law development has been accomplished in a sufficiently disciplined manner to limit the likelihood of the development of errors that could impact on aircraft safety.

However, development assurance can only minimise the system development risk. An additional difficulty is that errors may remain latent until they occur.

The project aimed to investigate the introduction of flight control law monitors to detect errors. It was set up to improve the EASA certification standards, and to support the evaluation of new designs proposed by aircraft manufacturers. Potential control law errors should be identified, and their criticality needs to be determined. Multiple monitors to detect such errors should be proposed without taking into account the necessary effort entailed.

The main challenges were that:

- the detection is effective when the detection means are sufficiently independent from the item being monitored;
- the independent monitoring needs to be designed with thresholds and confirmation times set not so high as to not trigger when not needed and also not so low as to lead to spurious detections; and
- it may be difficult from monitoring the aircraft behaviour to determine whether the aircraft response comes from a flight control law error, a normal behaviour in a given phase of the flight, and/or an external perturbation.

Potential independent monitors were to be assessed towards these challenges and the related effort. The expected outcome was the determination of suitable independent monitors which can detect errors without compromising the availability/operation of the flight control system in Normal Mode.

1.3 Tasks and deliverables

The tasks and deliverables had been specified by the contracting authority as follows:

Task 1: Establishment of an aircraft model

An aircraft model representative of modern large transport aircraft needs to be established comprising flight dynamics and flight control laws, flight control computers, actuators, sensors, etc… The model will serve as a platform to evaluate the monitors proposed, enabling the performance of state-of-the-art flight dynamics simulations covering the standard stability and control parameters and allowing the simulation of different aircraft configurations and flight manoeuvres or phases.

Simplifications in the flight dynamics simulation model could be used provided they will not adversely impact on the investigation/expected result. Preliminary simulations will be performed to ensure the functioning of the aircraft model.

Task 2: Identification of potential errors

The flight control laws will be investigated in detail with the intent to identify possible control law errors (e.g. gain, sign, aircraft model errors). The severity/criticality of these errors should be assessed to enable the selection of the most critical ones.

Such investigation will be based on existing scientific literature, safety occurrence reports, in-service event reports available publicly. EASA may support the contactor in obtaining access to additional reports not available in the public domain.

Task 3: Determination and definition of potential monitors

Based on the identified list of errors (D2-1), potential monitors will be proposed (independent of the required effort for their implementation). For example, the monitors could be based on checking the aircraft reaction (acceleration, attitude change/drift, loads) or control law outputs (resulting in surface runaway/hardover/oscillations/freeze, estimated high loads on wing or stabiliser, mistrim). The monitors need to be independent from the item being monitored. Task 3 might include a search for already available monitors for flight control law errors. The details of the monitors (required inputs, threshold, confirmation time, system reaction, etc.) should be specified for software coding and then integrated into the aircraft simulation model. The proposed monitors, including their details, should be captured in the deliverable 'List of proposed monitors' (D 3-1).

A technical workshop for Stakeholders (e.g. manufacturing industries, research centres) will be organised by the contractor to present the project objectives and initial results from Tasks 2 and 3 and invite them to share their comments (D 3-2). The workshop will allow physical or remote attendance, its location will be defined during the project. EASA will support the contractor for the organisation of such workshop.

Task 4: Definition of test conditions

The test conditions to demonstrate the effectiveness of the monitors needs to be defined.

The definition of the test conditions for which the proposed monitors should be shown to be robust (e.g. manoeuvres including abrupt ones, such as avoidance, wind, turbulence, icing) is also necessary.

Task 5: Evaluation of potential monitors

The proposed monitors will be evaluated in simulations using the defined test conditions (from Task 4). The evaluation should include at least the investigation of the effectiveness and robustness of the flight control law monitors and identification of the advantages or disadvantages, as well as the flight phases that could be covered or not.

The results of these investigations will be documented in the deliverables 'Evaluation results of the effectiveness tests' (D 5-1) and 'Evaluation results of the robustness tests' (D 5-2).

Together with the report on simulation exercises performed and the obtained results, the test datasets, the simulation model definition, scripts or source code developed as well as comprehensive user guidelines shall be delivered to the Contracting Authority (D 5-3). The source code shall include comments and it should be documented in a manner adequate for possible re-use. In case a commercial simulation platform or proprietary simulation code is used, a user license shall be provided to the Contracting Authority, with a validity of at least three years at the time of delivery.

Task 6: Propose suitable monitors

A qualitative assessment of the proposed monitors will be performed in respect to the required efforts and constraints for their implementation and their maintenance in the context of large transport aircraft operations (e.g. considering additional sensors required, software design and validation, processing capacity, etc.).

Based on the evaluation results, the most suitable monitors will be identified and taken into account in the trade-offs between performances and the required efforts for their implementation.

The results of these assessments should be documented in the deliverables 'Assessment of required effort' (D 6-1) and 'Substantiated list of suitable monitors' (D 6-2).

The final report (D 7) will provide a summary or restatement of the conclusions already reached in the relevant parts of the project. It will draw the main recommendations from the contractor to prepare the deployment of the identified flight control laws monitors, on the remaining open issues to address as well as on the potential evolutions to bring to the airworthiness certification standards (EASA CS-25 for Large Aeroplanes).

A final dissemination event for the Stakeholders (e.g. manufacturing industries, research centres) will be organised by the contractor to present the main results obtained. The workshop will allow physical or remote attendance. Its location will be at EASA premises in Cologne. EASA will support the contractor for the organisation of such workshop.

1.4 Overview of deliverables

The following deliverables had been requested by the contracting authority. Please note that "T1" refers to the project start date on October 04, 2022:

Task	Deliver-able	Deliverable name	Due by
1	D-1.1	Aircraft model description and model validation test results	T1 + 4m
2	D-2.1	List of potential errors in flight control laws	T1 + 7m
3	D-3.1	List of proposed monitors	T1 + 11m
3	D-3.2	Technical workshop presentations and notes	T2 + 12m
4	D-4.1	Test conditions for effectiveness tests	T1 + 13m
4	D-4.2	Test conditions for robustness tests	T1 + 14m
5	D-5.1	Evaluation results of the effectiveness tests	T1 + 16m
5	D-5.2	Evaluation results of the robustness tests	T1 + 18m
5	D-5.3	Simulation model and scenarios, platform, source code, user manual and related documentation	T1 + 19m
6	D-6.1	Assessment of required effort for implementation	T1 + 22m
6	D-6.2	Substantiated list of suitable monitors	T1 + 23m
6	D-7	Final report and presentation materials	T1 + 24m
KM	D-KM.1	Communication, dissemination and knowledge-sharing plan and actions	T1 + 2m
KM	D-KM.2	Final report on Task KM	T1 + 24m
PM	D-PM	Project Management Plan	T1 + 1m
PM	D-RMR	Risk Management Register	T1 + 1m
PM	D-QRxx	Quarterly Reports	15 calendar days after each quarter

Table 1-1: Project Deliverables

1.5 Project planning

Figure 1 shows the project planning in respect to the timeline.

The project started on October 04, 2022, and was closed on October 03, 2024.

				2022			2023												2024								
		Due	Draft due*	Okt	Nov	Dez	Jan	Feb	Mrz	Apr	Mai	Jun	Jul	Aug	Sep	Okt	Nov	Dez	Jan	Feb	Mrz	Apr	Mai	Jun	Jul	Aug	Sep
Tasks																											
Task 1	Establishment of an aircraft model	31.01.23																									
Task 2	Identification of potential errors	30.04.23																									
Task 3	Determination and definition of potential monitors	30.09.23																									
Task 4	Definition of test conditions	30.11.23																									
Task 5	Evaluation of potential monitors	30.06.24																									
Task 6	Propose suitable monitors	30.09.24																									
Technical Deliverables																											
Kick-off	Inputs EASA (CRI Background / Lessons learned / Reports)	31.10.22		x																							
D-1.1	Aircraft model description and model validation test results	31.01.23					x																				
D-2.1	List of potential errors in flight control laws	30.04.23								x																	
D-3.1	List of proposed monitors	31.08.23												x													
D-3.2	Technical workshop presentations and notes	30.09.23													x												
D-4.1	Test conditions for effectiveness tests	31.10.23														x											
D-4.2	Test conditions for robustness tests	30.11.23															x										
D-5.1	Evaluation results of the effectiveness tests	12.07.24	09.06.24																								
D-5.2	Evaluation results of the robustness tests	30.06.24	09.05.24																					x			
D-5.3	Simulation model and scenarios, platform, source code, user manual and related documentation	12.07.24	09.06.24																						x		
D-6.1	Assessment of required effort for implementation	31.07.24	12.07.24																								x
D-6.2	Substantiated list of suitable monitors	31.08.24	10.08.24																								x
D-7	Final report and presentation materials	30.09.24	09.09.24																								x
Project Management Deliverables																											
D-KM.1	Communication, dissemination and knowledge-sharing plan and actions	31.01.23					x																				
WS-KM.1	Technical workshop on project objectives and initial results	31.08.23												x													
WS-KM.2	Final workshop on results obtained	25.09.24																									x
D-KM.2	Final report on Task KM	30.09.24																									x
D-PM	Project Management Plan	31.01.23					x																				
D-RMR	Risk Management Register	31.01.23					x																				
D-QRxx	Quarterly Reports	Q+15 days				x			x			x			x			x			x			x			x

Figure 1: Project Planning

2 Technical Report

2.1 D1.1 „Aircraft model description and model validation test results"

To evaluate the proposed monitors TU Berlin has provided an aircraft model of the VFW614-ATD aircraft. The VFW614-ATD flight simulation software was developed as part of an engineering flight simulation facility at Airbus Hamburg and was donated to TU Berlin in 2004. Since 2005, the VFW614-ATD simulation runs on TU Berlin's SEPHIR[1] Research Flight Simulator in two parallel tasks on two CPUs under UNIX.

Based on software of the SEPHIR flight simulator, the department Flight Mechanics, Flight Control and Aeroelasticity (FMRA) has developed a one CPU version for Windows PCs. This flight simulation software is the main part of the *VFW614-ATD Flight Simulation Environment* (*FSEnv*). The implementation is performed in MATLAB / Simulink.

The FCL SW and the desktop FSEnv of the VFW614-ATD flight dynamics are representative for a modern Fly-by-Wire aircraft. This desktop flight simulation was prepared in Task 1 of the EASA.2021.HVP.28 project and extended by failure injection means. The documentation comprises a user manual [1], a programmer's guide [2] and a validation report [3].

[1] Simulator for Education and Highly Innovative Research

2.2 D-2.1 „List of potential errors in flight control laws"

In Task 2, potential FCL errors were identified, classified and delivered as a list, see reference [4]. Due to the complexity of the FCL and the high number of functions, an exhaustive list with all possible errors was not the focus in the context of this project. Instead, failures of the FCS that are caused by FCL development errors were identified and categorized.

As the number of potential accident and incident examples is low and the relevant literature gives only rough concepts, an alternative approach was selected to identify and classify failures that are caused by FCL development errors. The failure classification approach that is described in reference [4] does not identify specific examples of FCL development errors. Instead, effects of FCL errors and the resulting erroneous FCL commands that can have hazardous or catastrophic consequences were determined. These FCL failures were categorized.

Two methods for failure classification were proposed:

- Classification method based on the type of a function,
  - **Failures in the mode logic (LOG):**
    Erroneous behaviour in primary control functions (pitch, roll, yaw) that is caused by erroneous switching of the modes of operation of NL (Ground Mode, Flight Mode) or by an erroneous activation of a protection function.
  - **Failures in the flight control functions (FCF):**
    Erroneous behaviour in primary flight control functions (pitch, roll, yaw) within the limits of the normal flight envelope (see Figure 2-2), where the protection functions are not active.
  - **Failures in envelope protection functions (PRT):**
    Erroneous behaviour in primary control functions (pitch, roll, yaw) when a protection function is active and the respective activation conditions are correct.
- Classification method that considers the dependency of a failure on the input signals of the FCL SW
  - Input-independent failures: failures in the FCL functions that affect the output independently from input signals (**active class**),
  - Input-dependent failures: failures in the FCL functions that affect the output in dependence of input signal (**reactive class**).

The classes of both methods are combined as designated in Table 2-1. Potential failures that are caused by errors in the VFW614-ATD FCL SW were assigned to the categories that are defined above.

Table 2-1: Combination of Failure Classes.

Functional Classes	Active (A)	Reactive (R)
FCF	A-FCF	R-FCF
LOG	A-LOG	R-LOG
PRT	A-PRT	R-PRT

The methods for simulation of active and reactive failures differ significantly. Active failures can be triggered by insertion of simple errors into the software. As their effect on the flight controls is similar to actuator-like failures (i.e. runaway), a simplified simulation of these failures by direct manipulation of the FCL output for pitch, roll and yaw control axes is recommended. To trigger reactive failures, additional manipulation of FCL source code was necessary.

2.3 D-3.1 „List of proposed monitors"

In Task 3, potential monitors were proposed and delivered as a list, see reference [5]. The monitors can check the aircraft reaction or the FCL output. The advantages of the monitoring levels were discussed, and two concepts for monitoring functions were described:

- Comparators, and
- Plausibility Checks.

Comparators compare the results of redundant (but functional independent) FCL. A fault is detected when the outputs of the variants differ. This check works on FCL SW-level. Plausibility Checks verify that the behaviour of the FCL software is acceptable and plausible rather than correct, based on predictions on the anticipated system state. The plausibility check monitor can work on aircraft and FCL level.

The objective of the Independent Monitor of Flight Control Laws (IM-FCL) is to increase the safety of the FCS while maintaining highest rates of availability. The following design objectives were defined. The IM-FCL

- shall detect failures, i.e. erroneous function (malfunction), of the FCS caused by FCL development errors, and
- shall be functionally independent from the normal law FCL, and
- shall have a significantly lower level of complexity than normal law FCL, and
- shall only detect failure conditions which are classified as catastrophic, and
- shall be robust under any foreseeable operational condition.

A total of 24 Independent Monitor Functions (IMFs)[2] were proposed. The proposed monitors and their details were captured in a list of requirements that was used to design the proposed monitors. Table 2-2 summarizes the proposed monitoring functions.

[2] An Independent Monitor of Flight Control Laws is composed of several IMFs.

Table 2-2: List of proposed monitoring functions.

Concept	IMF	Parameter
Limit Check	Pitch Angle Limit Check	θ
	Overspeed Limit Check	V_{CAS}
	Bank Angle Limit Check	ϕ
	Normal Load Factor Limit Check	n_z
	Angle of Attack Limit Check	α
Behaviour Check	Roll Rate Hands-free Check	p
	Bank Angle Hands-free Check	ϕ
	Normal Load Factor Hands-free Check	n_z
	Lateral Load Factor Hands-free Check	n_y
	Sideslip Angle Hands-free Check	β
	Roll Rate Sign Check	p
	Pitch Rate Sign Check	q
	Normal Load Factor Sign Check	n_z
	Roll Rate Controllability Check	p
	Flight Path Controllability Check	$\dot{\gamma}$
Command Check	Bank Angle Protection Function Check	ξ_{cmd}, (ϕ)
	Overspeed Protection Function Check	η_{cmd}, (V_{CAS})
	Angle of Attack Protection Function Check	η_{cmd}, (α)
	Pitch Angle Protection Function Check	η_{cmd}, (θ)
	Aileron Command Sign Check	ξ_{cmd}
	Pitch Trim Drift Check	THS command
Comparator	Elevator Command Comparison	η_{cmd}
	Aileron Command Comparison	ξ_{cmd}
	Rudder Command Comparison	ζ_{cmd}

2.4 D-4.1 „Test conditions for effectiveness tests"

In Task 4, the test conditions for evaluation of Independent Monitor Functions (IMFs) effectiveness and robustness were defined. Additionally, a simplified aircraft recoverability assessment after the failure has been detected was proposed, see reference [6]. Effectiveness test conditions comprised:

- initial flight condition (trim point),
- an FCL failure, and
- flight manoeuvres.

Representative trim points for the operational flight envelope of the VFW614-ATD aircraft were selected. The focus of the investigation lied on the high and medium altitude trim points, as the aircraft is operated within this area of the flight envelope most of the time. Additionally, some trim points at low altitudes were selected.

To evaluate the effectiveness of the IMFs, runaway-like failures on all control surface commands were defined. The runaway can be positive or negative, and slow or fast. Additionally, command freeze of the elevator and aileron commands, that reduce the controllability of the aircraft, were selected. Also, reactive failures of all functional failure classes are selected. I.e., erroneous ground mode and protection activations, high gains in the FCF that lead to unstable aircraft dynamics and sign failures in the PRT functions.

Representative flight manoeuvres were selected for the effectiveness test conditions. Typical flight manoeuvres of cruise flight phase and a landing approach were selected. The following manoeuvres were defined:

- hands-free (i.e., no pilot input),
- climb,
- descent,
- turn,
- turn and climb,
- turn and descent, and
- landing approach.

The total set of effectiveness test conditions is the combination of the selected trim points, flight manoeuvres, and selected FCL failures. However, one design objective of the IM-FCL is that it shall only detect failure conditions which are classified as catastrophic (CAT). Therefore, the hazard of the selected failures was assessed. FCL failures that did not lead to CAT conditions were not considered for effectiveness evaluation. In addition, some combinations are not plausible, e.g. landing manoeuvre at high and medium altitude trim points, and were not considered for effectiveness evaluation.

The full combination of trim points, flight manoeuvres and failures is documented in reference [6]. A total of 857 effectiveness test conditions were defined and investigated.

2.5 D-4.2 „Test conditions for robustness tests"

In Task 4, the test conditions for evaluation of Independent Monitor Functions (IMFs) effectiveness and robustness were defined. Robustness test conditions comprise foreseeable flight conditions during failure free operations. They are a combination of:

- an initial flight condition (trim point),
- flight manoeuvres, and
- external disturbances (e.g., turbulence, gusts).

Representative trim points for the operational flight envelope of the VFW614-ATD aircraft were selected. The focus of the investigation lied on the high and medium altitude trim points, as the aircraft is operated within this area of the flight envelope most of the time. Additionally, some trim points at low altitudes were selected.

The manoeuvres from the effectiveness tests were reused for the robustness tests. The full list of normal operation manoeuvres is given in reference [6]. Additionally, high-gain manoeuvres (e.g.

emergency decent, fast turn, etc.) were defined to bring the aircraft and the FCL close to the operational limits.

To evaluate the robustness of the IMFs, external disturbances were selected. The atmospheric disturbances were introduced either with a CS-AWO turbulence model [7] or by script. Three different turbulence intensities were selected. Additionally, discrete gusts of 1-cos shape were defined. The gust intensities are based on the CS-25 [8] and SAE AS94900 [9] standards. The CS-25 discrete gust has a probability of occurrence of 1 in 70,000 flight hours. This gust is used to estimate the maximum A/C gust loads. In the context of IMF robustness evaluation, this gust represented the most critical gust encounter during which IMFs shall not trigger false alarms. Gust intensities based on the SAE AS 94900 were selected, to investigate gusts with lower intensities and higher probabilities of occurrence (1 in 1000 flight hours).

The total set of robustness test conditions is the combination of the selected trim points, flight manoeuvres, and external disturbances. The full combinations of trim points, flight manoeuvres and external disturbances is documented in reference [10]. A total of 1348 robustness test conditions were defined and investigated.

2.6 D-5.1 „Evaluation results of the effectiveness tests”

In Task 5, the Independent Monitor Functions (IMFs) were evaluated based on the simulation results of the effectiveness and robustness test conditions. The percentage of detection (POD) was used to evaluate the effectiveness of the Independent Monitor of FCL (IM-FCL), consisting of the 24 proposed IMFs described in reference [5], and the individual IMFs.

It is important to note, that the POD is highly dependent on the defined effectiveness test conditions. Therefore, the POD can only be used as an indicator of effectiveness. It was required that the POD of the independent monitor is 100 %. However, a POD of 75 % or higher is considered acceptable. It was assumed that the effectiveness can be improved with little effort by adjusting the thresholds and confirmation times. However, a POD of less than 75 % is an indicator that design changes may be required, and additional investigation is necessary.

In addition, the recoverability of the aircraft is also an important aspect to determine the effectiveness of the monitor. In this project, a simplified approach was selected to assess the recoverability of the aircraft. It was assumed that the FCS switches to an alternative FCL, e.g. Direct Mode after a failure has been detected. It was further assumed that the aircraft can be recovered, if the IMF detects the failure two seconds before a CAT failure condition occurs.

The evaluation of effectiveness test conditions showed that the combination of 24 IMFs to an Independent Monitor of Flight Control Laws (IM-FCL) can effectively detect all investigated failures. Exceptions were the erroneous activation of the high speed (AHISPD) and pitch angle protection (ATHPRT). Both failures reduce the pitch manoeuvrability of the aircraft.

The Flight Path Controllability Check did not detect this failure in several cases because the pilot model did not generate large pitch commands. It is assumed, that a pilot would increase the side stick pitch inputs, if no aircraft reaction is visible. This would activate the IMF and eventually trigger an alarm.

The effectiveness test results also showed that several failures were detected by more than one IMF. A simpler IM-FCL consisting of only eleven IMFs was able to effectively detect all investigated failures. The eleven IMFs were selected based on their contribution to the POD of the IM-FCL. Additionally, redundancies were taken into account to reduce the overall number of IMFs that comprise the reduced IM-FCL. The following IMFs were selected:

- **Pitch Angle Limit Check** (redundant to Angle of Attack, Normal Load Factor and Overspeed Limit Checks),
- **Bank Angle Limit Check**,
- **Bank Angle Hands-free Check**,
- **Sideslip Hands-free Check** (redundant to Lateral Load Factor Hands-free Check and Ruder Command Comparison),
- **Roll Rate Controllability Check**,
- **Flight Path Controllability Check**,
- **Pitch Rate Sign Check** (relevant for ATHPRT failure),
- **Angle of Attack Protection Check** (relevant for AAOA failure),
- **Elevator Command Comparison**, and
- **Aileron Command Comparison**.

The effectiveness test results also showed that the percentage of detection does not change significantly when recoverability is considered. A detailed evaluation of the effectiveness of each IMF is documented in reference [11].

2.7 D-5.2 „Evaluation results of the robustness tests"

The goal of the IMFs is to increase the safety of the FCS while maintaining today's availability of flight control systems in their Normal Mode. Assuming that tripping of the IMF will lead to a system reconfiguration from Normal Mode to a backup mode to be defined, any IMF false alarm will reduce the state-of-the-art availability of the Normal Mode. This, in turn, can be interpreted as a reduction of the current level of safety, which has to be avoided. Therefore, the overall objective for the IMFs is to be robust against false alarms under all foreseeable operational conditions.

Thus, it is recognised that any false alarm during the operation of an aircraft, regardless of its probability, is unacceptable and that the IMF designs that show false alarms will have to be improved for robustness. However, the objective of this project is to evaluate the general feasibility of concepts for Independent Monitoring of Flight Control Laws. Therefore, somewhat relaxed criteria for "acceptable" and "good" IMF robustness were defined. That is, certain probabilities of false alarms are considered acceptable for the sake of this initial feasibility study. The details of this approached are given below in this section. Considering the limited time and small team, the approach and the preliminary required false alarm probabilities to assess robustness are considered valid.

In Task 5, the Independent Monitor Functions (IMFs) were evaluated based on the simulation results of the effectiveness and robustness test conditions. An indicator of monitor robustness is the percentage of false alarms (PFA). Acceptable values of PFA were defined based on the probabilities of occurrence of the test conditions. One design goal was, that the IMF should not reduce the availability of the normal mode FCL that was assumed to be 10^{-7}. It represents the design goal for good robustness. Furthermore, it was assumed that an annunciated switch to the direct mode FCL is classified as major. Therefore, the IMF false alarm rate was required to be below 10^{-5}.

It is important to note, that the PFA is highly dependent on the defined robustness test conditions. The test conditions can be manipulated to achieve PFAs that meet the required values. Therefore, the PFA can only be used as an indicator but not as proof for robustness. The probability of occurrence of each test condition has to be defined and each false alarm analysed individually to assess the robustness.

The evaluation of robustness test conditions showed that the Pitch Angle, Bank Angle and Overspeed Limit Checks, the Bank Angle Hands-free Check, and the Overspeed and Bank Angle

Protection Checks are robust. Also, the Normal Load Factor Limit Check, the Roll Rate Controllability Check, and the Pitch Trim Drift Check showed acceptable robustness. However, additional conditions, e.g. wake vortex encounter should be investigated to conclusively demonstrate the robustness of the IMFs.

Most of the remaining IMFs showed the potential to achieve the desired robustness with simple adjustments in their design parameters. Increasing the thresholds and/or confirmation times of most IMFs will be sufficient to improve their robustness. It must be investigated if the IMFs are still effective. IMFs that are not effective or that have unacceptable robustness cannot be used. As they would trigger false alarms and thus reduce the availability of the NM FCL with an unacceptable high probability.

A detailed evaluation of the robustness of each IMF is documented in reference [12].

2.8 D-6.1 „Assessment of required effort for implementation"

In Task 6, a qualitative assessment of the proposed Independent Monitor Functions (IMFs) is performed in respect to the required efforts and constraints for their implementation, and the most suitable IMFs are taken into account in the trade-offs between performance and the required effort for their implementation.

The objective of this implementation effort assessment was to provide a qualitative comparison for the different types of proposed IMFs between each other rather than to compare the implementation effort of a flight control system without IMFs to a flight control system with IMFs. However, the latter aspect will be subject to further discussions complementing results obtained in this project.

It is important to note that the real implementation effort for such IMFs will largely depend on the development toolchain and approaches used (e.g. model-based development approaches acc. DO-331), the flight control system work shares between the airframer and suppliers (e.g. flight control functionalities developed fully in-house at airframer or shared between airframer and supplier) as well as on the experience and know-how of the particular airframer.

In this project a very simple, qualitative implementation effort rating scale was applied. This can only give a rough hint on the level of implementation effort required for the different considered IMFs. The rating scale consists of three implementation effort levels: low, medium and high implementation effort. A low implementation effort, when compared to the other IMFs is classified as *good*. A high implementation effort when compared to the other IMFs is classified as *bad*. Everything in between (medium) is considered *acceptable*.

The implementation effort assessment takes into account the development steps and focuses on the criteria: IMF algorithm complexity, validation and verification effort and expected IMF tuning effort. The following development steps are required to implement IMFs:

- **Analysis of Considered Failure Modes and Effects** (is the same for all IMFs),
- **IMF System Requirements Capture** (is similar for most IMFs),
- **IMF Design and Preparation of Closed-Loop Simulation** (is specific for the different types of IMFs),
- **Monitor Validation** (is similar for most IMFs),
- **High-level SW Requirements Capture** (is specific for the different types of IMFs),
- **SW-Design and Implementation** (is specific for the different types of IMFs), and
- **Monitor Verification** (is similar for most IMFs).

The implementation effort was assessed as specified in Table 2-3. The detailed assessment of the implementation effort is documented in reference [13].

Table 2-3: Implementation Effort of different IMF types.

IMF type	Implementation Effort	Comment
Limit Checks	**Low**	Simple algorithm, V+V activities easy to set up, low effort for tuning activities expected
Hands-free Checks	**Medium**	Simple algorithm, V+V activities easy to set up, medium effort for tuning activities expected
Sign Checks	**Medium**	More complex algorithm, V+V activities set up require more effort, medium effort for tuning activities expected
Controllability Checks	**Medium**	More complex algorithm, V+V activities set up require more effort, medium effort for tuning activities expected
Protection Function Checks	**High**	More complex algorithm, V+V activities set up require more effort, high effort for tuning activities expected
Command Sign Check	**High**	More complex algorithm, V+V activities set up require more effort, high effort for tuning activities expected
Pitch Trim Drift Check	**Medium**	More complex algorithm, V+V activities set up require more effort, medium effort for tuning activities expected
Command Comparison	**Medium**	Simple algorithm, V+V activities set up require more effort, medium effort for tuning activities expected

2.9 D-6.2 „Substantiated list of suitable monitors"

In Task 6, a qualitative assessment of the proposed Independent Monitor Functions (IMFs) is performed in respect to the required efforts and constraints for their implementation, and the most suitable IMFs are taken into account in the trade-offs between performance and the required effort for their implementation.

The three evaluation criteria (robustness, effectiveness and implementation effort) were used to identify suitable IMFs. Each criterion has a different weighting in the evaluation of suitable IMFs. The robustness is the most important criterion and has a weighting of 60 %. The effectiveness of IMFs is the criterion with the second highest weighting of 30 %. The weighting of the implementation effort is 10 %. The detailed identification of suitable IMFs is documented in reference [14].

It is important to note that the results of the robustness and effectiveness evaluations described in references [11] and [12] are highly dependent on the selected test conditions. Therefore, the results presented in this project are only valid for the test conditions investigated.

All limit check IMFs can be recommended. The five IMFs can detect failures that lead to extreme aircraft attitudes and exceedance of the safe flight envelope limits with high effectiveness. The Pitch Angle Limit Check is redundant to the Overspeed, Normal Load Factor and Angle of Attack Limit Checks and can replace them without reducing the effectiveness of the Independent Monitor of FCL (IM-FCL)[3]. However, this may not be the case for other failure conditions that were not investigated in this project.

The limit check IMFs are robust under the simulated test conditions. And their implementation effort is low compared to other IMFs. However, limit check IMFs cannot detect failures that result in reduced manoeuvrability of the aircraft. This type of failures is best detected by the controllability check IMFs. Overall, the controllability check IMFs showed good[4] effectiveness and acceptable robustness. Although their implementation effort is higher when compared to other IMFs, these IMFs can be recommended.

Also recommended are the Pitch Trim Drift Check, Elevator Command Comparison and Aileron Command Comparison IMFs. The first showed good effectiveness and acceptable robustness. The command comparison IMFs detect command runaway like failures with high effectiveness. However, their robustness needs to be improved. Also, the constraining condition of these IMFs is that the aircraft is operated in the normal flight envelope. The risk of a command-runaway-like-failure manifesting itself in the normal flight envelope is lower than at the corners of the flight envelope. Overall, both comparator check IMFs are an indirect plausibility check of the FCL commands. They can replace hands-free check and sign check IMFs.

The Rudder Command Comparison IMF is the exception. It is questionable if the IMF can remain effective while improving its robustness. This IMF can be replaced by the Sideslip Angle or Lateral Load Factor Hands-free Checks. Both hands-free IMFs can be recommended.

Most hands-free IMFs require further improvements in terms of robustness. Also, it is questionable if the constraining conditions are met in a realistic scenario. These IMFs showed potential but require more development effort. It is considered that most hands-free check IMFs can be replaced by other concepts. An exception is the Bank Angle Hands-free Check, which showed acceptable effectiveness and robustness. Therefore, the Bank Angle Hands-free Check is recommended.

The sign check IMFs require further improvements in terms of robustness. These IMFs are suitable to detect failures that lead to control reversal. They showed potential but require more development effort.

Also, the protection function check IMFs did not show good effectiveness. These IMFs require more development effort to achieve an acceptable level of robustness and effectiveness. It has to be investigated if protection function checks can supplement the IM-FCL to increase effectiveness in the corners of the flight envelope.

The Aileron Command Sign Check did not prove to be effective nor robust. Although, the robustness may be improved by adjusting the thresholds of the IMF, it remains questionable if the monitor can be effective. Therefore, the Aileron Command Sign Check is **not recommended**.

[3] An Independent Monitor of FCL comprises several IMFs.
[4] Although the POD of these IMFs was lower than expected, their effectiveness is assumed to be high under more realistic conditions.

To summarise and for a better overview, here is the list of recommended IMFs[5]:

- **Pitch Angle Limit Check**,
- **Bank Angle Limit Check**,
- **Angle of Attack Limit Check**,
- **Overspeed Limit Check**,
- **Normal Load Factor Limit Check**,
- **Roll Rate Controllability Check**,
- **Flight path Controllability Check**,
- **Pitch Trim Drift Check**,
- **Bank Angle Hands-free Check**,
- **Sideslip Angle or Lateral Load Factor Hands-free Check**,
- **Elevator Command Comparison**, and
- **Aileron Command Comparison**.

[5] Additional IMFs may be required to improve the effectiveness of the IM-FCL in the corners of the flight envelope. The protection function check IMFs may be suitable for this purpose.

3 Conclusion

As presented in the final dissemination workshop[6] held at the EASA premises in Cologne on the 25th of September 2024, the results and conclusions of this project are based on the scope of this project, as well as limitations and assumptions made in this project. The following sections summarize the main aspects of this project.

3.1 Motivation

With increasing complexity of FCLs the risk of undetected development errors increases. Full validation coverage of all combinations of operating conditions is difficult, if not impossible. It is postulated that development errors may be hidden in the FCL requirements. A possible solution to mitigate the risk of such development errors is the introduction of independent FCL monitors.

3.2 Scope and Assumptions

The aim of the project was to investigate the general feasibility of introducing flight control law monitors to detect FCL development errors. All statements and results are based on the premise that FCL monitors are introduced. An assessment of the safety benefits of FCL monitors in general or compared to other approaches was **not** within the scope of this project.

Tripping of the FCL monitors will ultimately lead to some kind of FCS reconfiguration. However, reconfiguration strategies were **not** within the scope of this project. It is assumed that failure detections result in an automatic switch to a backup mode (Direct Mode type) FCL providing full authority control to the flight crew. The backup mode FCL is an alternative to the Normal Mode FCL, which is functionally independent and simpler. It was therefore assumed that the Direct Mode FCL is error free.

FCLs include command and stability augmentation functions and flight envelope protection functions. Input monitoring and consolidation functions are not a part of the Normal Mode FCL to be monitored. It is therefore assumed that all inputs to the FCL and to the Independent Monitor are correct.

Within this project, focus was on the investigation of failure modes impacting flight dynamics and aircraft controllability. Failure modes impacting the structural integrity of the aircraft were **not** in the scope of this project.

3.3 Approach and Objectives

A survey on documented accidents or incidents did not reveal any specific examples of incidents directly related to FCL development errors. It is assumed that the FCL failure modes defined and investigated within this project are representative. It is also recognised that the risk of FCL failures occurring within the normal operational flight envelope may be lower than at the corners of the flight envelope.

A design objective of the Independent Monitor is that it shall not reduce the availability of the normal mode FCL, which was assumed to be 10^{-7}. However, for the sake of this first feasibility study, a false alarm probability of 10^{-5} was considered acceptable. It is recognised, that a design

[6] Link to project webpage: Monitoring of flight control laws | EASA (europa.eu).

objective of zero false alarms should be pursued in real development projects. However, given the limited time and small team, a relaxed design objective was accepted to have a larger amount of IMFs with the aim to allow a more comprehensive comparison of the different concepts.

Twenty-four simple monitoring functions have been proposed and investigated regarding their effectiveness and robustness. It is recognised that none of these single functions will meet the requirements for effectiveness. An effective Independent Monitor is a combination of several monitoring functions. The results of this project are a comparison between these functions. Other concepts and functions may be required and may be more appropriate for different aircraft.

For a detailed list of assumptions and description of the chosen approach for monitor evaluation, refer to references [4], [5], [6], [10], [11], [12], [13] and [14].

3.4 FCL Monitor Evaluation Results

The evaluation of the effectiveness test conditions showed that the combination of 24 IMFs to an Independent Monitor of Flight Control Laws (IM-FCL) can effectively detect all investigated failures. Sufficient **monitoring effectiveness** is **achievable** for CAT failure conditions. The effectiveness test results also showed that several failures were detected by more than one IMF.

Further evaluation revealed that a simpler IM-FCL, consisting of only eleven IMFs, was able to effectively detect all the failures investigated. The test results also showed that the percentage of detection does not change significantly when recoverability is considered.

The evaluation of the robustness test conditions showed that **robustness is a challenge**. Further evaluation and tuning are required. However, the results give confidence that sufficient robustness can be achieved with minor changes. However, these improvements for robustness may also increase the complexity of the functions and their development effort. In addition, it needs to be investigated whether sufficient effectiveness can still be achieved.

It is important to note, that the effectiveness and robustness results are highly dependent on the selected test conditions. It is therefore necessary to validate that the test conditions investigated are representative and sufficient to assess the effectiveness and robustness of the Independent Monitor. Additional conditions, e.g. wake vortex encounter, should be investigated to conclusively demonstrate the robustness of the IMFs. In addition, the effects of false alarms and their hazard need to be assessed and validated.

Additional aspects still to be investigated are related to crew-alerting (CAS), FCL reconfiguration and pilot-in-the-loop assessments. Therefore, **further research is proposed** in **collaboration** with airframers, research organisations and authorities.

3.5 Summary

1. Considering all aspects and assumptions described above, the Independent Monitor **shows potential to achieve the level of trust** that the risk for potential development errors in the FCL in all foreseeable flight conditions is mitigated sufficiently.
2. Sufficient **monitoring effectiveness** is **achievable** for CAT failure conditions.
3. Monitoring **robustness is a challenge** and requires further evaluation and tuning. This will improve the results; at the same time, it may also increase the complexity of the functions and the development effort.

4 List of Figures

5 List of Tables

6 Bibliography

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