Monitoring of Flight Control Laws

The EASA Horizon Europe Project on Monitoring of Flight Control Laws – Project Closure Meeting

Cologne, Sept. 25, 2024

This project has received funding from the European Union's Horizon Europe Programme

LIEBHERR

Liebherr-Aerospace Lindenberg GmbH

In partnership with

TU berlin
INSTITUT FÜR LUFT- UND RAUMFAHRT
FACHGEBIET FLUGMECHANIK, FLUGREGELUNG, UND AEROELASTIZITÄT

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Agenda

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   - Additional Aspects and Challenges
   - Monitor Concepts – some examples of monitor designs
3. **FCL Monitoring – Evaluation Approach**
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Project Introduction
Overview

Overview

This project has received funding
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Motivation:

- EASA generic CRI on „Common Mode Failures and Errors in Flight Control Functions”
- General demand for increased means for common mode mitigation in complex systems

Objectives:

- Investigate the introduction of flight control law monitors to detect errors
- Improve the EASA certification standards
- Support the evaluation of new designs proposed by aircraft manufacturers.

Realization:

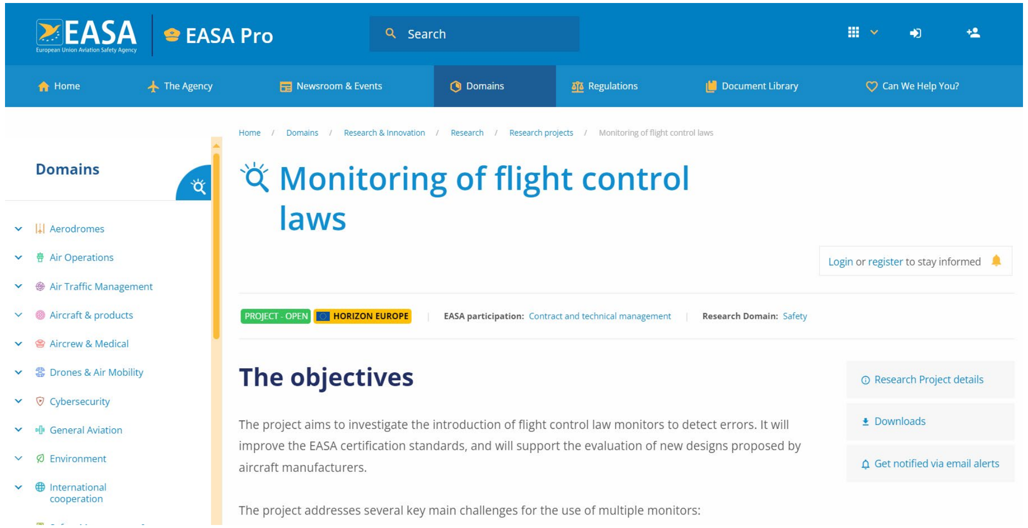
- Development of observer-like FCL monitors, based on independent set of requirements

Challenges:

- Robust and effective FCL monitor design
- Avoidance of added complexity and reduced availability

EASA contracted project in the frame of the European Union’s Horizon Europe Programme

Monitoring of flight control laws | EASA (europa.eu)



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Project Introduction
Problem Statement

Problem Statement

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Flight Control Laws

— Are developed according highest development assurance levels (DAL A)

— Including extensive validation activities (are the requirements correct, consistent, and complete?)

Due to increasing FCL complexity

— The risk for undetected requirements errors increases

— e.g. full validation coverage of all combinations of operating conditions is difficult or not feasible at all

It is postulated, that **hidden development errors might be present in FCL requirements**

Problem Statement Represented in V-Model

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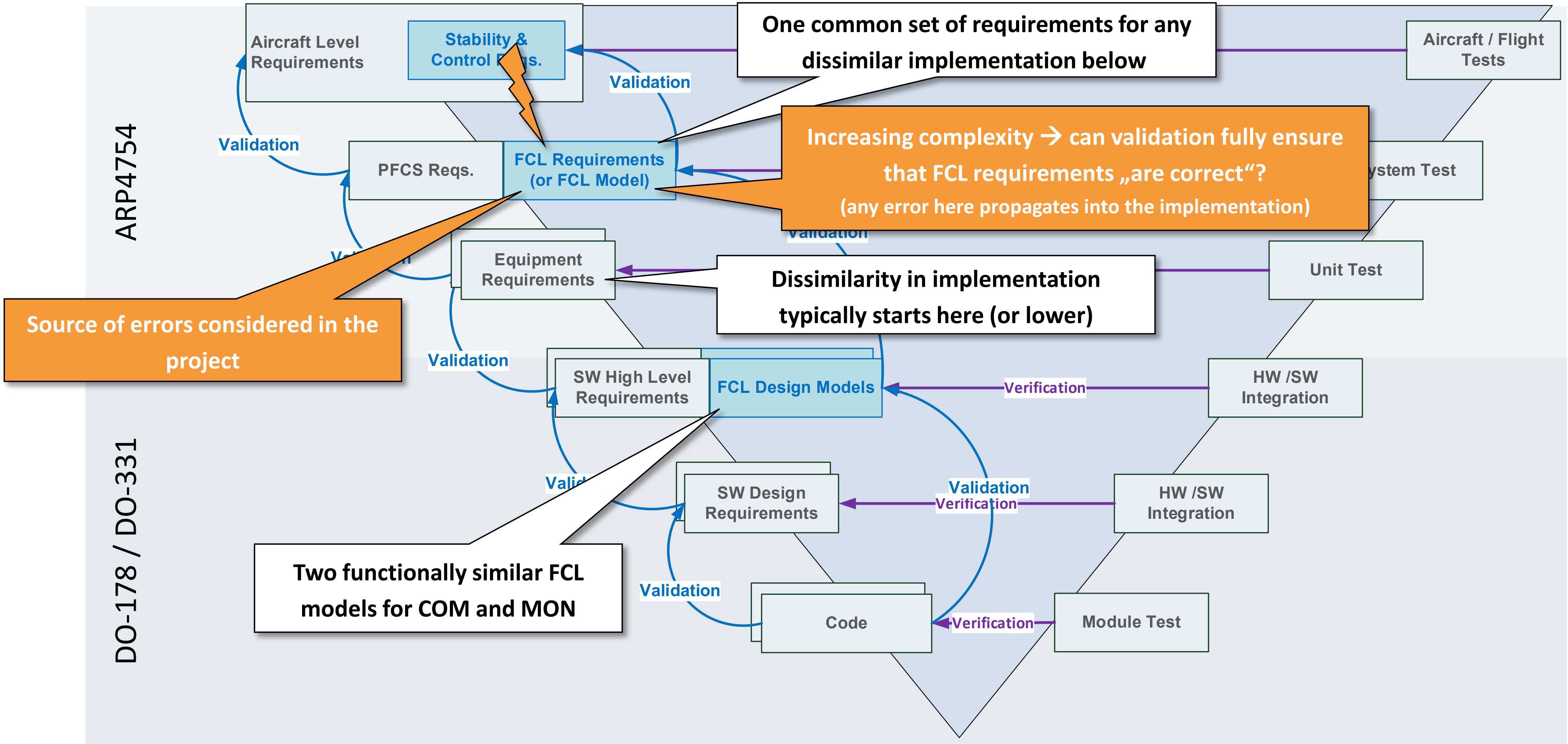

Problem Statement Represented in Duo-Duplex Architecture

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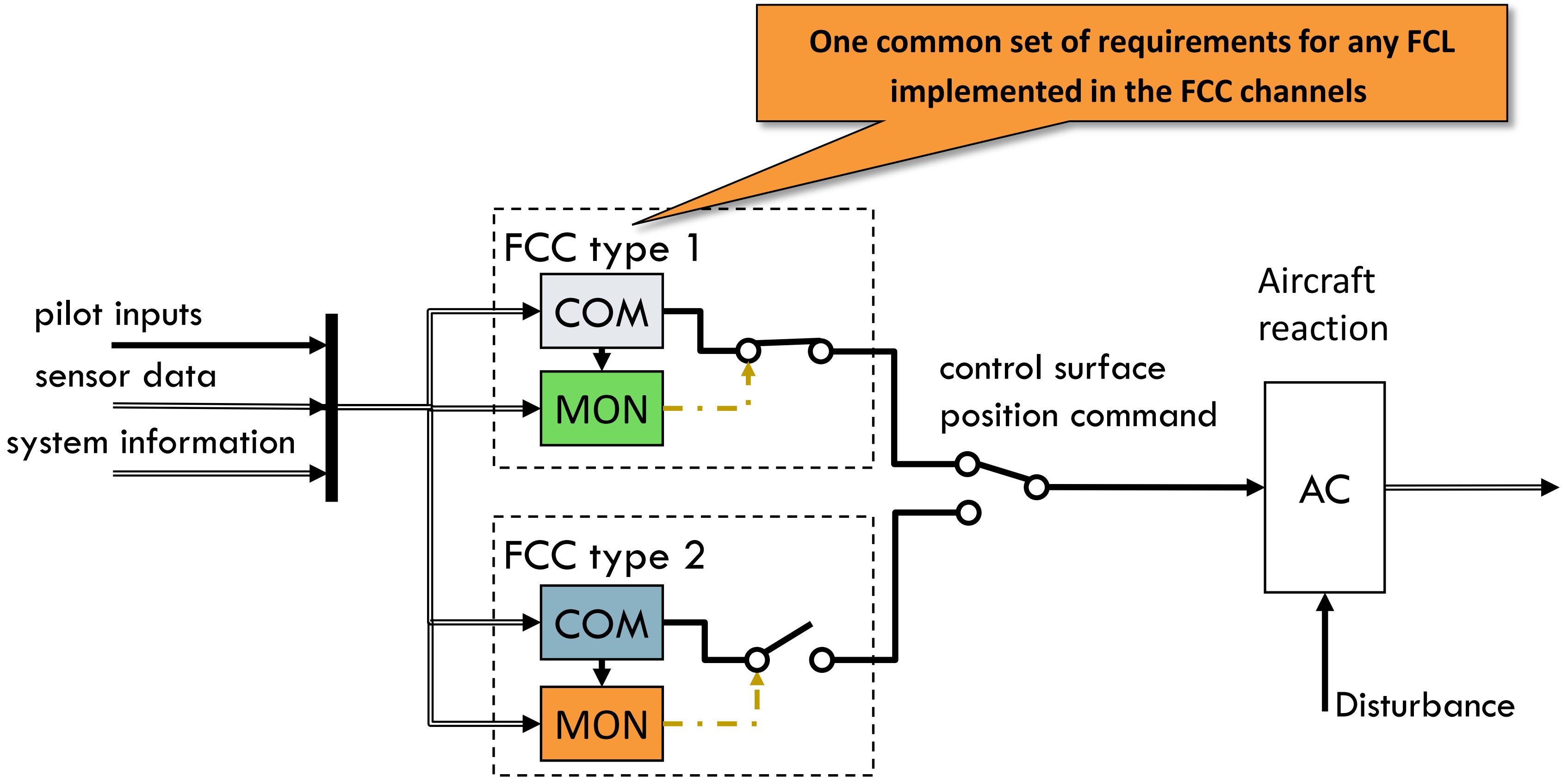

- Integrity of both FCC type 1 and 2 is ensured by dissimilar COM/MON (covers implementation errors, sporadic failures)
- Availability (also in case of common mode HW failures) is ensured by dissimilar FCC type 1 and 2
- **But: FCL implemenations in all 4 lanes based on one common set of requirements**

Project Introduction
Schedule and Team

Project Schedule and Status

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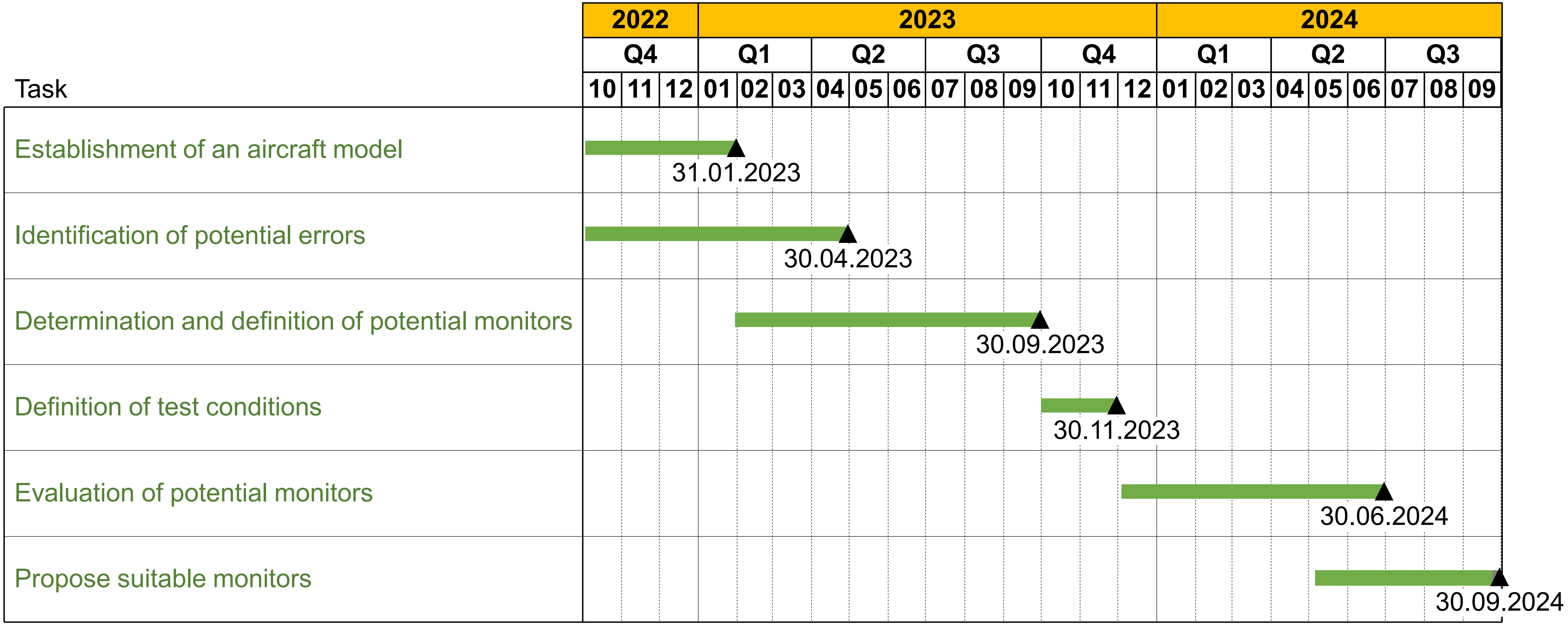

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Project Team

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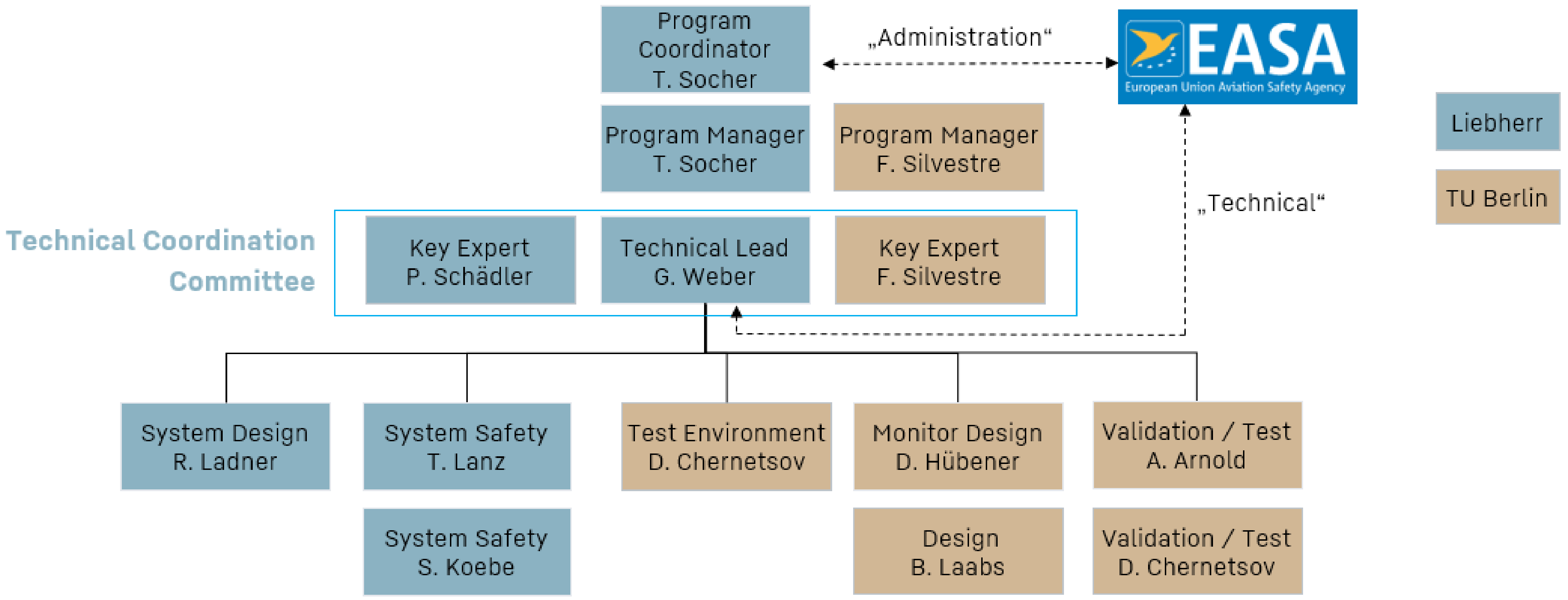

FCL Monitoring – Concepts & Considerations
Scope and Boundary Conditions

Scope and Boundary Conditions

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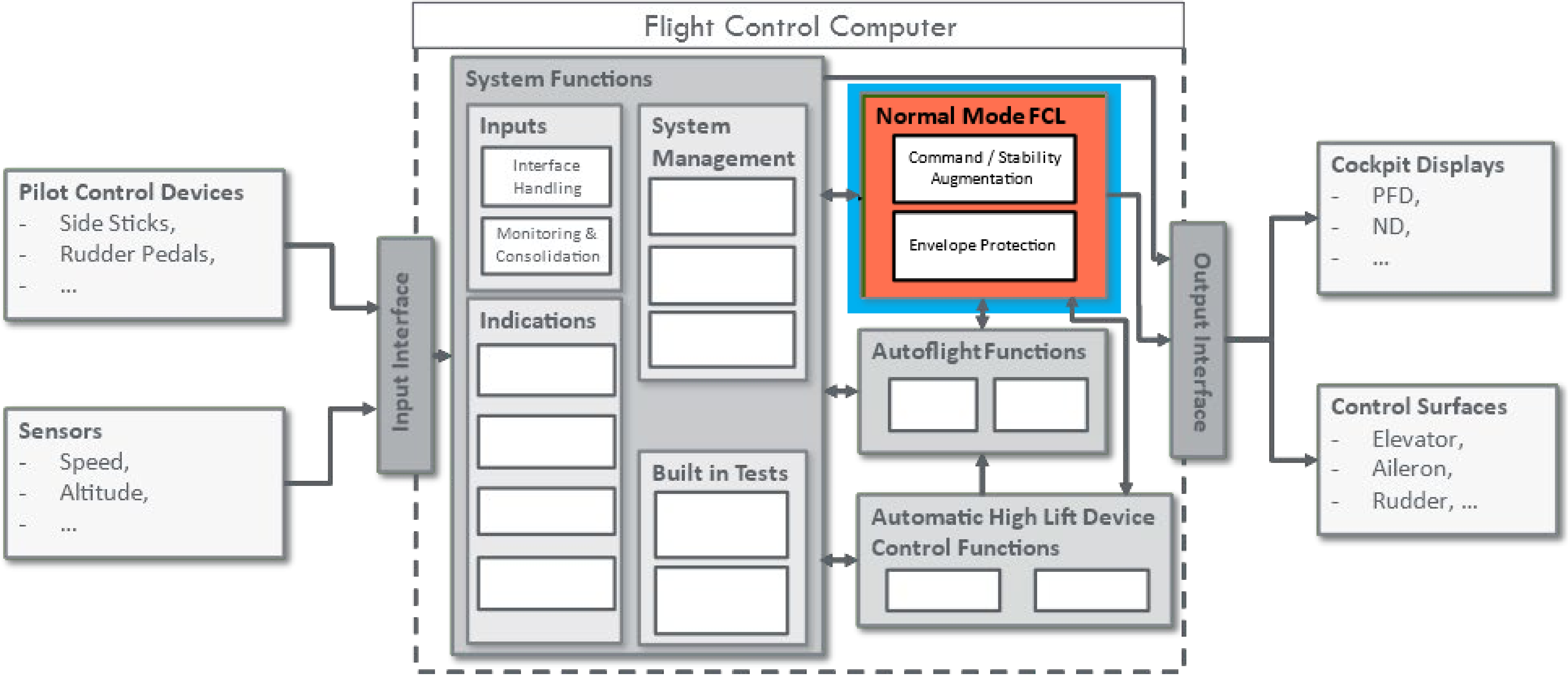

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Scope and Boundary Conditions

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- FCL inputs are monitored and consolidated outside FCL → **FCL inputs are considered valid**
  (…but yes, many of the reviewed in-service events were related to corrupted input data…)
- The FCL monitor task is to assess FCL commands & aircraft state **vs high-level aircraft (safety of flight) requirements**
- Aircraft requirements are generic and error-free
- The critical effect of an FCL error is the **malfunction of the Normal Law FCL**, not the loss of function
- The FCL Monitor can complement but **not replace redundant architectures (e.g. COM/MON)**

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Scope and Boundary Conditions

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Focus within this project is on:

- Development of possible FCL monitor concepts
- Assessment of FCL monitor concepts regarding effectiveness and robustness

Out of Scope for this project:

- Reconfiguration strategies: What is the reaction once FCL Monitors have tripped?
- Operational aspects: What are the fleet consequences in case FCL Monitors have tripped?

FCL Monitoring – Concepts & Considerations
Additional Aspects and Challenges

Additional Aspects and Challenges

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1. **Incident / accident reports**
   - No evidence was found for incidents directly related to FCL errors (mention (PIO) events during development tests…)
   - How do we quantify safety improvement by FCL monitors?
2. **What is an „FCL error“ or a „FCL malfunction“?**
   - Classic unintended functions? Unvalidated (inadvertent) behavior in corners of the operational envelope? Inadvertent FCL behavior in abnormal situations?
   - Functionality based on conscious but wrong assumptions in CLAW design?
     - Example: PIOs… classic pilot quote: “I thought the system was malfunctioning“ …when everything worked as designed.
3. **Observer Approach: If we compare FCL monitor to flight crew monitoring the aircraft behavior**
   - Ensure situational awareness, especially in abnormal situations
   - Manage to “stay ahead of airplane“, comprehend FCL decisions, especially in abnormal situations

Additional Aspects and Challenges

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Challenges from the objective of FCL monitors:

- Use **simple algorithms** (and less input data/knowledge) to assess decisions of complex FCLs
- Straightforward simple monitors will work only in situations when basic functionality is involved
- Complex functionality is engaged during highly dynamic maneuvers, corners of the flight envelope

Flight Condition	Involved functionality	Potential risk of errors involved = need for monitor	Potential of simple FCL monitor
Straight and level flight, slight maneuvers	Simple	Low	High
Dynamic maneuvering	Mid	Mid	Low
Operation at edges of flight envelope	Complex	High	Low

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FCL Monitoring – Concepts & Considerations
Monitor Concepts

Monitor Concepts – Design Objectives

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The Independent FCL Monitor:

- shall **detect failures**, i.e. erroneous function (malfunction), of the FCS caused by FCL development errors,
- shall be **functionally independent** of the normal mode FCL,
- shall **only detect failure conditions** that are classified as **catastrophic,**
- shall be **robust** against false detections under all foreseeable operational conditions (any **decrease of FCL availability shall be avoided** as it would decrease the established level of safety)
- shall **be as simple as possible** (its level of complexity shall be significantly lower than Normal Mode FCL)

Monitoring Architecture – Considerations

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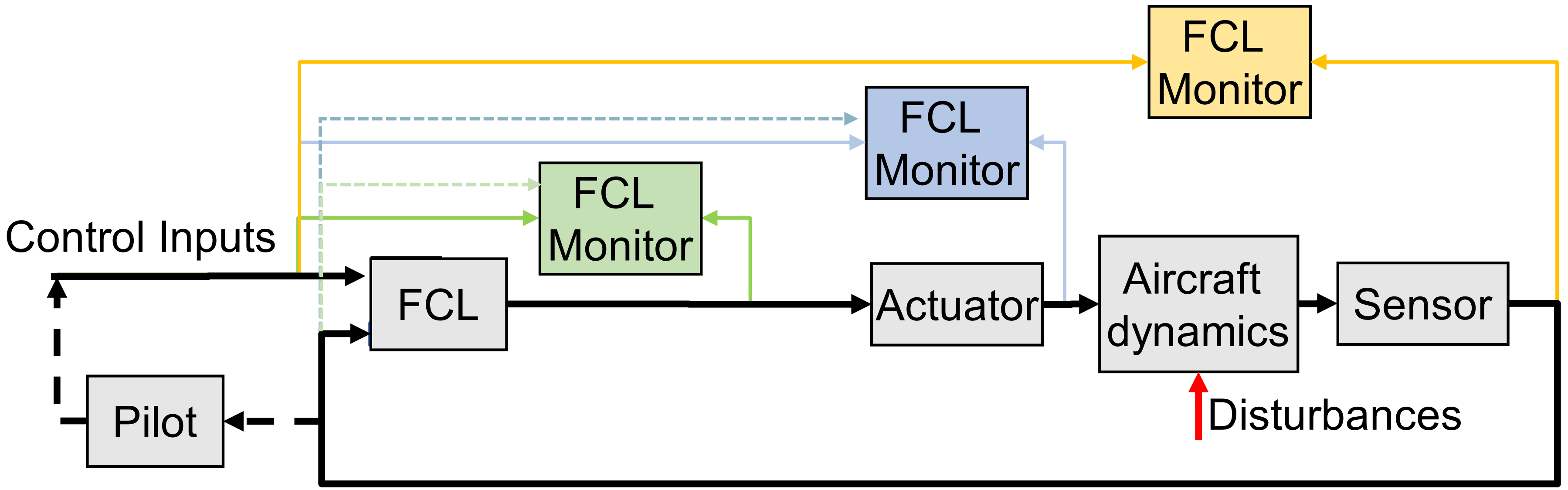
- **Green monitor checks if the FCL output fits the control inputs.**
  Difficulty: develop independent requirements for the monitor.
- **Blue monitor checks if the actuator deflections fit the control inputs.**
  Difficulty: develop independent requirements for the monitor and isolate the source of the failure.
- **Yellow monitor checks if the aircraft reaction fits the control inputs - like an instructor observing a student pilot.**
  Difficulty: unknown disturbances may significantly impact the aircraft reaction.



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Monitoring Architecture – Considerations

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Green monitor

+ early failure detection,
+ detected failures can be directly localised to the FCL → simplifies fault isolation,
− achieving functional independence between monitor and FCL is a challenge,
− critical control surface transients must be derived from a/c level hazard assessment.

Blue monitor

+ early failure detection,
− actuator is part of the monitored system:
  - actuator failures may result in spurious FCL monitor trips → requires provisions for fault isolation,
  - state of the art monitoring covers actuator failures already.

If actuator is failure free → same advantages and challenges as green monitor.

Yellow monitor

+ hazard assessment of failure conditions is straightforward,
+ functional independence between monitor and FCL,
− influence of external disturbances has to be taken into account.

Monitoring Architecture

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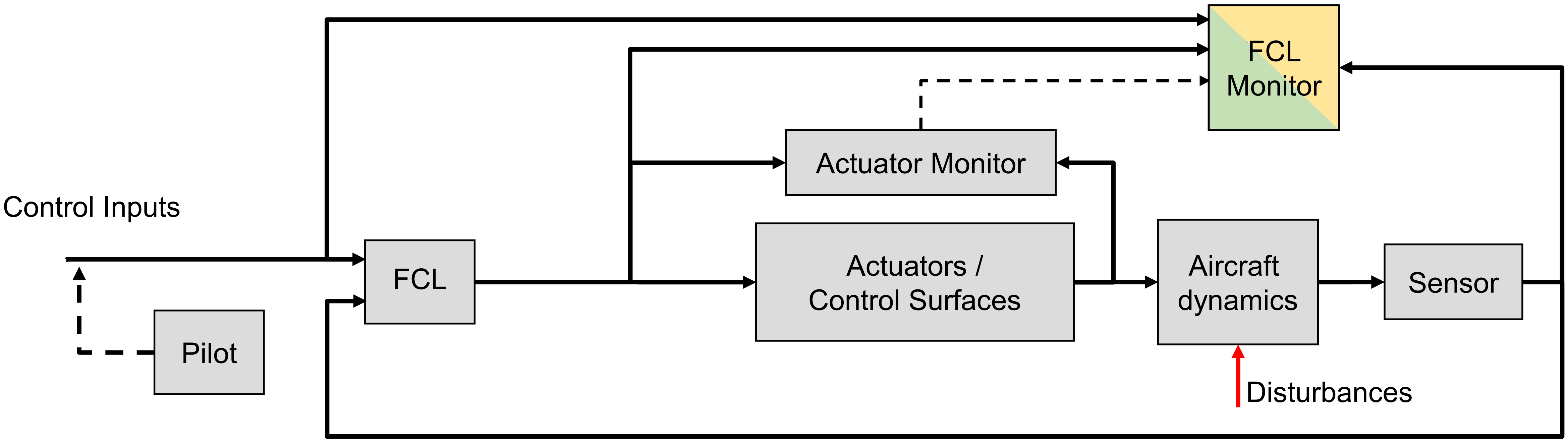

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List of Proposed Monitors

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Function	Monitored Parameter	Type
Limit Checks	V_{CAS}, n_z, θ, α and ϕ	Plausibility Check – AC level
Handsfree Checks	p, ϕ, n_z, β and n_y	
Sign Checks	p, q, and n_z	
Controllability Checks	p and γ	
Protection Function Checks	η_{cmd} and ξ_{cmd}	Plausibility Check – FCL level
Command Sign Check	ξ_{cmd}	
Pitch Trim Drift Check	THS command	
Command Comparison	η_{cmd}, ξ_{cmd} and ζ_{cmd}	Comparator

Total of 24 monitoring functions proposed.

FCL Monitoring – Evaluation Approach
Flight Simulation Environment

The Flight Simulation Environment

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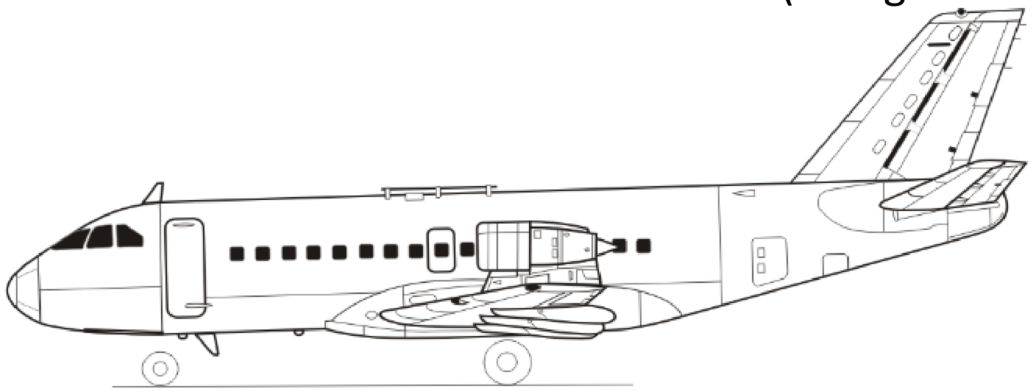
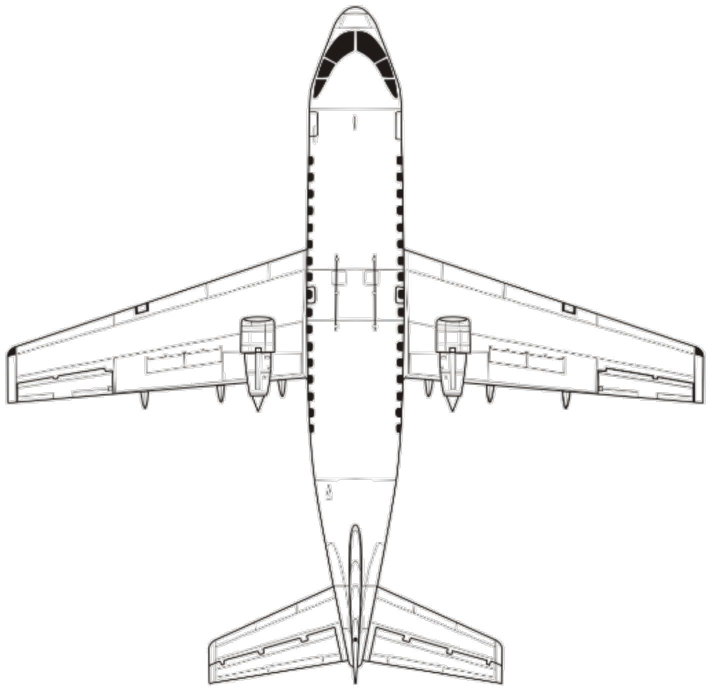
- TUB provides an aircraft model that **is highly representative of modern fly-by-wire aircraft and the complexity of current flight control laws.**
- The simulated aircraft is the twin jet **VFW 614-ATD (**Advanced Technology Demonstrator).
- The Flight Mechanical Model:
  - Implements the nonlinear dynamics of the VFW 614-ATD aircraft,
  - Covers all flight phases, aircraft configurations, manoeuvres, and environmental conditions
  - Contains an idealised FCS architecture (a single lane is simulated)





FSEnv Architecture

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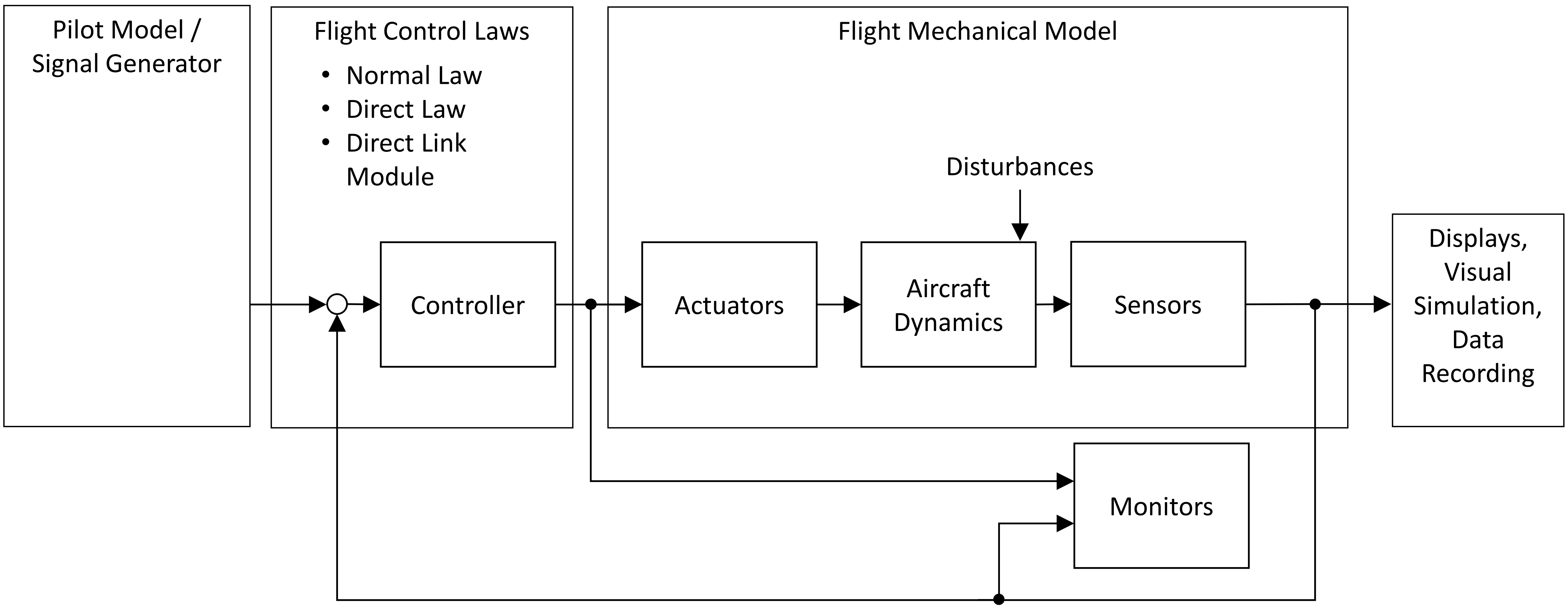

FCL Monitoring – Evaluation Approach
Evaluation Approach and Trim Points

General Approach

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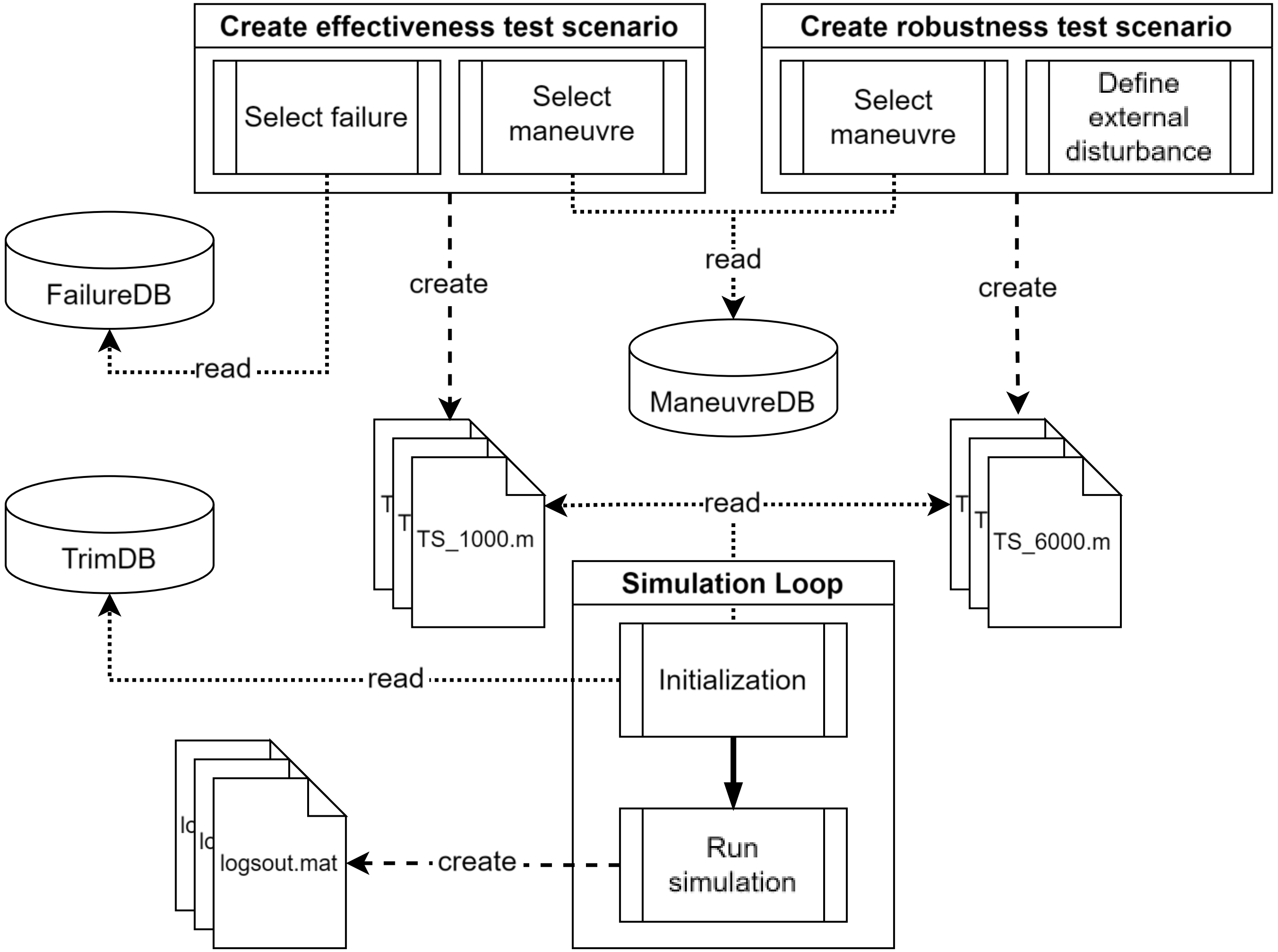
Effectiveness test conditions comprise:

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

Robustness test conditions comprise:

- initial flight condition (trim point),
- external disturbance, and
- flight maneuvers.



Selected Trim Points

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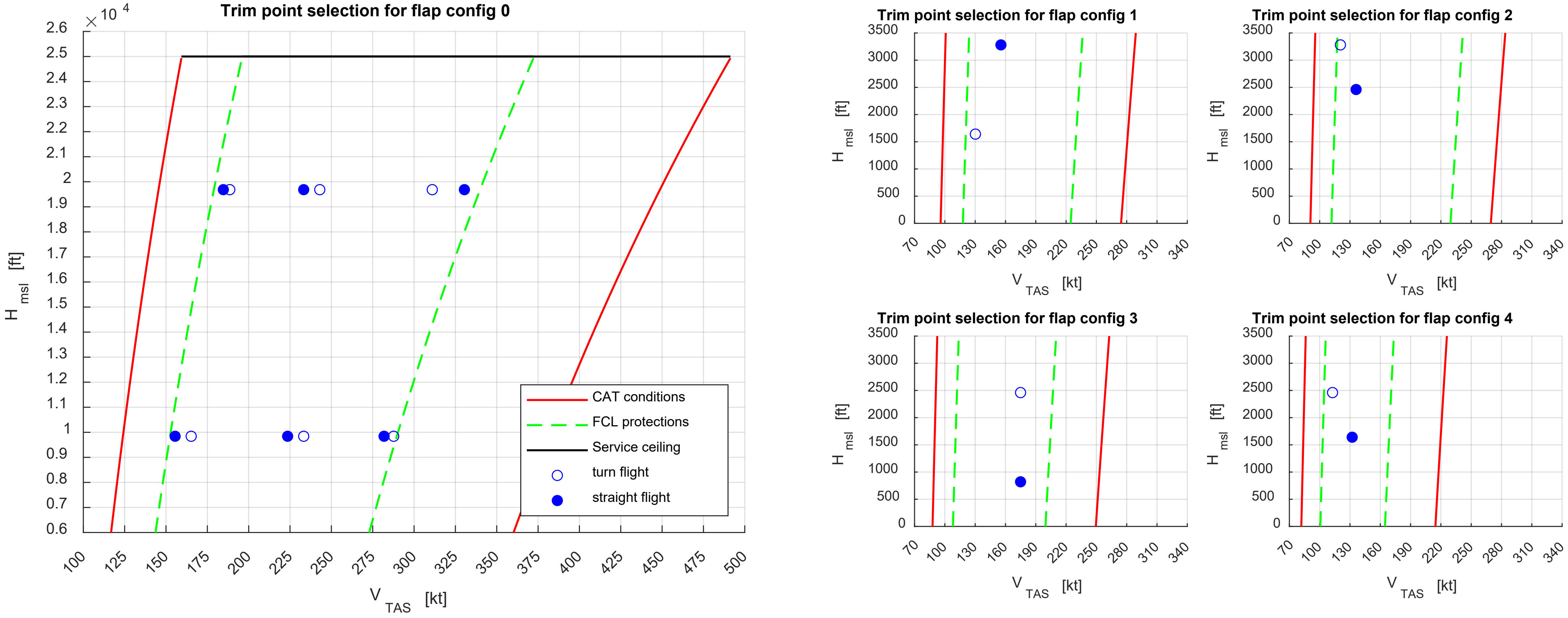

Total of 12 trim points at middle and high altitudes and 8 trim points at low altitudes selected.

FCL Monitoring – Evaluation Approach Investigated Failures

Assumptions and Approach – Failure Identification

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- Consider **only CAT failure** conditions (because of FCL development errors),
- No specific examples of FCL requirement or design errors were identified,
- Use of the Normal Law (NL) of VFW 614-ATD for investigation of failure conditions,

→ Identification and **classification of the effects** (failures) of FCL errors.

→ Two classification approaches:

1. Based on source of failure – functional classification
2. Based on the dependency of inputs – active failures / reactive failures

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Failure Classes – Functional Classes

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Functional classification:

LOG

- Erroneous switching of the modes
- Erroneous activation of PRT

FCF

- Erroneous behaviour in primary control functions

PRT

- Erroneous behaviour when PRT is active

ATD FCL Normal Law Functions
NORMAL LAW MODE LOGIC FUNCTIONS (LOG)
• Normal Law Modes (Ground Mode, Flight Mode)
• Protection Activation
CONTROL & STABILITY/FLIGHT CONTROL FUNCTIONS (FCF)
• Pitch Normal Law
• Roll Normal Law
• Yaw Normal Law
PROTECTION FUNCTIONS (PRT)
• Load factor protection
• High Speed Protection
• Pitch Attitude Protection
• High AoA Protection
• Bank Angle Protection

Failure Classes – Dependency on the Input Signals

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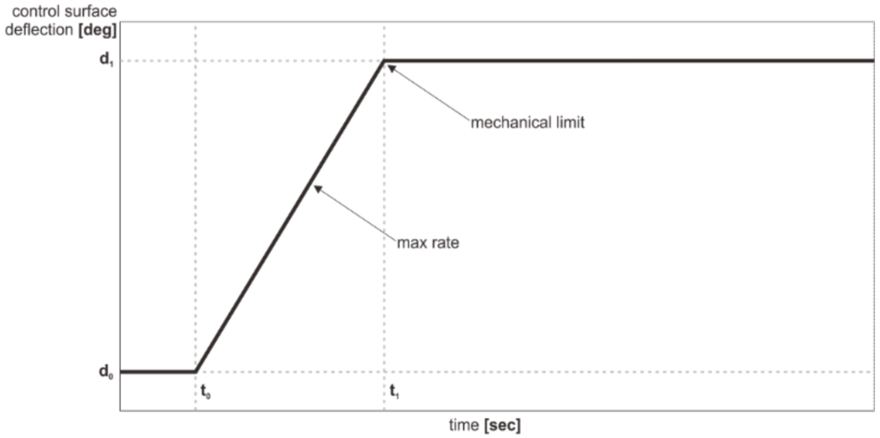

Classification in Dependency on Input Signals

Active failure class:

- Failures are independent of the FCL input signals,
- Failure effect can vary in amplitude, time response, etc.
- ➢ Failures show typical actuator-like outcome signature (e.g. runaway).

Reactive failure class:

- Failure effects highly dependent on FCL input signal(s) (sensors, pilot),
- Failures increase PIO tendency, reduce the damping of flight dynamic modes, reduce handling qualities, etc.
- ➢ Failures show no typical signatures and require specific investigation.

Failure Generator

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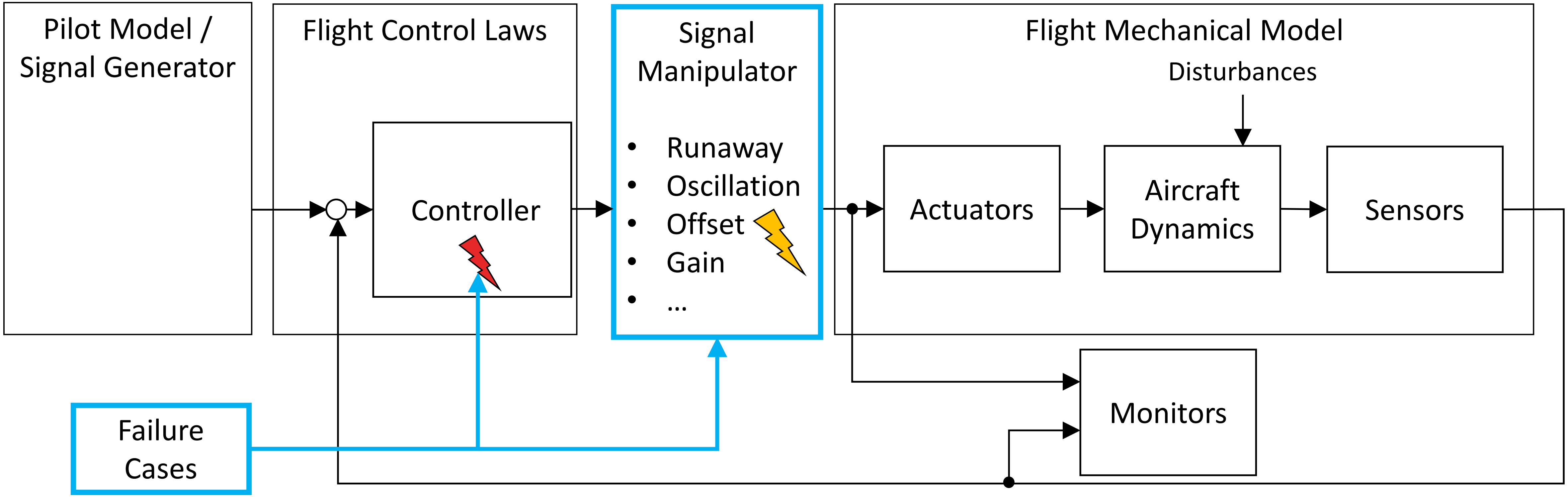

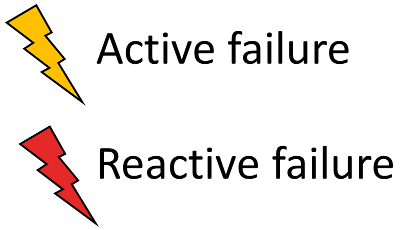

Total of 22 active and 11 reactive failure types investigated.

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Failure Condition Hazard Assessment

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If limits of table are exceeded, continued safe flight and landing is **not** possible.

* Assumption: Exceeding V_{FE} by $50kt$ is assumed to be CAT.

** Not recoverable stalls are considered CAT. Stalls are assumed to be recoverable for H > 1000 m.

Configuration [1]	0	1	2	3	4
Flap deflection η_F [°]	-6	1	5	14	35
$V_{CAS,max}$ [kt]	330.0	275.0*	270.0*	250.0*	215.0
$V_{CAS,min}$ [kt]**	107.0	96.0	91.0	88.0	82.0
$n_{z,min}$ [-]	$n_z < -1.5$	$n_z < -0.5$			
$n_{z,max}$ [-]	$n_z \geq 4$	$n_z \geq 3$			
$\|\Phi\|$ [°]	$\|\Phi\| > 90°$	$\|\Phi\| > 80°$			
α_{max}[°]**	12.9	14.4	14.5	13.3	11.2
$n_{y,max}$ [-]	1 g				

A/C is maneuverable if:

- $n_z \leq 0.8\ g$ within **2 s** after a push-over maneuver, AND
- $n_z \geq 1.3\ g$ within **2 s** after a pull-up maneuver, AND
- $|\Delta\Phi| \geq 45°$ within **3.8 s***** after a full roll input.

***Requirement from MIL-F-8785C

FCL Monitoring – Evaluation Approach Investigated Maneuvers and Disturbances

Proposed Maneuvers

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ID	Description
HF	Hands-free
CLB	1000ft climb manoeuvre, 2000ft/min rate of climb
DSNT	1000ft descent manoeuvre, -2000ft/min rate of descent
TURN	Initiate a 90-degree turn, with turn rate of $r = 3\ °/s$
TCLB	Stationary turn, 1000ft climb manoeuvre
TDSNT	Stationary turn, 1000ft descent manoeuvre
LND	Landing approach with lateral offset to localiser with pilot model
FCLBPS	3000ft fast climb manoeuvre, $\dot{H} > 5000 ft/min$ rate of climb, if target altitude is reached high push command.
FDSNTPL	3000ft fast descent manoeuvre, $\dot{H} < -5000 ft/min$ rate of descent, if target altitude is reached high pull command.
EDSNT	Emergency descent, full spoiler, thrust 0, $\dot{H} = -6000 ft/min$ rate of descent.
FTURN	Initiate a 180-degree turn, with turn rate of $\dot{\chi} > 5\ °/s$, high pull-up command allowed, constant altitude +-500ft.
TFCLB	fast 3000ft climb manoeuvre and turn with turn rate of $\dot{\chi} > \ 5\ °/s$, then level flight.
TFDSNT	fast 3000ft descent manoeuvre and turn with turn rate of $\dot{\chi} > 5\ °/s$, then level flight.
LNDHG	Landing approach with high lateral offset to localiser with pilot model, high gain pilot.

Proposed Disturbances

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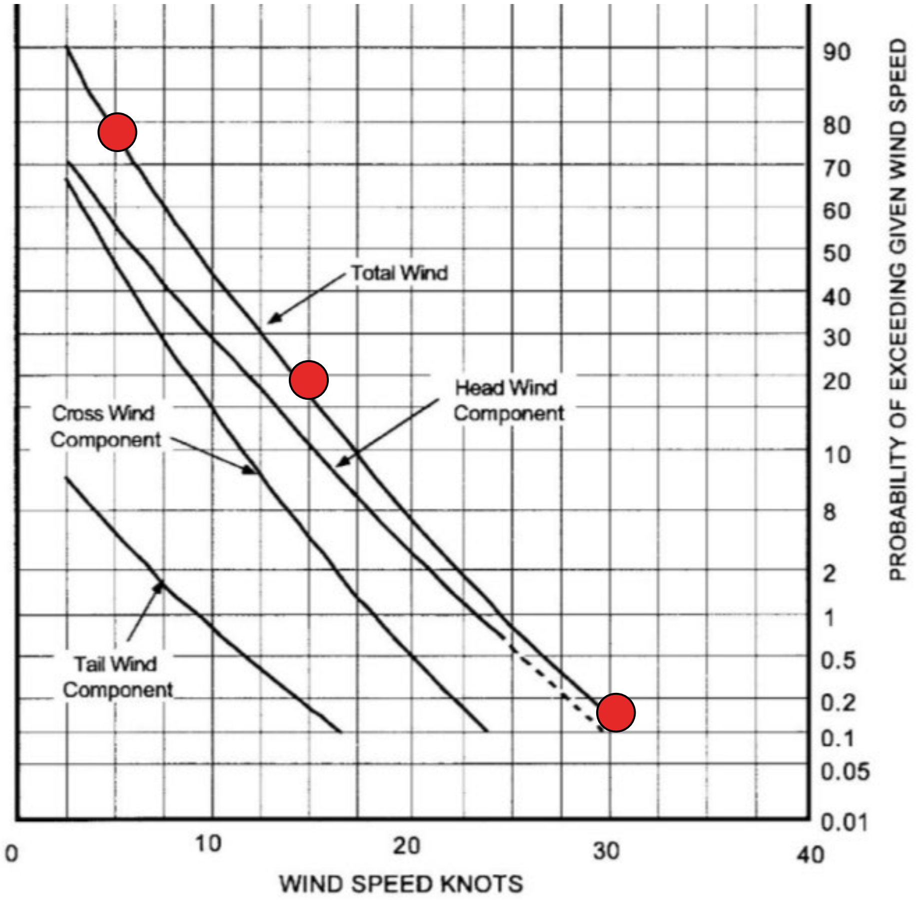
Turbulence according to CS-AWO wind model 1:

- Altitude independent model for H > 1000 m
- Altitude dependent model for H < 1000 m

Discrete gusts according to:

- CS-25.341
  - 1 in 70,000 flight hours
- SAE AS94900
  - 1 in 1,000 flight hours

Total of 21 external disturbances selected.



Test Conditions

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Effectiveness test conditions comprise:

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

Total of **857** effectiveness test conditions

Robustness test conditions comprise:

- initial flight condition (trim point),
- external disturbance, and
- flight maneuvers.

Total of **1348** robustness test conditions

Monitor Performance Evaluation

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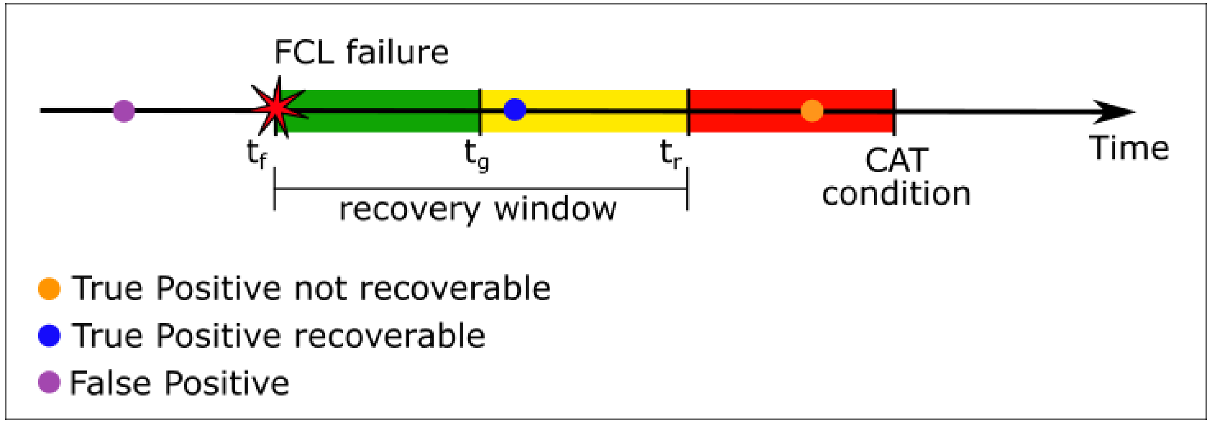
FCL condition / output	FCL failure	Failure-free
failure detected	True Positive N_{TP}	False Positive N_{FP}
failure not detected	False Negative N_{FN}	True Negative N_{TN}

Effectiveness Evaluation:

- percentage of detection (POD)

$$POD = \frac{N_{TP}}{N_{TP} + N_{FN}}$$

$$REC = \frac{N_{TP*}}{N_{TP*} + N_{FN*}}$$



Robustness evaluation:

- percentage of false alarms (PFA)

$$PFA = \frac{N_{FP}}{N_{FP} + N_{TN}}$$

FCL Monitoring – Evaluation Results

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Evaluation Results Effectiveness – Longitudinal Motion

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FAILURE	THS RUNAWAY SLOW NEGATIVE	THS RUNAWAY FAST NEGATIVE	ELEVATOR RUNAWAY FAST POSITIVE	ELEVATOR RUNAWAY FAST NEGATIVE	ELEVATOR RUNAWAY SLOW POSITIVE	ELEVATOR RUNAWAY SLOW NEGATIVE	ELEVATOR COMMAND FREEZE	ACTIVATION OF AOA PROTECTION	ACTIVATION OF HIGH-SPEED PROTECTION	ACTIVATION PITCH ATTITUDE PROTECTION	HIGH GAIN IN PITCH NORMAL LAW	ERRONEOUS AOA PROTECTION	ERRONEOUS HIGH-SPEED PROTECTION
POD	100%	100%	100%	100%	100%	100%	91.7%	76.5%	66.7%	37.5%	91.7%	100%	100 %
RECY	100%	100%	100%	100%	100%	98.1%	91.7%	76.5%	66.7%	37.5%	91.7%	71.4%	85.7 %

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Evaluation Results Effectiveness – Examples

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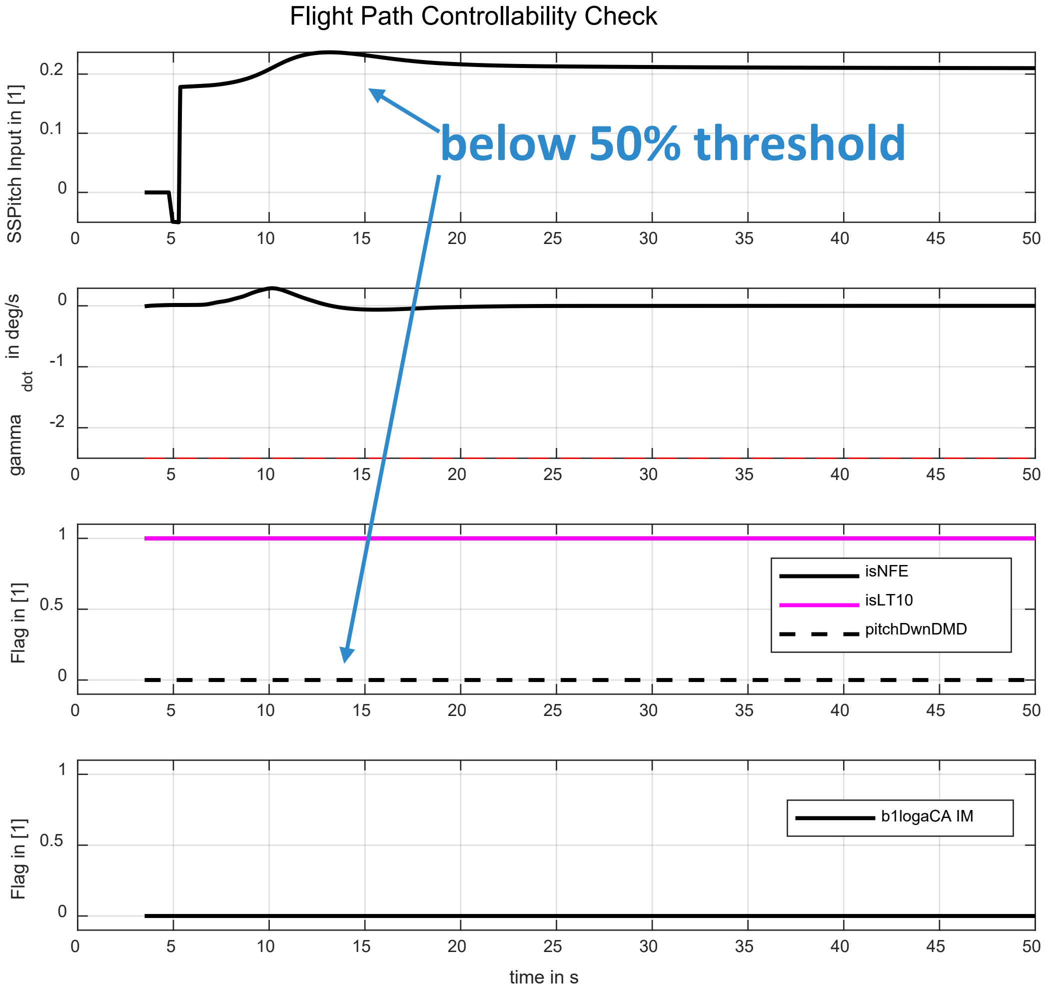
Flight Path Controllability Check:

- Cruise Condition
- Descent + ATHPRT
- Simplified Pilot Model
- No large pitch inputs generated

→ **Function** **cannot** **detect failure!**



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Evaluation Results Effectiveness – Examples

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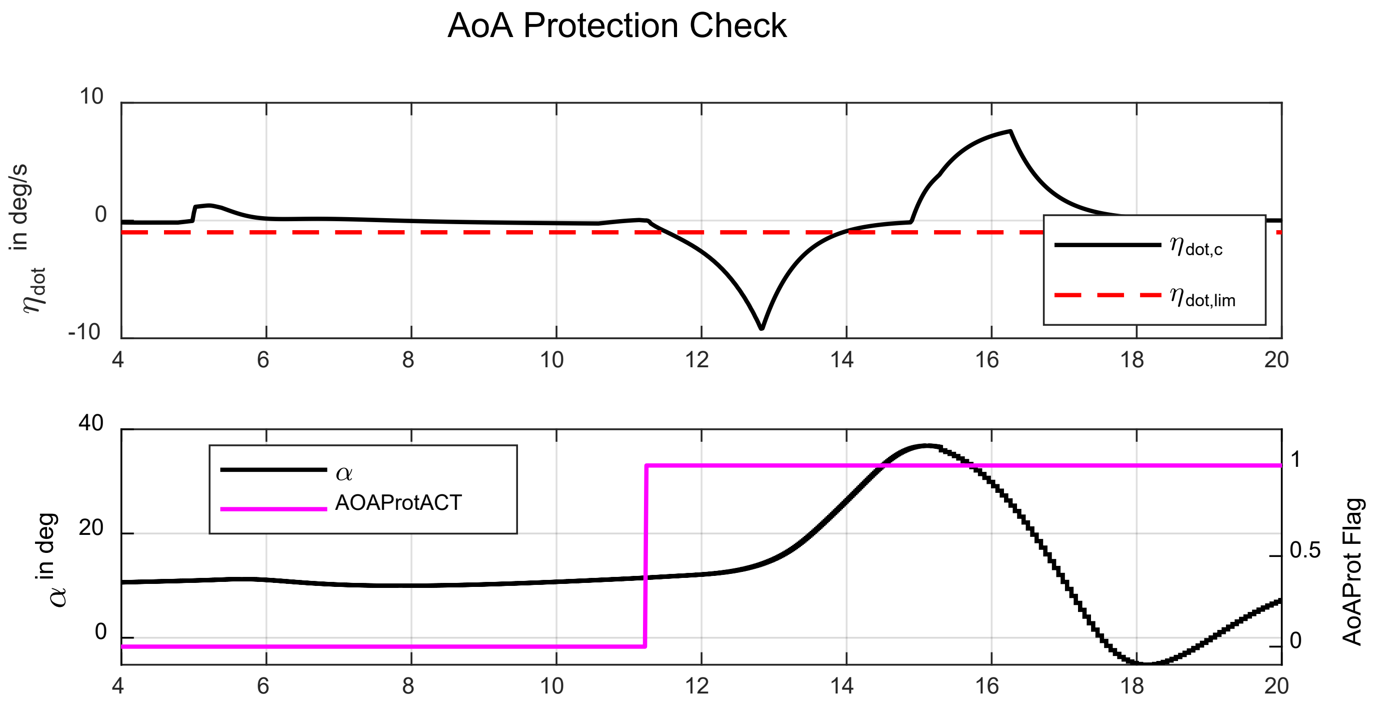
AOA Protection Check:

- Approach Condition
- Erroneous AOA function
- AOA protection active at t = 11.5 s
- CAT AOA at t = 12.5 s

→ **Failure not recoverable!**



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Evaluation Results Effectiveness – Lateral Motion

FAILURE	SLOW AILERON RUNAWAY RIGHT WING DOWN	FAST AILERON RUNAWAY RIGHT WING DOWN	SLOW AILERON RUNAWAY LEFT WING DOWN	FAST AILERON RUNAWAY LEFT WING DOWN	AILERON COMMAND FREEZE	RUDDER RUNAWAY FAST POSITIVE	RUDDER RUNAWAY SLOW POSITIVE	RUDDER RUNAWAY FAST NEGATIVE	RUDDER RUNAWAY SLOW NEGATIVE	SPOILER RUNAWAY RIGHT WING DOWN	SPOILER RUNAWAY LEFT WING DOWN	ACTIVATION ROLL ATTITUDE PROTECTION	HIGH GAIN IN ROLL NORMAL LAW
POD	100%	100%	96.7%	100%	80%	100%	100%	100%	100%	100%	96.7%	80.4%	100 %
RECY	100%	53.3%	96.7%	75.9%	80%	81.3%	100%	100%	100%	100%	96.7%	80.4%	100 %

Evaluation Results Effectiveness – Examples

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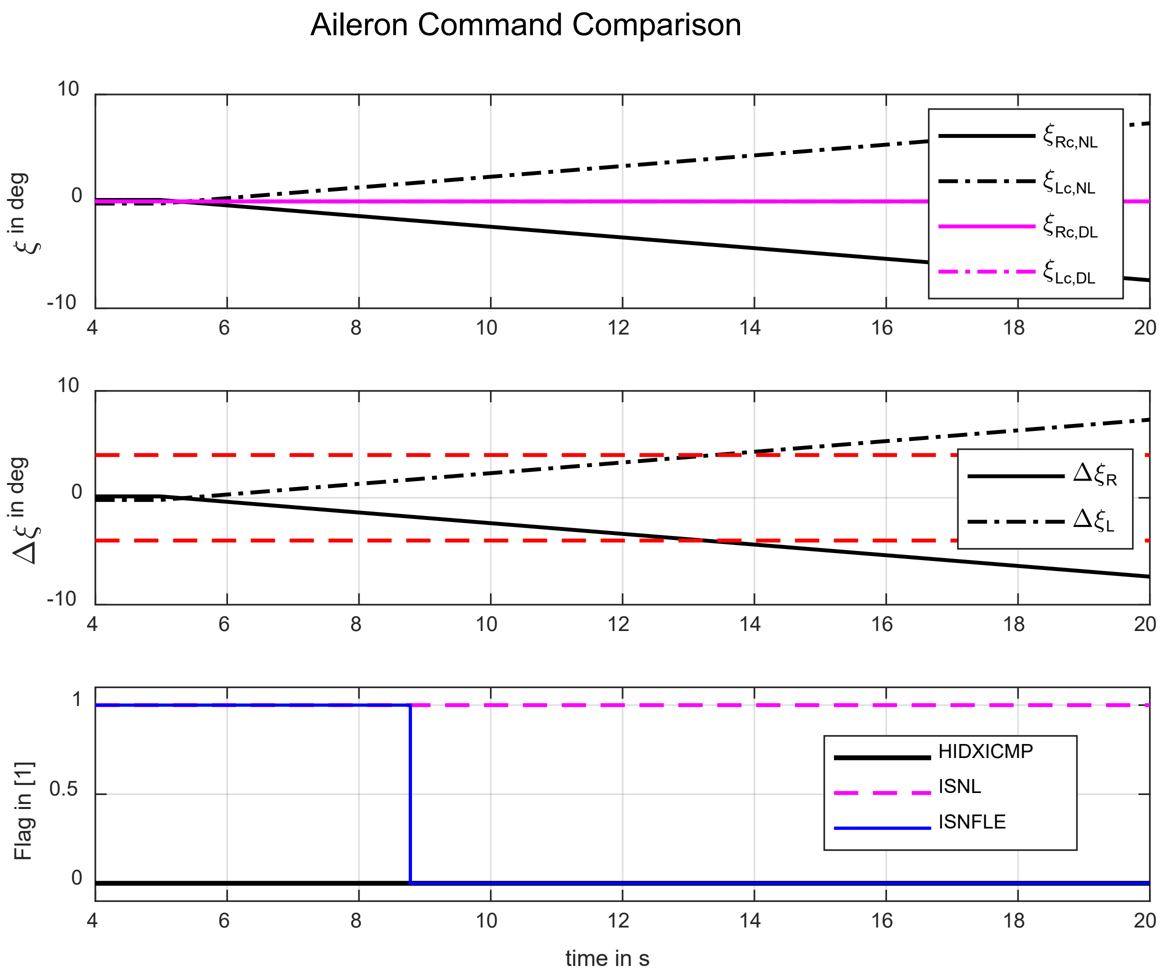
Aileron Command Comparison:

- Steady Turn Condition
- Hands-free + slow aileron runaway right wing down
- Normal flight envelope exited before thresholds exceeded

→ **Monitor function does not detect failure!**

… but covered by different monitor function.



Evaluation Results Effectiveness – Qualitative Assessment

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Good	IMFs that contributed the most to overall percentage of detection **and** that allow recoverability.
Acceptable	IMFs that contributed the most to overall percentage of detection, **but that do not** allow recoverability.
Bad	IMFs that **do not** contribute to overall percentage of detection.

IMF = Independent Monitor Function

Evaluation Results Effectiveness

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	Limit Checks					HF Checks					SGN Checks			CTRL Checks		Prot. Checks				ξ SGN	Trim Drift	Comparator		
IMF	V	nz	Θ	α	Φ	p	Φ	nz	β	ny	p	q	nz	p	$\dot{\gamma}$	α	V	Θ	Φ	-	-	η	ξ	ζ
GOOD			x	x		x	x		x	x		x		x	x*	x					x	x	x	x
ACCEPT.	x	x			x										x									
BAD								x			x		x				x	x	x	x				

*Recategorization based on assumptions.

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Evaluation Results Robustness

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Acceptable values of percentage of false alarm (PFA) are defined based on the probabilities of occurrence of the test conditions.

Four groups are defined:

Group	Probability of occurrence
Normal operations	1
SAE gust	10^{-3}
HG manoeuvre	$3.7 \cdot 10^{-5}$
CS-25 gust	$1.43 \cdot 10^{-5}$

Goal:

Mantain availability of normal mode FCL.

Accepted:

Probability for event meets requirement for ‚MAJOR' events ($<10^{-5}$).

Evaluation Results Robustness – Percentage of False Alarm

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	Limit Checks					HF Checks					SGN Checks			CTRL Checks		Prot. Checks				ξ SGN	Trim Drift	Comparator		
IMF	V	nz	Θ	α	Φ	p	Φ	nz	β	ny	p	q	nz	p	$\dot{\gamma}$	α	V	Θ	Φ	-	-	η	ξ	ζ
NORMAL OP.	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	4.9%	15.5%	2.8%	0%	0%	1.4%	0%	0%	0%	0%	0%	0%	0%	0%
SAE GUST	0%	0%	0%	0.4%	0%	0%	0%	0%	0%	0%	4.8%	10.8%	4.0%	0%	0%	1.1%	0%	0%	0%	0.6%	0%	0%	0%	0%
H.G. MAN.	0%	1.4%	0%	5.9%	0%	0%	0%	0%	0%	0%	41.7%	24.1%	8.3%	0.2%	16.2%	1.4%	0%	0.7%	0%	0%	0.2%	5.4%	0%	0%
CS-25 GUST	0%	0%	0%	21.6%	0%	22%	0%	22%	14.8%	12.7%	3.4%	12.3%	8.1%	1.3%	0%	7.6%	0%	1.3%	0%	0.8%	0%	3.4%	7.6%	16.9%

Evaluation Results Robustness – Examples

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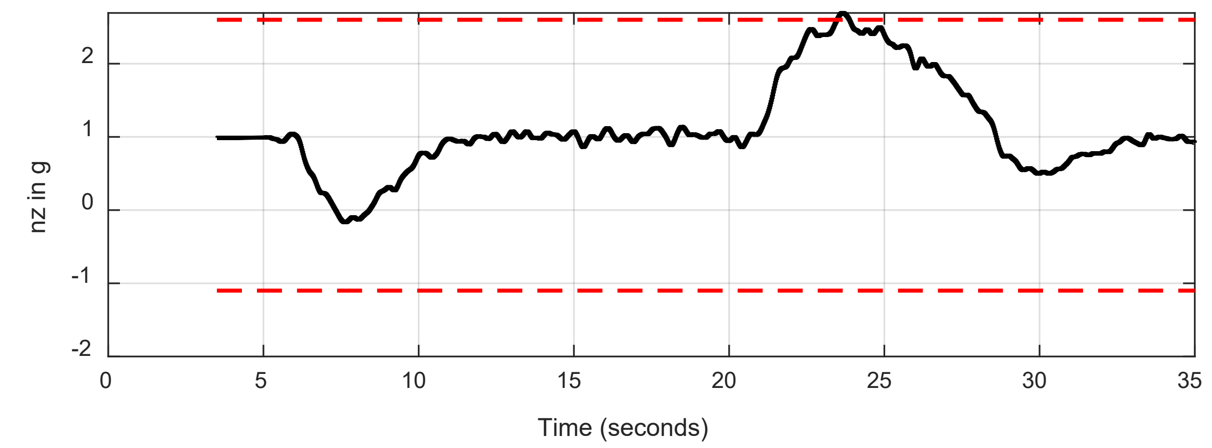
Normal Load Factor Limit Check

- Cruise Condition
- Fast-Descent and Pull-Up + Turbulence
- Pull-up Command + Turbulence

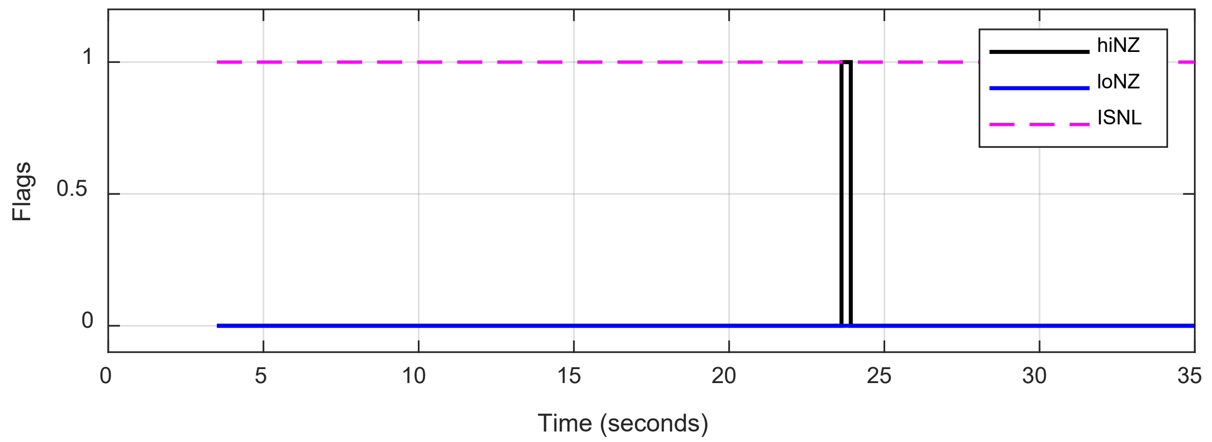
→ **Threshold exceeded at t = 24 s**



Probability of occurrence:

$$3.7 \cdot 10^{-6}\ 1/fh^{*}$$

→ **Acceptable**



*Assumption: high gain manoeuvre occurs once in a pilot lifetime.

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Evaluation Results Robustness – Examples

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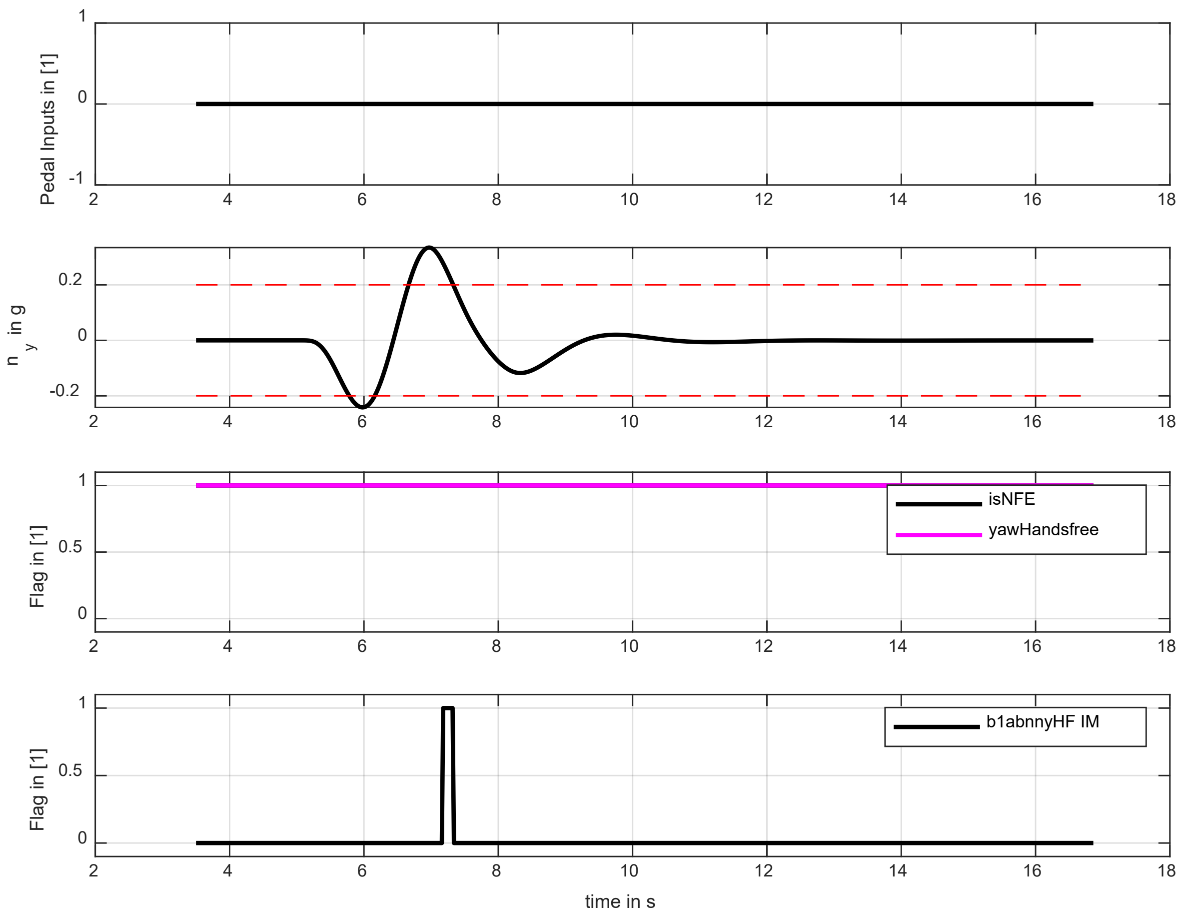
Lateral Load Factor Hands-free Check

- Cruise Condition
- Hands-free + CS-25 left crosswind gust
- Max. gust velocity at t = 6 s
- FCL counteracts + gust ends at t = 7 s

Probability of occurrence:

$$1.43 \cdot 10^{-5}\ 1/fh$$

→ not acceptable



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Evaluation Results Robustness – Examples

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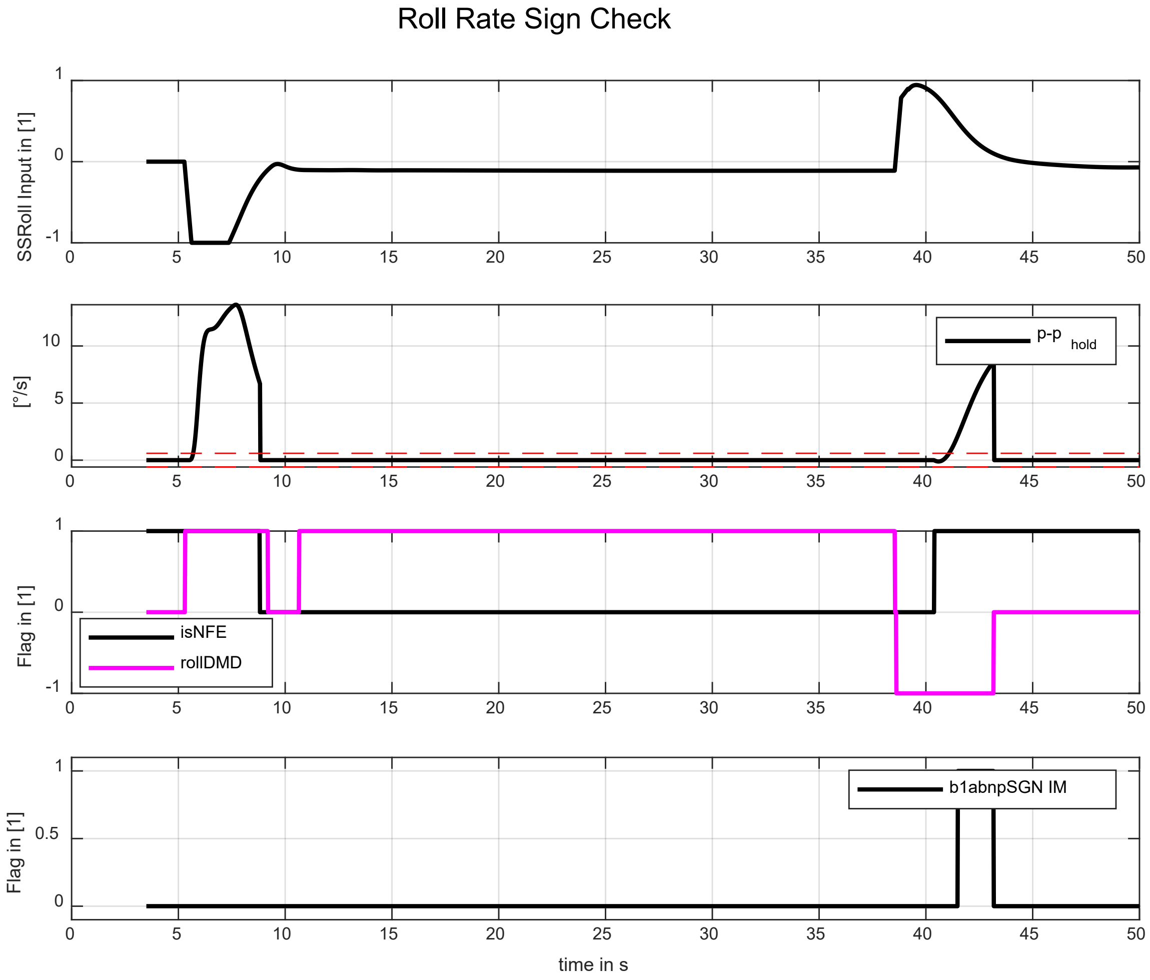
Roll Rate Sign Check

- Cruise Condition + TURN
- Inconsistent computation of Δp
- False alarm at t = 42 s

Probability of occurrence:

$$1 \cdot 1/fh$$

→ not acceptable



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Evaluation Results Robustness – Examples

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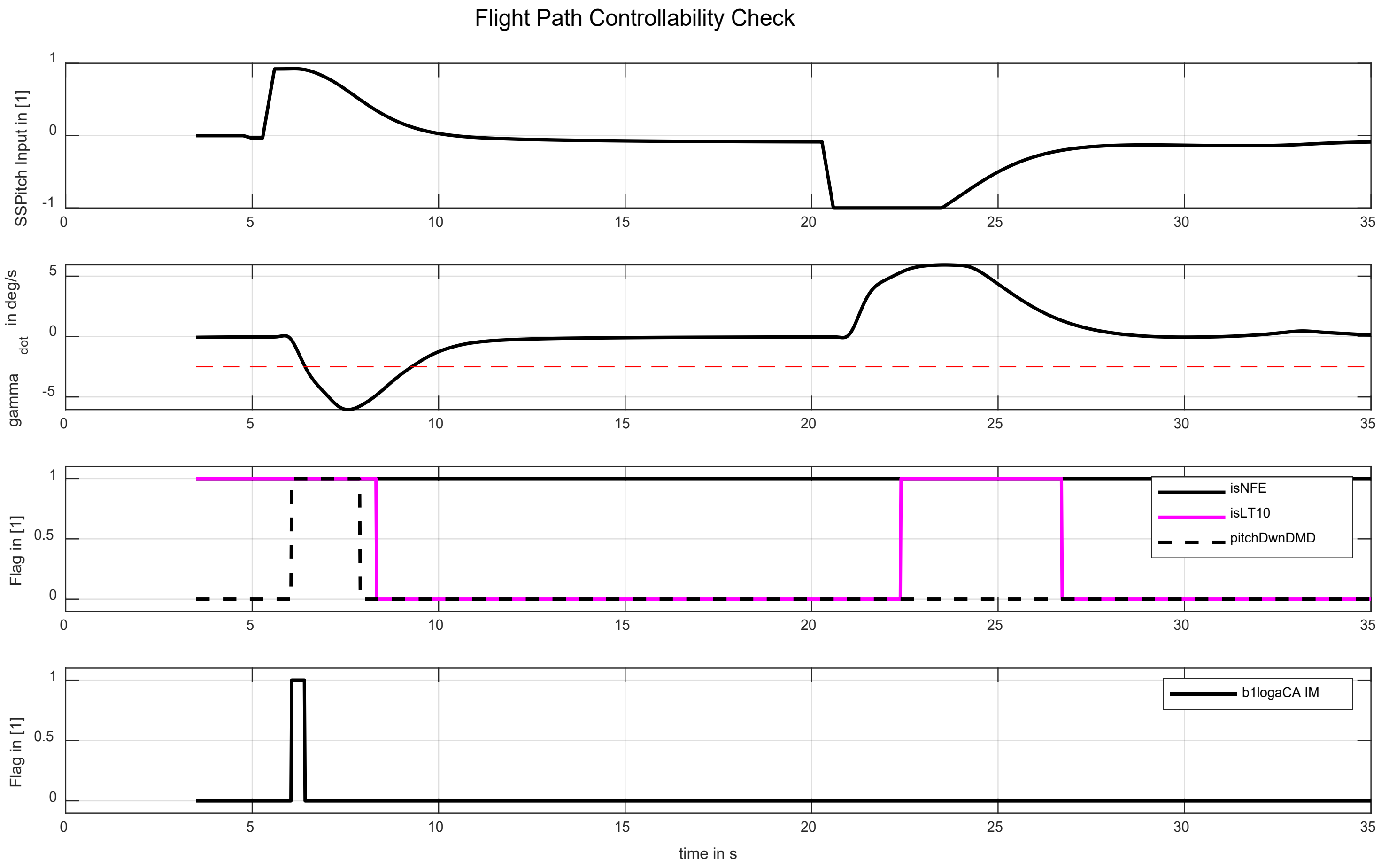
Flight Path Controllability Check

- Cruise Condition
- Fast-Descent and Pull-Up
- a/c reaction as expected but "too late"

→ Conf. time req. tuning



Probability of occurrence:

$$3.7 \cdot 10^{-5} \; 1/fh$$

→ not acceptable

Evaluation Results Robustness – Examples

This project has received funding
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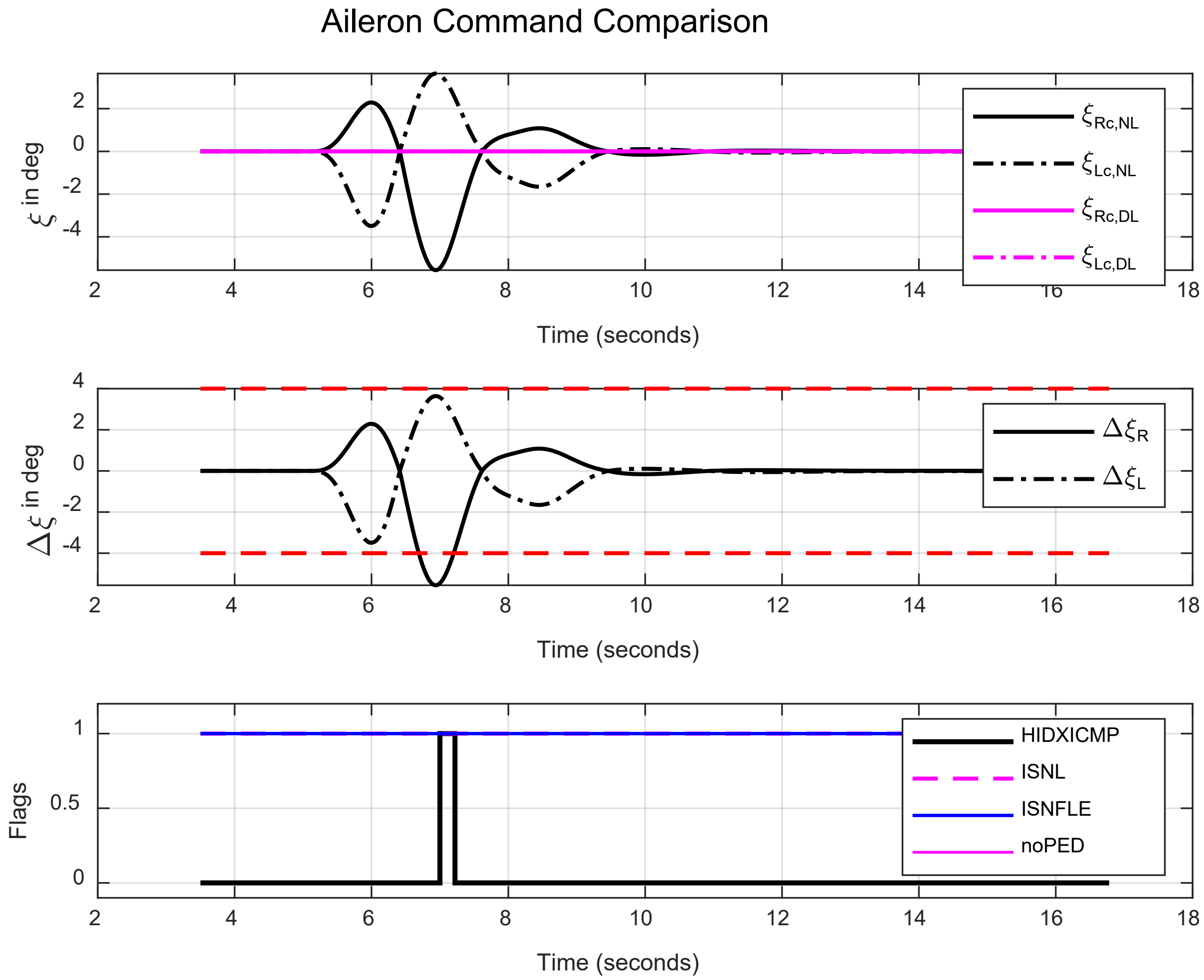
Aileron Command Comparison

- Cruise condition
- Hands-free + CS-25 left crosswind gust
- Max. gust velocity at t = 6 s
- FCL counteracts + gust ends at t = 7 s

Probability of occurrence:

$$1.43 \cdot 10^{-5}\ 1/fh$$

→ not acceptable



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Evaluation Results Robustness – Recategorization

This project has received funding
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Several monitoring functions did not show acceptable robustness.

- Preliminary design not mature

  → Low thresholds

  → Confirmation times do not match aircraft dynamics

  → **Parameter tuning required!**

Assumption:

- Parameter tuning & simple adjustments are sufficient to achieve acceptable robustness for most monitoring functions.

  → **Robustness results can be recategorized.**

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Evaluation Results Robustness – Qualitative Assessment

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Good	IMFs that do not reduce the availability of the Normal Mode FCL (probability for loss of NM is assumed with 10^(−7) $1/fh$).
Acceptable	IMFs that produced false alarms with a probability between 10^(−5) and 10^(−7) $1/fh$.
Bad	IMFs that produced false alarms with a probability higher than 10^(−5) $1/fh$.

IMF = Independent Monitor Function

Evaluation Results Robustness

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	Limit Checks					HF Checks					SGN Checks			CTRL Checks		Prot. Checks				ξ SGN	Trim Drift	Comparator		
IMF	V	nz	Θ	α	Φ	p	Φ	nz	β	ny	p	q	nz	p	$\dot{\gamma}$	α	V	Θ	Φ	-	-	η	ξ	ζ
GOOD	x		x		x		x										x		x					
ACCEPT.		x		x*		x*		x*	x*	x*	x*	x*	x*	x	x*	x*		x*			x	x*	x*	x*
BAD				x		x		x	x	x	x	x	x		x	x		x		x		x	x	x

*Recategorization based on assumptions.

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Evaluation Results Implementation Effort

This project has received funding
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Qualitative assessment compares the implementation effort between different types of IMFs

- Based on the required development steps
- Three categories: low, medium, high

Quantitative assessment or qualitative assessment compared to whole FCS development effort not feasible

- Requires knowledge of real commercial development project, including processes and tools used, etc.

Development Steps	IMF type specific?
Analysis of Considered Failure Modes and Effects	same for all IMFs
IMF System Requirements Capture	similar for all IMFs
IMF Design and Preparation of Closed-Loop Simulation	specific for different types of IMFs
Monitor Validation	similar for all IMFs
High-level SW Requirements Capture	specific for the different types of IMFs
SW-Design and Implementation	specific for the different types of IMFs
Monitor Verification	similar for all IMFs

Implementation Effort Estimation

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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
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
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

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Overall Monitor Assessment – Approach

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The three evaluation criteria

- Robustness (60%) – 60 to 0 points,
- Effectiveness (30%) – 30 to 10 points, and
- Implementation Effort (10%) – 10 to 1 points.

Four categories based on total score:

- highly recommended ($85 \leq total\ score$),
- recommended ($55 \leq total\ score < 85$),
- requires effort ($41 \leq total\ score < 55$), and
- not recommended ($total\ score < 41$).

Result\Criterion	Robustness	Effectiveness	Implementation Effort	Total Score
good	60	30	10	100
acceptable	30	20	5	55
bad	0	10	1	11

Overall Monitor Assessment

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IMF type	Robustness	Effectiveness	Effort	Assessment
Limit Checks	accept.-good	accept.-good	good	highly recommended/ recommended
Pitch Trim Drift Check	acceptable	good	acceptable	recommended
Controllability Checks	acceptable*	good*	acceptable	recommended
Command Comparison	acceptable*	good	acceptable	requires effort
Protection Function Checks	accept.*-good	bad - accept.	bad	requires effort
Sign Checks	acceptable*	bad - good	acceptable	requires effort
Hands-free Checks	accept.*-good	bad - good	acceptable	requires effort
Command Sign Check	bad	bad	bad	not recommended

*Recategorization based on assumptions.

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Summary
Motivation

Motivation

This project has received funding
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There is a growing concern about potential development errors in complex flight control laws.

Development Assurance alone is not necessarily sufficient to mitigate the risk of development errors.

Additional mitigation techniques are requested by authorities.

An Independent Monitor could be such a mean to achieve fault tolerance against the development errors.

Summary
Approach

Independent Monitor Development Approach

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1. **FCL failure modes defined.**
2. **Flight Conditions / Trim Points are defined for the simulated flights.**
3. **Failures are induced in FCL and at FCL output.**
4. **Independent Monitor Functions are evaluated for Effectiveness, Robustness and Implementation Effort.**

Approach - Effectiveness Evaluation

This project has received funding
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Effectiveness Evaluation Criteria:

- Does at least one function of the Independent Monitor detect a failure before the conditions for Continued Safe Flight and Landing are violated?
- Is the aircraft recoverable when failures are detected?

11 out of the 24 developed Monitor Functions are sufficient to detect all simulated failures.

Approach - Robustness Evaluation

This project has received funding
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Robustness Evaluation Criteria:

— Does any function of the Independent Monitor trigger a false alarm under failure-free conditions?

— Design goal is to maintain state-of-the-art availability of NM FCL.

Robustness is a challenge.

Few Monitor Functions are robust.

Most Monitor Functions showed potential to achieve acceptable robustness through additional parameter tuning.

Approach – Implementation Effort

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The assessment of implementation effort is challenging: (requires insight in real-life commercial FCS development, including processes and tools).

→ The implementation effort is assessed in a qualitative way, as comparison between IMF types.

IMF type	Implementation Effort
Limit Checks	Low
Hands-free Checks	Medium
Sign Checks	Medium
Controllability Checks	Medium
Pitch Trim Drift Check	Medium
Command Comparison	Medium
Protection Function Checks	High
Command Sign Check	High

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Overall Evaluation Results

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The three evaluation criteria (robustness, effectiveness and implementation effort) are used to identify suitable Monitor Functions

Each criterion has a different weighting

Robustness is the most important (60%)

Followed by Effectivity (30%)

Least important is the Effort (10%)

IMF type	Assessment
Limit Checks	Highly recommended/recommended
Pitch Trim Drift Check	recommended
Controllability Checks	recommended
Command Comparison	Requires effort
Protection Function Checks	Requires effort
Sign Checks	Requires effort
Hands-free Checks	Requires effort
Command Sign Check	Not recommended

Summary
Conclusion

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Conclusion

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1. Considering all aspects, 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 monitoring functions and the development effort.

4. Further **research is proposed** with regards to crew-alerting (CAS), FCL reconfiguration and pilot-in-the-loop assessments. Further **collaboration** with airframers, research organizations and authorities will be **highly appreciated**.

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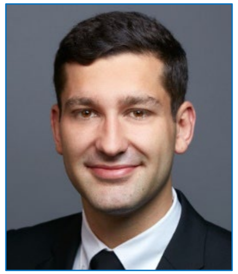

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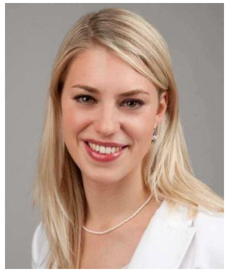

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Thank You

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