Monitoring of Flight Control Laws

Horizon Europe Project: Flight Control Laws and Air Data Monitors

LIEBHERR

Liebherr-Aerospace Lindenberg GmbH

In partnership with

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

Agenda

1. **Project Introduction**
2. TUB Simulation Capabilities / Aircraft Model
3. FCL Failure Classification
4. FCL Monitoring - Considerations & Concepts
5. Example Monitor Design

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Monitoring of Flight Control Laws

Overview

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 (see also MOC SC-VTOL)

Objectives:

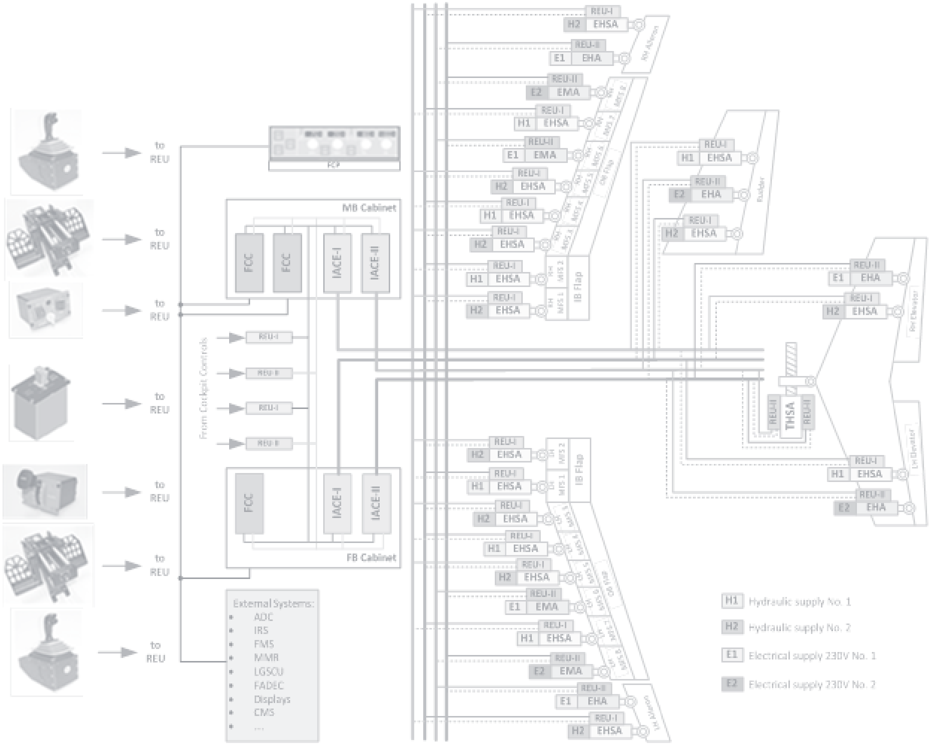
- Improve flight safety of complex systems
- Increase robustness against common mode development errors
- Develop possible solutions in response to CRI „Consideration of Common Mode Failures and Errors in Flight Control Functions"

Realization:

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

Challenges:

- Robust and effective FCL monitor design
- Avoidance of added high complexity



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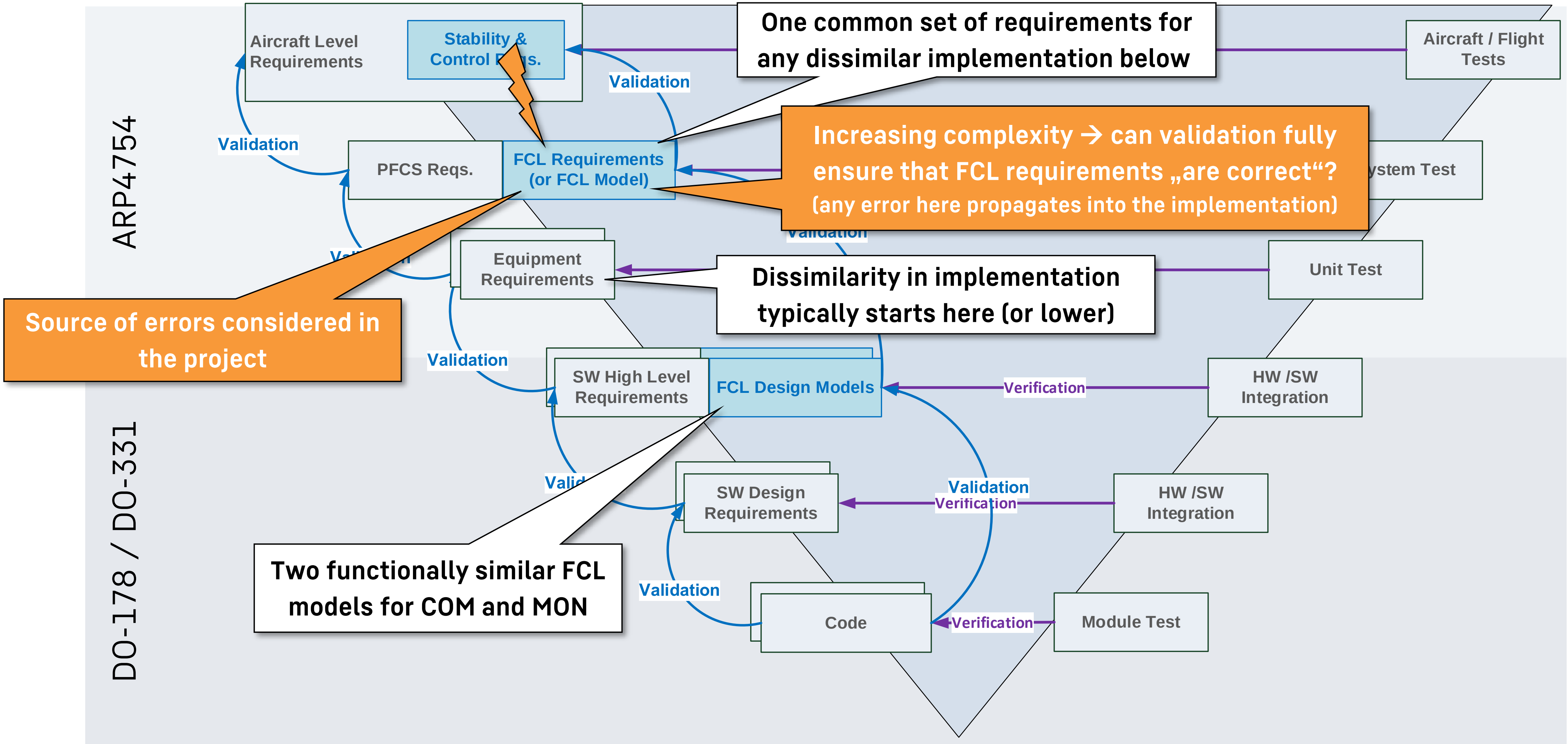
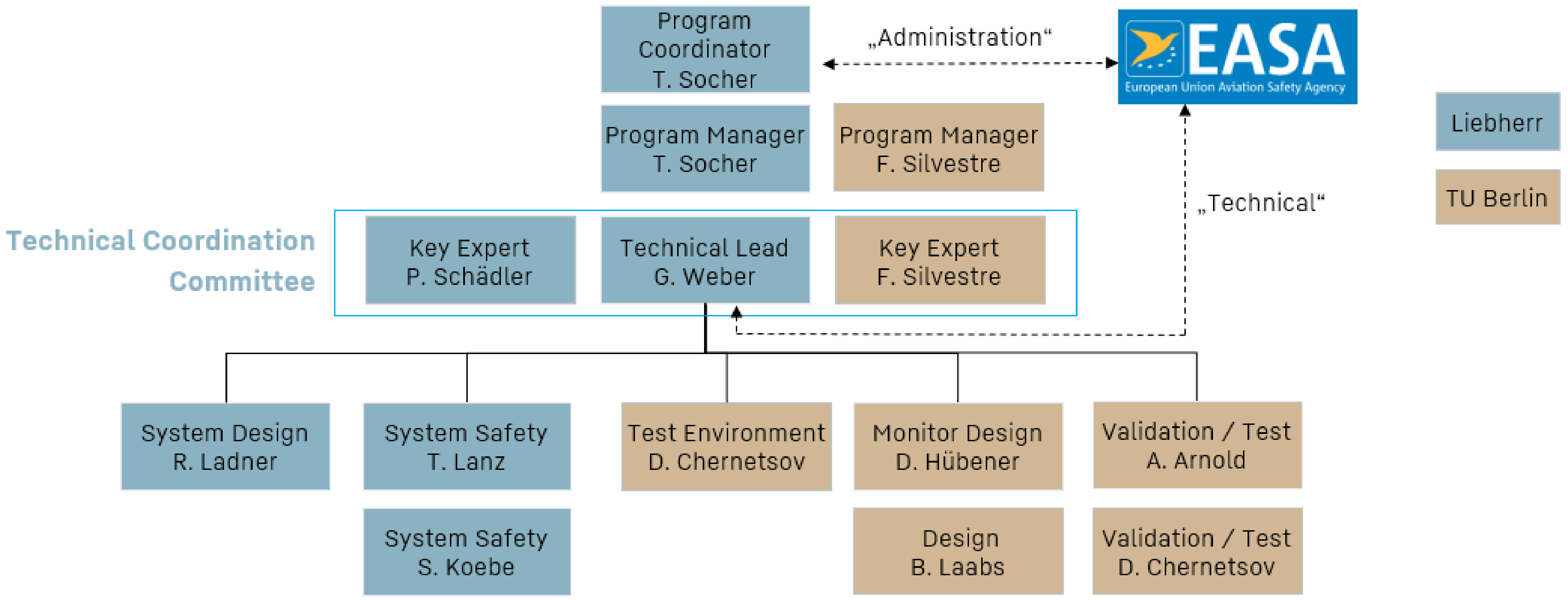
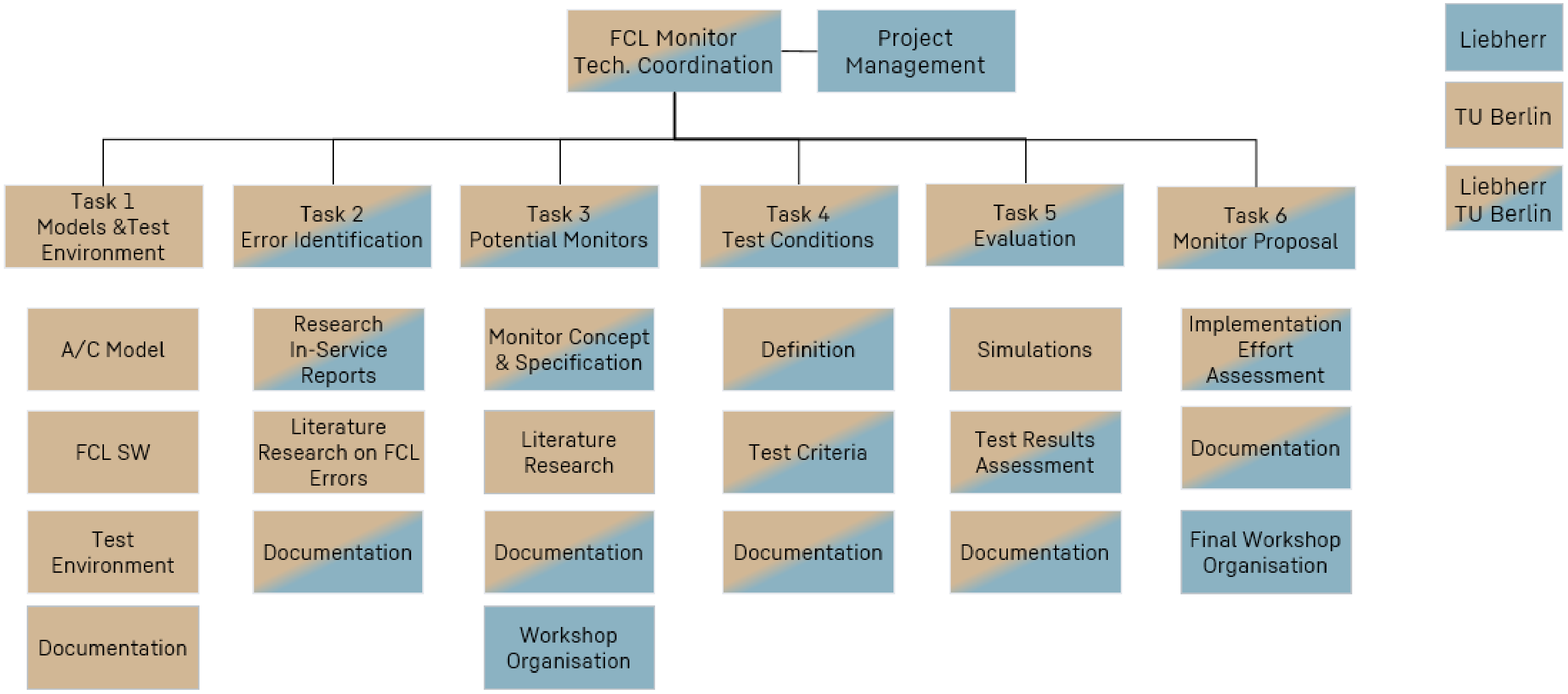
Problem Statement Represented in V-Model



Project Team



Work Breakdown Structure



Schedule Status

			October-22	November-22	December-22	January-23	February-23	March-23	April-23	May-23	June-23	July-23	August-23	September-23	October-23	November-23	December-23	January-24	February-24	March-24	April-24	May-24	June-24	July-24	August-24	September-24
		Month	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
Task 1	Establishment of an aircraft model		■	■	■	■																				
Task 2	Identification of potential errors		■	■	■	■	■	■	■																	
Task 3	Determination and definition of potential monitors						■	■	■	■	■	■	■	■												
Task 4	Definition of test conditions														■	■										
Task 5	Evaluation of potential monitors																■	■	■	■	■					
Task 6	Propose suitable monitors																					■	■	■	■	■

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TUB Simulation Capabilities / Aircraft Model

I. Establishment of the VFW 614-ATD Flight Simulation Environment

II. Validation

III. Interfaces

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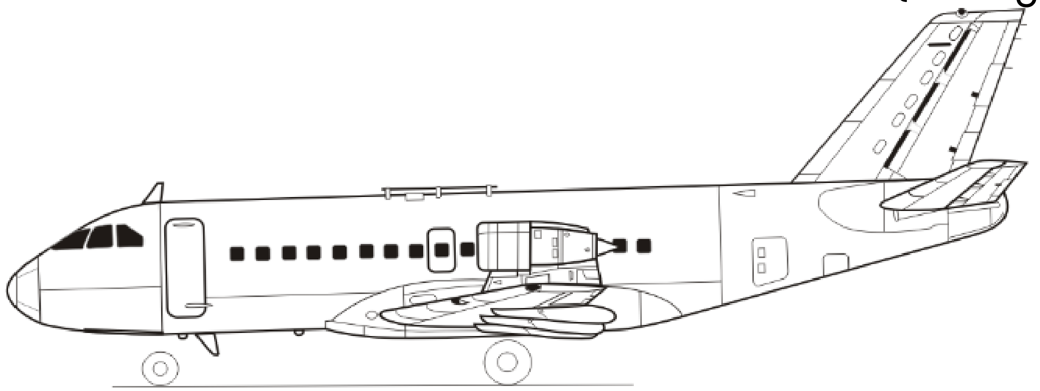
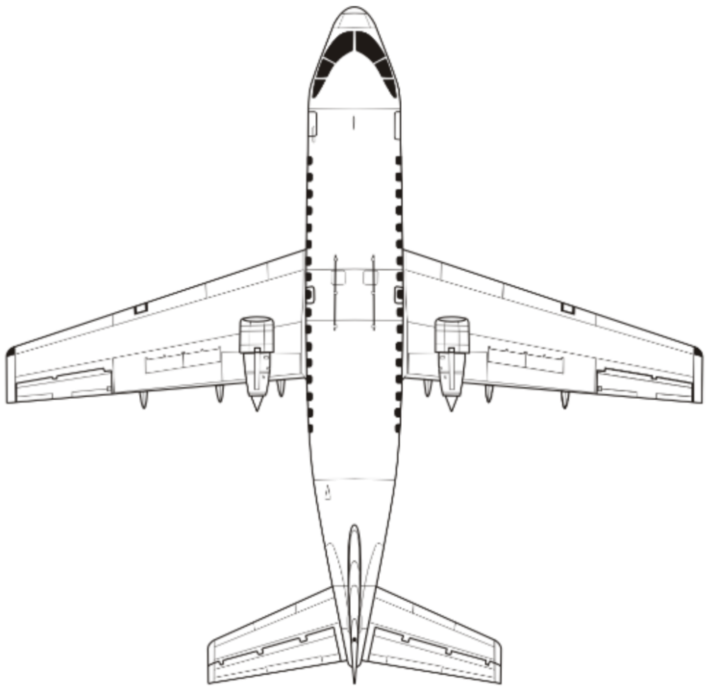
The Flight Simulation Environment

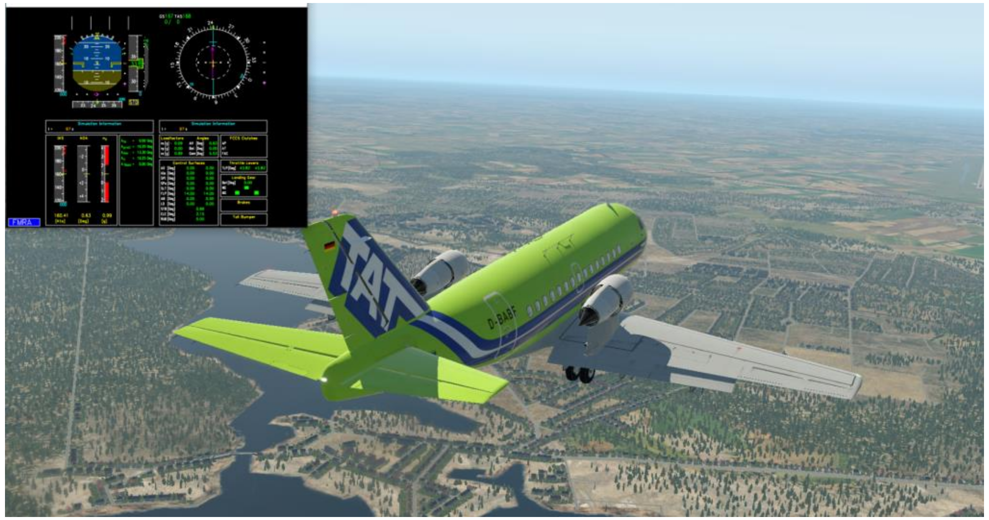
- TUB provides an aircraft model that **is highly representative of modern fly-by-wire aircraft and the complexity of current flight control laws.**
- The simulated aircraft is the twin jet **VFW 614-ATD (**Advanced Technology Demonstrator).
- The Flight Mechanical Model:
  - ➢ Implements the nonlinear 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)



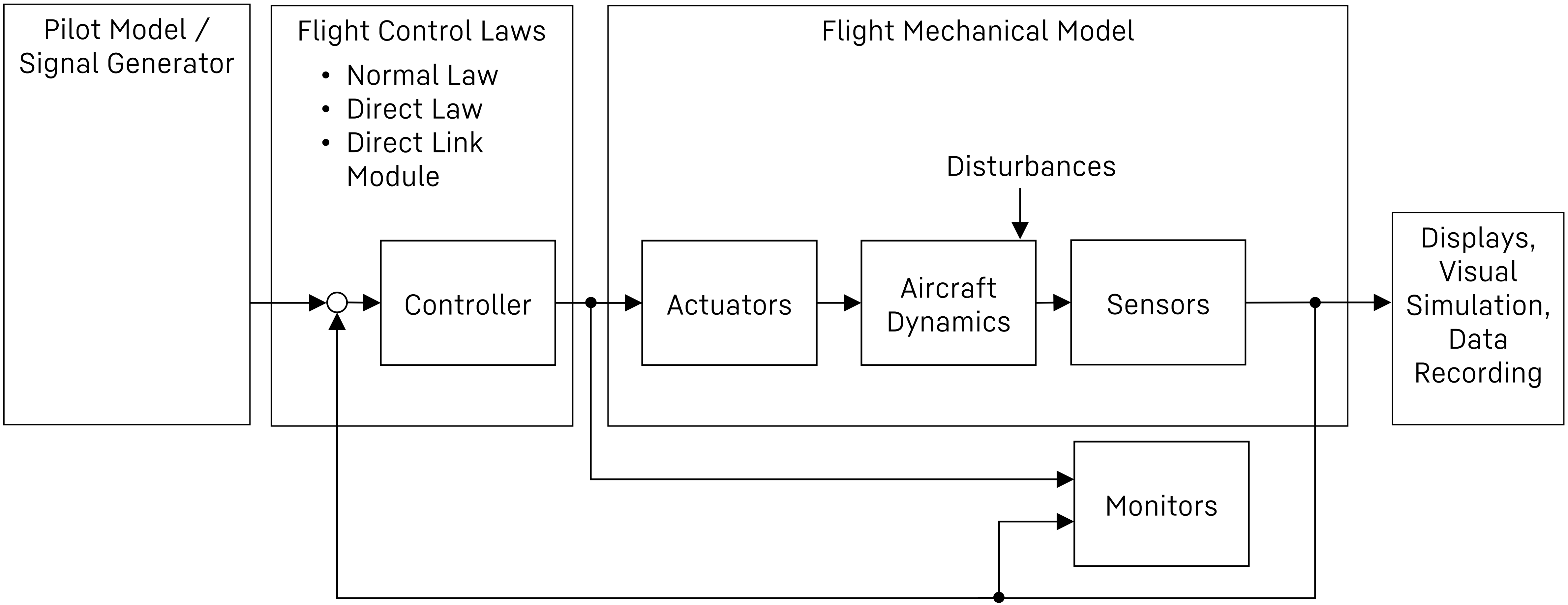


Establishment of the flight simulation environment

- The flight simulation environment (FSEnv) comprises:
  - ➢ Flight Mechanical Model (FMM),
  - ➢ ATD Flight Control Laws (FCL),
  - ➢ Inputs for test control: scripts and human-machine interfaces
  - ➢ Display software
  - ➢ Data recording and plotting software
  - ➢ FCL failure generator
  - ➢ FCL monitor software
- Model is capable of serving as platform to evaluate the proposed monitors
- Runs on Windows 10 OS and MATLAB/Simulink r2021b.

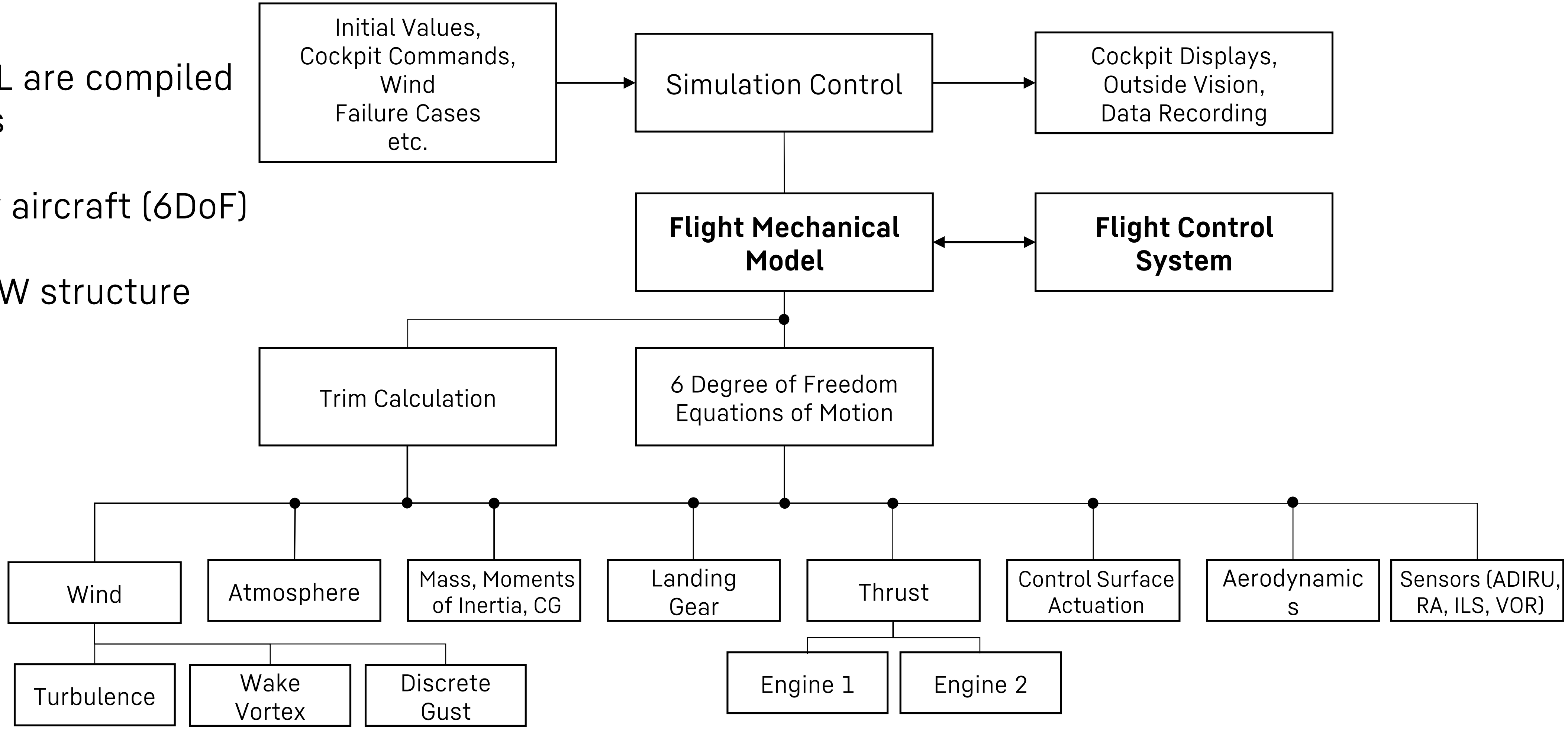


FSEnv Architecture

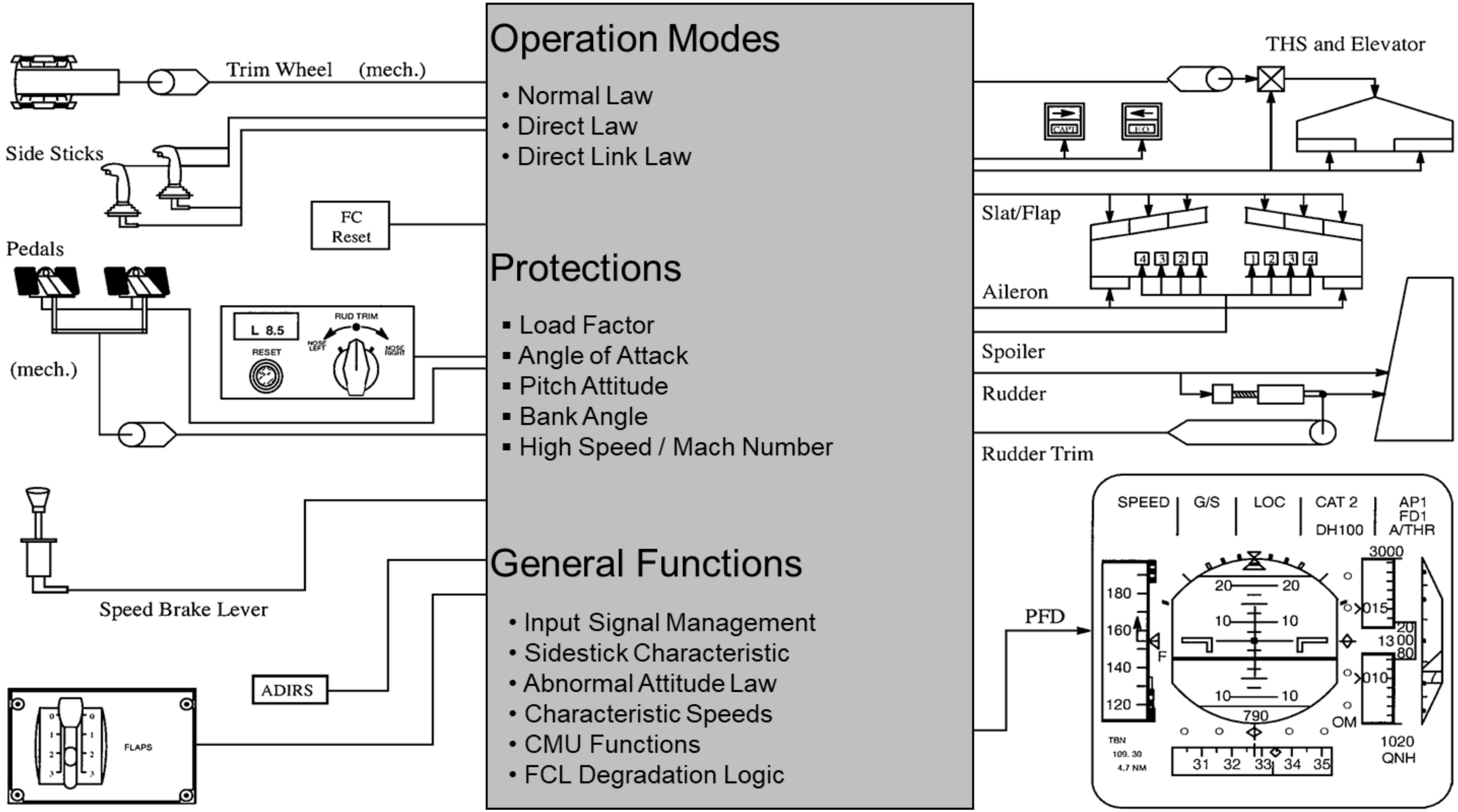


FSEnv Architecture

- FMM & FCL are compiled MEX-Files
- Rigid body aircraft (6DoF)
- Modular SW structure



Flight Control Law



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Validation

1. Analysis of trim results of the FSEnv and comparison with SEPHIR[1] trim states
2. Determination of stall speeds in comparison to the VFW 614 flight handbook and previous results
3. Repetition of software reference tests[2] + comparison to existing time histories
4. Comparison of A/C response after stimulation in Normal Law and Direct Law mode
5. Stimulation of flight envelope protections and analysis of simulation results
6. Engineering tests to prove correct interfacing of I/O tools

[1] SEPHIR Simulator for Educational Projects and Highly Innovative Research, a fix-based simulator at TU Berlin with VFW 614-ATD hardware and software.

[2] Results that Airbus Deutschland GmbH used for validation of the Flight Simulation Model in the Technology Project Electronic Flight Control System were available and used here as reference for the validation of the derived model.

Interfaces

TUBPlot – plots time histories in a standardised layout

X-Plane – 3D-visualization of the aircraft motion

Little Navmap – visualises the A/C flight path in a flight planner and navigation tool

EIS – Electronic Instruments Simulation, simulates Airbus-like cockpit displays and customised engineering displays

Simtool – stimulates failures of electric, hydraulic, and electronic components of the FCS and failures of control surfaces of the VFW 614-ATD

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FCL Failure Classification

I. Assumptions

II. Failure Classes

III. Failure Examples

IV. Summary / Conclusion

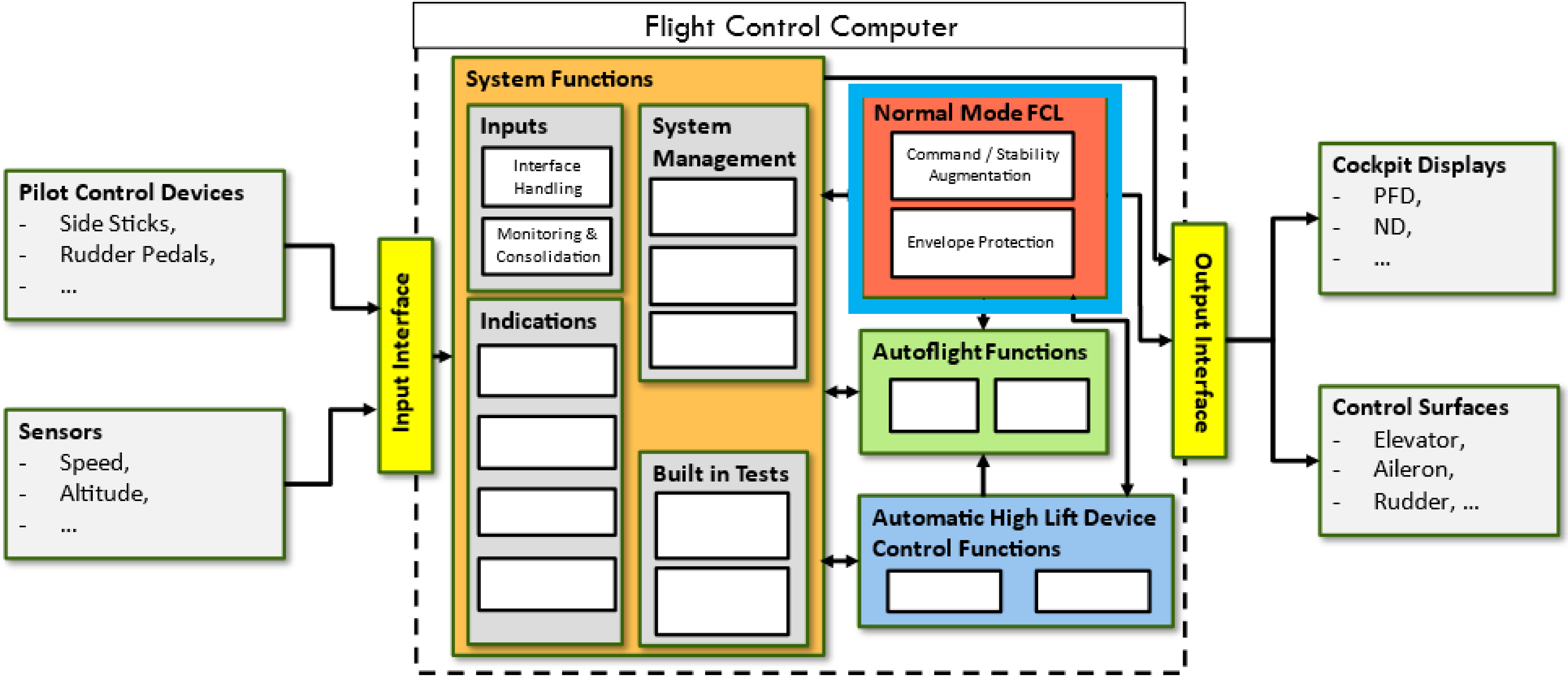
Assumptions and Approach

- The FCL SW correctly implements the FCL requirements,
- The errors are introduced during FCL development (FCL requirements or FCL design) on system level,
- Consider only CAT and HAZ failure conditions (because of FCL development errors),
- Use of the Normal Law (NL) of VFW 614-ATD for investigation of failure conditions,
- Due to its simplicity, the Direct Law is assumed to be error-free and is available as backup,
- NL is representative for FCS of modern CS-25 aircraft,
- Structural damages and their effects on flight controls are not considered,
- Focus on cruise flight condition.

➢ No specific examples of FCL requirement or design errors are identified,

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

Scope of FCL


Flight Control Computer
System Functions
Inputs
Interface Handling
Monitoring & Consolidation
Indications
System Management
Built in Tests
Normal Mode FCL
Command / Stability Augmentation
Envelope Protection
Autoflight Functions
Automatic High Lift Device Control Functions
Pilot Control Devices
- Side Sticks,
- Rudder Pedals,
- …
Sensors
- Speed,
- Altitude,
- …
Input Interface
Output Interface
Cockpit Displays
- PFD,
- ND,
- …
Control Surfaces
- Elevator,
- Aileron,
- Rudder, …

Failure Classes – Functional Classes

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

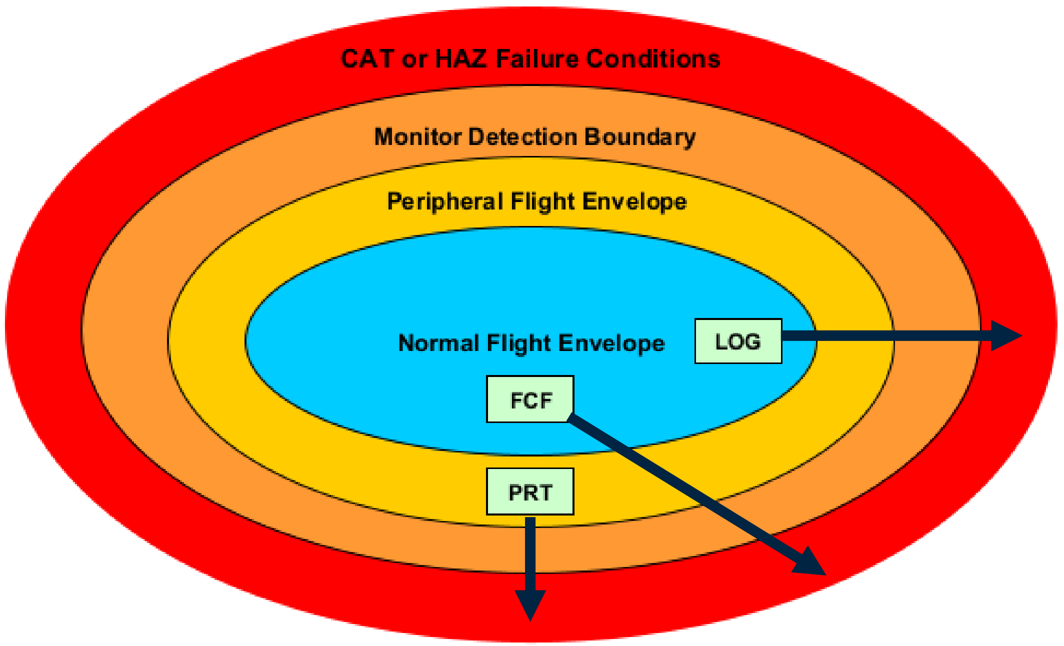
Failure Classes – Functional Classes

Functional classification:

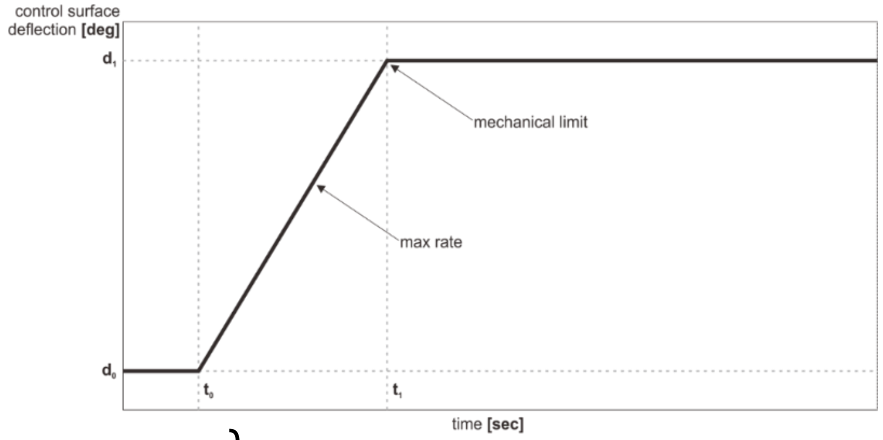
LOG
- Erroneous switching of the modes
- Erroneous activation of PRT

FCF
- Erroneous behaviour in primary control functions

PRT
- Erroneous behaviour when PRT is active



Failure Classes – Dependency on the Input Signals



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 Classes – Combination of Classification Methods

Combination matrix

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

Failure Description	Erroneous computation of the elevator command (load factor control)
Category	A-FCF
Outcome	Erroneous elevator command
Potential Consequences	• a/c stalls • exceedance of maximal structural loads • ground contact • hard landing

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Failure Classes – Combination of Classification Methods

Combination matrix

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

Failure Description	Erroneous load factor control function
Category	R-FCF
Outcome	• Erroneous short period motion characteristics • Reduced damping
Potential Consequences	• Pilot-induced oscillations • Reduced accuracy of the glideslope tracking during approach • Hard landing • Exceedance of critical structural loads

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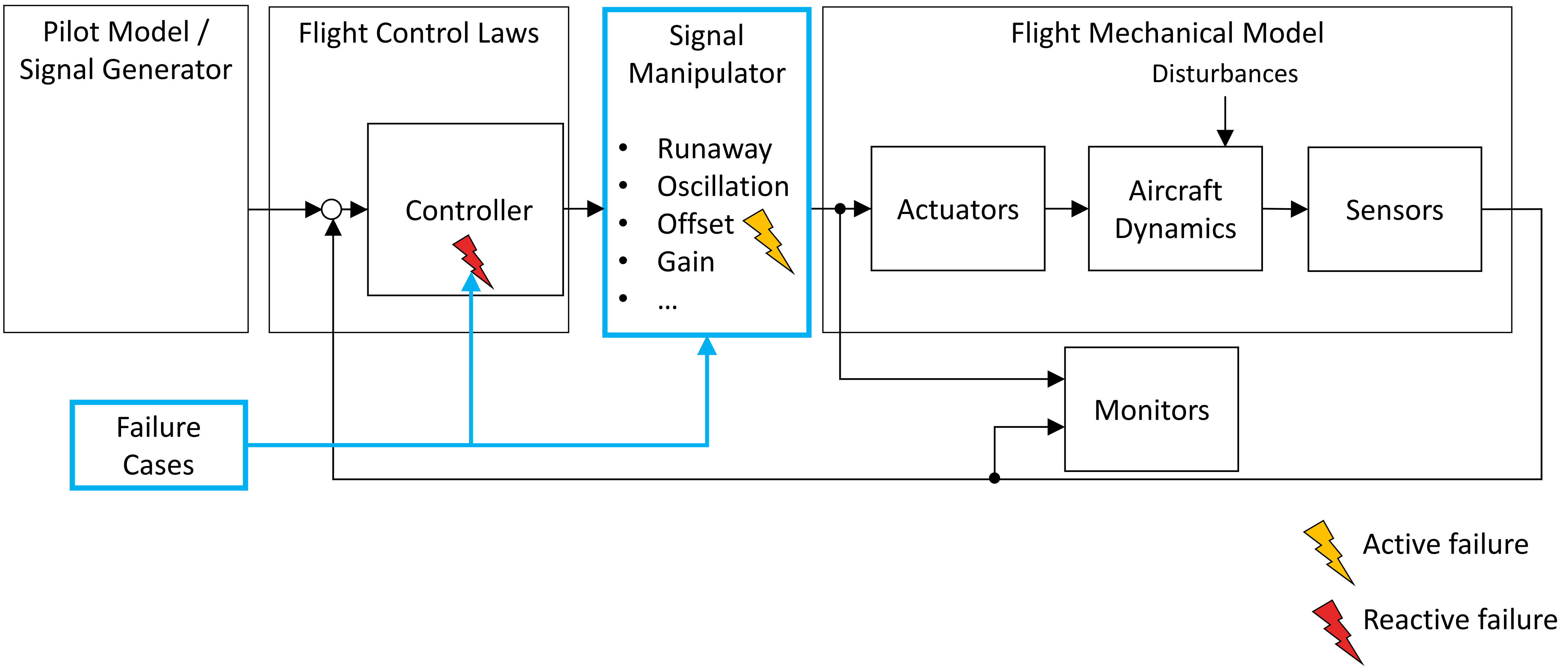
Failure Generator



Conclusion

- Two failure classification approaches are identified,
- The functional class is considered a subclass of the active and the reactive class,
- Active failures lead to actuator-like failures (e.g. runaway),
- Reactive failures potentially cause PIOs or other dangerous flight conditions,
- In the simulation:
  - active failures can be inserted by manipulation of FCL outputs,
  - reactive failures can be inserted by manipulation of FCL source code,
- Failures shall be investigated in different flight envelope domains.

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Monitor Design Objectives

The Independent Monitor:

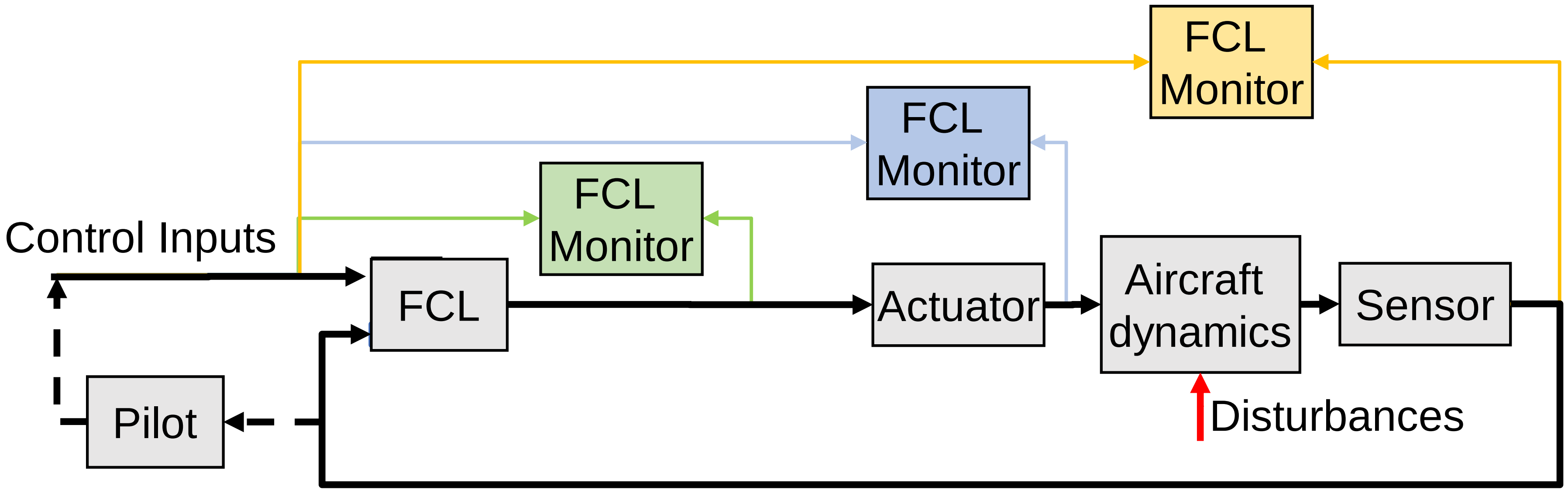
- shall **detect failures**, i.e. erroneous function (malfunction), of the FCS caused by FCL development errors,
- shall be **functionally independent** of the normal mode FCL,
- shall **only detect failure conditions** that are classified as **hazardous or catastrophic,**
- shall be **robust** against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

Monitoring Architecture – Considerations

- **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

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

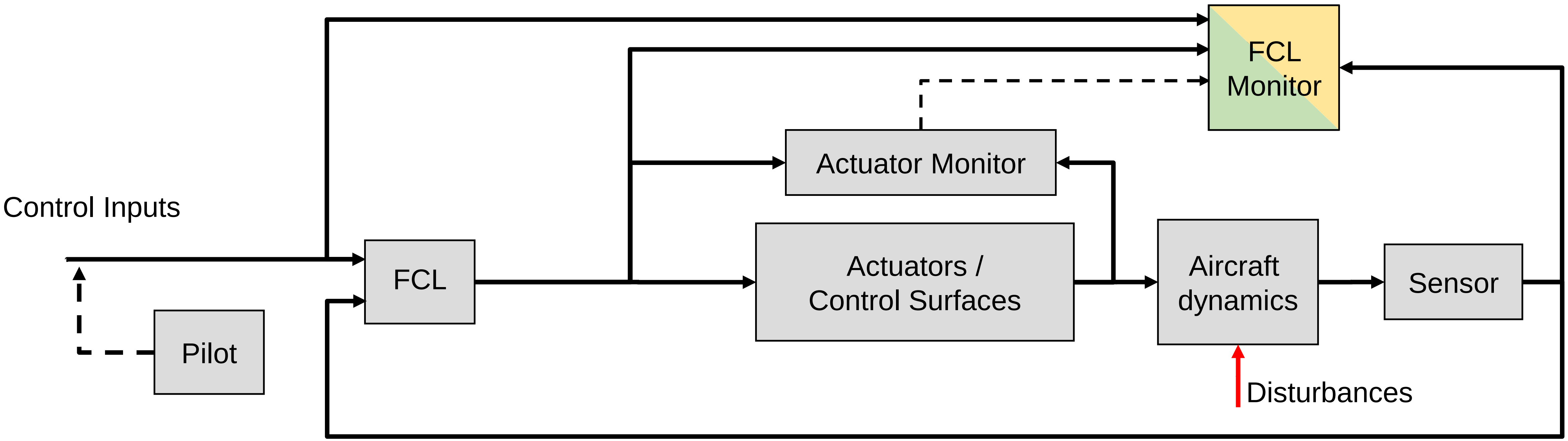
+ early failure detection,
– actuator is part of the monitored system:
  - actuator failures may result in spurious FCL monitor trips → requires provisions for fault isolation,
  - state of the art monitoring covers actuator failures already.

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



FCL Monitor Concepts

Failure detection measure

- **Comparator**

  Definition:
  This concept compares at least two functions to verify the correct functionality of the system. Dissimilarity in the HLR of the variants is required.

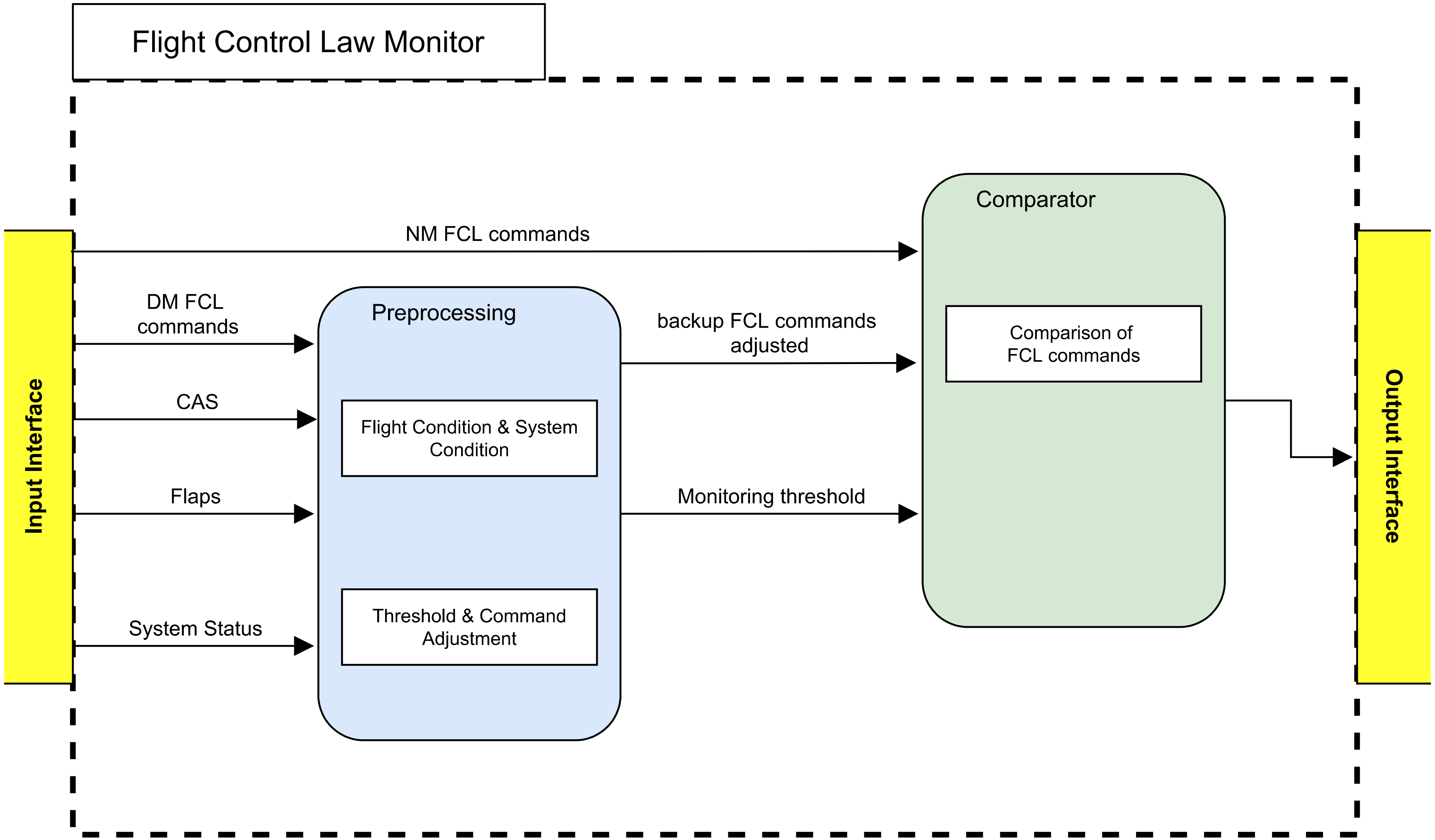
- **Plausibility check**

  Definition:
  This concept verifies that a systems behaviour is acceptable based on the anticipated system state, derived from A/C and system requirements. HLR of the FCL shall not be used to develop plausibility checks

- **Hybrid**

  Definition:
  This concept is a hybrid of the Comparator and Plausibility Check concepts.

Comparator Concept



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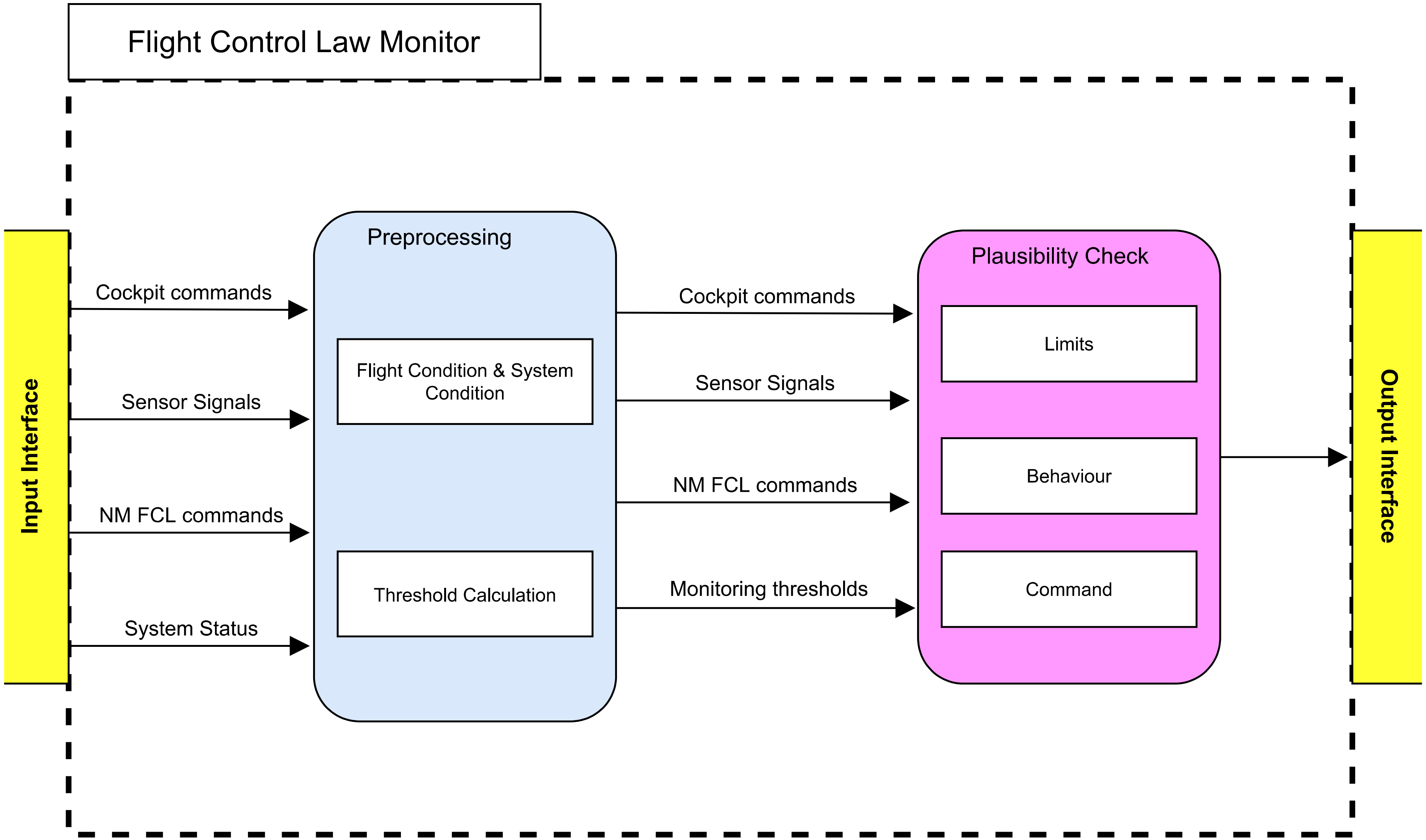
Plausibility Check Concept



Agenda

List of Proposed Monitors

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	V_{CAS}, α, θ and ϕ	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

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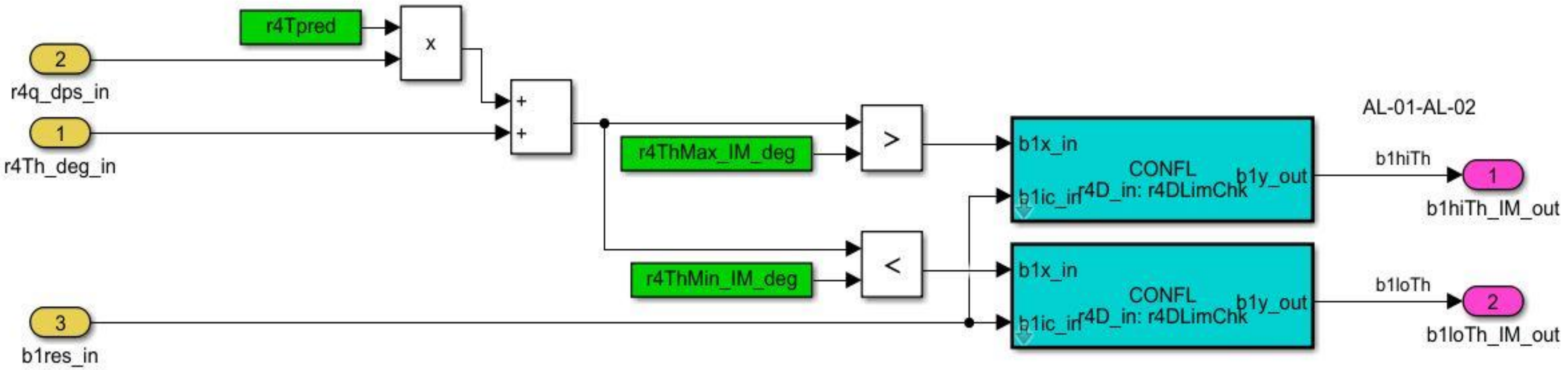
Limit Checks – Pitch Angle Limit

AL-01	IM shall trip if the aircraft pitch angle θ exceeds 32°.
Rationale:	High pitch angles can lead to stalls and/or spatial disorientation. Threshold value: $\theta_{max} = 30°$ [13]* plus 2° margin.
Inputs	θ
Type	Limit Check

*[13] VFW 614-ATD FCS Specification



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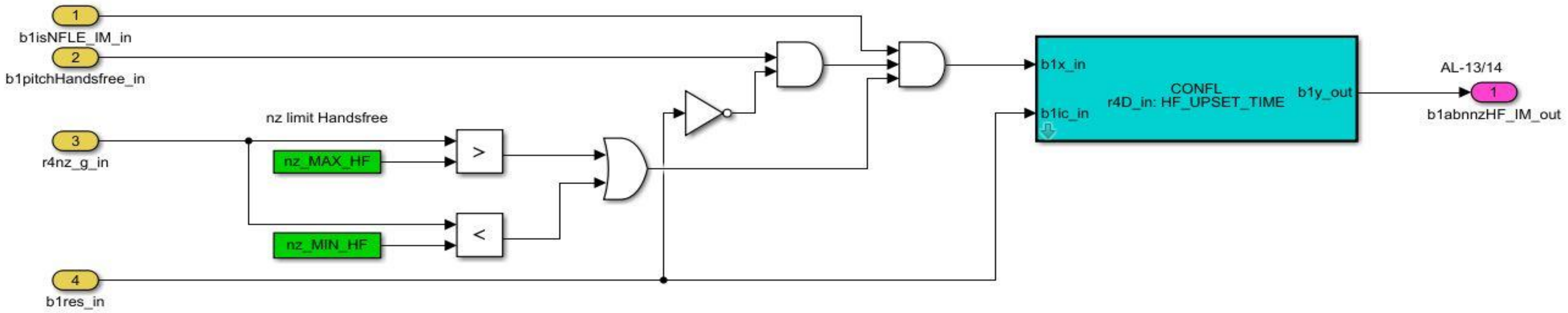
Handsfree Checks – Normal Load Factor Limit

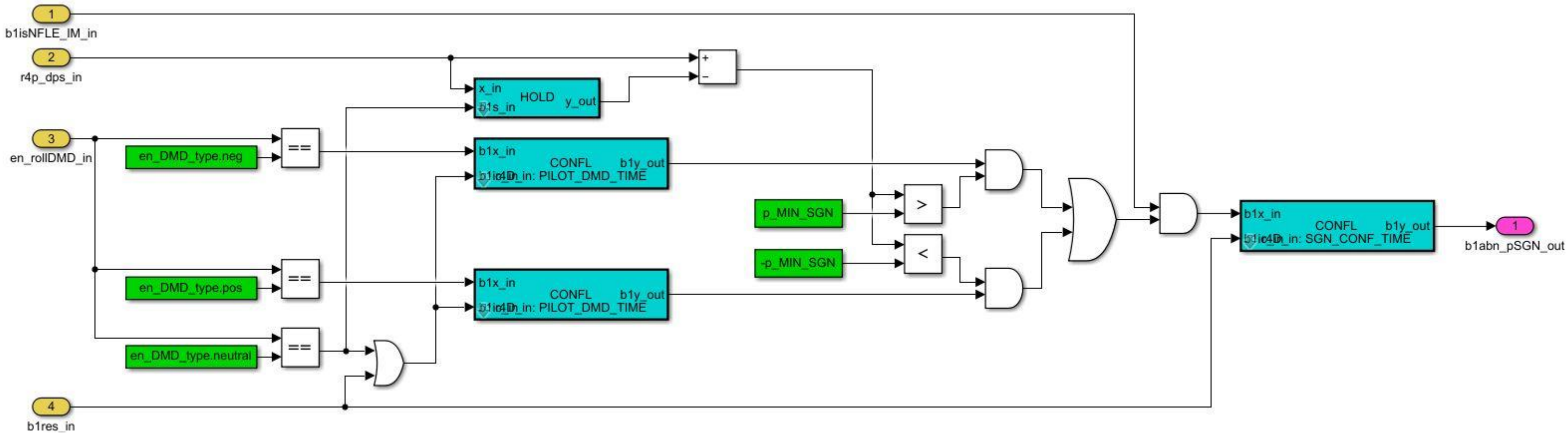
AL-13	IM shall trip if normal load factor n_z exceeds 1.6 g, AND no pilot pitch input, AND aircraft operated in normal flight envelope.
Rationale:	Aircraft normal load factor should not exceed limit if pilot does not demand a change of the flight path angle. Threshold value: $n_z = 1.6$ g equals 50% positive pilot load factor demand on the side stick [13] and the upset limit specified in [16]*.
Inputs	n_z and SS_η
Type	Behaviour Check

*[16] Engineering data from a representative commercial Liebherr-Aerospace GmbH development project, 2009



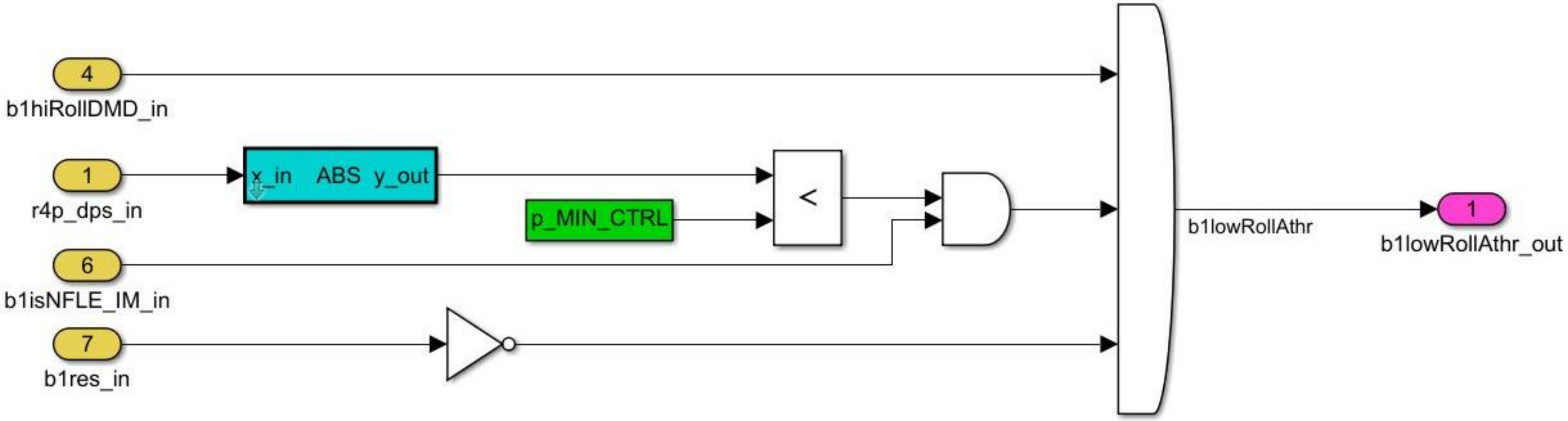
Sign Checks – Roll Rate Sign

AL-17	IM shall trip if roll rate p is positive/(negative), AND pilot gives left/(right) wing down input, AND aircraft operated in normal flight envelope.
Rationale:	Aircraft reaction should correspond to pilot demand, if no protection reduces pilot authority.
Inputs	p and SS_{ξ}
Type	Behaviour Check



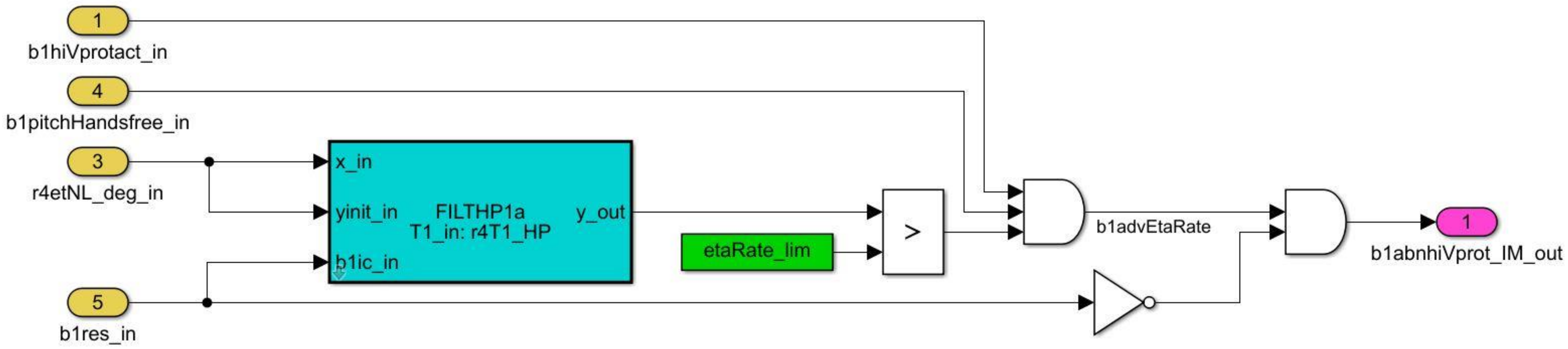
Controllability Checks – Low Roll Rate

AL-20	IM shall trip if pilot right wing down/(left wing down) input exceeds 50%, AND roll rate p falls short of 3.4 °/s / (stays above -3.4 °/s), AND AEO, AND aircraft operated in normal flight envelope.
Rationale:	Lateral control must be enough to provide a peak roll rate necessary for safety. Roll response must allow normal manoeuvres (such as recovery from upsets produced by gusts and the initiation of evasive manoeuvres). Threshold value: 100% pilot roll rate demand on the side stick have to result in an absolute roll rate $\|p\| \geq 8.5$ °/s [15], AMC 25.147 (d)+(f). Therefore, $\|p\| = 3.4$ °/s have to be acquired with 40% pilot roll rate demand at 50% roll input on the side stick [13]
Inputs	p and SS_ξ
Type	Behaviour Check



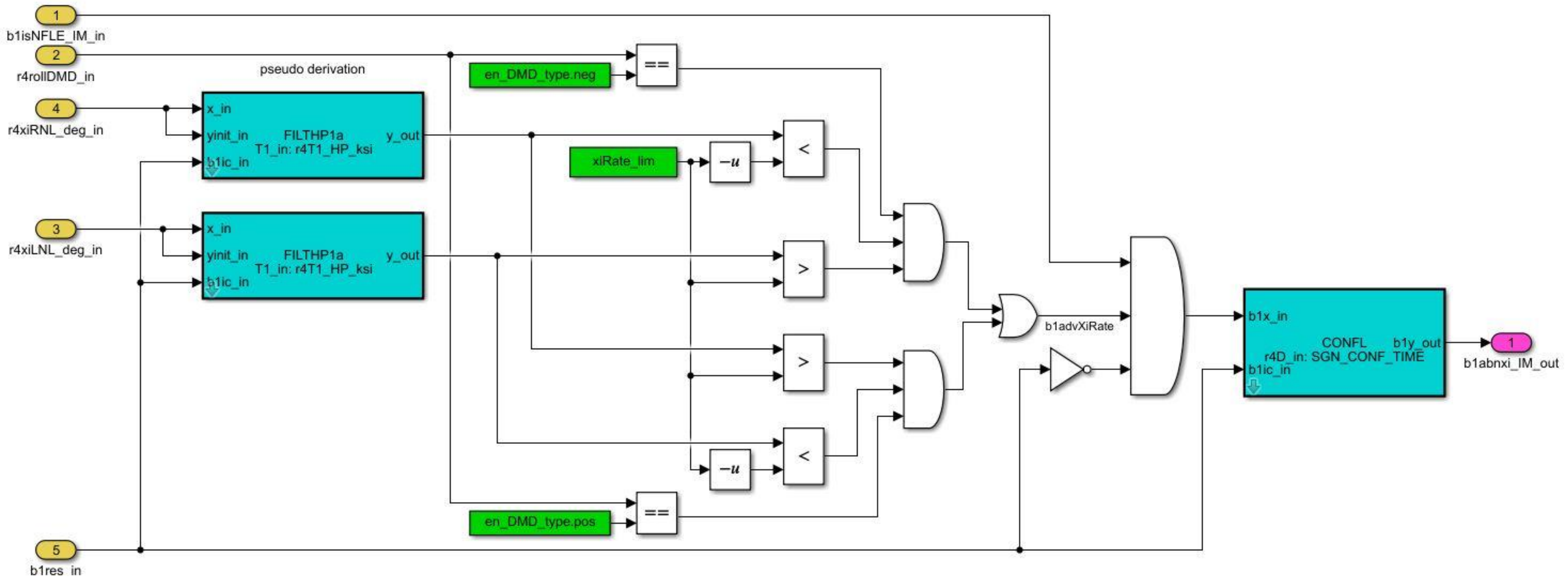
Protection Function Checks – Overspeed

SL-03	IM shall trip if the overspeed protection is active, AND no pilot pitch input, AND the FCL commands elevator deflections that lead towards an increasing airspeed.
Rationale:	Above the speed limit V_{MO}, the overspeed protection should generate elevator commands (positive load factors) that return the A/C to airspeed range $V_{CAS} \leq V_{MO}$ [13].
Inputs	η_{cmd} and SS_η
Type	Command Check



Command Sign Check

SL-07	IM shall trip if the pilot commands right wing down (/left wing down), AND initial aileron commands induce left wing down (/right wing down) roll acceleration, AND aircraft operated in normal flight envelope.
Rationale:	In the normal flight envelope, the initial aileron command after changes of the pilot input should correspond to the pilot demand.
Inputs	ξ_{cmd} and SS_ξ
Type	Command Check



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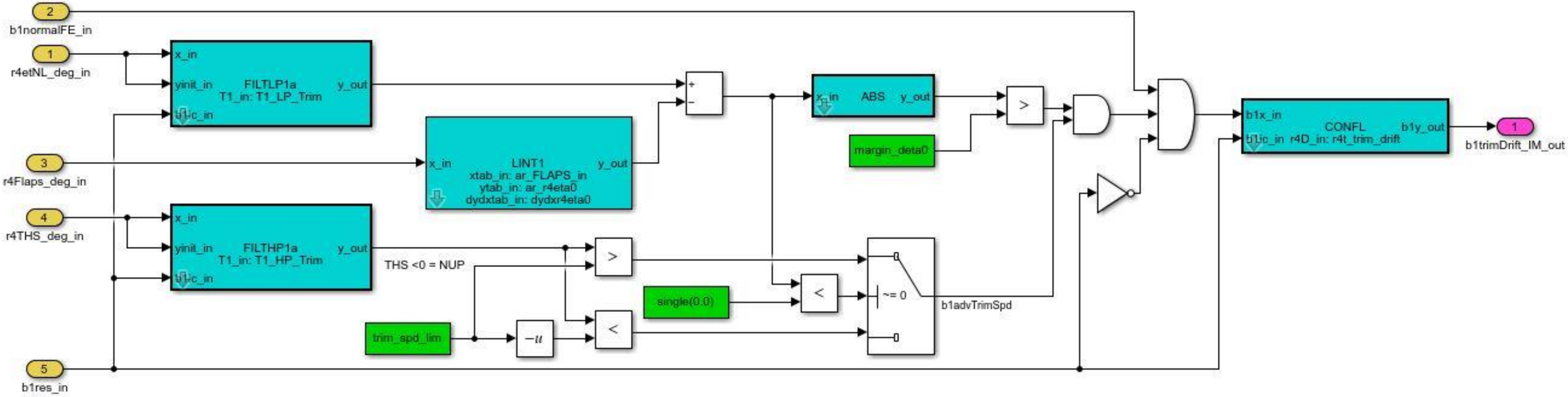
Pitch Trim Drift Check

SL-08	IM shall trip if the elevator command η_{cmd} exceeds (/falls below) the neutral elevator deflection η_0, AND the THS command rate is nose-up (/nose-down), AND aircraft operated in normal flight envelope.
Rationale:	The automatic trim function should decrease the elevator hinge moment.
Inputs	η_{cmd} and THS_{cmd}
Type	Command Check



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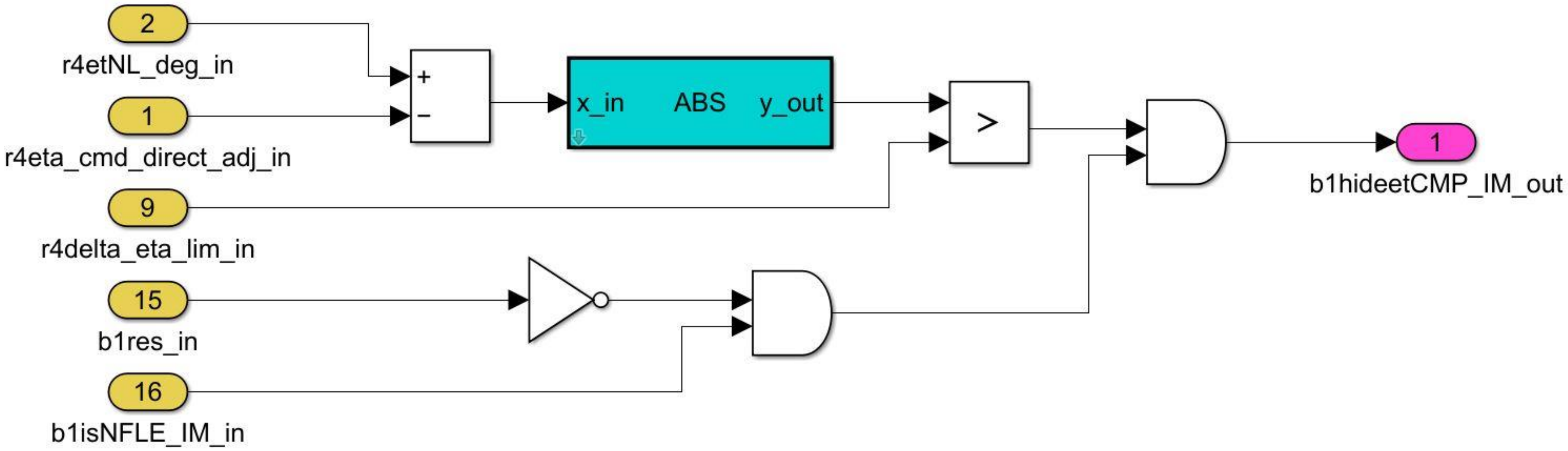
Command Comparison – Elevator Command

SL-09	IM shall trip if the elevator command of normal law η_{cmd} and direct law $\eta_{DL,cmd}$ significantly differ, AND aircraft operated in normal flight envelope.
Rationale:	The flight control law outputs should be similar when considering the effects of dynamic pressure and flight envelope protections are inactive.
Inputs	η_{cmd} and $\eta_{DL,cmd}$
Type	Comparator



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Thank You