Collaborative Functional Design Using Explainable Machine Learning (X-ML)

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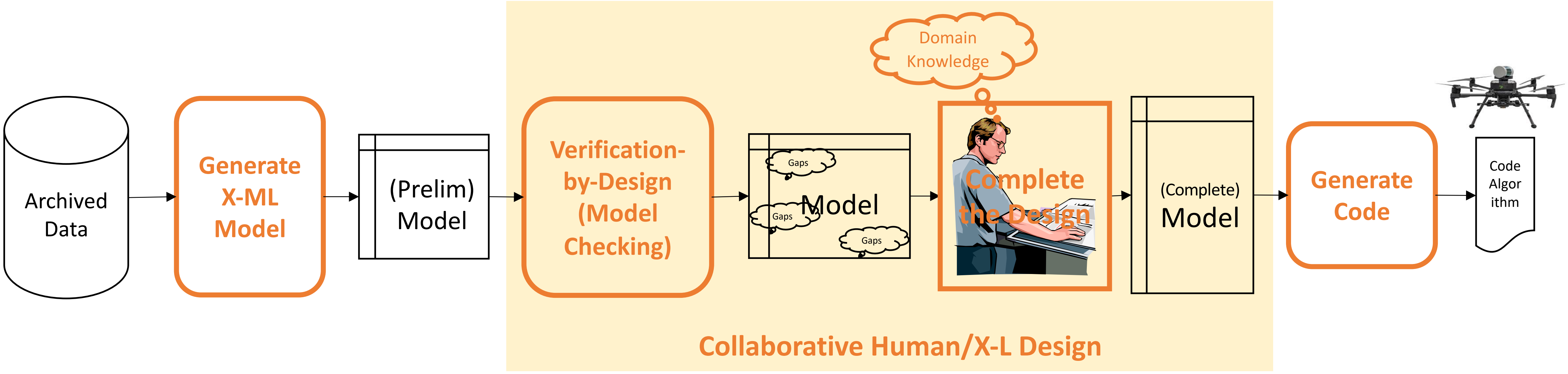
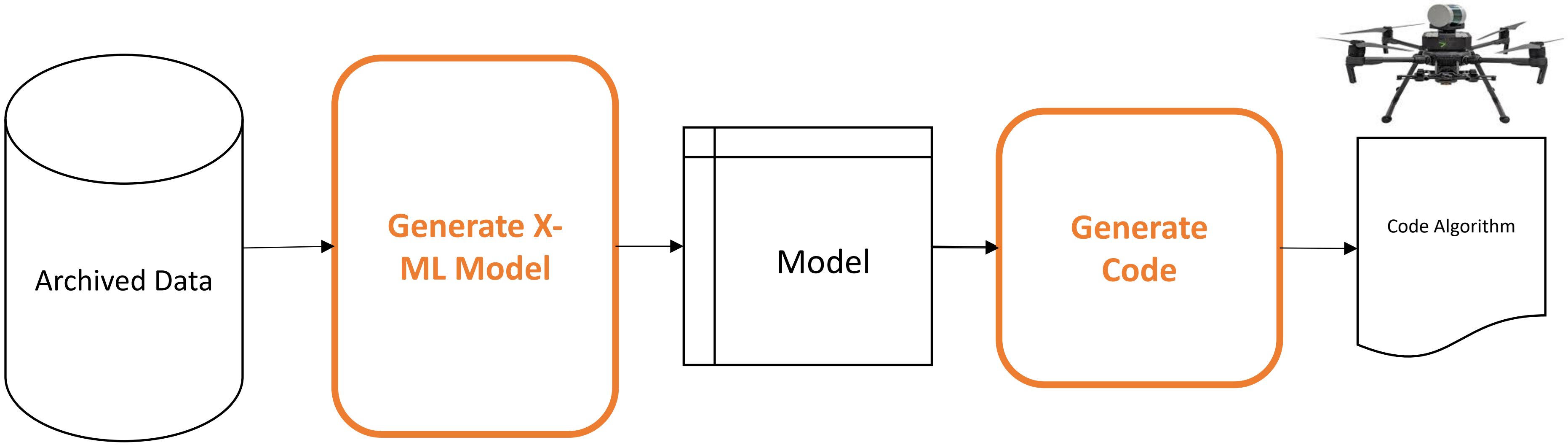
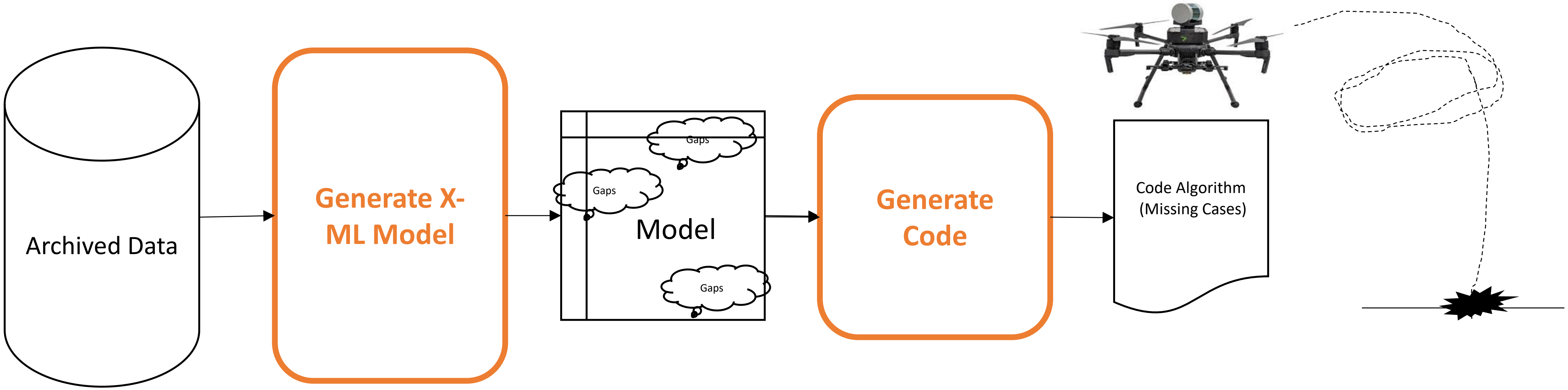


The AI Advertising



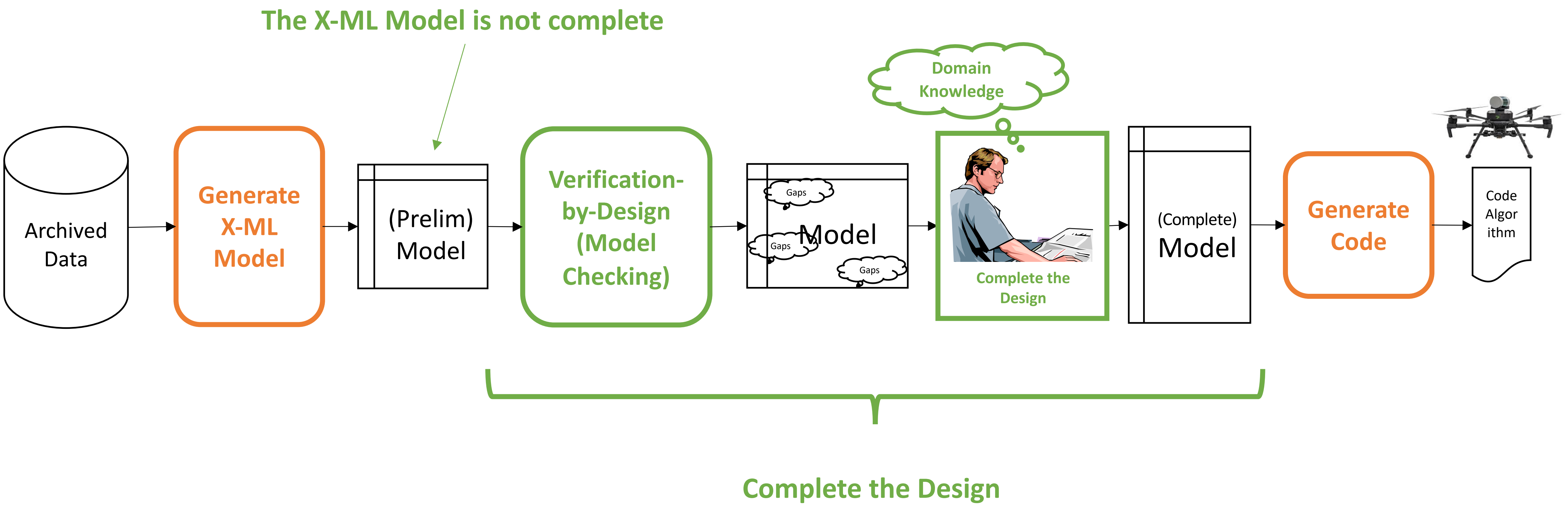
The Reality



Archived Data
Generate X-ML Model
Gaps
Gaps
Model
Gaps
Generate Code
Code Algorithm (Missing Cases)

The Solution:

Collaborative Functional Design Using Explainable Machine Learning (X-ML)



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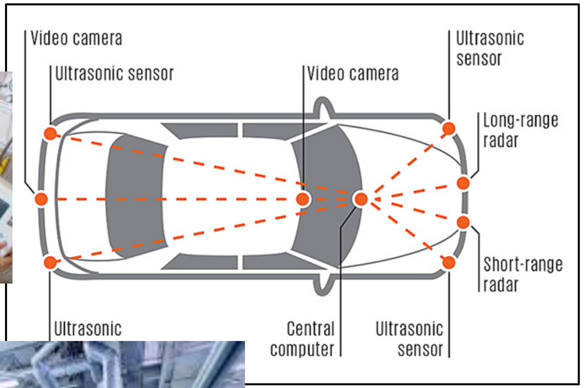
Operationally Embedded Control Systems

- Embedded on vehicle or plant
- Provide Guidance and Control functions to perform Mission
- Complex
  - Over 200 input signals
  - Over 10 actuator command outputs

Operationally Embedded Control Systems

- Operationally embedded control systems are widely used:
  - military applications
  - vehicle guidance and control
  - robot manipulation
  - mission planning
  - health diagnosis



Operationally Embedded Control Systems

- functional behavior of a typical military operationally embedded control system is complex
  - over 200 input signals
  - 10 outputs actuator commands
- Many applications require operational reliability of at least five-nines for “airworthiness” approval
  - Interpretable:
    - System Description Documents
    - Training Manuals
    - Operator User-interfaces
  - Executable
  - Certifiable (e.g. DO-178)

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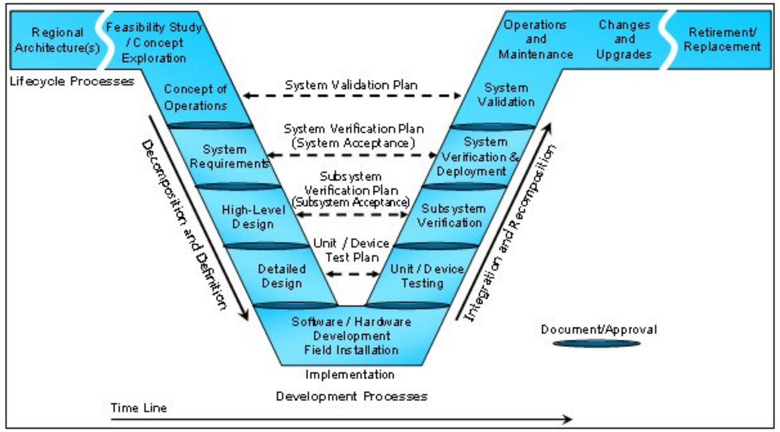
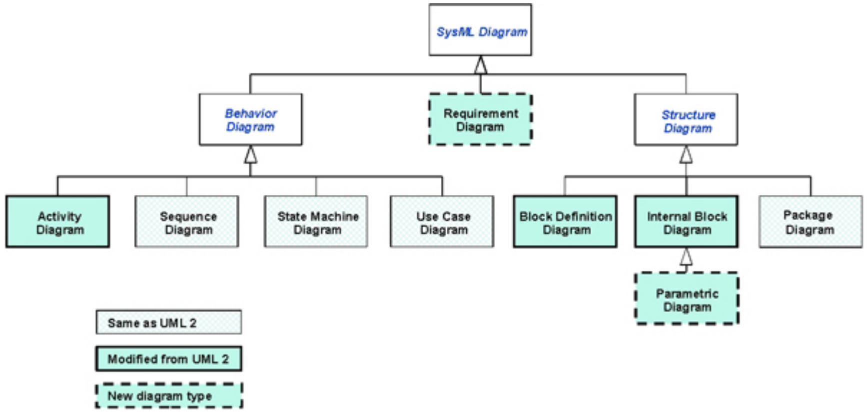
Operationally Embedded Control Systems

- Traditional System Engineering practice:
  - specifies the functional requirements for the operationally embedded control systems
  - a manual engineering process
    - engineers collaborate with operators to define what the automation should do at all times.
- Specifications take the form of functional descriptions of behavior
  - map inputs representing the state of the operational environment to outputs (commands to actuators or guidance/alerts on displays)
- Functional behavior requirements can be specified using several modeling language constructs including combinations of:
  - “shall” requirements
  - Action Diagrams
  - Functional Flow Block Diagrams
  - state-charts, logic diagrams
  - control law diagrams
- When the modeling construct is executable it can be used to:
  - automatically generate code
  - provide verification by analysis of the design





Operationally Embedded Control Systems

- Traditional System Engineering practice:
  - specifies the functional requirements for the operationally embedded control systems
  - a manual engineering process
    - engineers collaborate with operators to define what the automation should do at all times.
- Time consuming
  - 1-2 years in design, coding and testing
- Subject to errors
  - Three Design Error Archetypes
    1. Fail to cover situations that can occur in operations
       1. Missing input
       2. Missing combination of input/states
    2. Fail to specify the appropriate behavior to situations that can occur in operations.

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Machine Learning for OECS

- Generate functions with complex behaviors
  1. Process massive amounts of data (input: output pairs)
  2. Supervised Learning
  3. Test
  4. Deploy

- Capture complex behavior with little/no engineering effort
- Potential to significantly reduce development time!

- Can this potential be fulfilled? What are the limitations

Machine Learning for OECS

- AI/ML technologies provide **potential** to develop and field functions
  - Increased complex functional behavior
  - Lower Development costs and time
  - Safer (through increased complex functional behavior)
    - Better than humans?

- Can this potential be fulfilled? What are the limitations

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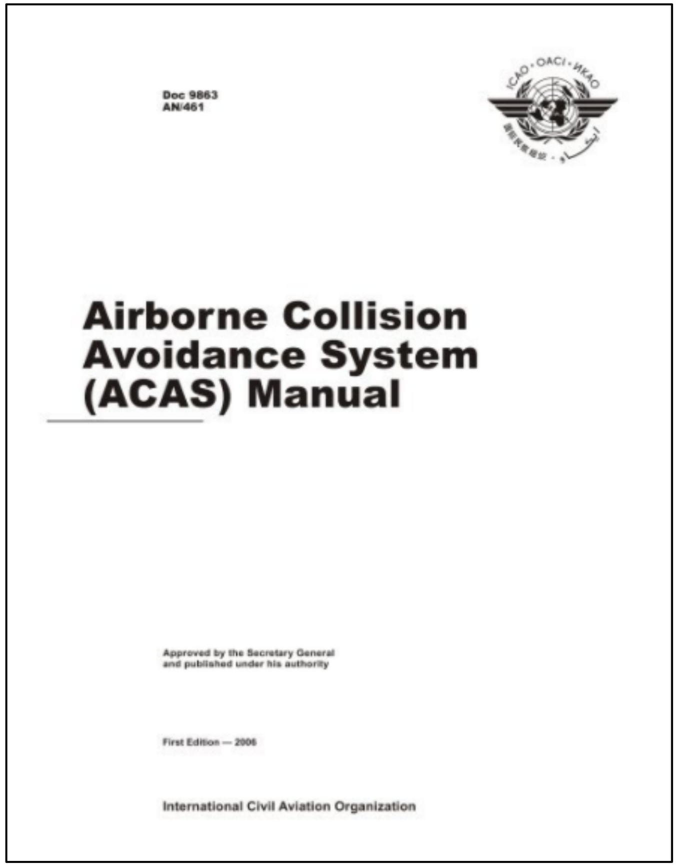
1. Operationally Embedded Control Systems (OECS)
2. Design and Testing for OECS
3. Machine Learning for OECS
4. Case Studies
5. Research Objective
6. Collaborative Functional Design Using X-ML

Case Study: ACAS



Doc 9863
AN/461

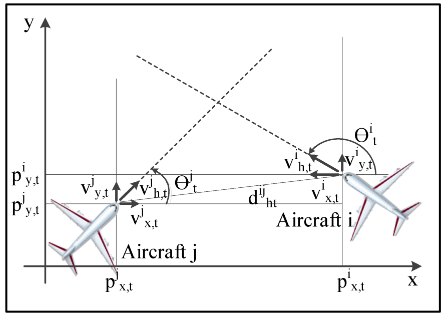
Airborne Collision Avoidance System (ACAS) Manual

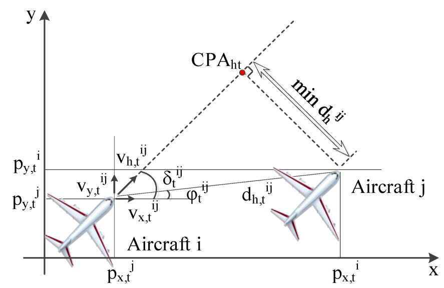
Approved by the Secretary General
and published under his authority

First Edition — 2006

International Civil Aviation Organization

- Decision logic
- Finite “collision geometry design-space”
- Each “collision geometry” has defined response





Case Study: HSCT – VNAV G&CF

- NASA High Speed Civil Transport (HSCT) Flight Management System (FMS)
  - HSCT FMS is based on MD-11 FMS

- Generated FOQA data from simulation flights
  - ~18,000 “Guidance and Control” scenarios
  - Scenarios included rare-events (e.g. Engine-out)
  - Data had to balanced to increase frequency of rare-event situations
    - ~ 26,000 “Guidance and Control” scenarios

Case Study: X-ML Model Accuracy Parameters

```
Precision: [1. 1. 1. 1. 1. 1. 1. 1. 1. 1. 1. 1. 1.]
Recall: [1. 1. 1. 1. 1. 1. 1. 1. 1. 1. 1. 1. 1.]
Fscore: [1. 1. 1. 1. 1. 1. 1. 1. 1. 1. 1. 1. 1.]
Support: [220 167 193 183 203 236 195 187 199 210 206 195 208]
Train Accuracy:  1.0
Test Accuracy:  1.0
```

```
Confusion matrix:
[[220   0   0   0   0   0   0   0   0   0   0   0   0]
 [  0 167   0   0   0   0   0
 [  0   0 193   0   0   0   0
 [  0   0   0 183   0   0   0   0   0   0   0   0   0]
 [  0   0   0   0 203   0   0   0   0   0   0   0   0]
 [  0   0   0   0   0 236   0   0   0   0   0   0   0]
 [  0   0   0   0   0   0 195   0   0   0   0   0   0]
 [  0   0   0   0   0   0   0 187   0   0   0   0   0]
 [  0   0   0   0   0   0   0   0 199   0   0   0   0]
 [  0   0   0   0   0   0   0   0   0 210   0   0   0]
 [  0   0   0   0   0   0   0   0   0   0 206   0   0]
 [  0   0   0   0   0   0   0   0   0   0   0 195   0]
 [  0   0   0   0   0   0   0   0   0   0   0   0 208]]
```

No Type I or II Errors

but …

- VNAV and ACAS were “missing” Behavior

1. Missing Situations
    1. Missing Inputs
    2. Missing Input/State combinations
2. Missing Situation-Behavior Mapping

What are the Gaps in X-ML Designs?

- X-ML Design is Missing Input
  - Design is ***absent one or more of the required inputs*** (i.e. sensors/data feeds) to identify one or more of the operational situations that must be covered by the operationally embedded system
- X-ML is Missing Input/State Combinations
  - Given all the required inputs, the design is ***absent one or more combinations of input states*** to respond to *all* the operational situations that must be covered by the operationally embedded system
- X-ML is Missing Mapping between Input/State Combinations to Behaviors
  - Given the required inputs to support all the combinations of input states and all the combinations of input states, the design is ***absent one or more the correct mappings*** between operational situations and appropriate behaviors

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Research Objectives

- Demonstrate development of DO-178 certifiable Operationally Embedded Control System
  - Explainable Machine Learning
  - Model must be:
    - Interpretable
    - Executable
    - Compatible with existing airworthiness certification standards

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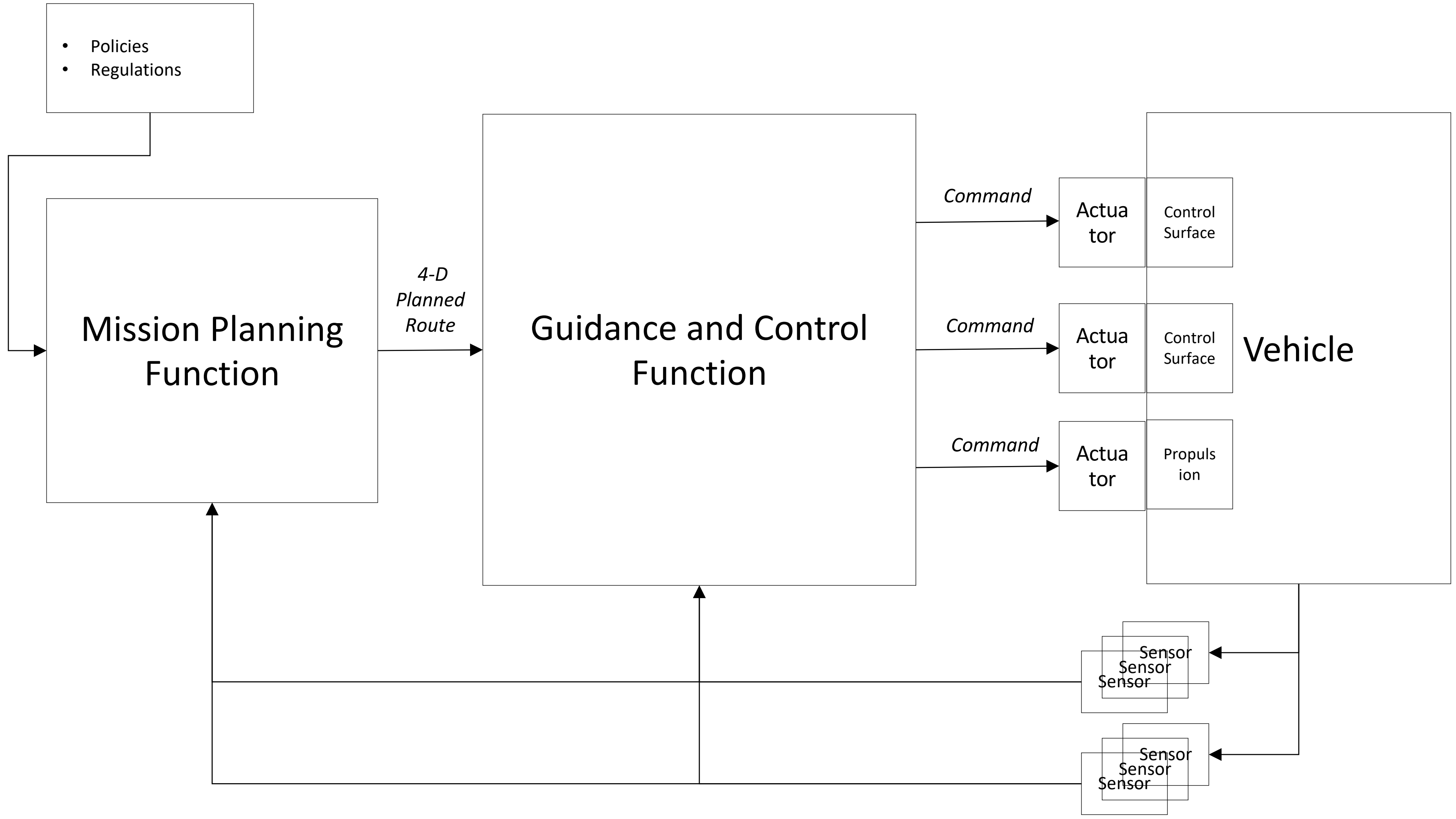
X-ML OECS Method

- Exploit “natural” architecture of Guidance and Control Systems to generate X-ML algorithms
  - X-ML algorithms can be:
    - converted to functional behavior models
    - mapped to situation/intent/behavior modes

Example OECS: Vehicle Guidance and Control Function

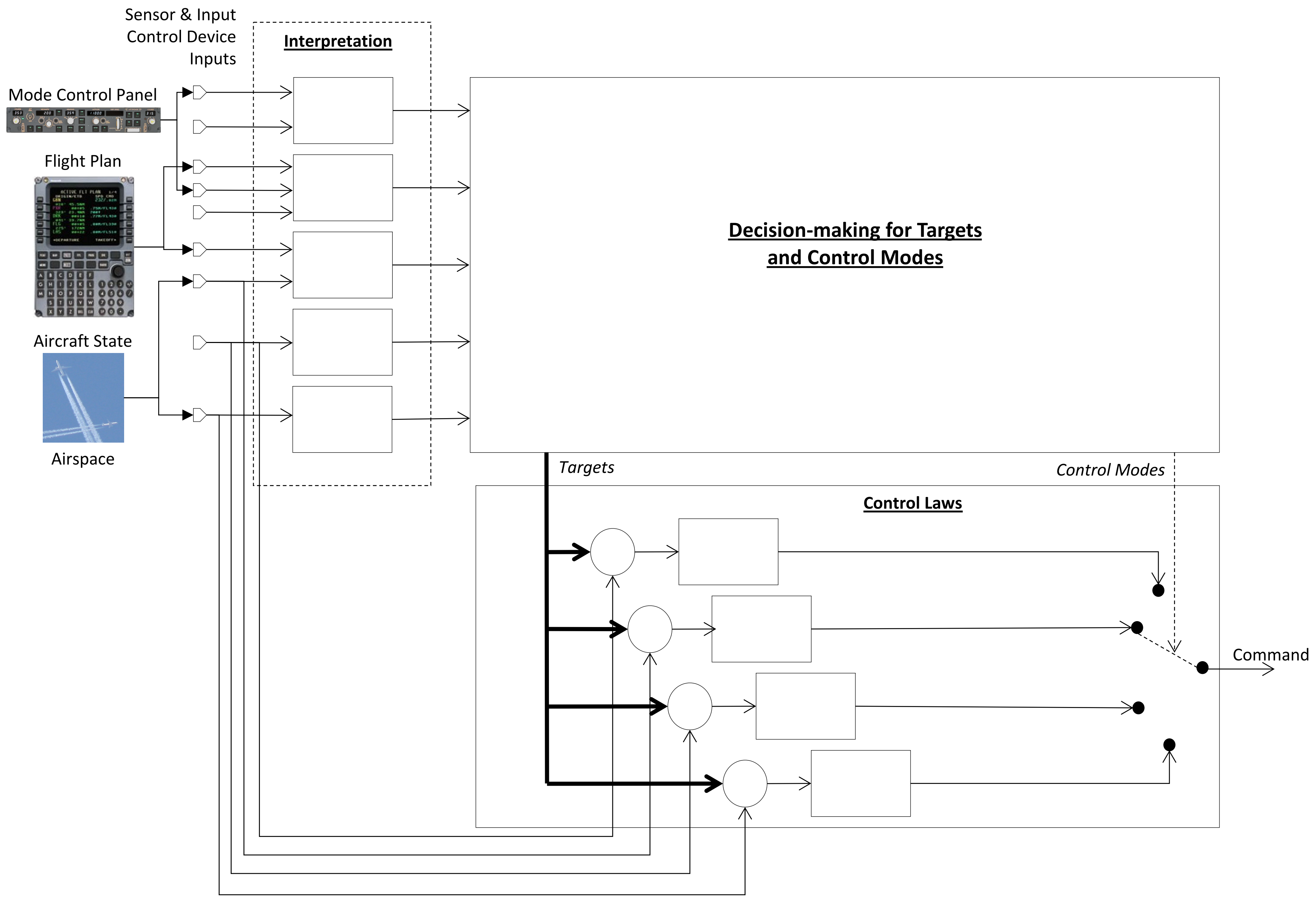


Example OECS: Vehicle Guidance and Control Function

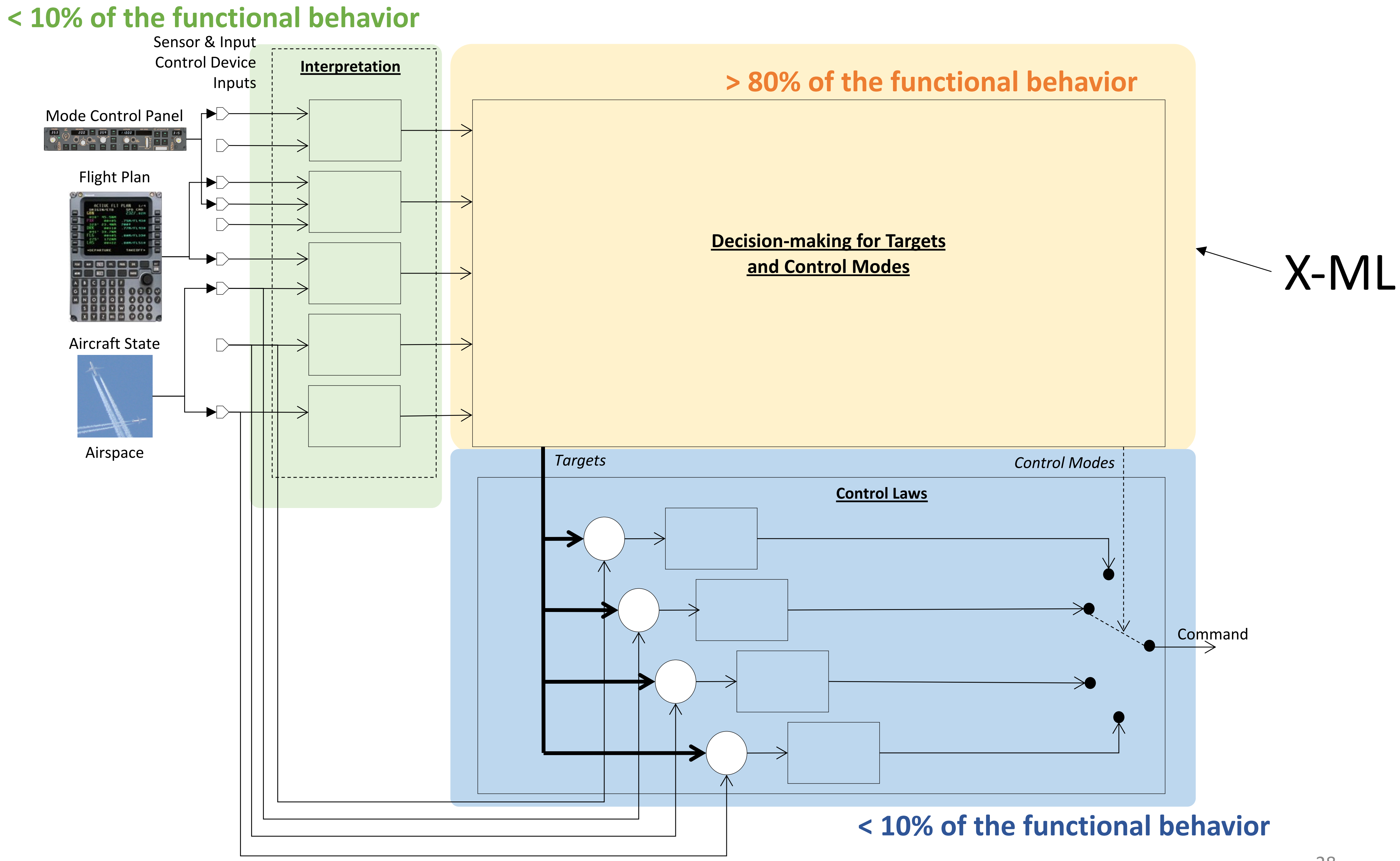
G&CF (Inputs, Outputs)	**Fixed Wing**	**Automobile**
Input: 4-D Planned Route	“Flight plan” • 4-D • Navigation Procedures • Air Traffic Control • Traffic avoidance • Terrain avoidance • Env. – Windshear	“Route” • 4-D • Roadway Rules • Signage and Traffic Lights • Traffic avoidance • Terrain avoidance • Env. – surface conditions, visibility
Output: Commands	• Elevator • Aileron • Rudder • Thrust	• Accelerator/Brake • Steering

Example OECS: Vehicle Guidance and Control Function

- Three components:
  1. Control Laws
     - Closed-loop control laws (continuous mathematics)
     - Designed based on models of vehicle and actuator dynamics
  2. Decision-making for Targets and Control Modes
     - Decision (logic)
     - Designed based on:
       - Closed-loop control law operational boundaries
       - Vehicle performance operational limits
       - Mission operational rules and constraints
  3. Interpretation
     - Translate sensor/user-interface input data into operationally meaningful mission data



Sensor & Input
Control Device
Inputs
Interpretation
Mode Control Panel
Flight Plan
Aircraft State
Airspace
Decision-making for Targets and Control Modes
Targets
Control Modes
Control Laws
Command



< 10% of the functional behavior
Sensor & Input Control Device Inputs
Interpretation
> 80% of the functional behavior
Mode Control Panel
Flight Plan
Aircraft State
Airspace
Decision-making for Targets and Control Modes
X-ML
Targets
Control Modes
Control Laws
Command
< 10% of the functional behavior

Decision-making (DM) for Targets and Control Modes (T&CM)

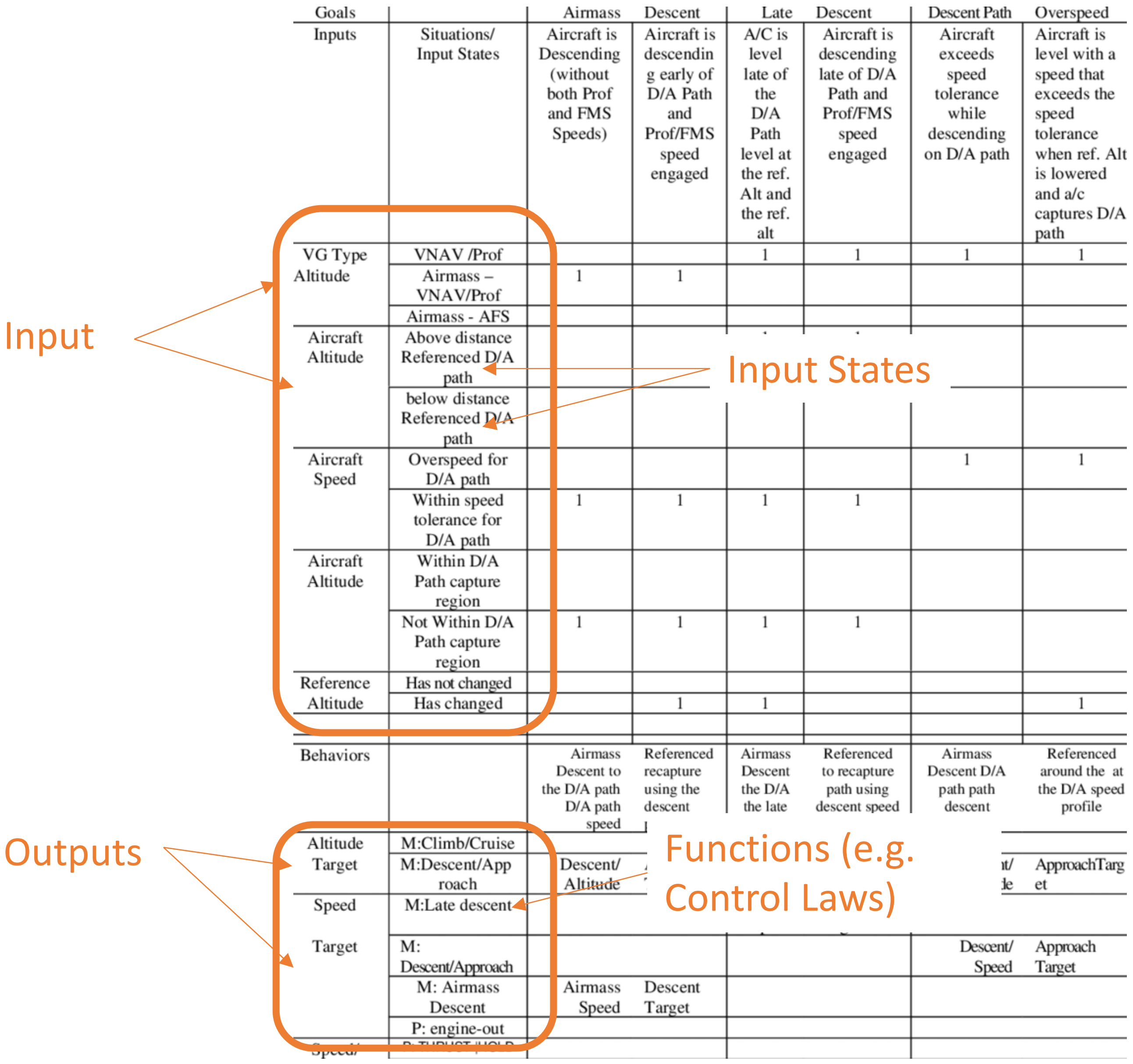
- Inputs to DM-T&CM
  - Inputs (States)
    - Examples
      - Landing Gear (Up, Down)
      - Flightphase (Taxi, Takeoff, Climb, Cruise ,. ….)
      - Aircraft Altitude (< Ref Alt – 250 ft, Between Ref Alt -250 ft and Ref Alt + 250 ft, > Ref Alt + 250 ft)
  - ~ 150 inputs (Avg 3 states)
- Outputs from DM-T&CM
  - Targets for Altitude, Airspeed, Vertical Speed
  - Control Mode

Formalism for Capturing DM for T&MC

- Situation-Goal-Behavior (SGB) Tables
- Properties of SGB Table
  - Formal model
    - Executable
    - Analyzable (e.g. logical inconsistencies)
  - Captures “Operations” from Operators Perspectives
    - What is doing now?
      - Goal
      - Behavior
    - Why is it doing that?
      - Situations

Goals		Airmass	Descent	Late	Descent	Descent Path	Overspeed
Inputs	Situations/ Input States	Aircraft is Descending (without both Prof and FMS Speeds)	Aircraft is descendin g early of D/A Path and Prof/FMS speed engaged	A/C is level late of the D/A Path level at the ref. Alt and the ref. alt	Aircraft is descending late of D/A Path and Prof/FMS speed engaged	Aircraft exceeds speed tolerance while descending on D/A path	Aircraft is level with a speed that exceeds the speed tolerance when ref. Alt is lowered and a/c captures D/A path
VG Type Altitude	VNAV /Prof			1	1	1	1
	Airmass – VNAV/Prof	1	1				
	Airmass - AFS						
Aircraft Altitude	Above distance Referenced D/A path			1	1		
	below distance Referenced D/A path						
Aircraft Speed	Overspeed for D/A path					1	1
	Within speed tolerance for D/A path	1	1	1	1		
Aircraft Altitude	Within D/A Path capture region						
	Not Within D/A Path capture region	1	1	1	1		
Reference Altitude	Has not changed						
	Has changed		1	1			1
Behaviors		Airmass Descent to the D/A path D/A path speed	Referenced recapture using the descent profile	Airmass Descent the D/A the late profile	Referenced to recapture path using descent speed	Airmass Descent D/A path path descent	Referenced around the at the D/A speed profile
Altitude Target	M:Climb/Cruise						
	M:Descent/Approach	Descent/ Altitude	Approach Target	Descent/ Altitude	ApproachTarget	Descent/ Altitude	ApproachTarget
Speed Target	M:Late descent			Late Speed	Descent Target		
	M: Descent/Approach					Descent/ Speed	Approach Target
	M: Airmass Descent	Airmass Speed	Descent Target				
	P: engine-out						
Speed/	P: THRUST |HOLD						

Situation-Goal-Behavior (SGB) Model for Op Embedded Control System



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	M:Descent/Approach	Descent/ Altitude					ApproachTarget
Speed	M:Late descent						
Target	M: Descent/Approach					Descent/ Speed	Approach Target
	M: Airmass Descent	Airmass Speed	Descent Target				
	P: engine-out						

How to read an SGB:

- Inputs
- Input/States
- Outputs
- Output/Functions

Situation-Goal-Behavior (SGB) Model for Op Embedded Control System

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Speed/	P: THRUST |HOLD						

Situation = combination of Input States

Behavior = Combination of Functions

How to read an SGB:

- Inputs
- Input/States
- Outputs
- Output/Functions
- Situations (combinations of Input States)
- Behavior (combinations of Functions)

Situation-Goal-Behavior (SGB) Model for Op Embedded Control System

Goals		Airmass	Descent	Late	Descent	Descent Path	Overspeed
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Speed/	P: THRUST |HOLD						

Situation = combination of Input States

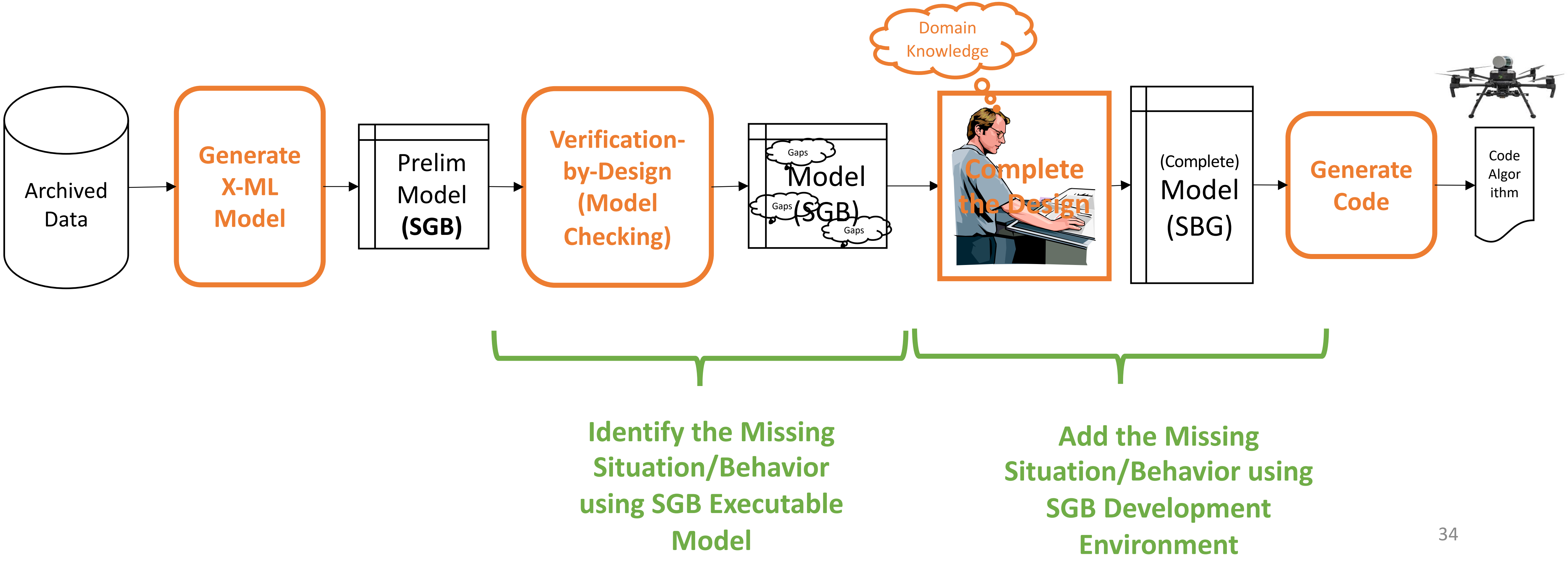
Behavior = Combination of Functions

SGB: one-stop-shopping for Certification (DO-178)

- Design-by-Verification
  - Logical Completeness
  - Logical Consistency
- Missing "behavior"

SGB: auto-generation of code

Collaborative Functional Design Using X-ML

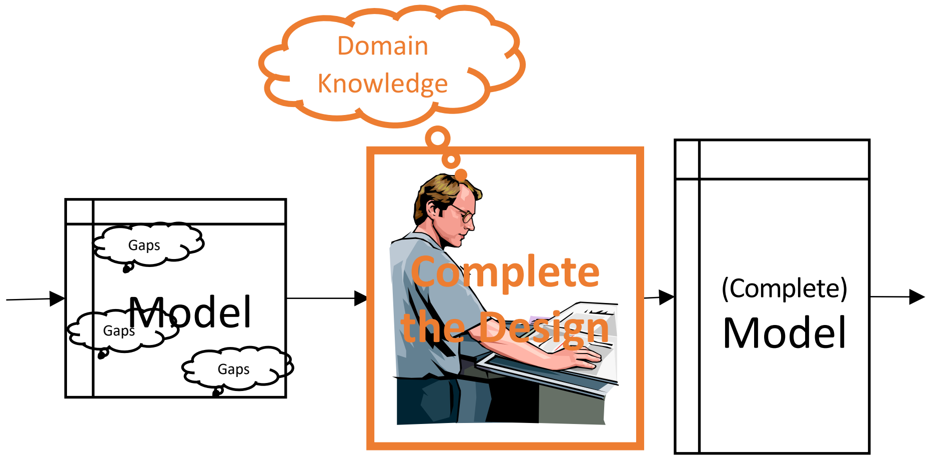


What are the Gaps in X-ML Designs?

- X-ML Design is Missing Input
  - Design is ***absent one or more of the required inputs*** (i.e. sensors/data feeds) to identify one or more of the operational situations that must be covered by the operationally embedded system
- X-ML is Missing Input/State Combinations
  - Given all the required inputs, the design is ***absent one or more combinations of input states*** to respond to *all* the operational situations that must be covered by the operationally embedded system
- X-ML is Missing Mapping between Input/State Combinations to Behaviors
  - Given the required inputs to support all the combinations of input states and all the combinations of input states, the design is ***absent one or more the correct mappings*** between operational situations and appropriate behaviors

Mitigating Gaps in X-ML Designs

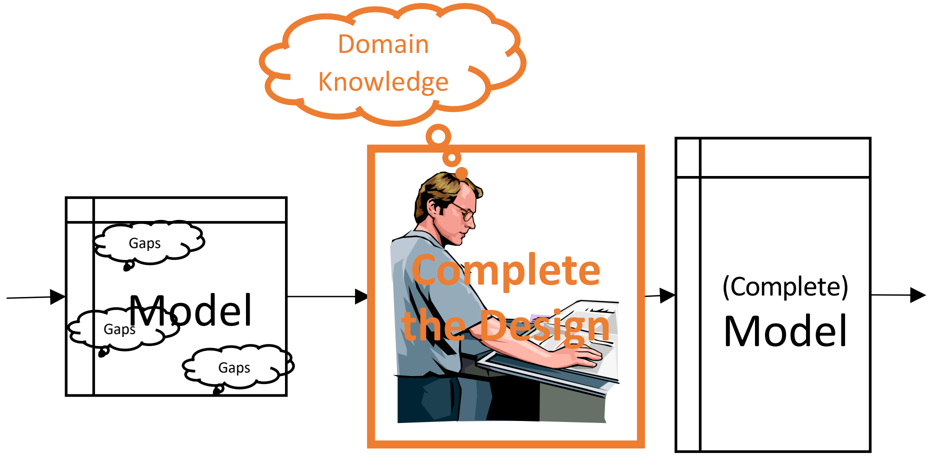
- <u>X-ML is Missing Input/State Combinations</u>
  - Given all the required inputs, the design is ***absent one or more combinations of input states*** to respond to *all* the operational situations that must be covered by the operationally embedded system
- Use SGB Model to generate Complete Design
  - Generate all the combinations of Input/States
- Use SGB Model to generate Consistent Design
  - Make sure no duplicate combinations of Input/States



Mitigating Gaps in X-ML Designs

- <u>X-ML is Missing Mapping between Input/State Combinations to Behaviors</u>
  - Given the required inputs to support all the combinations of input states and all the combinations of input states, the design is ***absent one or more the correct mappings*** between operational situations and appropriate behaviors

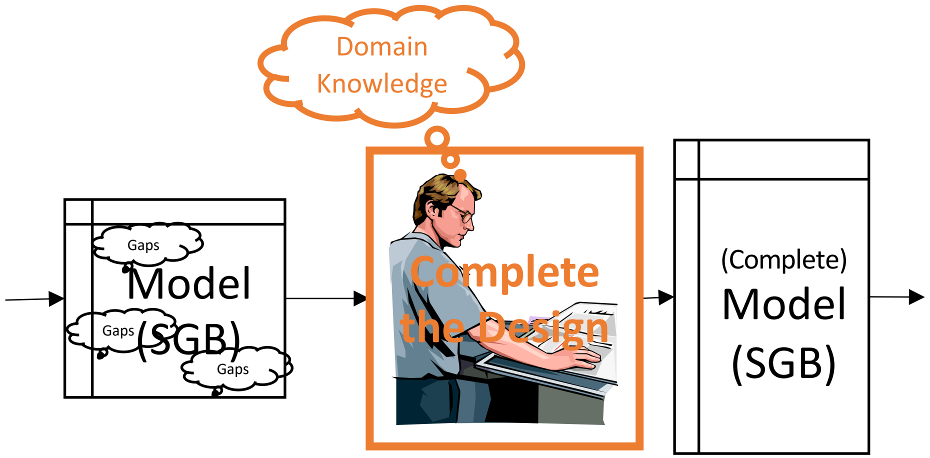
- Use SGB Model to generate Complete Design
  - Check each legal Behavior



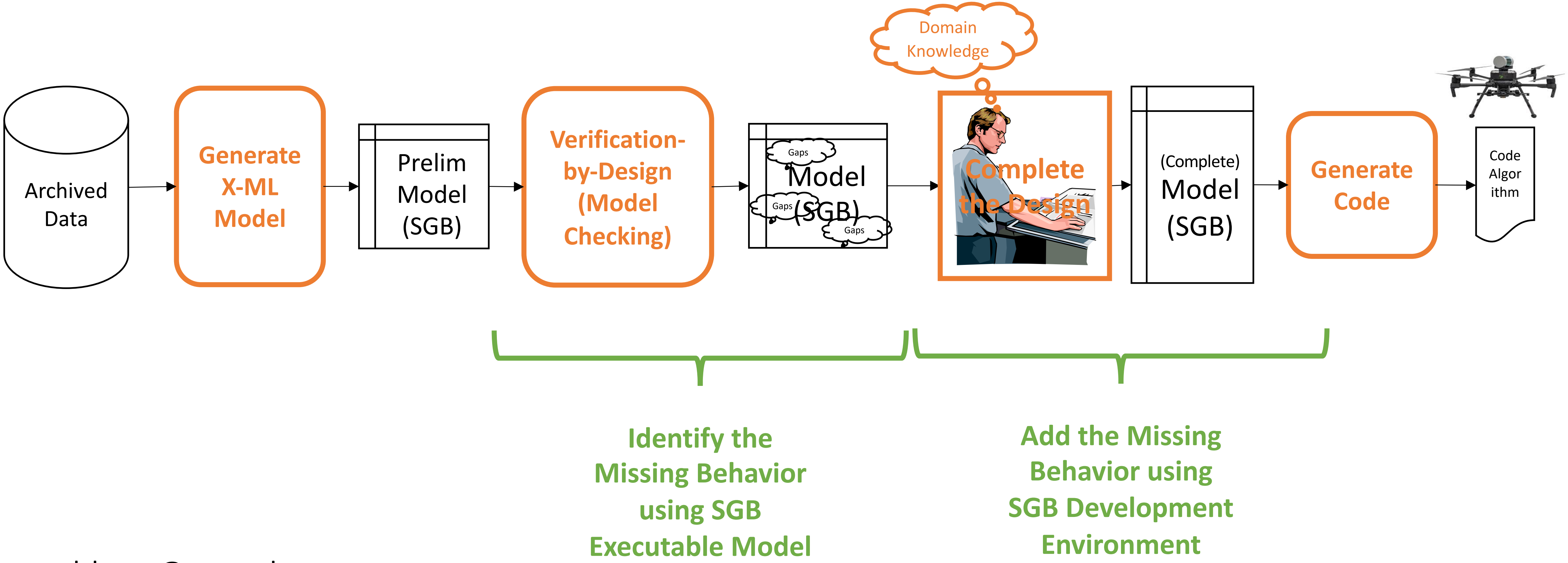
Mitigating Gaps in X-ML Designs

- <u>X-ML Design is Missing Input</u>
  - Design is ***absent one or more of the required inputs*** (i.e. sensors/data feeds) to identify one or more of the operational situations that must be covered by the operationally embedded system

- Scenario Analysis/Use Cases
- Hazard Analysis



Realistic Use of X-ML:
Collaborative Functional Design Using X-ML



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