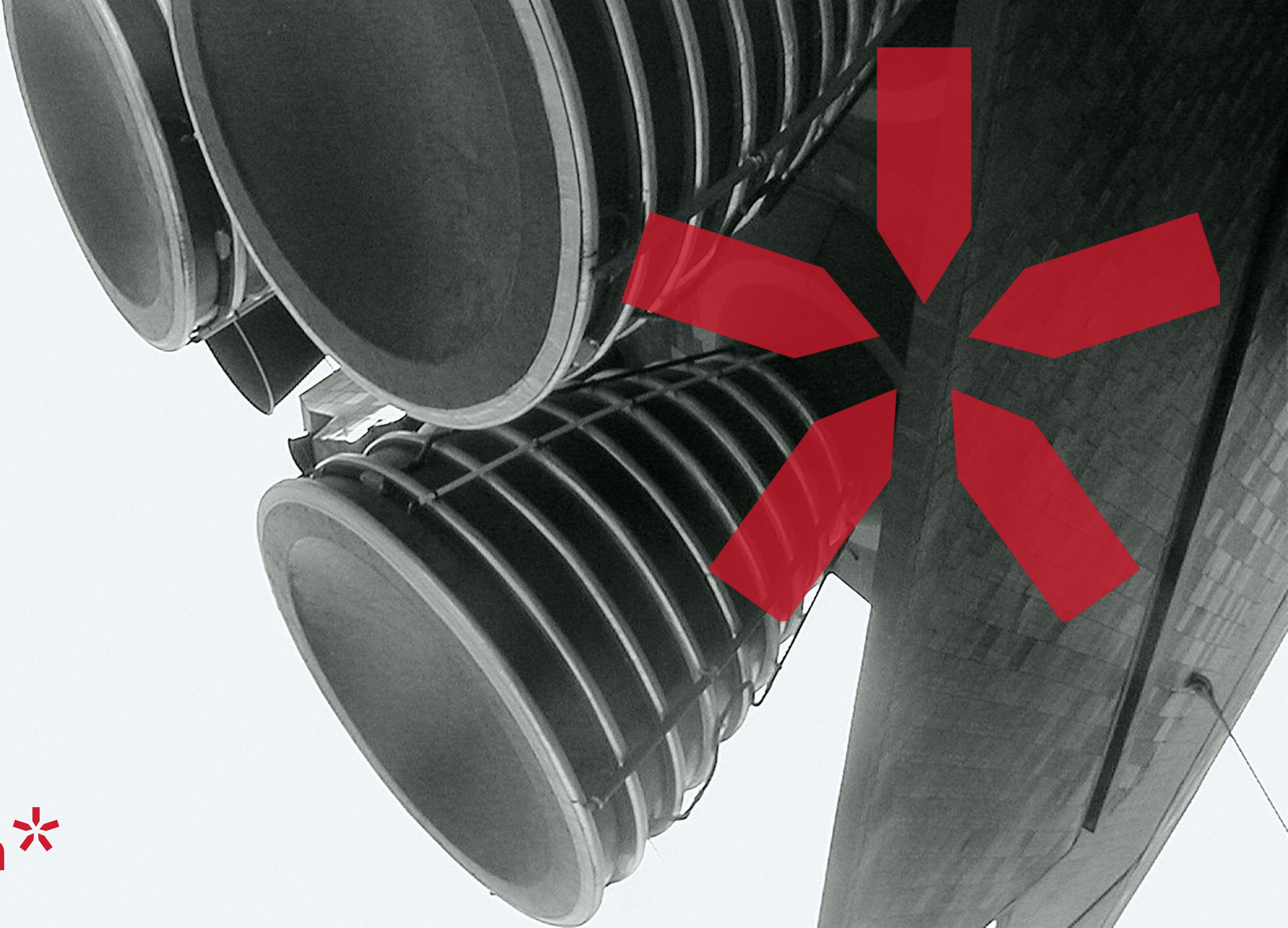

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Design Simulation and Software Validation for On-Board and Real-Time Optimal Guidance

Carlo Alberto Pascucci, Alvaro Fernandez, Juan Jerez,
Samir Bennani, Jean-Philippe Preaud, Jorgen Bru

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WHY DO WE NEED REAL-TIME OPTIMAL GUIDANCE?

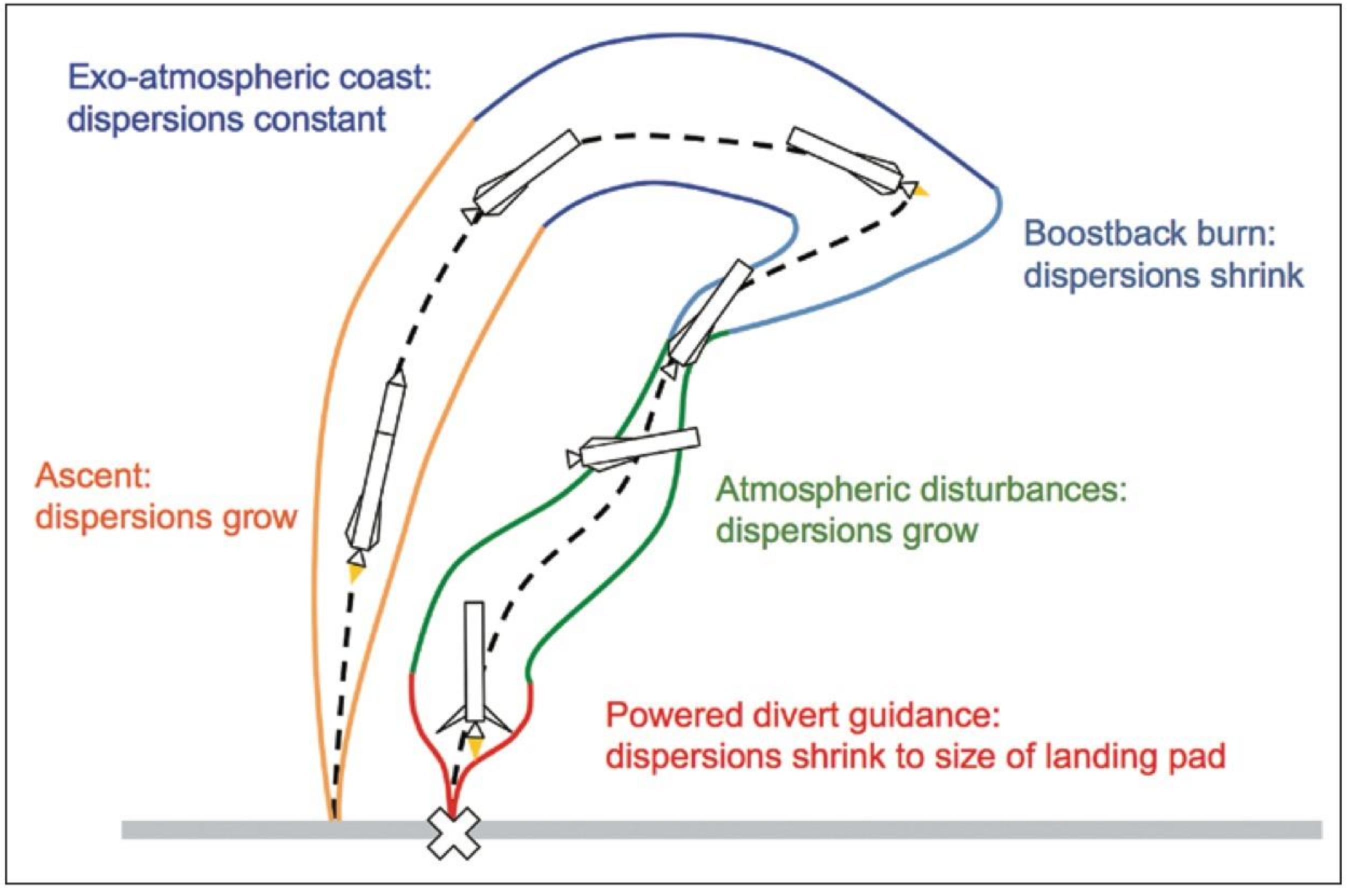

FIGURE 4 Phases of an F9R return-to-launch-site mission. The colored lines represent the largest possible variations in the trajectory, known as dispersions.

- Trajectory optimality under actual flight conditions
- Ensure mission completion under constraints and actual flight conditions
- Reduce missionization time
- Mid-flight replanning (mission flexibility)

On-line optimization enables autonomous space operations

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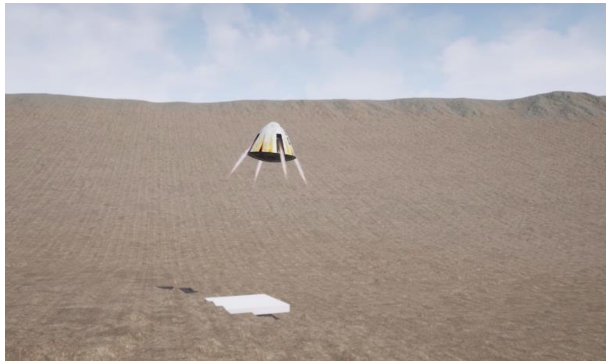
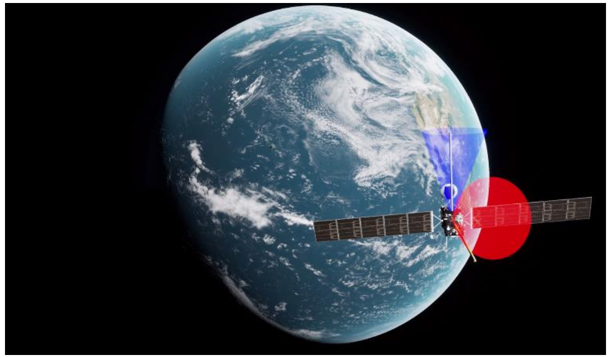
PROJECT TIMELINE

Phase 1
Feasibility study

2016 - 2017



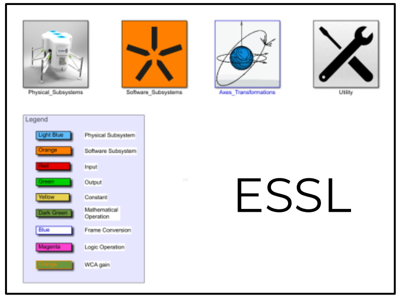
Constrained Powered Descent

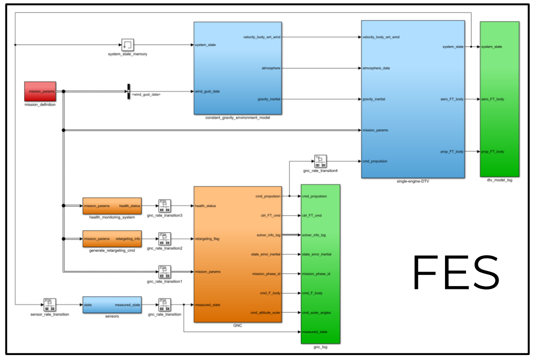


Constrained Attitude Guidance

Phase 2.1
Maturation and flight test plan

2018 - 2019





Problem 1 : *3-DoF, Non-Convex, Continuous-Time, Free-Final-Time, Minimum-Fuel Problem*

Cost Function

$$\underset{t_f, \mathbf{T}_{\mathcal{B}}(\cdot)}{\text{minimize}} \quad \int_{t_0}^{t_f} \|\mathbf{T}_{\mathcal{B}}(t)\| + \lambda_1 \|\dot{\mathbf{T}}_{\mathcal{B}}(t)\|^2 + \lambda_2 \eta(t)^2 \, dt \qquad (1)$$

subject to:

Boundary Conditions

$$m(t_0) = m_0 \qquad (2)$$

$$\mathbf{r}_{\mathcal{I}}(t_0) = \mathbf{r}_{\mathcal{I},0} \qquad \|\mathbf{r}_{\mathcal{I}}(t_f) - \mathbf{r}_{\mathcal{I},f}\| \le r_{tol} \qquad (3)$$

$$\dot{\mathbf{r}}_{\mathcal{I}}(t_0) = \dot{\mathbf{r}}_{\mathcal{I},0} \qquad \|\dot{\mathbf{r}}_{\mathcal{I}}(t_f) - \dot{\mathbf{r}}_{\mathcal{I},f}\| \le \dot{r}_{tol} \qquad (4)$$

Point-mass Dynamics

$$\dot{m}(t) = -\alpha \|\mathbf{T}_{\mathcal{B}}(t)\| \qquad (5)$$

$$\ddot{\mathbf{r}}_{\mathcal{I}}(t) = \frac{1}{m(t)} \mathbf{F}_{\mathcal{I}}(t) + \mathbf{g}_{\mathcal{I}} \qquad (6)$$

State Constraints

$$\mathbf{e}_1 \cdot (\mathbf{r}_{\mathcal{I}}(t) - \mathbf{r}_{\mathcal{I}}(t_{0,f})) \ge \tan(\gamma) \, \| \, [\mathbf{e}_2 \; \mathbf{e}_3] \cdot (\mathbf{r}_{\mathcal{I}}(t) - \mathbf{r}_{\mathcal{I}}(t_{0,f})) \, \| \qquad (7)$$

$$\|\dot{\mathbf{r}}_{\mathcal{I}}(t)\| \le v_{max} + \eta(t) \qquad (8)$$

$$\eta(t) \ge 0 \qquad (9)$$

Control Constraints

$$0 \le T_{min} \le \|\mathbf{T}_{\mathcal{B}}(t)\| \le T_{max} \qquad (10)$$

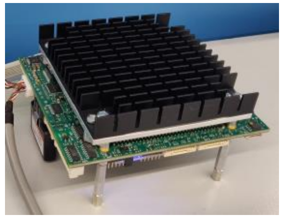
$$\dot{T}_{min} \le \dot{\mathbf{T}}_{\mathcal{B}}(t) \le \dot{T}_{max} \qquad (11)$$

$$\mathbf{e}_1 \cdot \mathbf{T}_{\mathcal{B}}(t) \ge \cos(\theta_{max}) \|\mathbf{T}_{\mathcal{B}}(t)\| \qquad (12)$$

$$\mathbf{e}_1 \cdot \mathbf{T}_{\mathcal{B}}(t)(1 + \nu_D) \le T_{max}(1 - \mathbf{e}_1 \cdot \mathbf{r}_{\mathcal{I}}(t)\beta) \qquad (13)$$

Continuous integration testing

SVF



Phase 2.2
Flight testing

2019 - 2020

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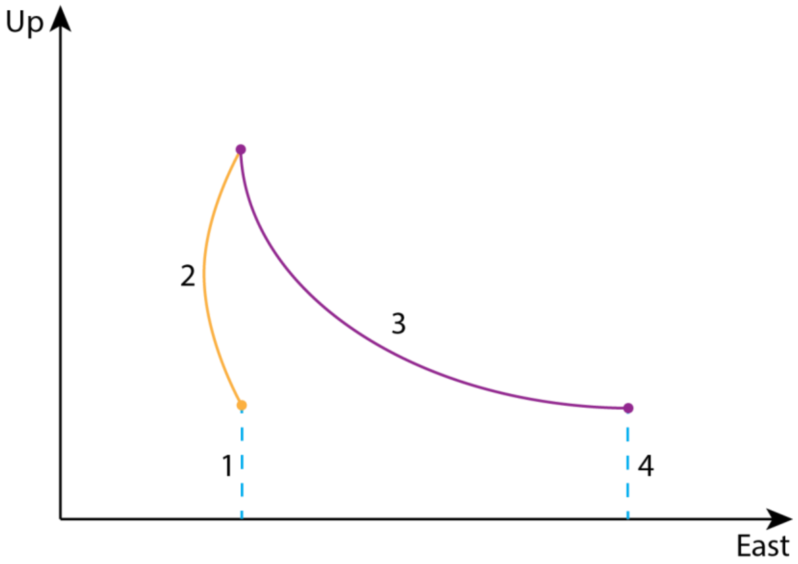
MISSION PROFILE

INCAS Demonstrator for Technology Validation: DTV

- Jet powered
- Vertical Takeoff and Landing
- Max thrust = 900N
- Weight = 60 - 70 Kg
- Hight = 1.2 m

End-to-End mission scenario



1. Vertical takeoff
2. Ascent (Real-Time Optimal Guidance)
3. Descent (Real-Time Optimal Guidance)
4. Vertical landing

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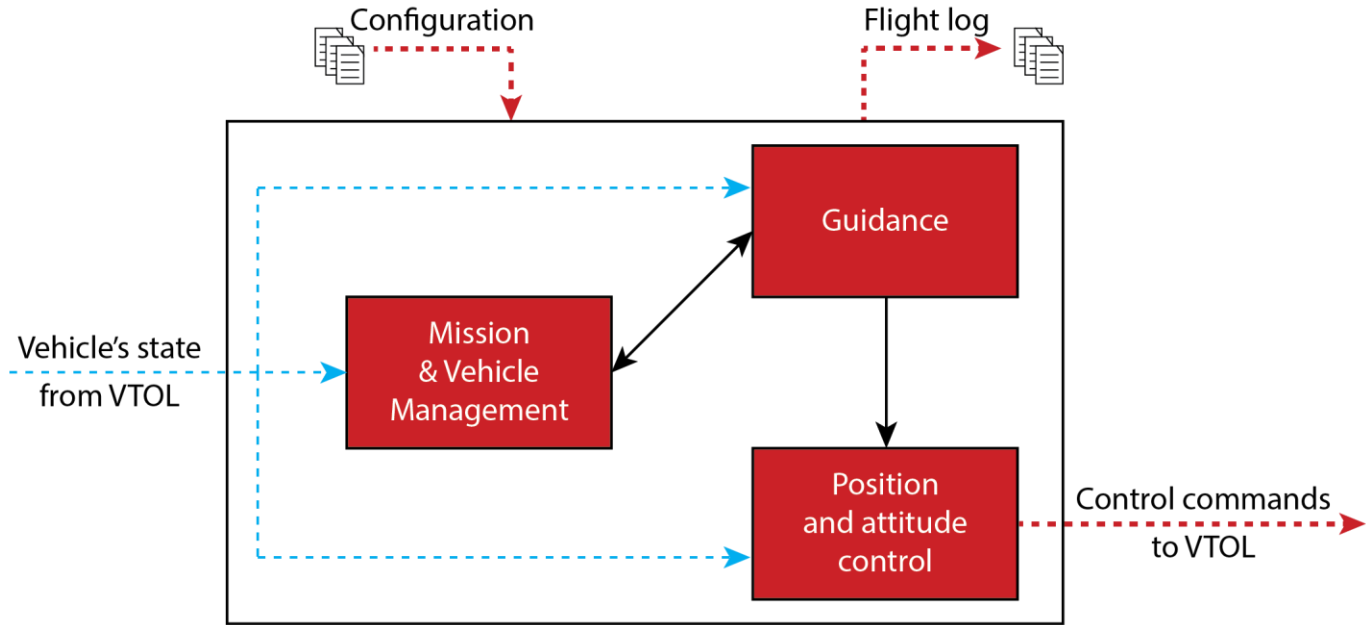
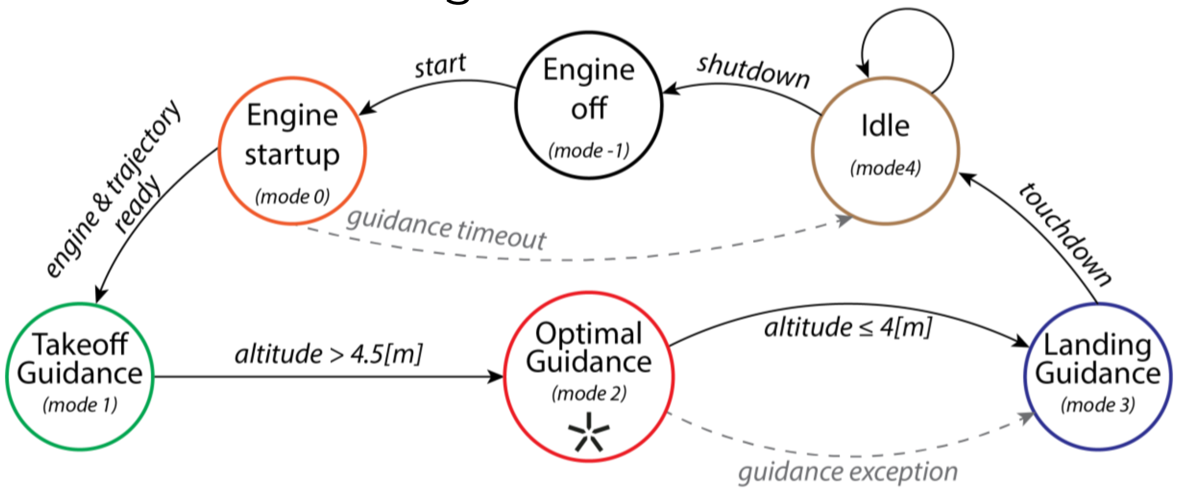
GUIDANCE AND CONTROL ARCHITECTURE



Flight mode selector



MVM

- Flight mode selector
- Target manager
- Handle exceptions
- Tracking errors
- Engine faults
- Retargeting
- Emergency landing

Guidance

- Constant velocity takeoff
- 3-DoF NLP optimal
- Constant velocity landing

Control

- LQR on position and attitude
- FF aerodynamics balancing

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OPTIMAL GUIDANCE

- Tested strategies

3-DoF convex

3-DoF convex with ToF lookup table

3-DoF non-convex

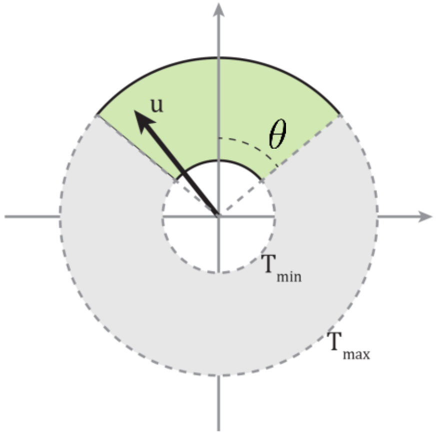
6-DoF non-convex

Minimize fuel consumption

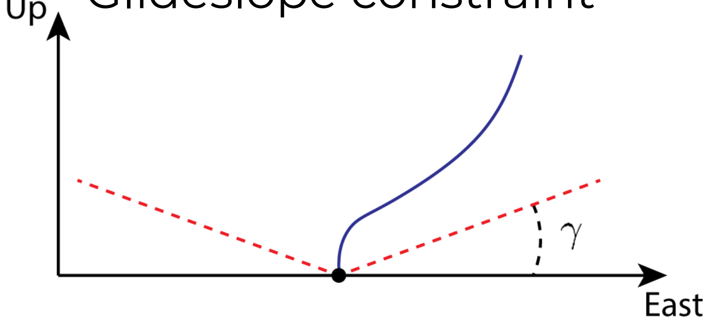
or

Minimize landing error

Thrust constraints



Glideslope constraint



Problem 1 : *3-DoF, Non-Convex, Continuous-Time, Free-Final-Time, Minimum-Fuel Problem*

Cost Function

$$\underset{t_f, \mathbf{T}_{\mathcal{B}}(\cdot)}{\text{minimize}} \quad \int_{t_0}^{t_f} \|\mathbf{T}_{\mathcal{B}}(t)\| + \lambda_1 \|\dot{\mathbf{T}}_{\mathcal{B}}(t)\|^2 + \lambda_2 \eta(t)^2 \, dt \tag{1}$$

subject to:

Boundary Conditions

$$m(t_0) = m_0 \tag{2}$$

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$$\dot{m}(t) = -\alpha \|\mathbf{T}_{\mathcal{B}}(t)\| \tag{5}$$

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State Constraints

$$\mathbf{e}_1 \cdot (\mathbf{r}_{\mathcal{I}}(t) - \mathbf{r}_{\mathcal{I}}(t_{0,f})) \geq \tan(\gamma) \; \| \; [\mathbf{e}_2 \; \mathbf{e}_3] \cdot (\mathbf{r}_{\mathcal{I}}(t) - \mathbf{r}_{\mathcal{I}}(t_{0,f})) \; \| \tag{7}$$

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$$\mathbf{e}_1 \cdot \mathbf{T}_{\mathcal{B}}(t)(1 + \nu_D) \leq T_{max}(1 - \mathbf{e}_1 \cdot \mathbf{r}_{\mathcal{I}}(t)\beta) \tag{13}$$

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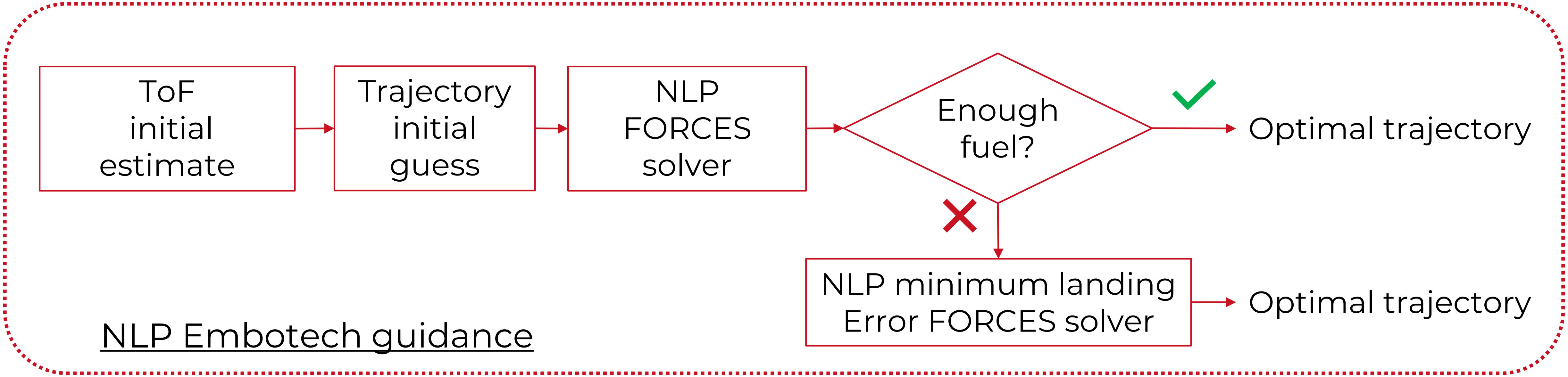
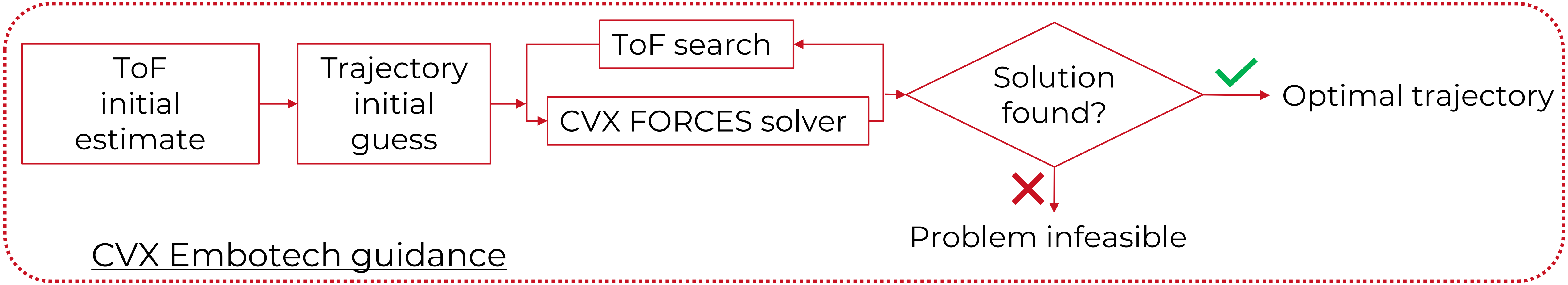
OPTIMAL GUIDANCE GUIDANCE





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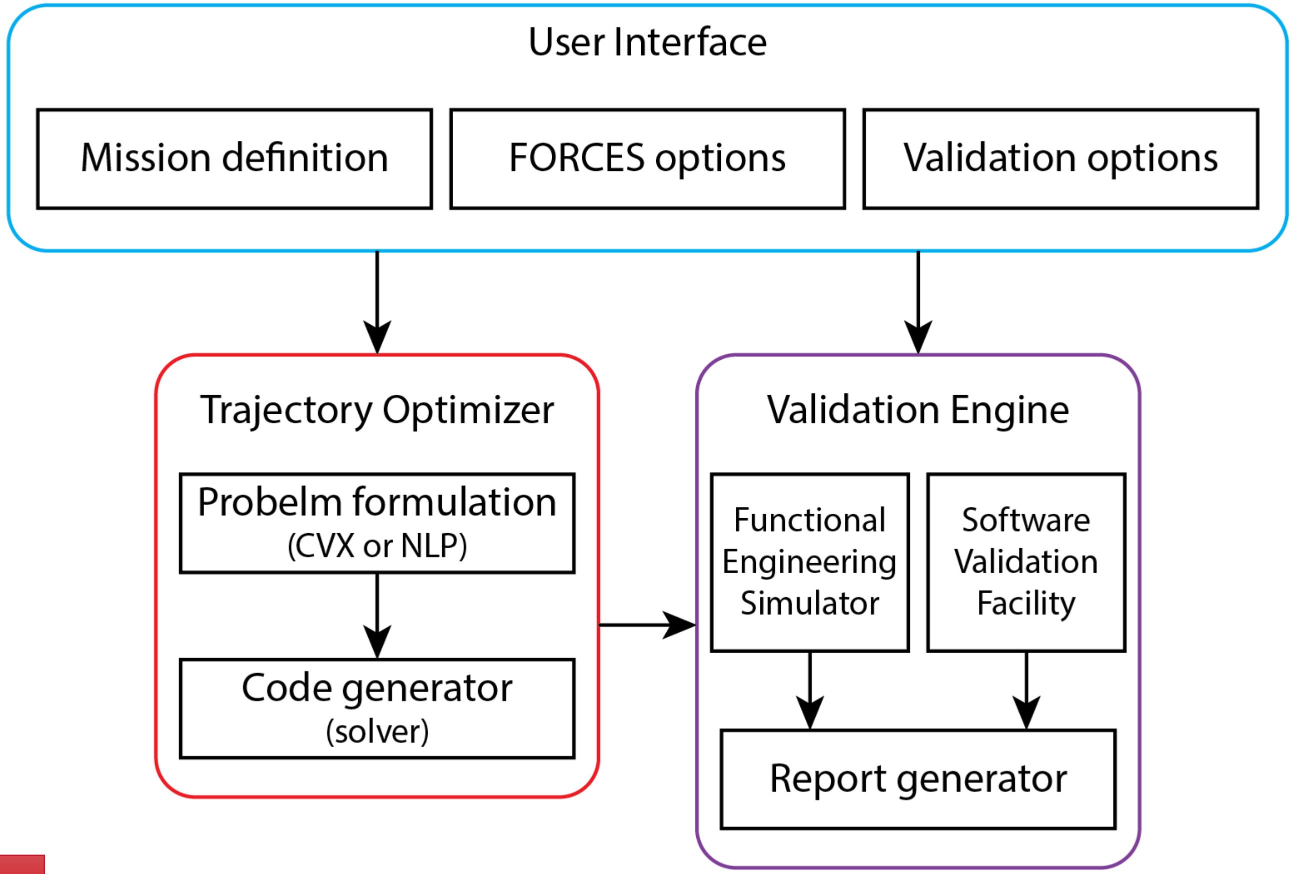
SOFTWARE FRAMEWORK

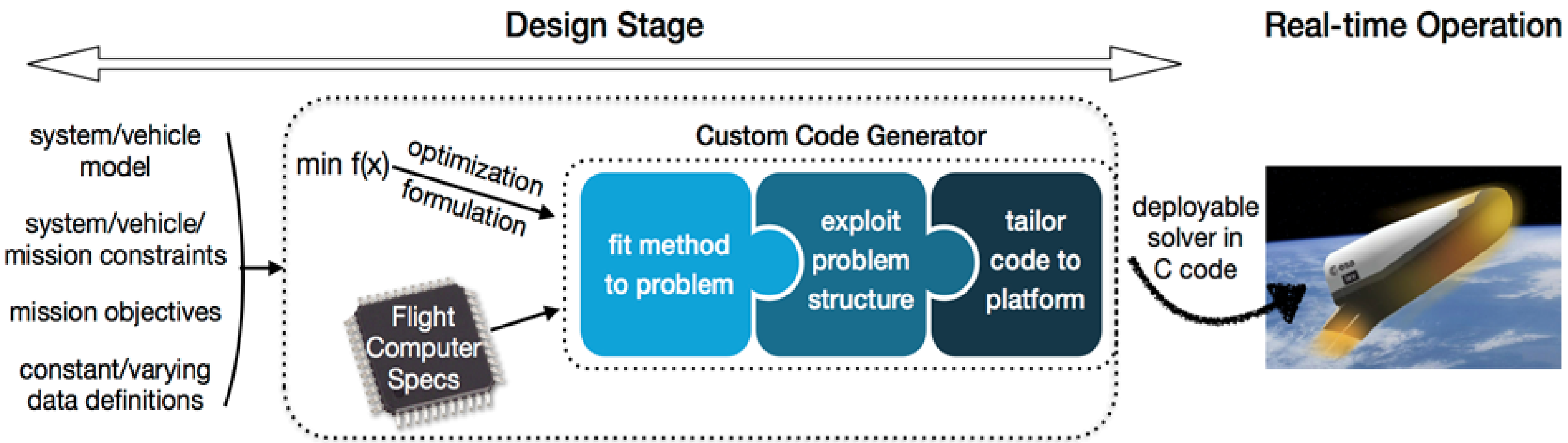
- A unifying framework designed to extensively evaluate and analyze the guidance and control performance
- Completely modular and extendable architecture
- Matlab/Simulink interface
- Support for automatic code generation and deployment on embedded platforms.



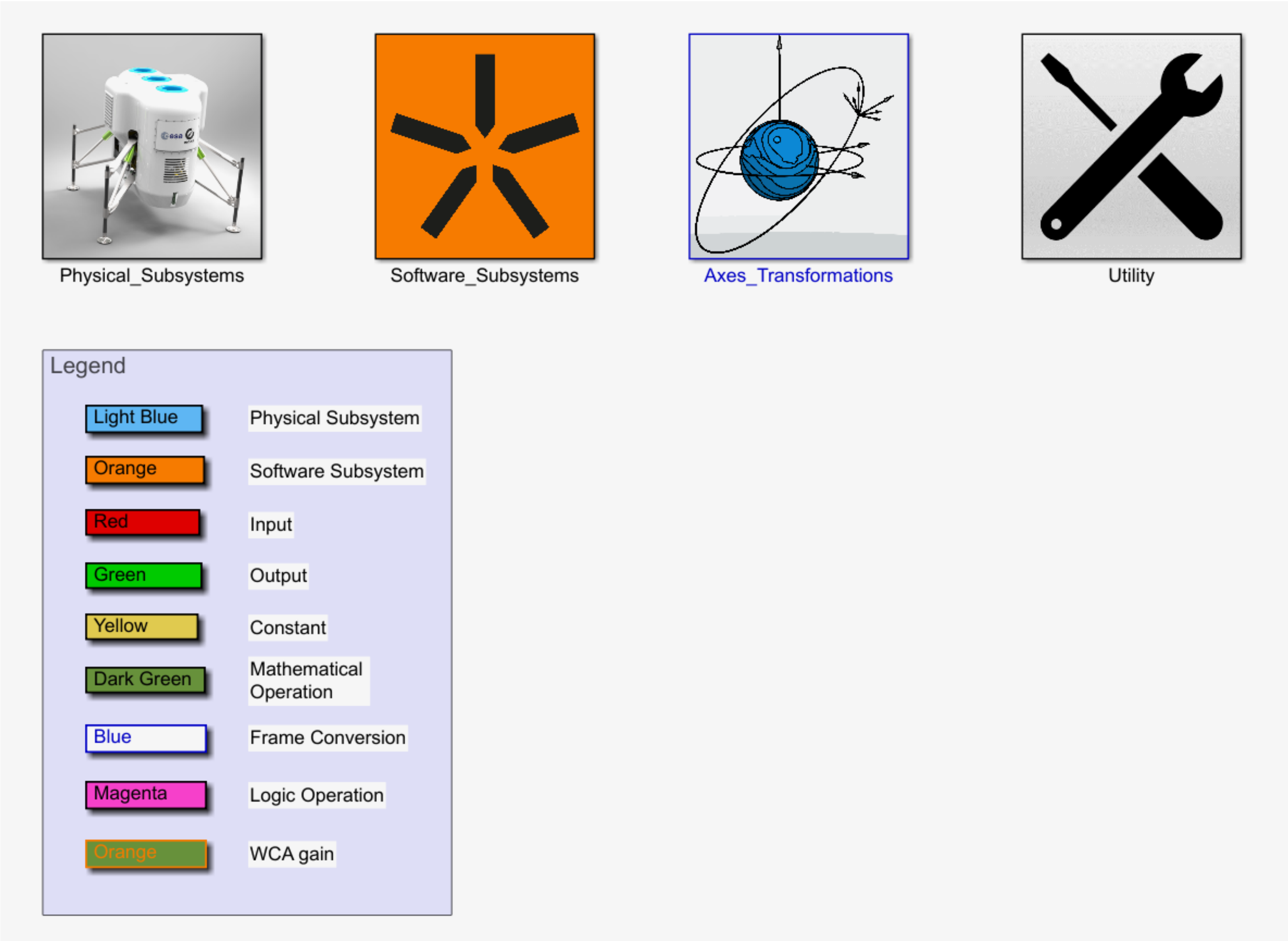
The generated C is embeddable on-board as part of the real-time flight code

FORCES PRO
Concept

- State-of-the-art client/server code generation system for optimization solvers
- C code tailored for deployment on embedded systems
- Uses only static memory allocation
- No dependency on external libraries
- MISRA C compliant
- Wide range of algorithmic options for LPs, QPs, QCQPs, SOCPs, NLPs and MI-NLPs
- Developed and professionally maintained by embotech AG



FUNCTIONAL ENGINEERING SIMULATOR (DTV)



An expandable simulation library built for INCAS' DTV

Initialization files:
- mass properties
- propulsion system
- environment

⋮

Library blocks

Simulators

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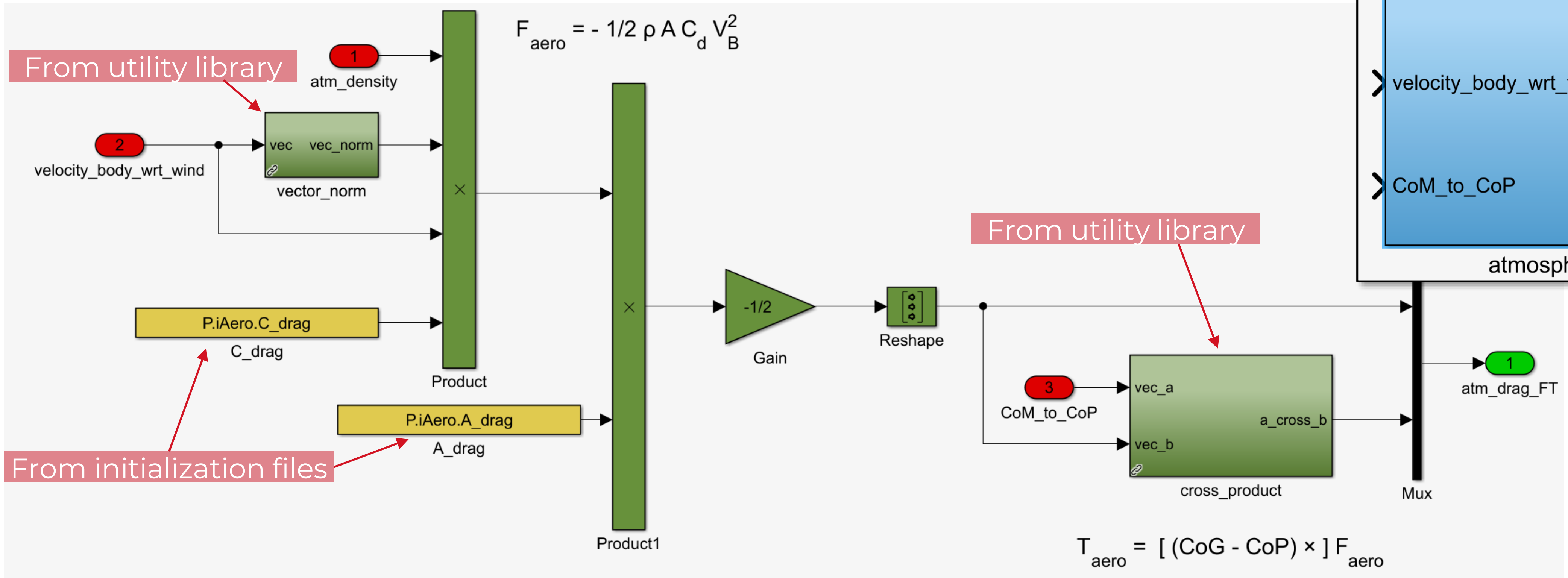
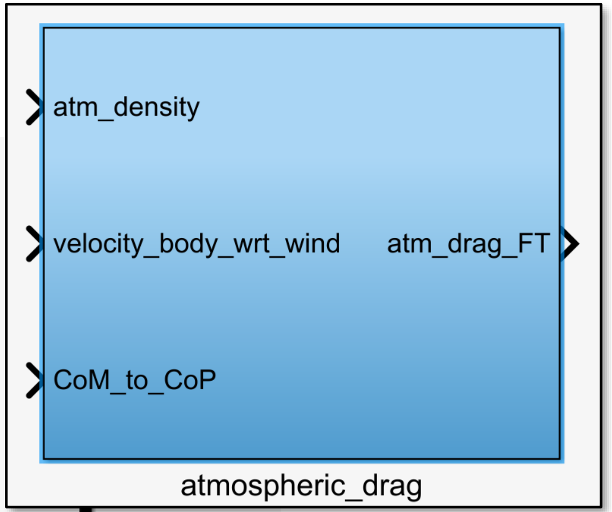
LIBRARY BLOCK EXAMPLE





Input	Units	Dimension
Atmosphere Density	kg/m^3	1
Velocity wrt Wind (body)	m/s	3
Attitude Quaternion	-	4
Lever Arm (CoG - CoP)	m	3

Output	Units	Dimension
Aerodynamic Drag Force (body)	N	3
Aerodynamic Torques (body)	N*m	3

Parameters	Units	Dimension
Drag Coefficient	-	1
Cross Sectional Area	m^2	1

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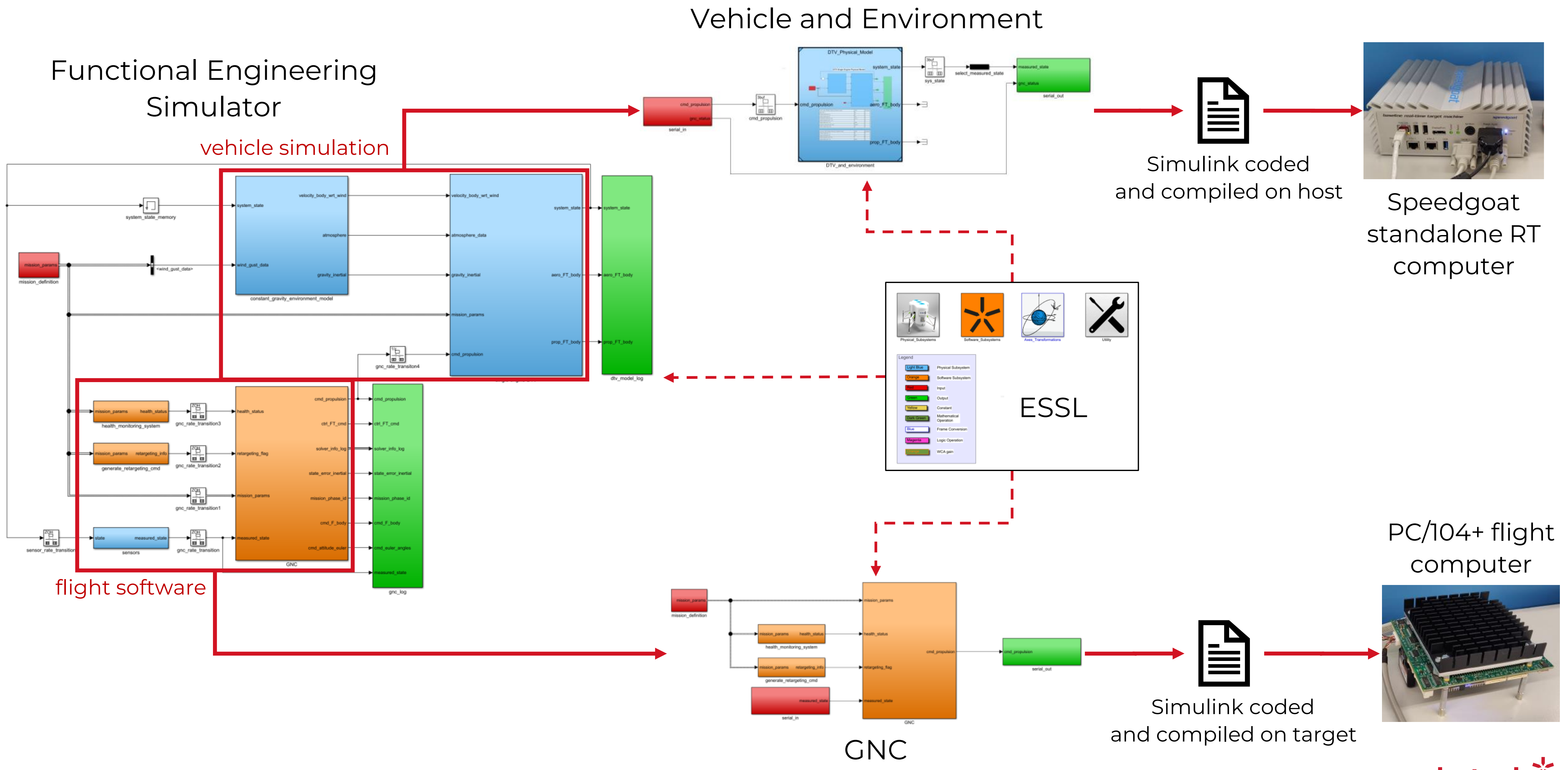
SIMULATION ENVIRONMENTS



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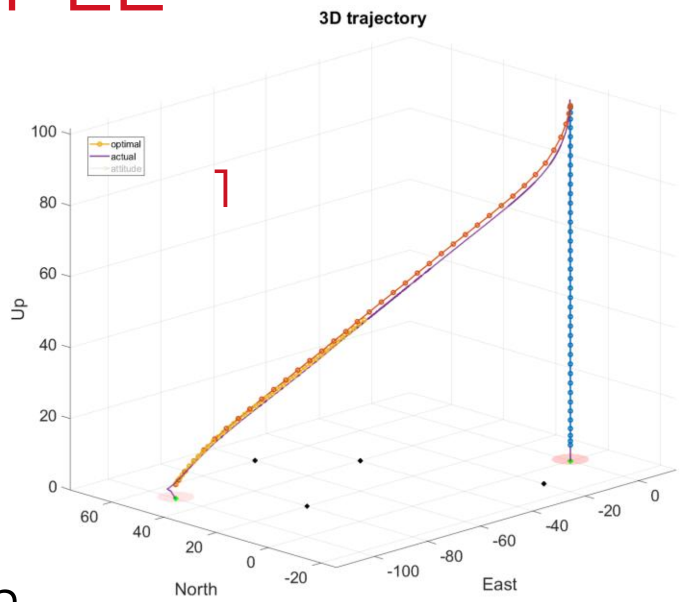
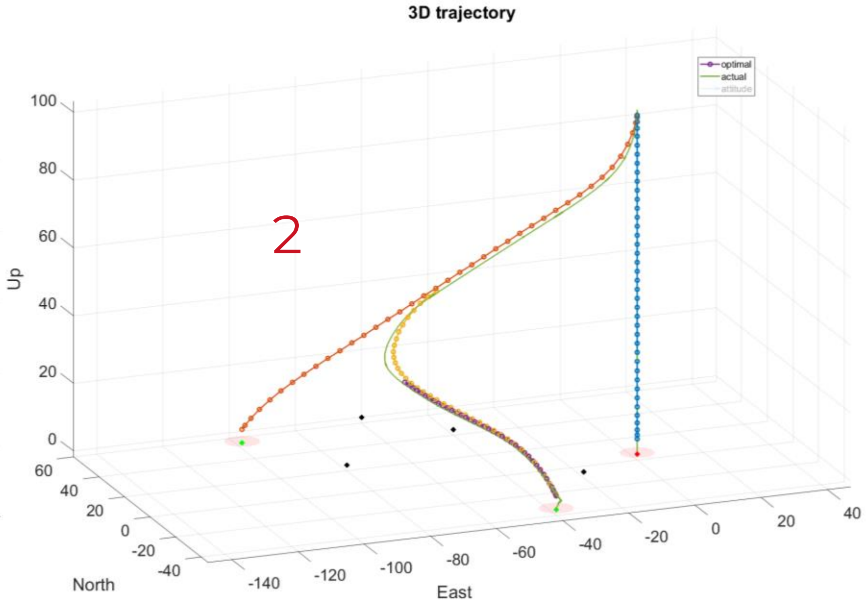
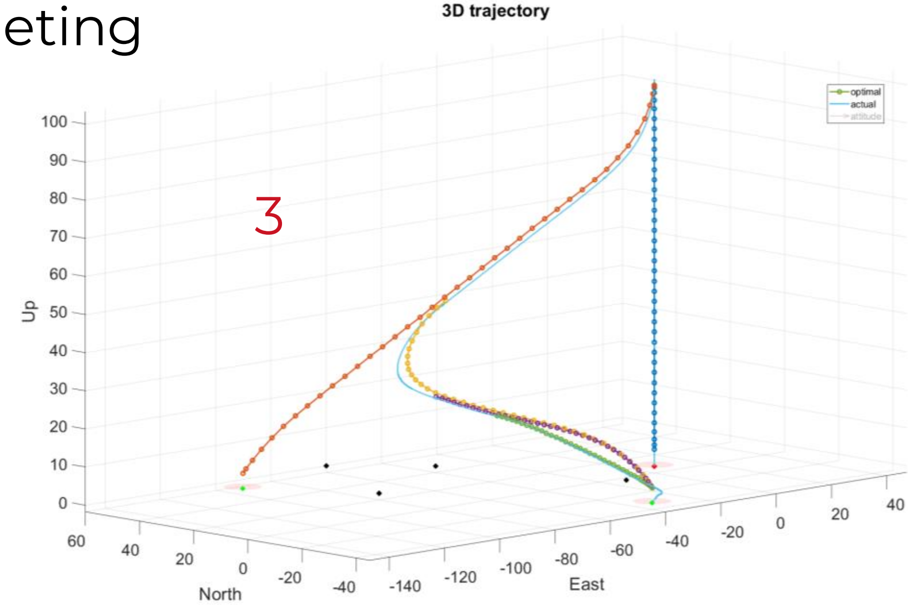
SIMULATION EXAMPLE

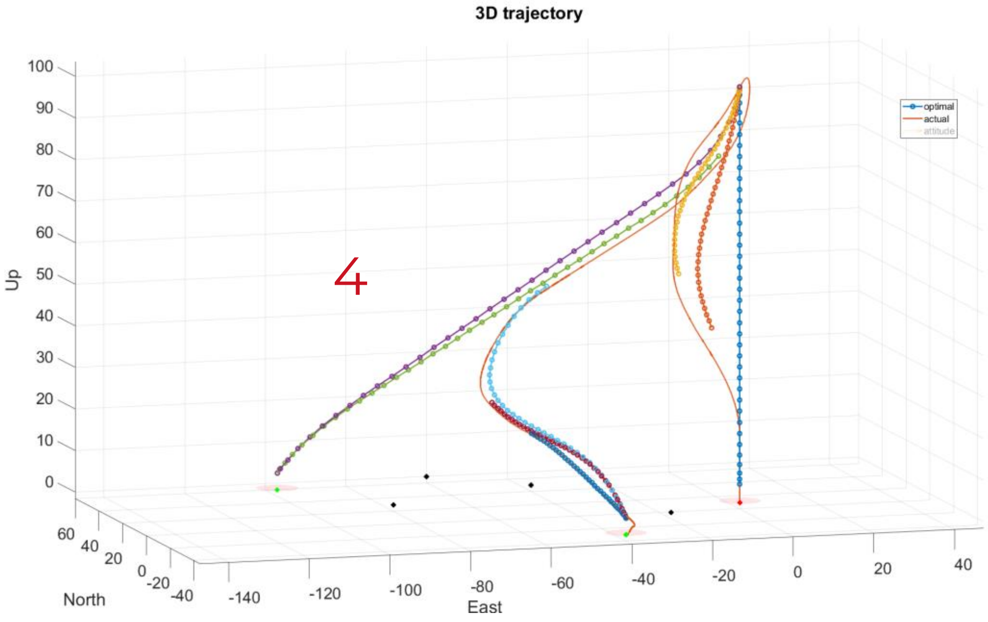
CPU	Median [s]	Max [s]	Min [s]
i7 8550U @ 1.8	0.07	0.15	0.04
Atom E3845 @ 1.9	0.25	0.55	0.19





1. Nominal end-to-end mission
2. Mid-flight retargeting
3. Engine fault
4. Wind on ascent





- Takeoff pad
- Landing pad
- Emergency pad

 Glideslope

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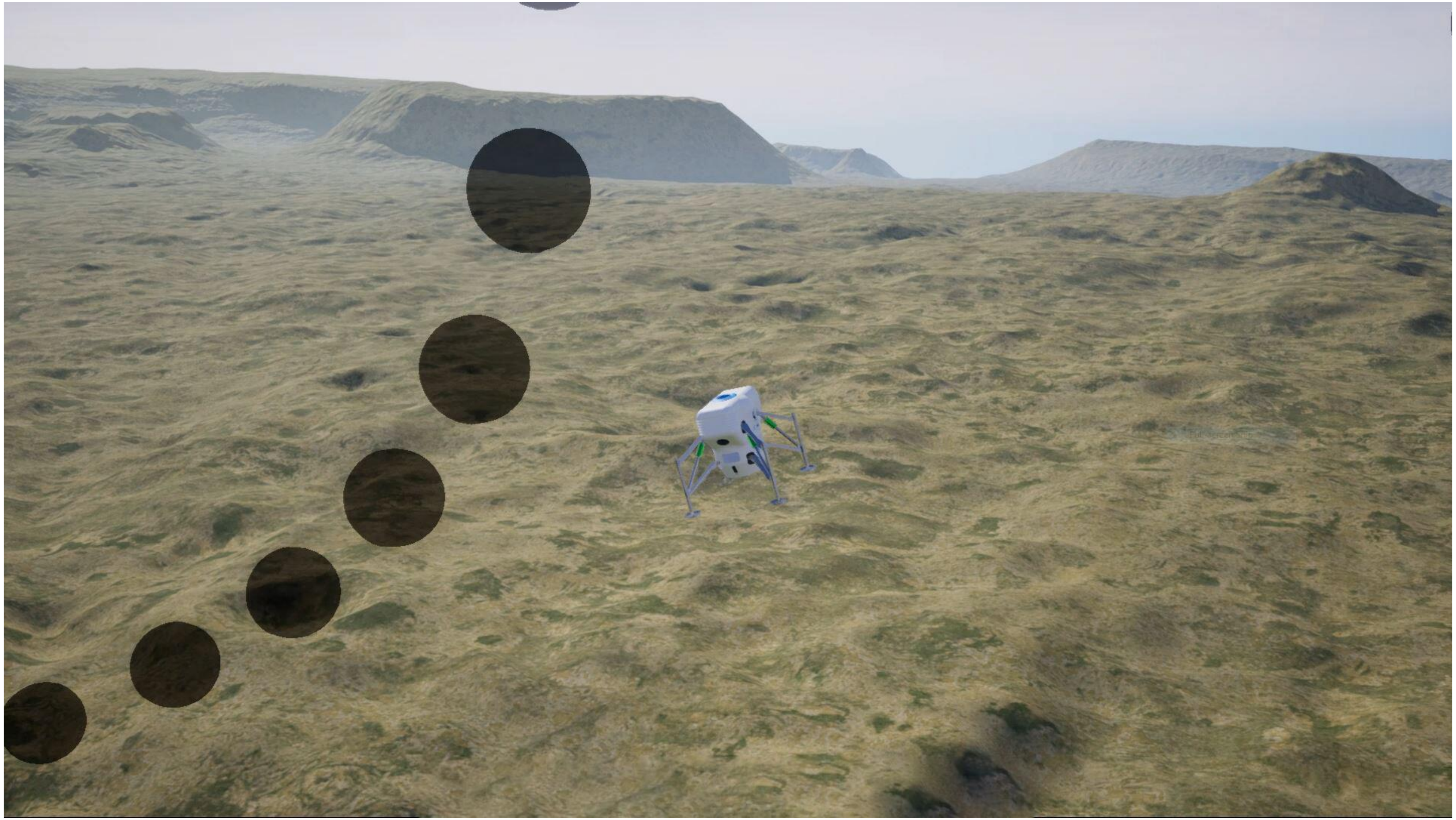
END-TO-END VTOL MISSION



https://youtu.be/srjEs1iFxl8

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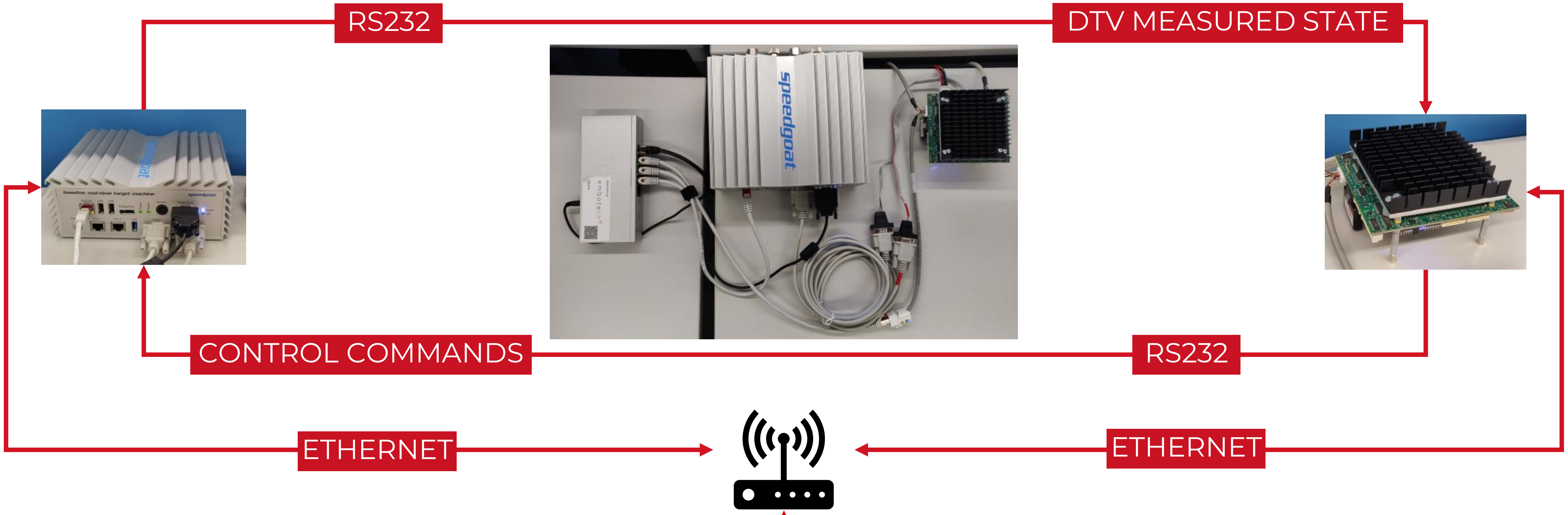
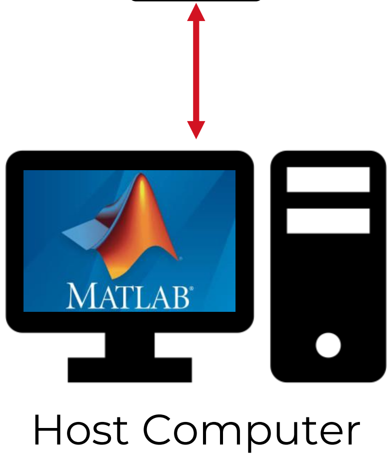
SOFTWARE VALIDATION FACILITY



Key Features:

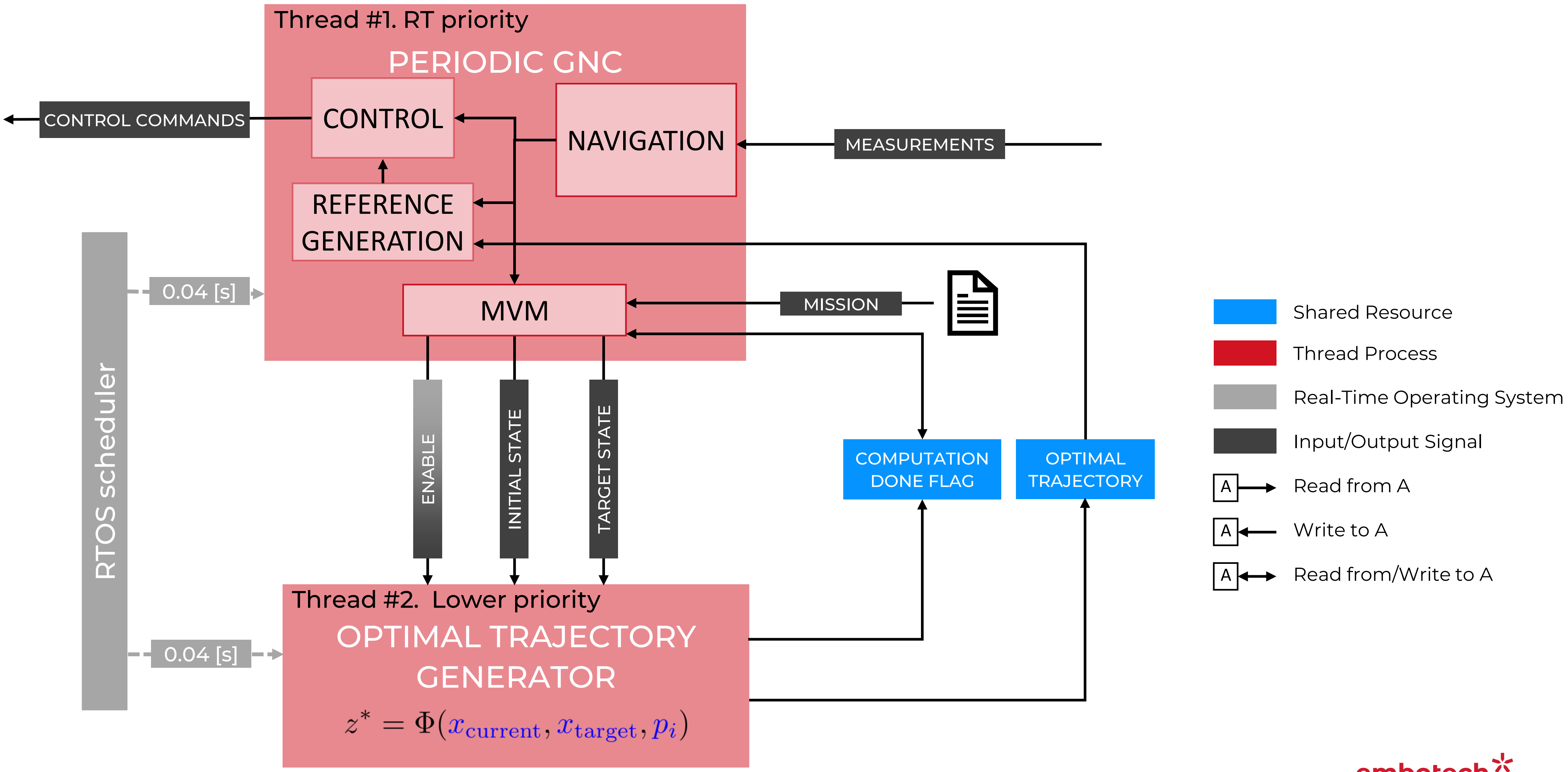
- PC/104+ & Speedgoat connected using two different serial cables;
- Communication between PC/104+ & Speedgoat at 25 Hz;
- Speedgoat & PC/104+ connected to the local embotech's network via Ethernet;
- Host computer accesses PC/104+ via SSH;
- Host computer accesses Speedgoat via Simulink Real-Time Explorer.



Host Computer Tasks:

- Code generation;
- Code loading into Speedgoat & PC/104+;
- Processes launch;
- Data log recovery;
- Results plotting & analysis.

REAL-TIME FLIGHT SOFTWARE



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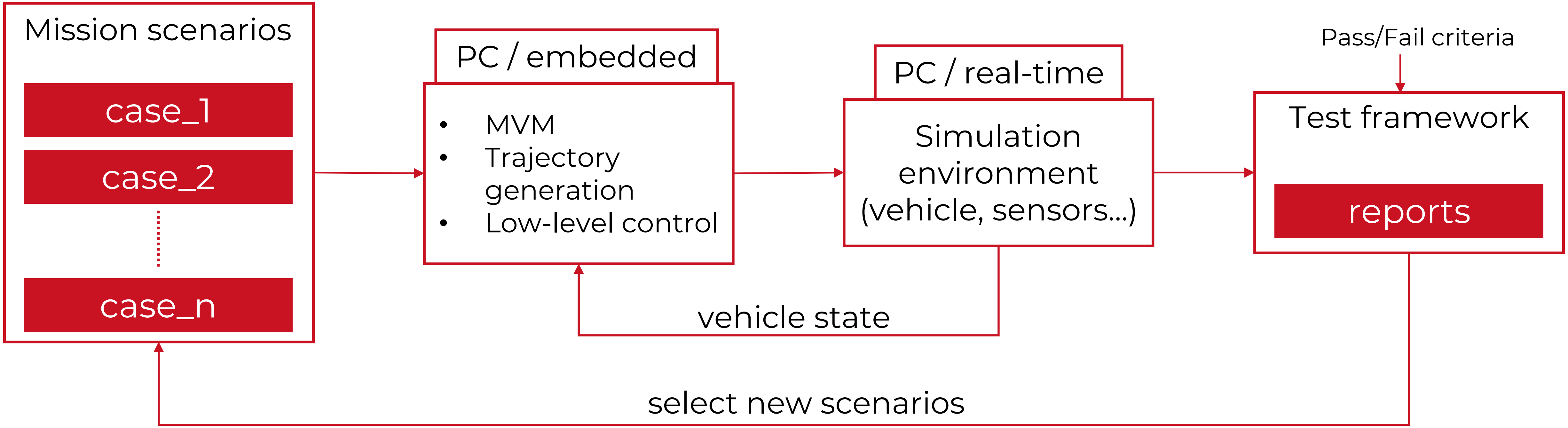
FLIGHT SOFTWARE QUALIFICATION

- Functional validation campaign
  - 2576 scenarios simulated under _nominal_, _robust_ and _fault_ conditions
  - Sensitivity analysis w.r.t. noise and dispersion

- Software validation campaign
  - Subset of scenarios necessary for full code coverage



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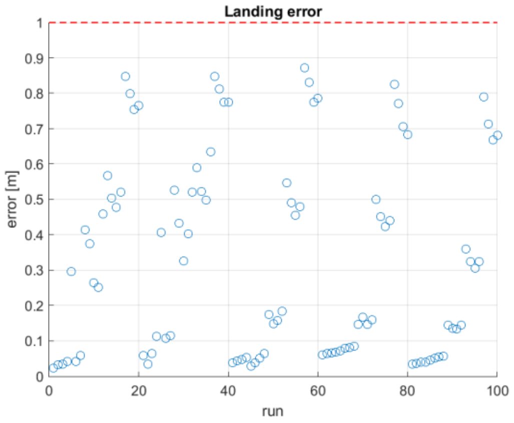
CONTINUOUS INTEGRATION

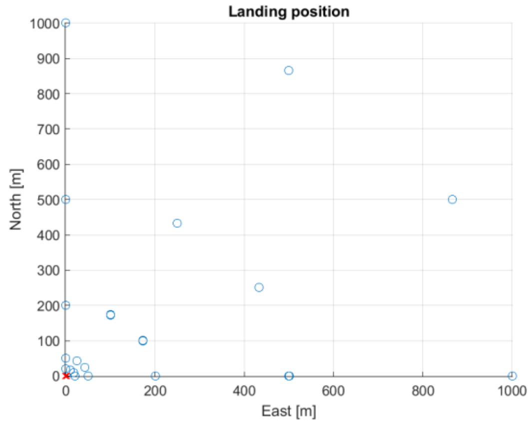
Summary Test Data

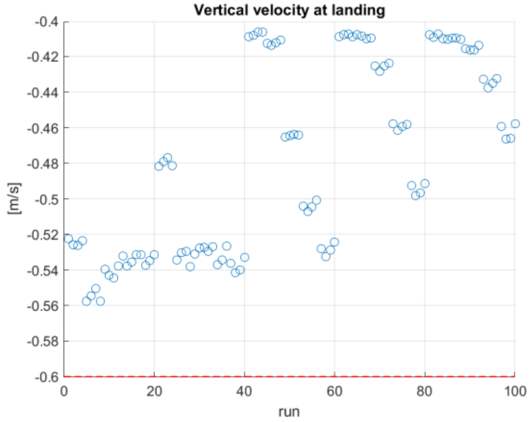
Statistical data

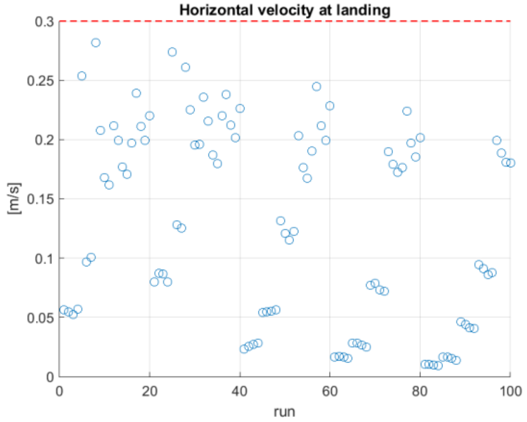
- Landing error:
  - Average = 0.33444
  - Median = 0.28023
  - Maximum = 0.87238
  - Minimum = 0.022803
- Vertical velocity at landing:
  - Average = -0.4777
  - Median = -0.48024
  - Maximum = -0.40606
  - Minimum = -0.55762
- Horizontal velocity at landing:
  - Average = 0.12794
  - Median = 0.12671
  - Maximum = 0.28195
  - Minimum = 0.0090332
- Tilt angle at landing:
  - Average = 0.18689
  - Median = 0.20057
  - Maximum = 0.39637
  - Minimum = 0.0226
- Angular rate norm at landing:
  - Average = 0.053015
  - Median = 0.039726
  - Maximum = 0.46695
  - Minimum = 0.0070554

Summary plots



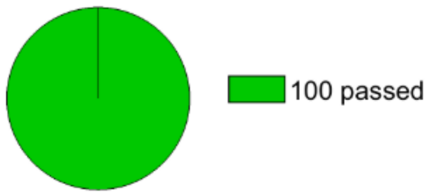






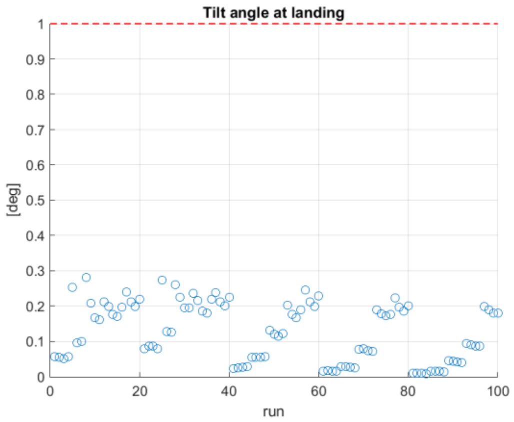
MATLAB® Test Report

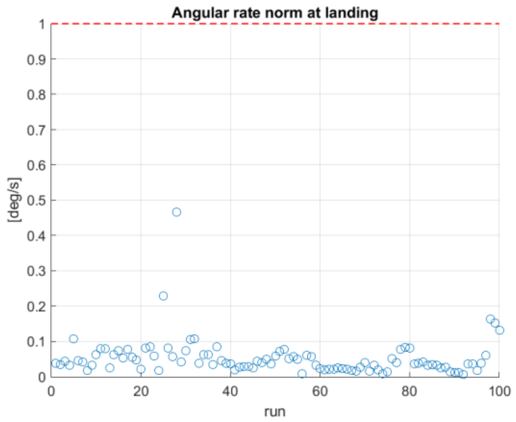
Timestamp:	06-Jun-2019 08:57:22
Host:	Jenkins-ESA
Platform:	win64
MATLAB Version:	9.4.0.949201 (R2018a) Update 6
Number of Tests:	100
Testing Time:	901.6306 seconds
Overall Result:	PASSED



Jenkins

Report generation after every batch of tests





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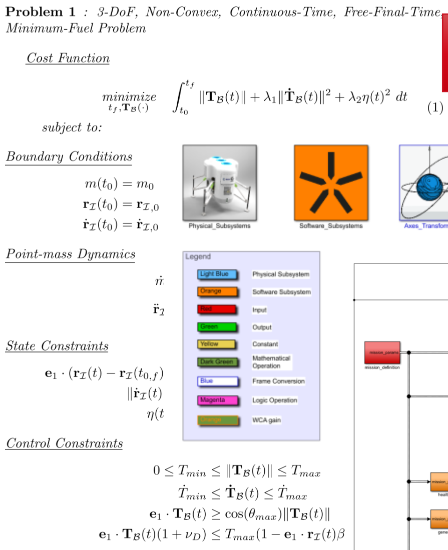
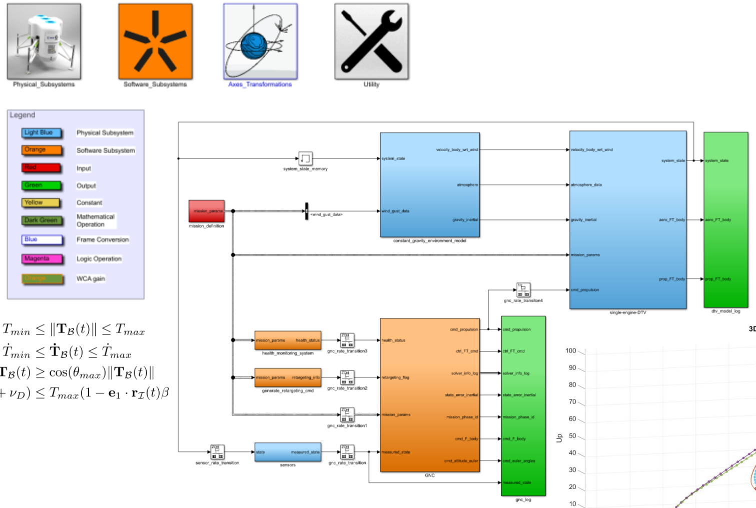
CONCLUSION

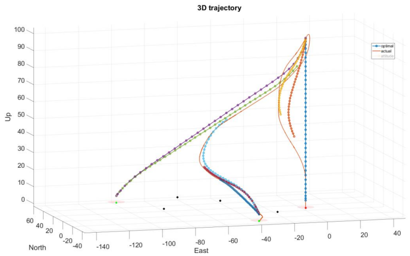
SpaceX



Design – Simulation – Validation

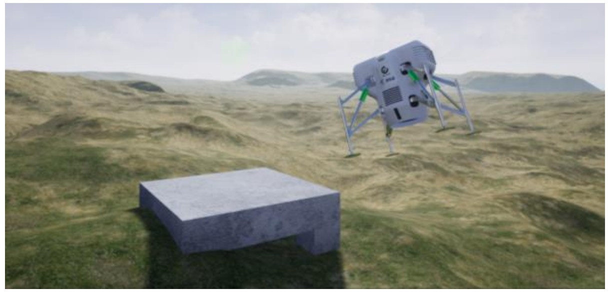


Jenkins



Flight Testing on INCAS DTV, Q3 2019

T0	T0+3	T0+6	T0+8	T0+12
Preliminary SW Checks	Harwdare Tests	Vehicle Integration	Flight Testing	



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