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HUMANS Research Project

Health and Usage Monitoring for Aerospace Next-generation Systems

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Seminar on Health Aware and Safe Control Design for Dynamic Systems
November 22nd 2023

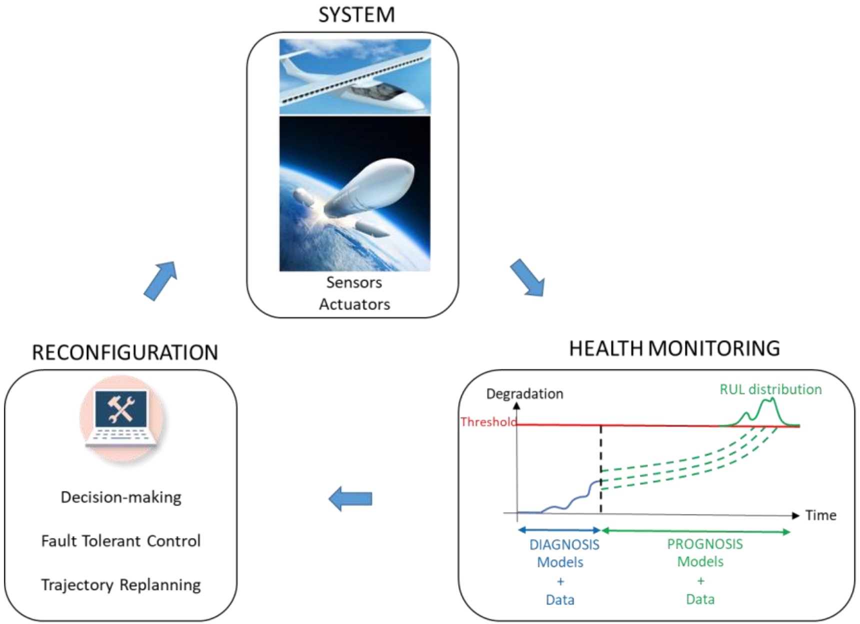
Outline

1. Presentation of the project
2. Case study - RETALT1 RLV
3. State-of-the-Art / Proposed methodologies
    3.1) Health Monitoring (Diagnosis and Prognosis)
    3.2) Fault Tolerant Control
    3.3) Trajectory Replanning
4. Conclusion

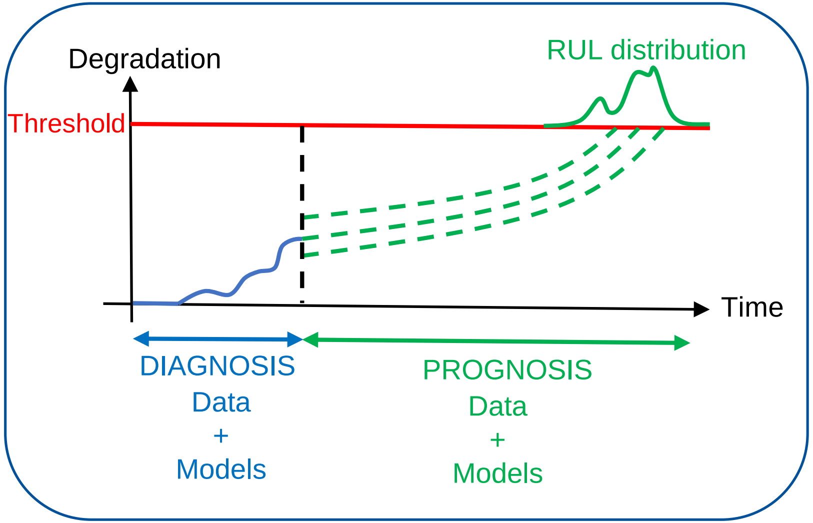
Objectives

Develop an architecture for system safety and risk mitigation

Health monitoring and reconfiguration modules to assess the health of the system and reconfigure the mission/system based on the estimated state of health and remaining useful life (RUL).



Health Monitoring module



Two different functions:

- Diagnosis : fault detection, isolation and identification
- Prognosis: Remaining Useful Life (RUL) estimation before failure

Different levels:

- Components level
- System level

Different methodologies:

- Model-based
- Data-driven

System Reconfiguration module

Decision-making

Fault Tolerant Control

Trajectory Replanning

Two fault recovery strategies:

- **Fault Tolerant Control (FTC)**
  - Maintain the control objectives (stability and performance) despite the occurrence of faults

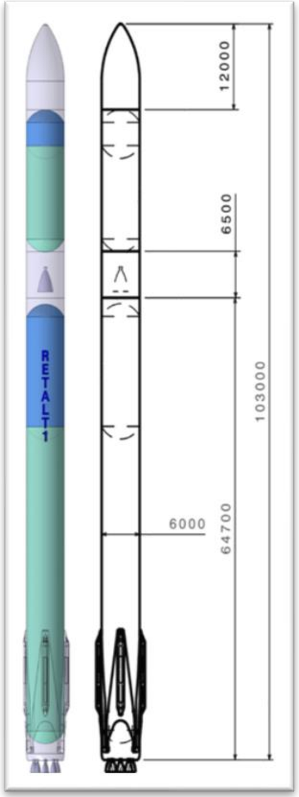
- **Trajectory replanning**
  - When FTC is not sufficient
  - Trajectory replanning takes the system State of Health information into account (Health-Aware)
  - Trajectory generation based on new safety and performance constraints under faulty conditions

Case study

❑ Case study

Reusable Launch Vehicle RETALT1

- RLV concept (similar to Falcon 9) from a European Project led by DLR (2019-2022). More info on: https://www.retalt.eu/
- Main characteristics:
  - Two stages with a total length of 103 m
  - Cluster of 9 liquid propulsion engines for the first stage
  - Different configurations for the aerodynamic control surfaces (petals, grid fins)



❑ Case study

Choice of the fault scenario

- During the first stage return phase (boostback burn and landing burn)
- Possible faults (must not be critical):
  - On the multi-engine cluster
  - Actuator and sensor faults
  - Loss of thrust, Thrust Vector Control faults, crack propagation, …

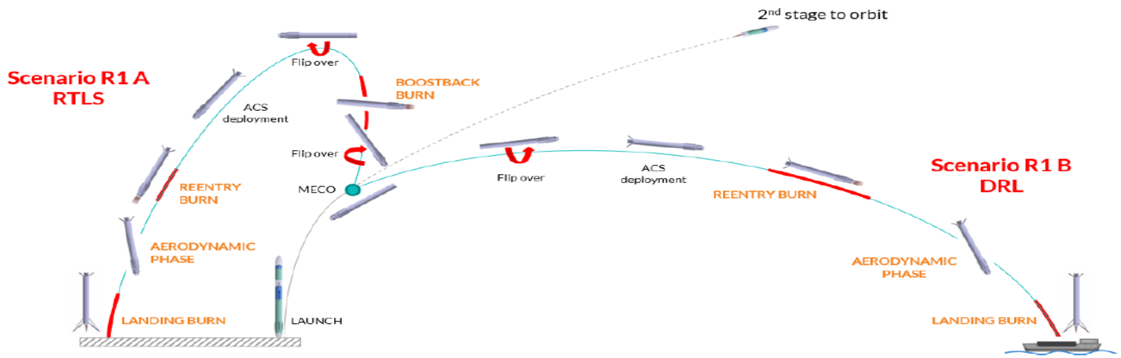


Figure. RETALT scenario

State-of-the-Art
Proposed methodologies

Health Monitoring module

Health monitoring module

Diagnosis and Prognosis

❑ **Prognosis methodologies:**

- Model-based (EKF, UKF, Particle filter, Reliability-based methods, Interval observers)

❑ **Diagnosis methodologies:**

- Model-based (Sequential Residual Generation method, state observers, …)
- Data-driven (Auto-encoders, Bayesian NNs)

❑ **Different levels:**

- Component level
- System level

❑ **Multi-engine cluster challenges for Fault detection and isolation (FDI):**

➢ Restricted number of sensors available in flight, numerous interconnected subsystems, and many possible sources of faults

➢ Needs a FDI system that considers the entire engine cluster and the influence between the engines

➢ Structural analysis to analyze the FDI possibilities

Diagnosis module

Structural analysis of a multi-engine cluster

PhD thesis, Renato Murata

- Cluster with 3 rocket engines
- Faults considered in the LOX feeding lines and rocket engines:
  - Feeding lines: LOX leakage

    $$f_{fL} = [f_m, f_{s1}, f_{s2}, f_{s3}]^T$$

  - Rocket engines: LOX leakage in the combustion chamber and valve blockage

    $$f_{en} = [f_{qOC}, f_{VGO}, f_{VCO}, f_{VGH}, f_{VCH}]$$

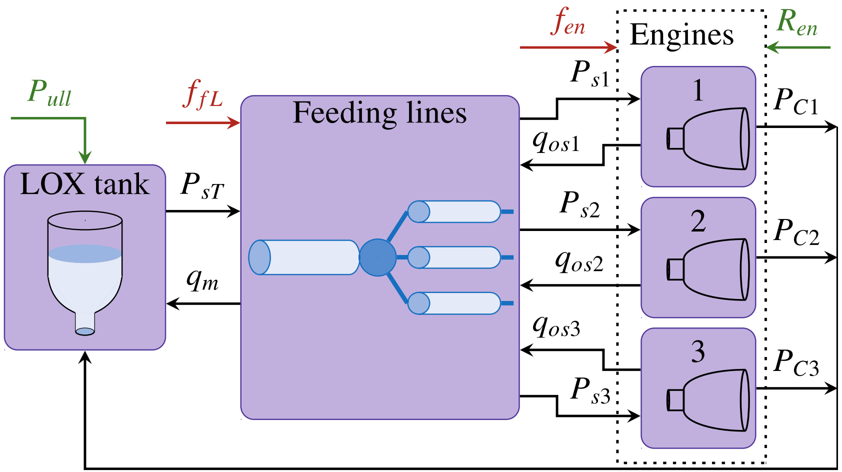


Figure. Multi-engine simulation model

Diagnosis module

Structural analysis of a multi-engine cluster

PhD thesis, Renato Murata

- **Two measurement scenarios are considered:**
  1. Scenario 1: Pressure measurements from feeding lines (P_{fL})
  2. Scenario 2: $P_{fL} + RMC + RMG + PCC + PGG$

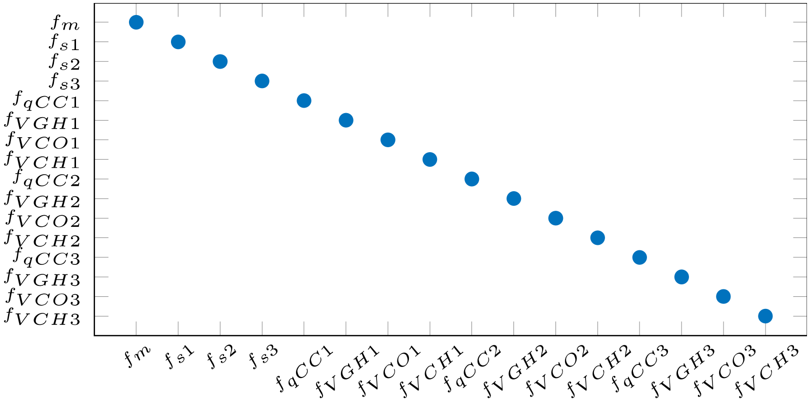


Figure. Fault isolability matrix for Scenario 2

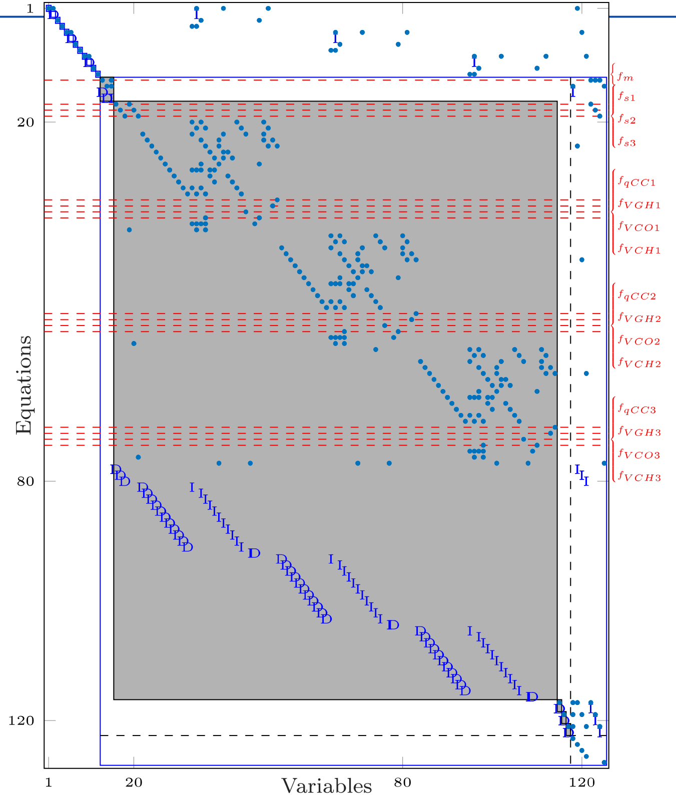


Figure. Dulmage-Mendelsohn decomposition of the structure matrix for Scenario 1

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Diagnosis module

Structural analysis of a multi-engine cluster

PhD thesis, Renato Murata

One advantage of structural analysis: compute residual generator candidates

- Subset of equations that can be solved independently
  - Sensitive only to the faults that affect the subset
- Increases exponentially with the number of measurements:
  - 4 candidates in Scenario 1
  - 40mil+ candidates in Scenario 2
- Simulation tests:
  - Three residuals were generated using candidates from Scenario 2
  - Sequential Residual Generation method

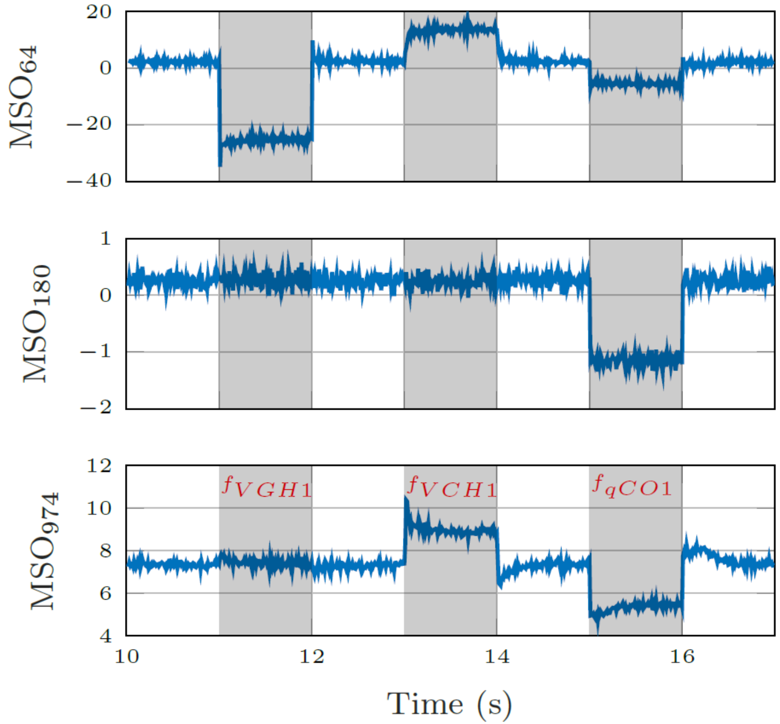


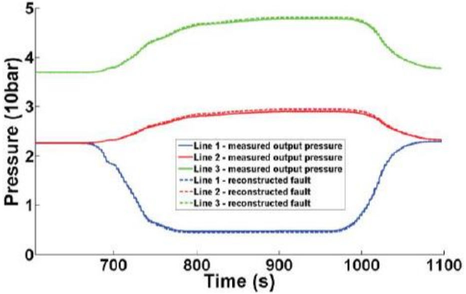
Figure. Simulation tests

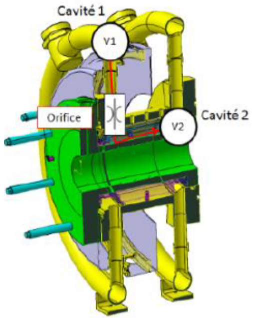
Diagnosis module

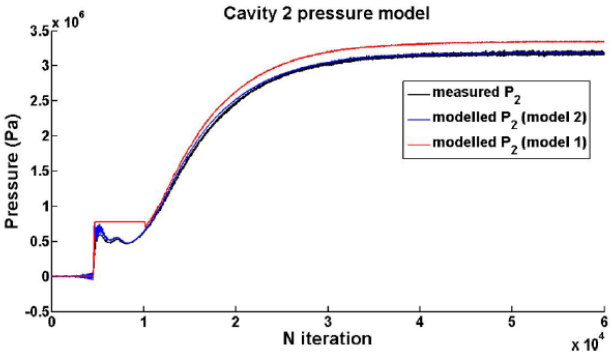
Model-based FDIR for Liquid-Propellant Rocket Engines

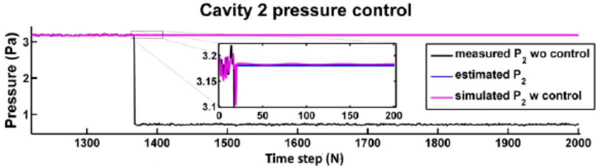
- Simplified ODE models of engine subsystems (cooling circuit, ergol lines)
- Methods: Parameter estimation (MLE), parity space, Kalman filters, Unknown Input Observers, LQ control
- Full Fault-Tolerant Control scheme validated on data and in simulation
- Preliminary system integration on MASCOTTE bench (replay mode)

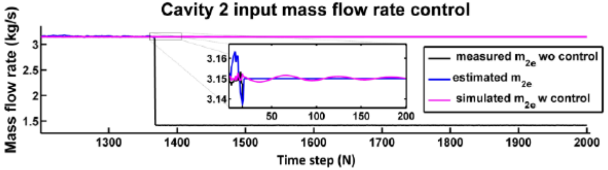
ONERA PhD (2016), Alessandra IANNETTI
ONERA PhD (2019), Camille SAROTTE











Prognosis module

Model-based Prognosis

- Observation phase: joint parameter/state estimation methods (Kalman filter, Particle Filter, Interval observer)
- Prediction phase: uncertainty propagation problem (Probabilistic methods, Interval techniques, Reliability-based techniques (Inverse FORM))
- Benchmark example: crack propagation (standard Paris law, composite materials)

ONERA PhD (2018), Elinirina ROBINSON

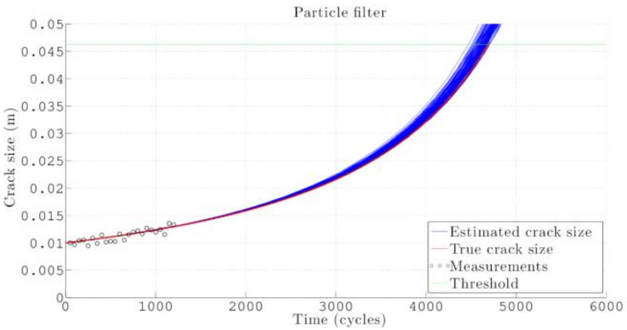


Figure. Crack prognosis with particle filter

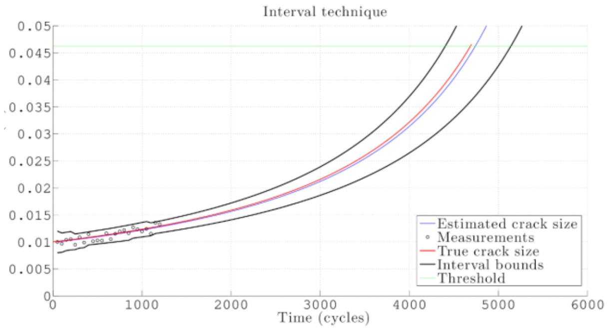


Figure. Crack prognosis with Interval techniques

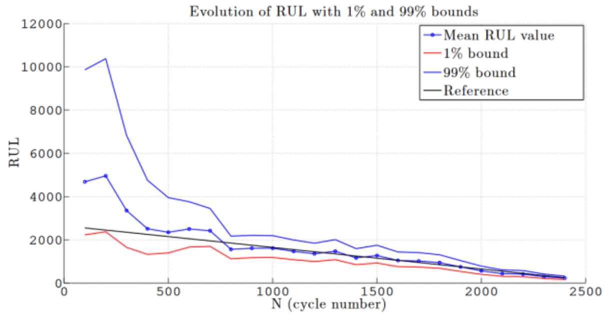


Figure. Crack prognosis with Inverse FORM

Fault Tolerant Control module

FTC module

FTC methodologies

- **Main FTC approach for aerospace applications**
  - Robust control (H∞)

- Andrés Marcos, Sérgio Waitman, Masayuki Sato, Fault tolerant linear parameter varying flight control design, verification and validation, Journal of the Franklin Institute, 2021
- A. Falcoz, "Contribution au développement de stratégies de diagnostic à base de modèles pour les véhicules spatiaux- Application à une mission de rentrée atmosphérique," PhD thesis, Université Sciences et Technologies- Bordeaux I, 2009.
- A. Zolghadri, D. Henry, J. Cieslak, D. Efimov, and P. Goupil, Fault Diagnosis and Fault-Tolerant Control and Guidance for Aerospace Vehicles: From Theory to Application, Advances in Industrial Control, Springer, Ed., 2014.

- **For launch vehicles**
  - Usually passive approaches (hardware redundancy) and limited active FTC schemes (e.g. adaptive augmentation control)
  - Robust control (H∞)

- N. Paulino et al., Fault Tolerant Control for a Cluster of Rocket Engines -Methods and outcomes for guidance and control recovery strategies in launchers, 12th International Conference on Guidance, Navigation & Control Systems (GNC), 2023

- **ONERA**
  - LQ (linear systems) and MPC (nonlinear systems) combined with Unknown Input Observers (UIO), EKF

C. Sarotte, "Improvement of monitoring and reconfiguration processes for liquid propellant rocket engine," PhD , Université Paris-Saclay, 2019.

FTC module

Actuator faults' modeling and fault-tolerant attitude control

- **Objective:** Design an attitude control law that is robust against actuator failures
- Increasing large literature on FTC for launch vehicles
- Focus on different actuator faults (see Figure)
  - Assume redundancy (?) in actuaction
  - **Actuators:** Thrust Vector Control (TVC), Reaction Control Systems (RCS), grid fins, etc

- **Kinematic and dynamic models**

$$\dot{\Theta} = f_{\Theta}(\Theta, u_f)$$
$$\dot{\Omega} = f_{\Omega}(\Omega, u_f)$$
$$\mathrm{u_f} = \Delta \cdot u + b$$

Θ : 3D orientation parameterization
Ω : 3D angular velocity vector
u : control input
Δ : diagonal matrix modeling actuator effectiveness
b : fault bias vector
u_f : fault-parameterized control input

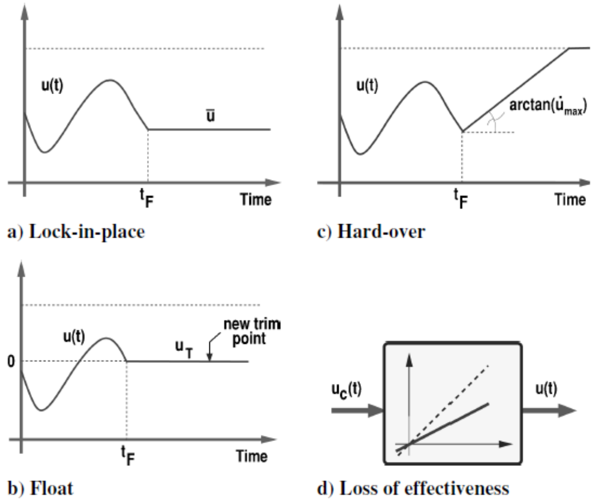


Figure. Types of actuator failures

FTC module

FTC with embedded safety and temporal specifications

Challenges

- Control design valid for **high angles-of-attack** (Toss-back)
- Accounting for actuator saturations and **safety constraints**
  - Due to structural rigid/flexible modes, fuel sloshing, …
- Guaranteeing **temporal specifications** of the closed-loop system
  - Prescribed convergence time
  - Prescribed performance (overshoot, rising time,)

Envisioned approach

- Time-varying Barrier-Lyapunov function (BLF) based control design
  - BLF to encode time-varying constraints and desired equilibria
  - **Passivity-based** or **backstepping** control designs

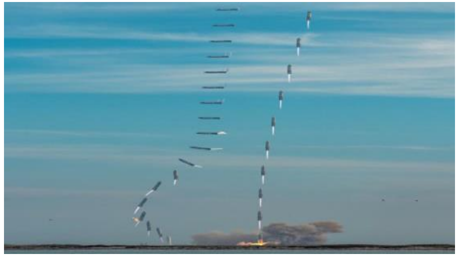


Figure. Toss-back and landing phases

Constraint set: $|\theta| < c_\theta$

Barrier fct: $B_\theta(\theta) = \frac{1}{2}\ln(\frac{c_\theta^2}{c_\theta^2 - \theta^2})$

BLF: $W_\theta(\theta) = \frac{1}{2}\theta^2 + B_\theta(\theta)$

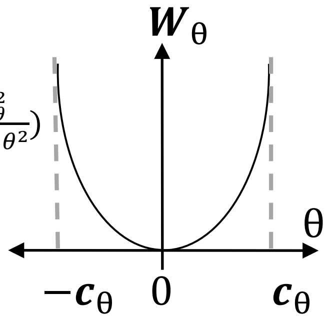
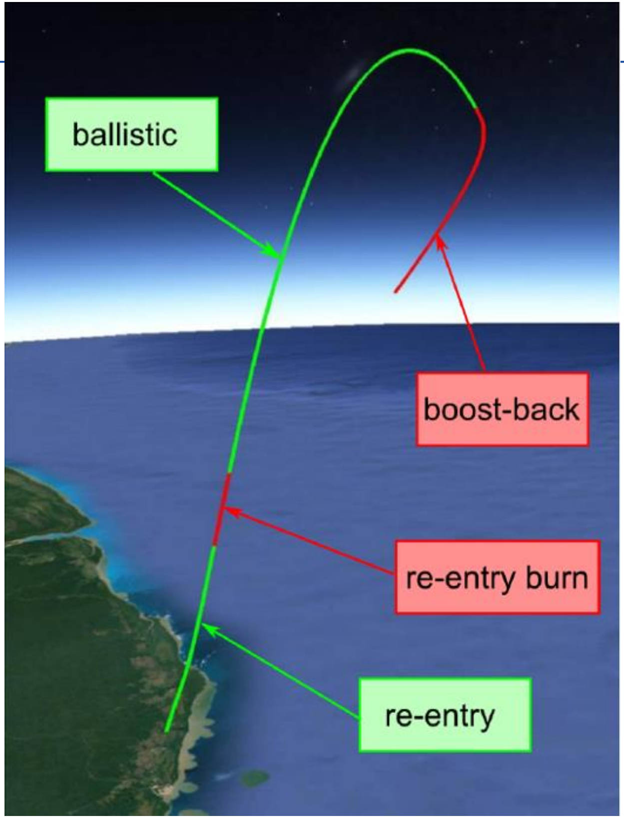


Figure. Example of a BLF

E. Restrepo, Commande en coordination de systèmes multi-agents robotiques autonomes sous contraintes, Thèse, Université Paris-Saclay, 2021.
I. Sarras, Smooth attitude stabilisation in prescribed-time of a rigid body despite uncertainties in inertia and additive disturbances, MED, 2022.

Trajectory replanning module

Trajectory replanning module
Context and objectives



Mission requirements
- Payload delivery on target orbit
- **First stage recovery**

System constraints
- **Control** : actuators saturations, fuel mass
- Physics : thermal / dynamic pressure / structural loads

Trajectory computation : solution of an optimal control problem

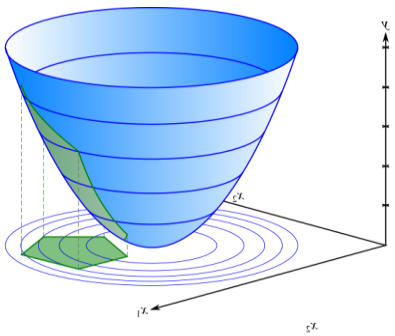
Nominal reference trajectory computed off line, allows for
- Use of high demanding iterative algorithms
- Precision, refining and exploration of the set of solutions

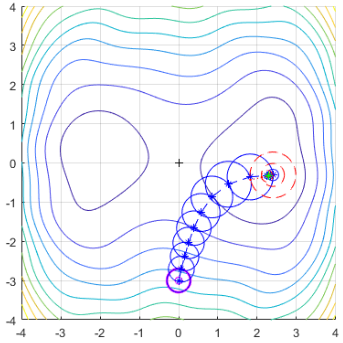
Embedded online trajectory replanning requirements
- Low computational load
- Guaranteed convergence properties of iterative algorithms

Trajectory replanning module

Successive Convex Optimization

Convex Optimization
- Efficient numerical algorithms and toolboxes
- Dedicated auto coders for embedded applications
- **Guaranteed convergence to global optimum**

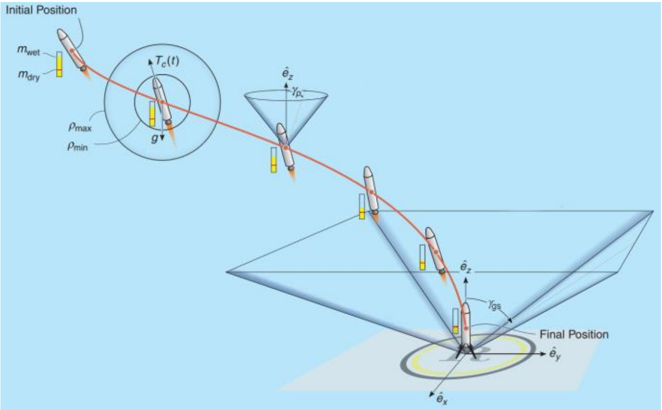




Successive / Sequential Convex Optimization
- Trust region based method (≠ line search)
- Convex approximation of non-convex problem
- Solve locally and iterate → **Convergence to a local minimum !**

Applied to optimal control problem
- Dynamics **linearized around previous iteration trajectory**
- Time discretization
- State and control variations constrained in a trust region

Aerospace applications
- Powered descent landing, **reusable launchers**
- Atmospheric reentry, Orbital rendezvous



[1] D. Malyuta et al., "Convex Optimization for Trajectory Generation" in IEEE Control Systems Magazine, Oct. 2022

Trajectory replanning module

Fault management

Preliminary : compute a nominal reference trajectory

Goal : after a fault detection and identification : compute a new trajectory to recover the first stage

Means : <u>update the optimal control problem</u> by

- Adding or adapting constraints according to the actuator fault, to account for :
    - Engine loss of power or extinction
    - TVC jamming or loss of power

- Changing or relaxing mission constraints : choosing another landing site

- Initializing the algorithm using current state and nominal trajectory

Result : new feasible trajectory + achievable inputs for FTC

Perspectives and Challenges

- Develop the simulation framework allowing the integration of the health monitoring based reconfiguration loop within the project
  - How to combine the modules? Online/Offline trajectory generation? Available inputs and required outputs from the modules?
- Need to analyze the fault criticality level up to which the FTC system can operate and define when trajectory replanning has to be done.
- Performance of the reconfiguration system
  - Computation time, on-board capabilities, time delays
- Which system to supervise
  - System/subsystems/components
- Availability of the models (system/components models, degradation behavior)
  - Mostly based on physical models, difficult to reproduce all possible faults during initial developments/tests.

➔ We are open to discussions and suggestions!

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