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ALBATROS

Applying STPA to Hybrid Hydrogen-Electric Aircraft: Critical Parameter Identification for System Health Monitoring

Pipistrel Vertical Solutions

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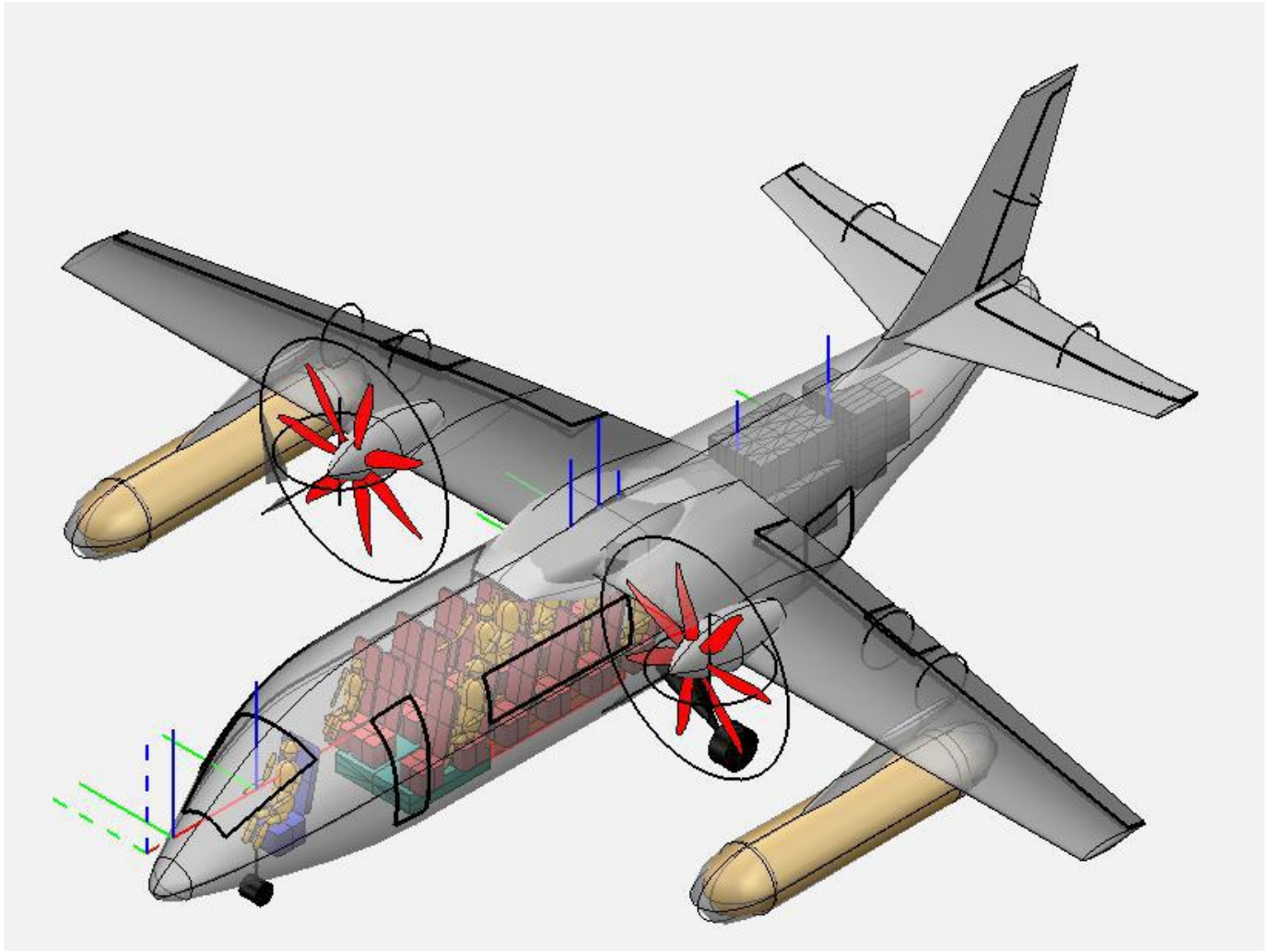
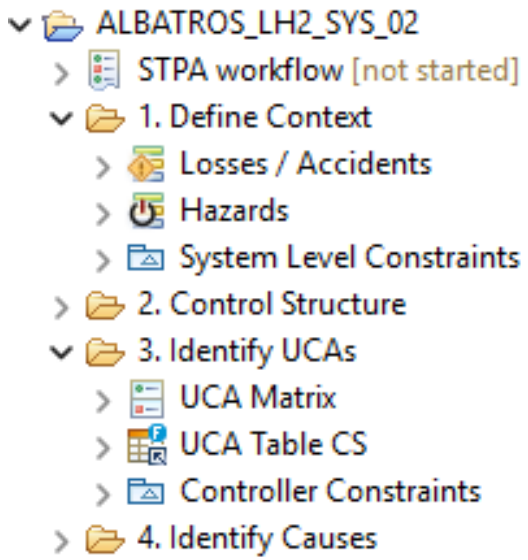
Reference Architecture: UNIFIER19 Aircraft Concept

- Hybrid hydrogen electric aircraft
- 29 passengers zero emmision air mobility
- Abstracted powertrain system:
  - Fuel Cell
  - High Voltage Batteries
  - Power Management
  - Electrical Propulsion Systems



STPA Execution



Task/Requirement	Checked	Related Artifacts	Checked By	Date of Check	Note
Define the Purpose of the Analysis	☐				
Identify Losses	☐	Losses / Accidents			Define Losses
Identify System-Level Hazards	☐	Hazards			Define Hazards and connect them to the Losses
Identify System Level Constraints	☐	System Level Constraints			Define SLC and connect them to the Hazards
Model the Control Structure	☐				
Identify Control Elements	☐				Define Controllers and Controlled Elements
Identify Control actions	☐				Define Control Connections and Control Actions
Identify Feedback	☐				Define Feedback Connections and Feedback

Defining the Purpose of the Analysis

Scope:

Powertrain monitoring and control during enroute flight phase.

Goal:

Identify critical parameters for operational health monitoring.

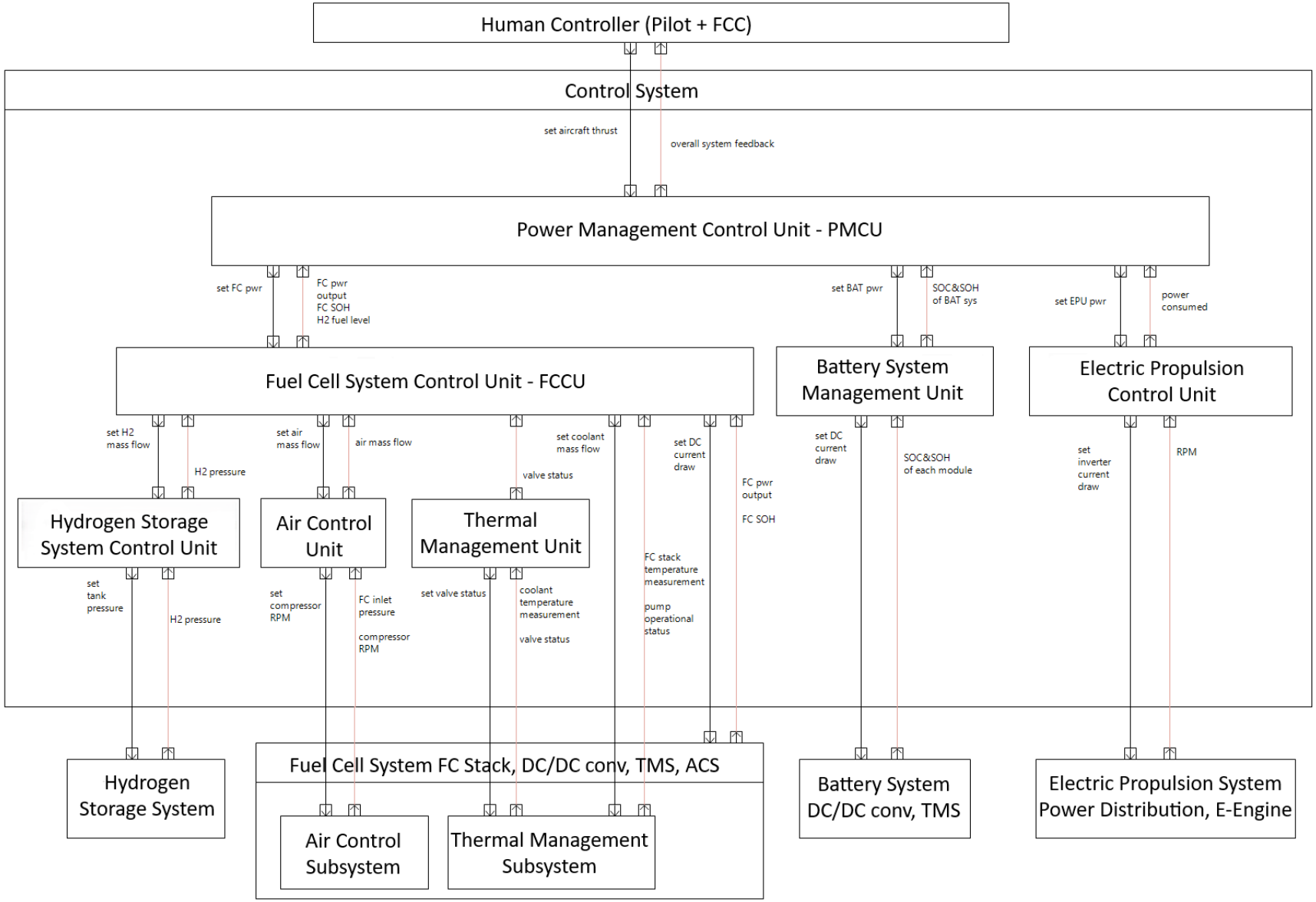
Losses to Stakeholder

- L-[1] Loss of life or injury to passengers
- L-[2] Structural damage to aircraft
- L-[3] Loss of hydrogen-electric powered flight mission

Defining the Purpose of the Analysis

System Hazards	System Constraints
H-[1] Aircraft doesn't have enough power for flight L-[2], L-[3]	SC-[1] Power must be provided
H-[2] Incorrect electrical power distribution L-[2], L-[3]	SC-[2] Power must be distributed accordingly
H-[3] Decreased engine handling on aircraft L-[2], L-[3]	SC-[3] Engine control must not decrease over a [TBD] threshold
H-[4] Violation of structural integrity of aircraft subsystems L-[1], L-[2], L-[3]	SC-[4] Structural integrity of aircraft must be maintained

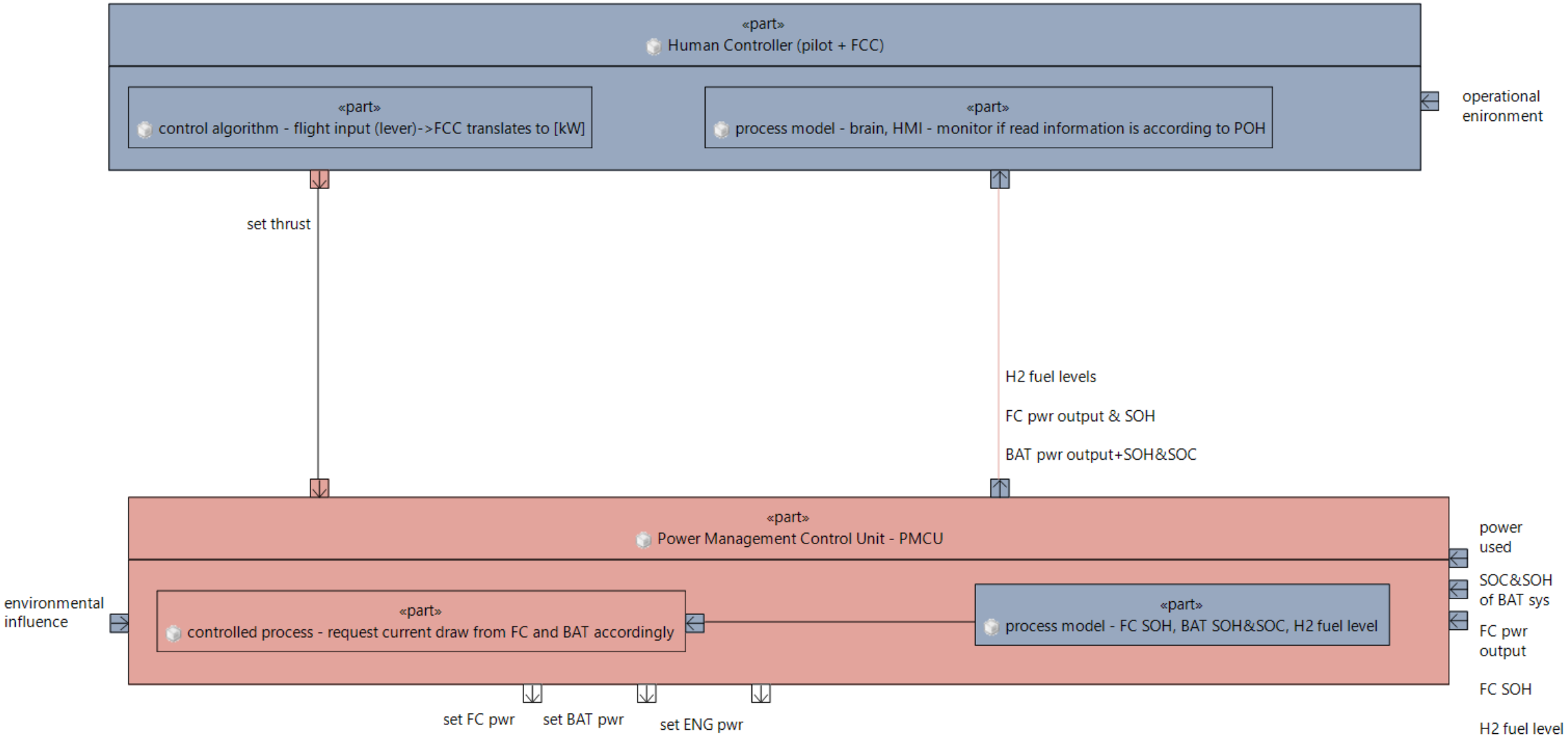
Modeling the Control Structure



Examples of Identified UCA and CC

Control Action	Unsafe Control Action	Hazard	Classification	Controller Constraints
HC -> PMCU				
[CA.1] set aircraft thrust	[UCA.1.1] Human controller doesn't set required trust to maintain flight during the mission	[H-1] Aircraft does Not have enough power for flight	HAZ	[CC-01] Human Controller must set accurate trust for a maintained flight
	[UCA.1.2] Human controller sets more than required thrust for the flight mission	[H-2] Incorrect Power Distribution in Aircraft	MAJ	[CC-02] Human Controller must respect the performance capabilities of the powertrain
PMCU -> FCCU				
[CA.2] set FC power	[UCA.2.1] PMCU doesn't set required FC power to meet the engine consumption during the flight mission	[H-1.1] Fuel Cells Not providing power needed for flight mission [H-2] Incorrect Power Distribution in Aircraft [H-4] Violation of Structural Integrity of Aircrafts Subsystems	HAZ	[CC-03] PMCU must request FC power provision to match the consumption of the engines
	[UCA.2.2] PMCU sets higher than required FC power production for the flight mission	[H-2] Incorrect Power Distribution in Aircraft [H-4] Violation of Structural Integrity of Aircrafts Subsystems	MAJ	[CC-04] PMCU must not exceed FC power production in the powertrain
FCCU -> ACU				
ACU -> FCS				
FCCU -> FCS				
FCCU -> HCU				
HCU -> H2S				
[CA.7] set tank pressure	[UCA.7.1] HCU doesn't set tank pressure to match the required H2 flow during the opertion creating a delta in reactant pressures	[H-4.1] Fuel Cells Overheat/Membrane Rupture [H-1.1] Fuel Cells Not providing power needed for flight mission	HAZ	[CC-13] HCU must adjust flow of H2 in accordance to FCCU request
	[UCA.7.2] HCU sets tank pressure above limit for the required operatioin creating overpressure in the tank	[H-4.2] Pressure Over Limit in LH2 Tank [H-4.4] H2 Fuel Leaking [H-1.1] Fuel Cells Not providing power needed for flight mission	CAT	[CC-14] No single point of failure must lead to the UCA [CC-15] HCU must respect the pressure limit of the tank and must have direct monitoring of pressures

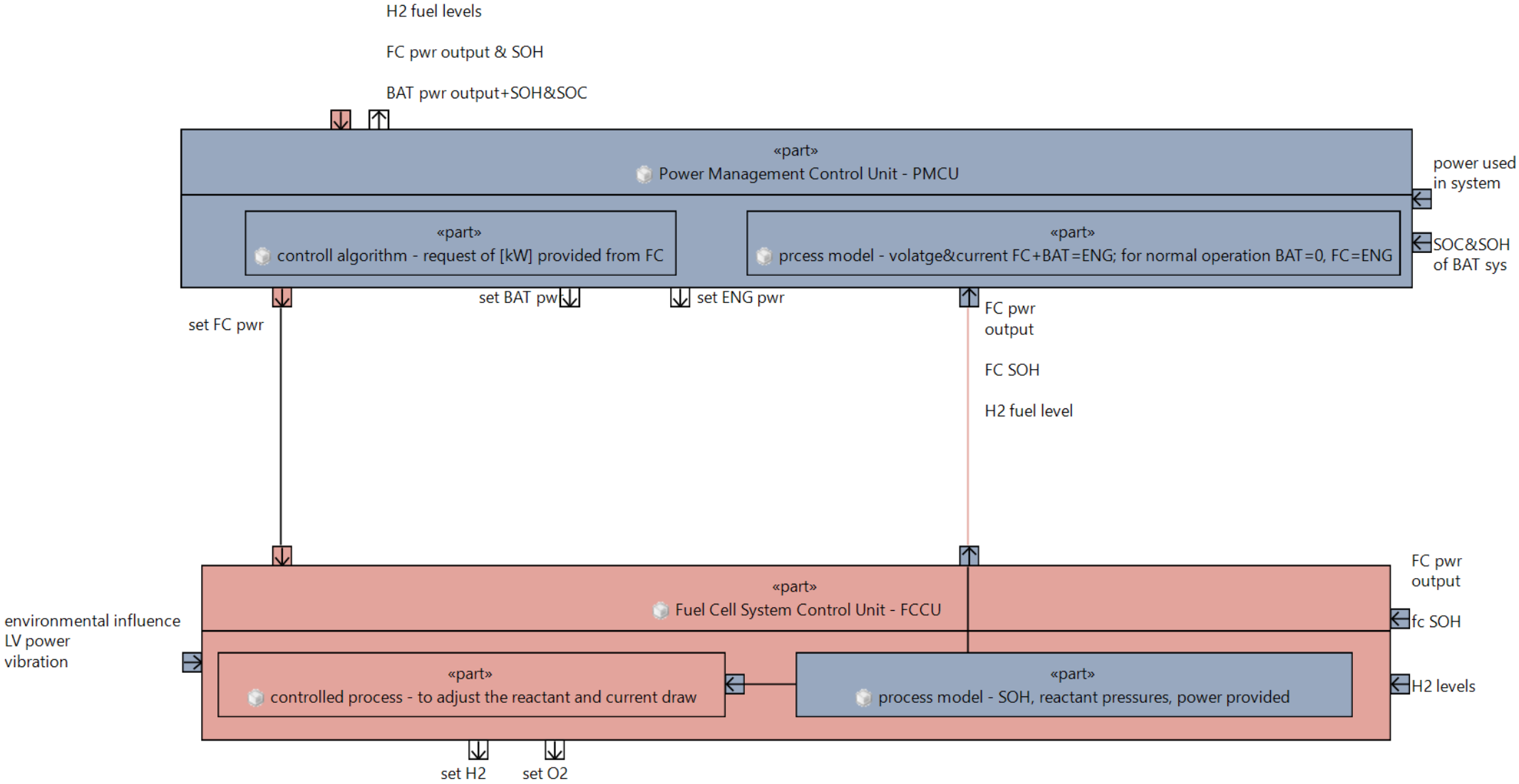
Example Control Loop CA.1



Example Causal Scenarios for UCA 1.1

- UCA1.1 Human controller doesn't set required trust to maintain flight during the mission
- Human interaction and operational factors
  - Set thrust is in response to aircraft conditions or ATC instructions.
  - Misinterpreted aircraft status due to incorrect or missing information on the flight display.
  - Received outdated or incomplete system information
- Controller and SW issues
  - FCC Incorrect translation of thrust commands into power request
  - PMCU incorrectly perceives aircraft state
  - Delayed feedback, processing overload
- Communication and Equipment failures
- Consequences: Aircraft doesn’t have enough power for flight
- Mitigations: Redundant control inputs, communication monitoring, FCC/PMCU fault detection, fault-tolerant displays, and verification of commanded versus delivered thrust

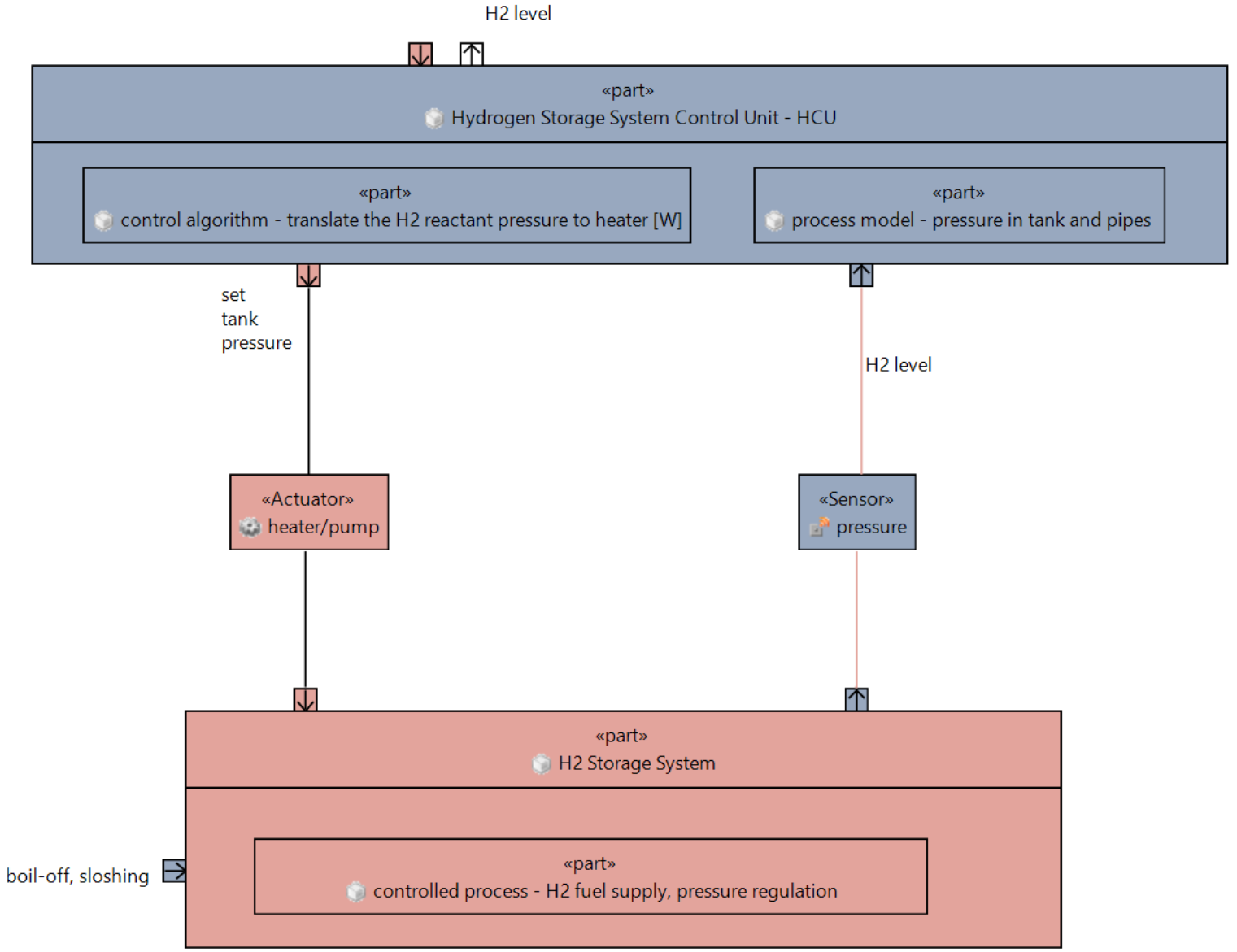
Example Control Loop CA.2



Example Causal Scenarios for UCA 2.1

- UCA 2.1 PMCU doesn't set required FC power to meet the engine consumption during the flight mission
- Controller and algorithm issues
  - Incorrect algorithm estimations and inaccurately processed system state
  - High voltage system information interference
- Communication and interface issues
- Feedback and system state awareness issues
- Consequences: Incorrect power distribution, insufficient power available for flight, and potential structural integrity concerns due to operation outside intended limits
- Mitigations: Algorithm validation, communication monitoring, controller fault detection, redundant communication paths, and real-time verification of power demand versus power delivery.

Example Control Loop CA.7



Example Causal Scenarios for UCA 7.2

- UCA 7.2 HCU sets tank pressure above limit for the required operation creating overpressure in the tank
- Incorrect calculation of the pressure required to support the requested power demand.
- Commanded excessive heating or pressure increase.
- Feedback and sensor issues
- Communication and interface failures
- Heater responds unexpectedly due to a fault or electrical disturbance.
- Tank pressure regulation system fails to respond to commands
- Consequences tank overpressure, hydrogen leakage, loss of propulsion power, and potential compromise of system integrity
- Mitigations: pressure sensors with voting logic, pressure limit monitoring, safety relief valves, fail-safe venting mechanisms, and independent verification of tank pressure.

Critical Parameters for Health Monitoring

Fuel Cells Stack	Hydrogen System	Air System	DC/DC Converter	Thermal Management
• Cathode and Anode differential pressure • Temperature	• H2 Mass Flow • Hydrogen Concentration • Tank Pressure • Temperature	• Air mass flow • Air Humidity & Temperature • Oxygen concentration	• System & Cell Voltage • Current Draw	• Coolant Temperature • Coolant Mass Flow • Pressure



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