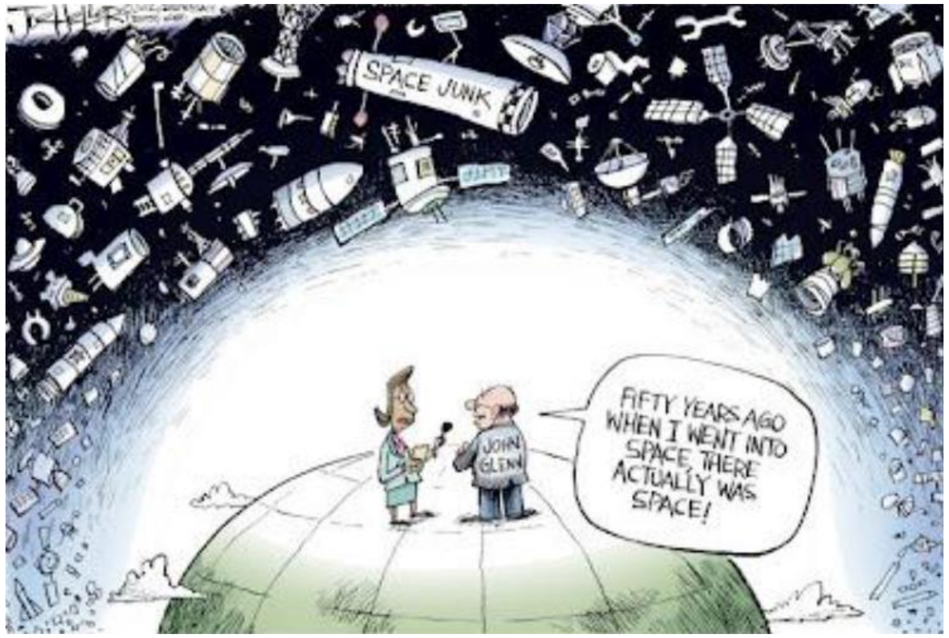
Robot Trajectory Optimisation for On-orbit Servicing and Uncooperative Rendezvous



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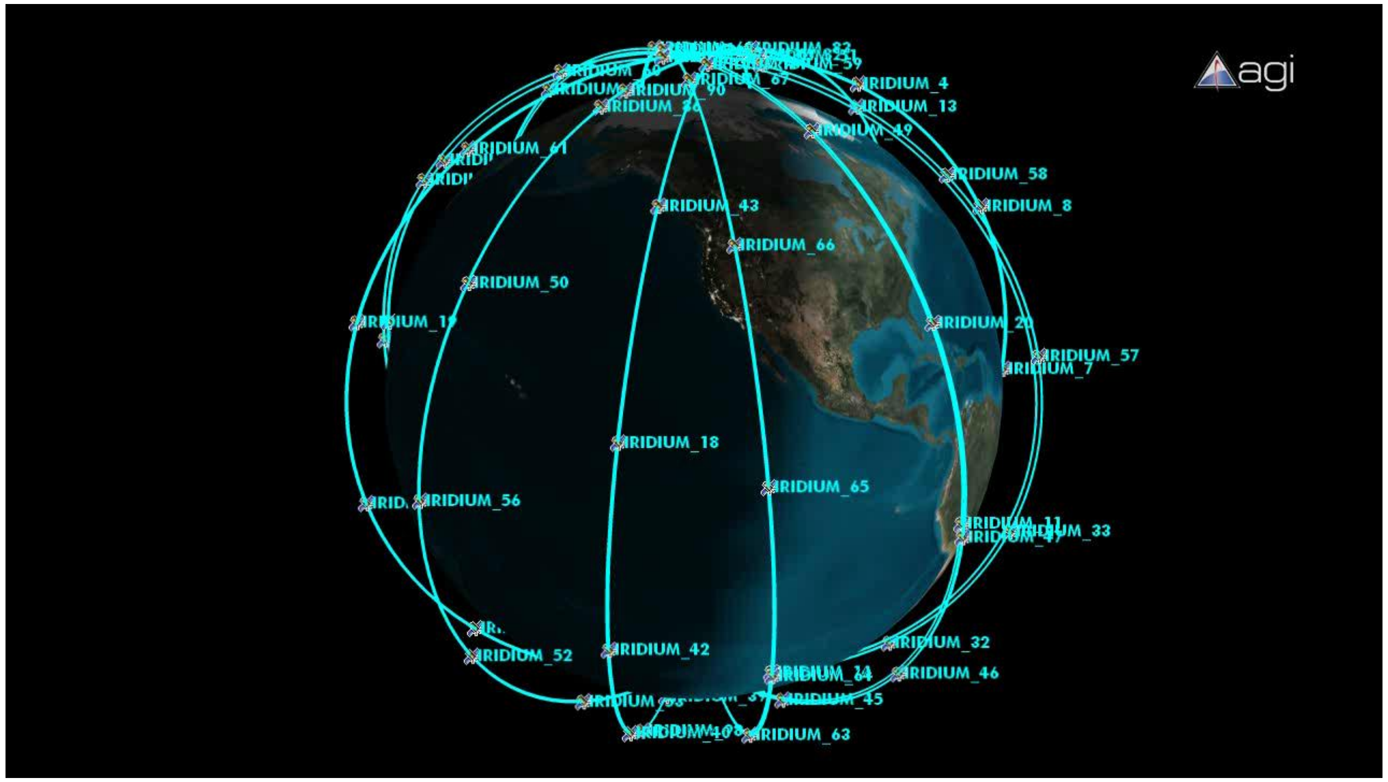
Outline

- Introduction
- Motivation and background
- Research topic overview
- Safe trajectories for autonomous rendezvous
- State-of-Art
- Problem formulation
- d.Deorbit mission
- Simulation results
- Conclusions

Introduction



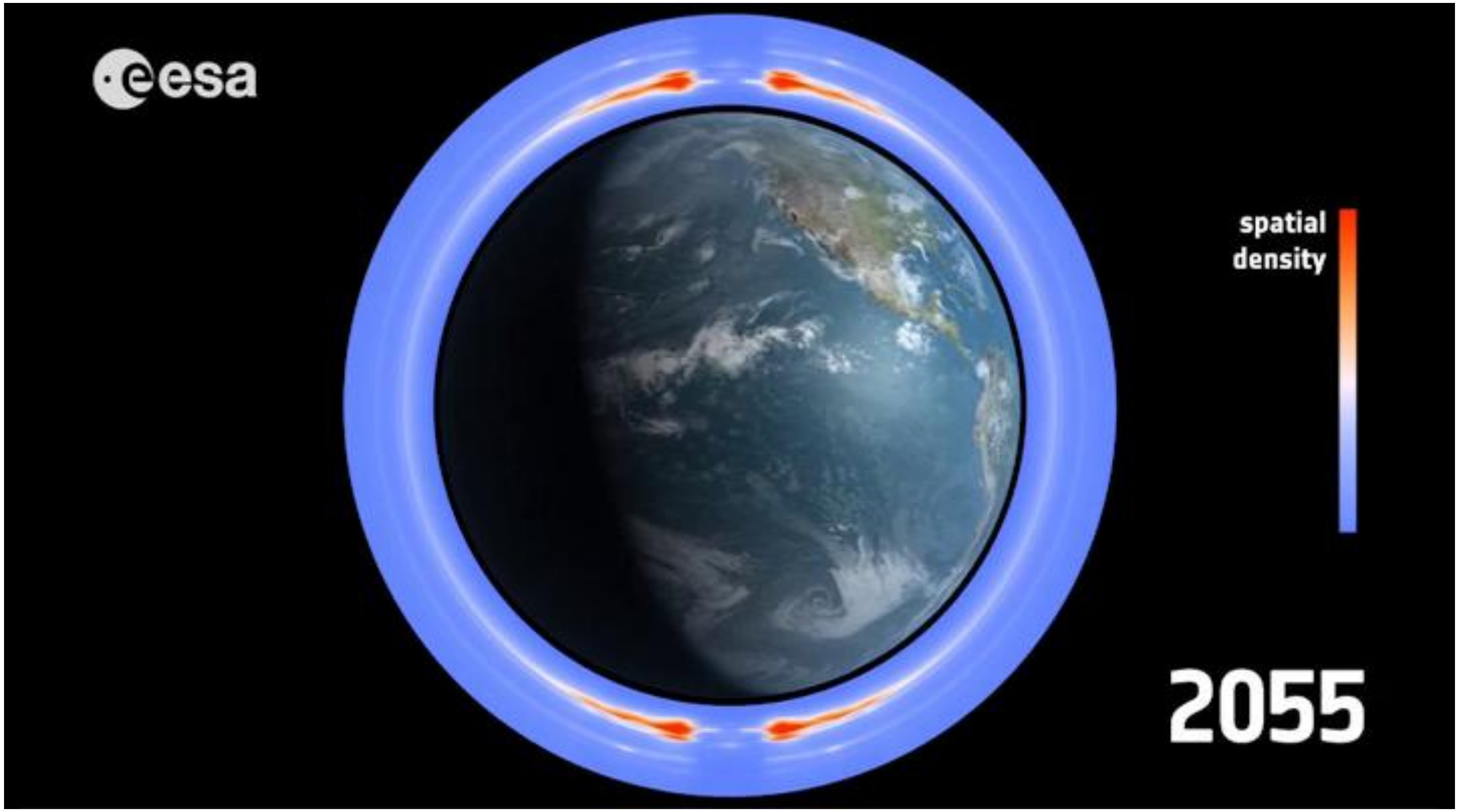
- On the 10th of February of 2009 the Iridium 33 and Cosmos 2251 satellites collided
- The collision was catastrophic producing tens of thousands of fragments large enough to catastrophically breakup other satellites.

Introduction

- Space Shuttle STS-109 Columbia Hubble Space Telescope Servicing Mission

Motivation and background

- What is ADR?
    - Why do we need?



Motivation and background

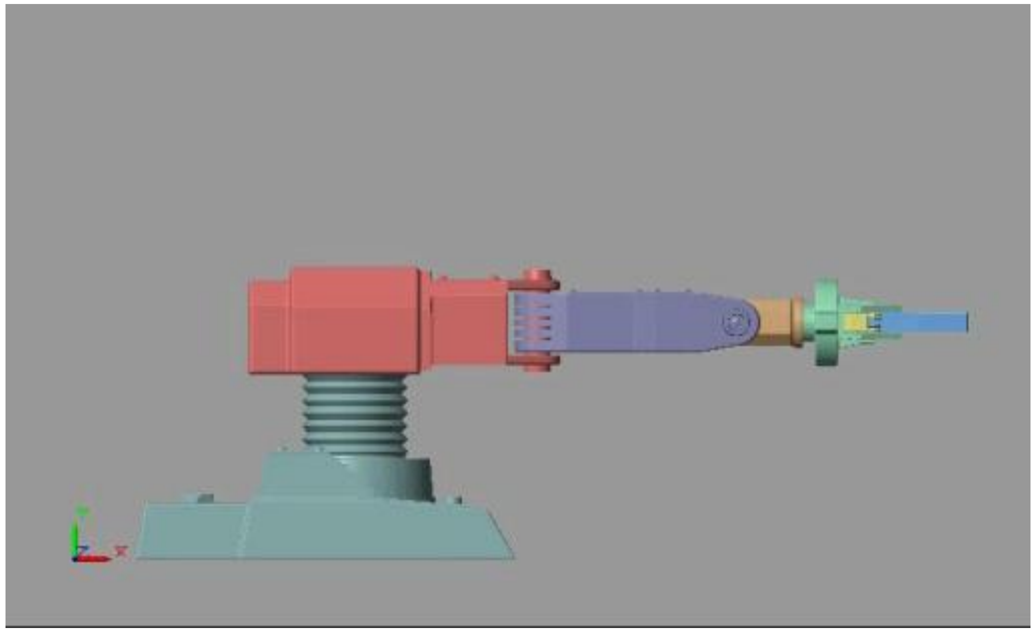
- What is On-orbit servicing?
  - Why do we need it?
    - Active Debris Removal
    - On-Orbit assembly of large structures
    - Servicing: refuelling, inspection and maintenance of space station or satellites.
    - To eliminate the need of dangerous and expensive astronaut servicing;
    - Inter-planetary missions.

Motivation and background

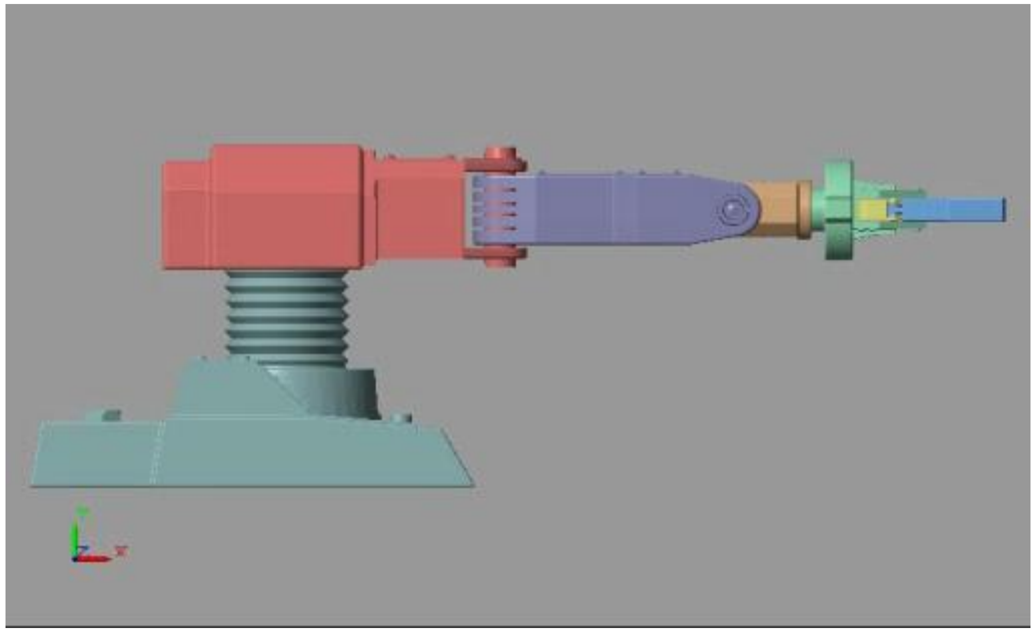
- What is a Space robot?

Motivation and background

- Space robot control modes:



Free-flying



Free-floating

- Space manipulators introduce new challenges:
  - Dynamic coupling between the robotic arm and spacecraft
  - Path dependent singularities -> Reduced workspace
  - Non-holonomic motion

Motivation and background

Space robot control modes:

- Free-floating
  - The GNC OFF
    - Less fuel expenses
    - High risk of collision

1. Mission failure
2. Increase of space debris

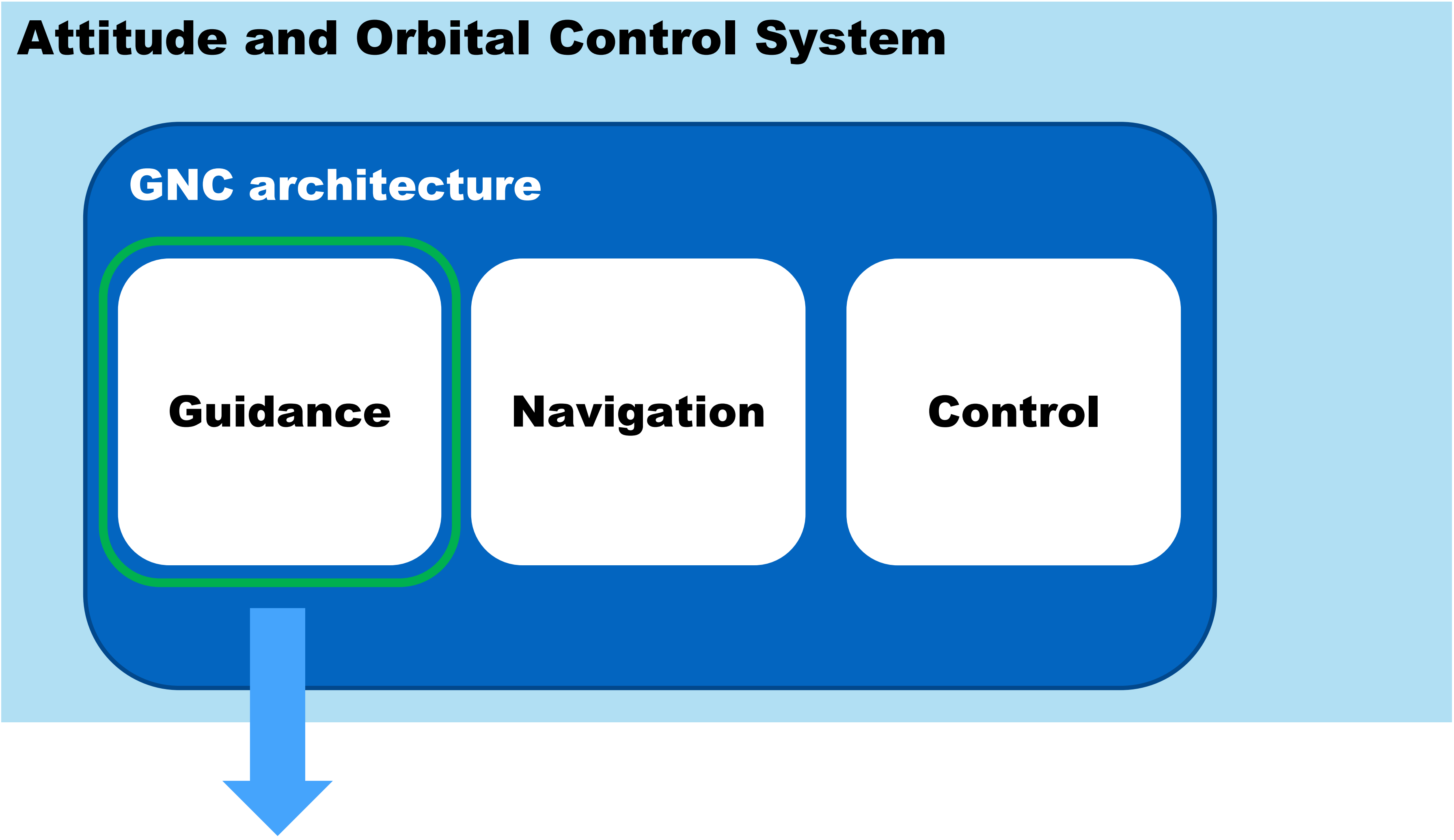
- Free-flying
  - GNC is ON
    - Large fuel consumption
    - Higher performance
    - CAM maneuvers

1. Extra load
2. Higher cost
3. Reduced lifetime

Increased safety!

Research topic overview

- The optimisation is needed!



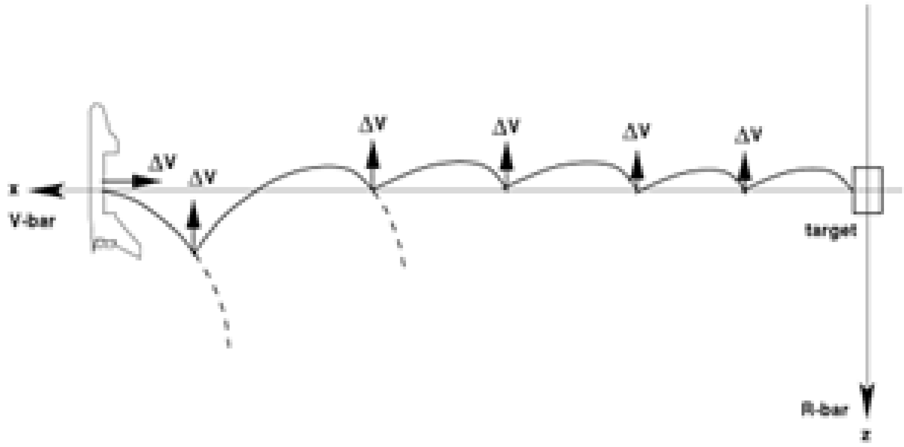
Path planning: Safe trajectory for Spacecraft + robotic arm

Safe trajectories for autonomous rendezvous

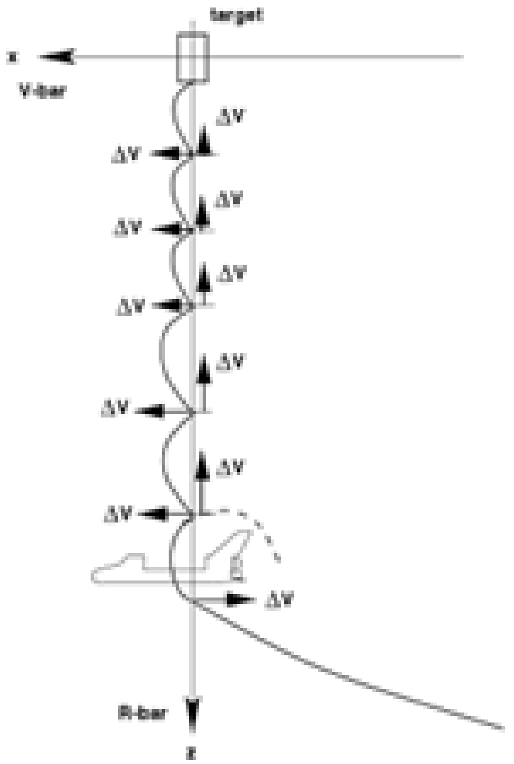
- The criticality of the trajectory is principally given by:
  - Safety requirements
  - Technical requirements:
    - Propellant consumption
    - Illumination (Power)
    - Communication (Antenna pointing)
    - Time
    - Robustness
    - Line of sight
    - Computational power → Limited number of algorithms that can be applied

Safe trajectories for autonomous rendezvous

- Some heuristic approaches:
  - Cooperative target
  - Non-tumbling target



V-bar approach



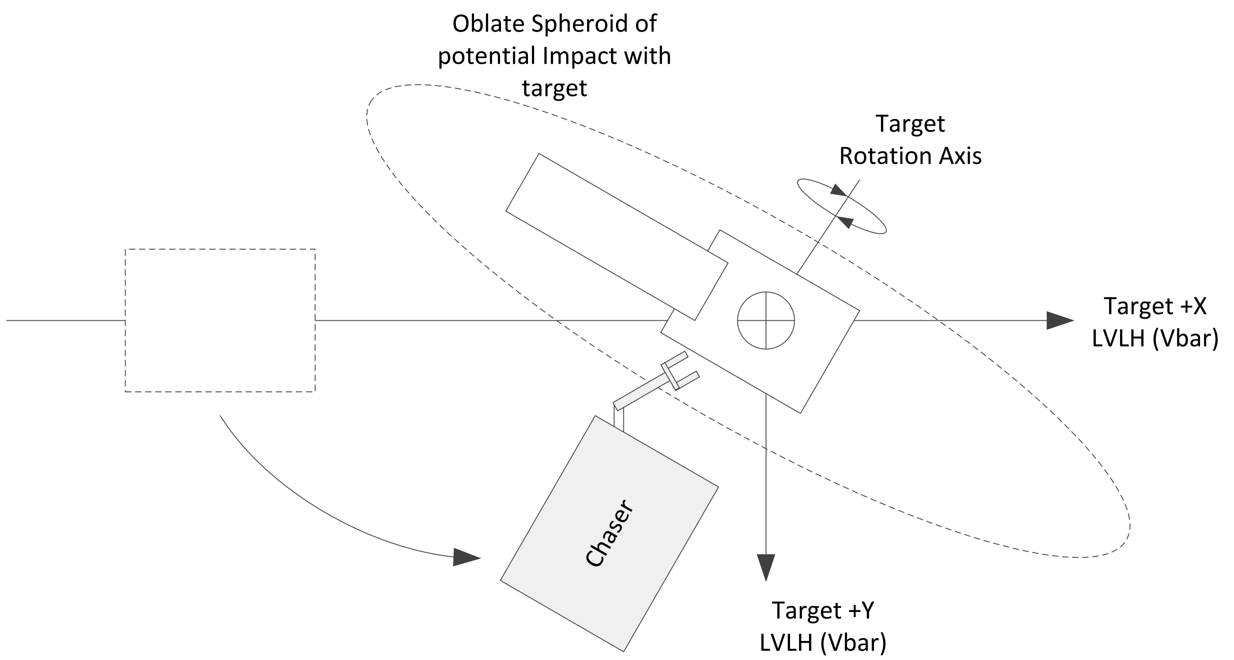
R-bar approach

Source: [1] W. Fehse, *Automated Rendezvous and Docking of Spacecraft*: Cambridge University Press, 2003.

Safe trajectories for autonomous rendezvous

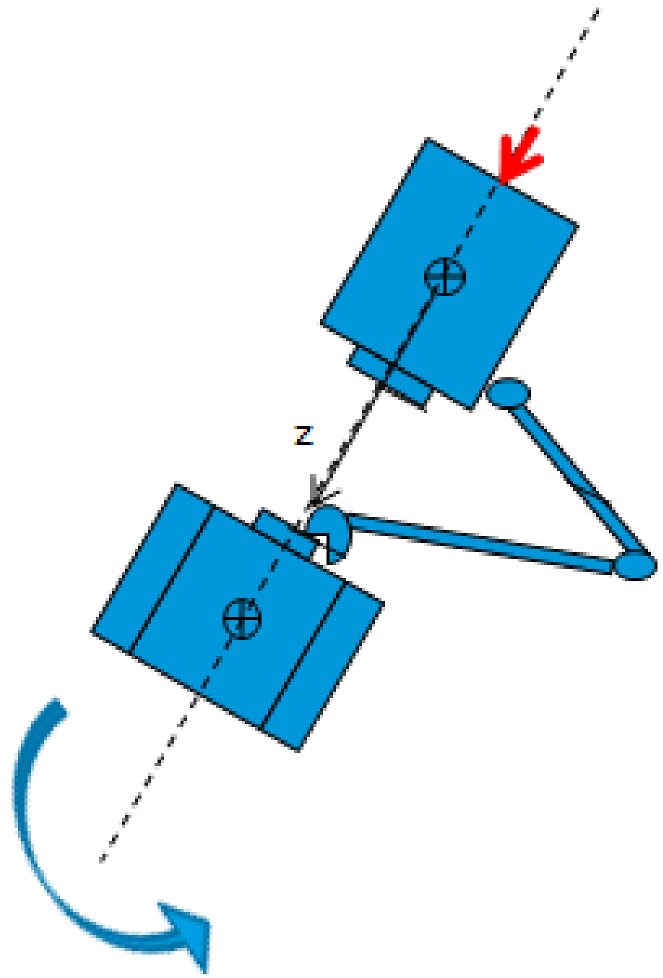
Synchronised motion:

- Advantages
  - Null relative motion
  - No forces or torques during the grasping
  - Safe approach
- Disadvantages:
  - Unknown rotation state
  - High fuel consumption



Forced approach through rotation axis:

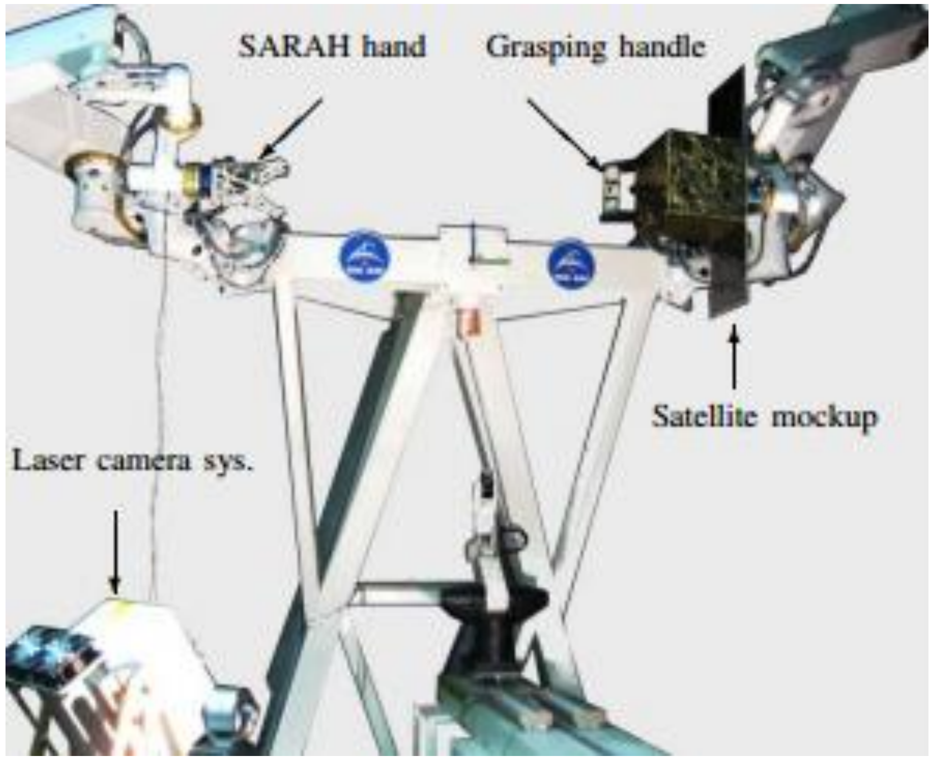
- Advantages:
  - Safe approach
- Disadvantages:
  - Unknown rotation state
  - High fuel consumption
  - Forces or torques during the grasping



State of Art

[1] A. Farhad, "Coordination control of a free-flying manipulator and its base attitude to capture and detumble a noncooperative satellite," in Intelligent Robots and Systems, 2009. IROS 2009. IEEE/RSJ International Conference on, 2009, pp. 2365-2372.

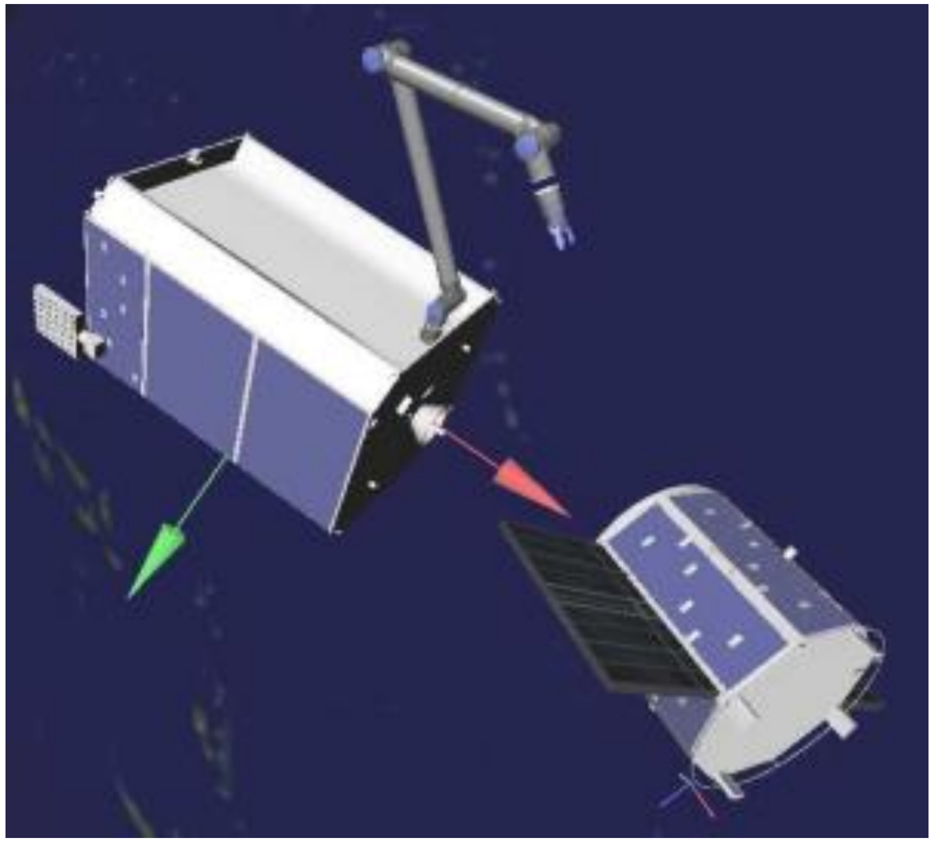
- Nonlinear trajectory optimization:
  - Offline optimisation for pre-capture and pos-capture
  - Free-flying dynamics
  - Null relative dynamics at grasping point
  - Time optimal
- Shortcomings:
  - Fuel consumption not optimised
  - No collision avoidance



State of Art

[2] R. Lampariello and G. Hirzinger, "Generating feasible trajectories for autonomous on-orbit grasping of spinning debris in a useful time," in Intelligent Robots and Systems (IROS), 2013 IEEE/RSJ International Conference on, 2013, pp. 5652-5659.

- Nonlinear trajectory optimization:
  - Offline optimisation
  - Collision avoidance
  - Free-floating dynamics
- Shortcomings:
  - Grasping point specified
  - Limited tumbling motion of the target
  - Transfer of angular momentum not treated
  - Data based system unable to respond to unexpected conditions



State of Art

[3] V. Dubanchet, D. Saussié, D. Alazard, C. Bérard, and C. Le Peuvédic, "Motion Planning and Control of a Space Robot to Capture a Tumbling Debris," in Advances in Aerospace Guidance, Navigation and Control, J. Bordeneuve-Guibé, A. Drouin, and C. Roos, Eds., ed: Springer International Publishing, 2015, pp. 699-717.

- Nonlinear trajectory optimization:
  - Trajectory generated to match: position, velocity and acceleration;
- Shortcomings:
  - Fuel consumption not optimised
  - No collision avoidance
  - System limitation no considered

Problem formulation

Mathematical model: Lagrangian approach

$$M_s\left(\begin{bmatrix} r_s \\ q_m \end{bmatrix}\right)\begin{bmatrix} \ddot{v}_s \\ \ddot{q}_m \end{bmatrix} + C\left(\begin{bmatrix} v_s \\ \dot{q}_m \end{bmatrix}, \dot{q}\right)\begin{bmatrix} v_s \\ \dot{q}_m \end{bmatrix} + g\left(\begin{bmatrix} r_s \\ q_m \end{bmatrix}\right) = \begin{bmatrix} f_s \\ \tau_m \end{bmatrix}$$ Free-flying dynamics

With:

r_s and v_s as the spacecraft position and velocity

q_m as the manipulator joint angles

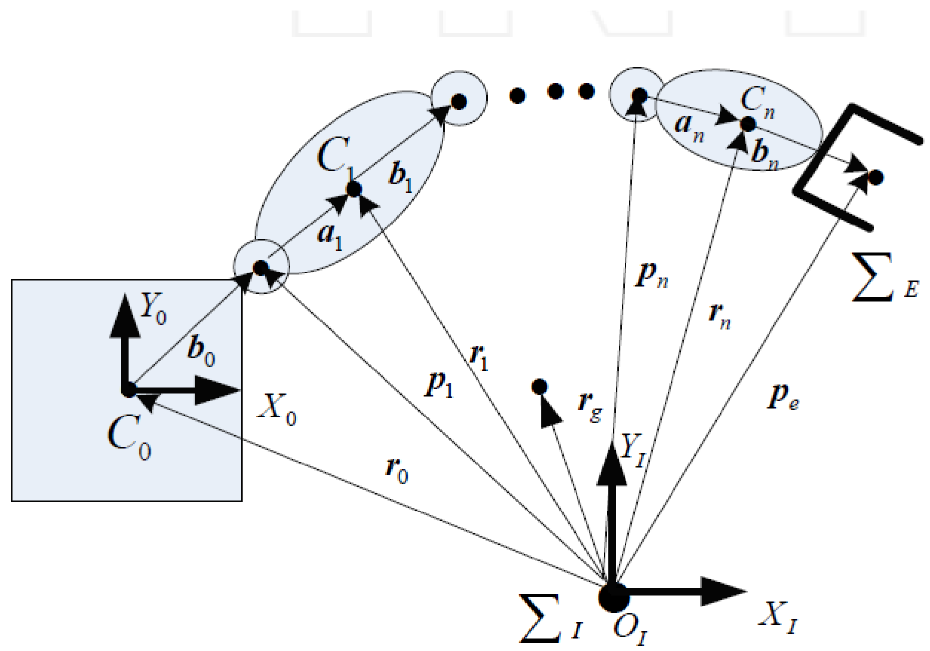
M_s as the generalized mass matrix

C as the generalized Coriolis and centrifugal effect

g the gravity vector

f_s the force and momentum on the base of the spacecraft

τ_m joint torque



Problem formulation

System constraints:

Mechanical limits
$$\begin{cases} q_{min} \leq q(t) \leq q_{max} \\ \dot{q}_{min} \leq \dot{q}(t) \leq \dot{q}_{max} \end{cases}$$

Minimum safety distance
$$\left\{ D(i) > d_{safety} \right.$$

Rendezvous constraints
$$\begin{cases} r_{EE}(t_f) - r_{grasp}(t_f) = 0 \\ \omega_s(t_f) - \omega_{target}(t_f) \leq \omega_{limit} \end{cases}$$

With:

r_{EE} end-effector position

r_{grasp} position of the grasping point

ω_s and ω_{target} angular velocity of the chaser and target

Problem formulation

Performance metrics:

- Safety
- Fuel usage
- Time
- Suitability to grasp and stabilisation
- System constraints:
  - Maximum thrust
  - Minimum Impulse Bit (MIB)

The cost function can be defined as a path integral:

$$P(v) = \int_{t_0}^{t_f} g(path_v(t))dt + h(path_v(t)) + l(path_v(t_f))$$

Problem formulation

- Objective: To find a trajectory to match at time t_f satisfies all the constraints and such that

$$v^* = min_v(P(v))$$

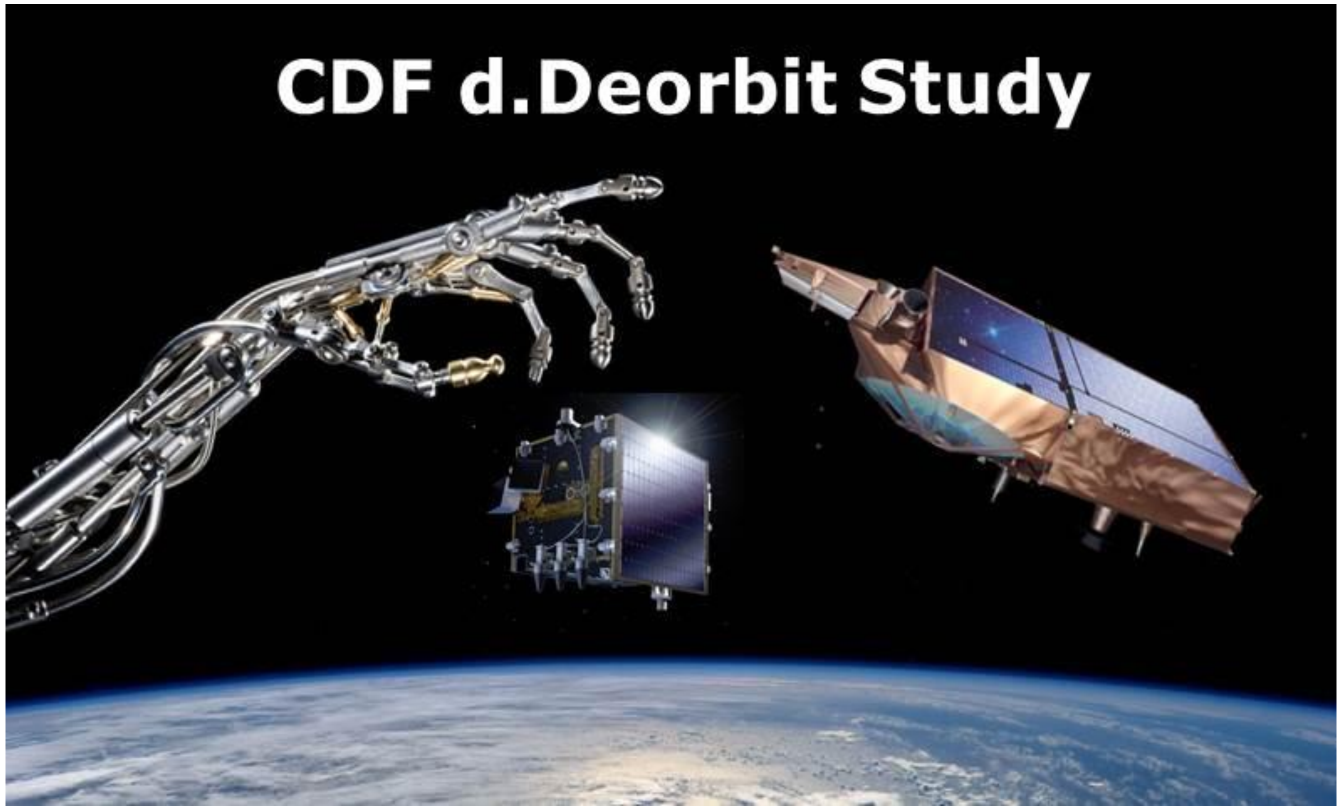
- Local minima problem: If the optimization routine search for the global minimum different solutions can be found:

1. Same cost
2. Different cost -> heuristic acceptable path good choice as starting point

- In order to relax the constraints and reduce the computational time, the algorithm can instead search for a solution that already satisfies the mission requirements.

d.Deorbit mission

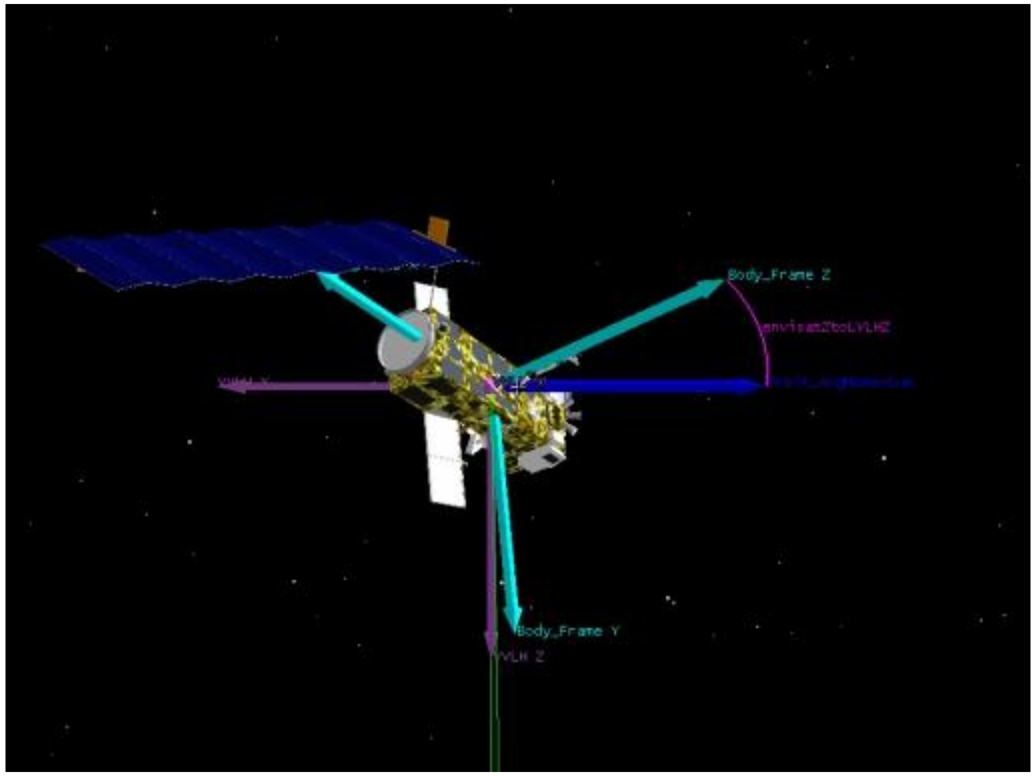
The ESA Clean Space Initiative requested a joint ESA/DLR study to be carried out in the CDF. This study, named d.Deorbit was a feasibility study of a joint ESA/DLR On-Orbit Demonstration mission designed to reduce the risk to the future e.Deorbit mission.



d.Deorbit mission

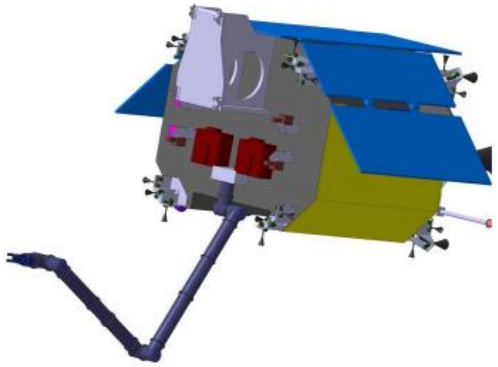
Mission scenario:

- Target vehicle: Envisat
  - Tumbling motion:
    - Spin axis in body frame is aligned with the +Zs axis.
    - Spin axis in LVLH frame is at an angle of 45 degrees with respect to the +H-bar axis and is fixed in an inertial reference frame.
    - Spin rate is 5 deg/s.

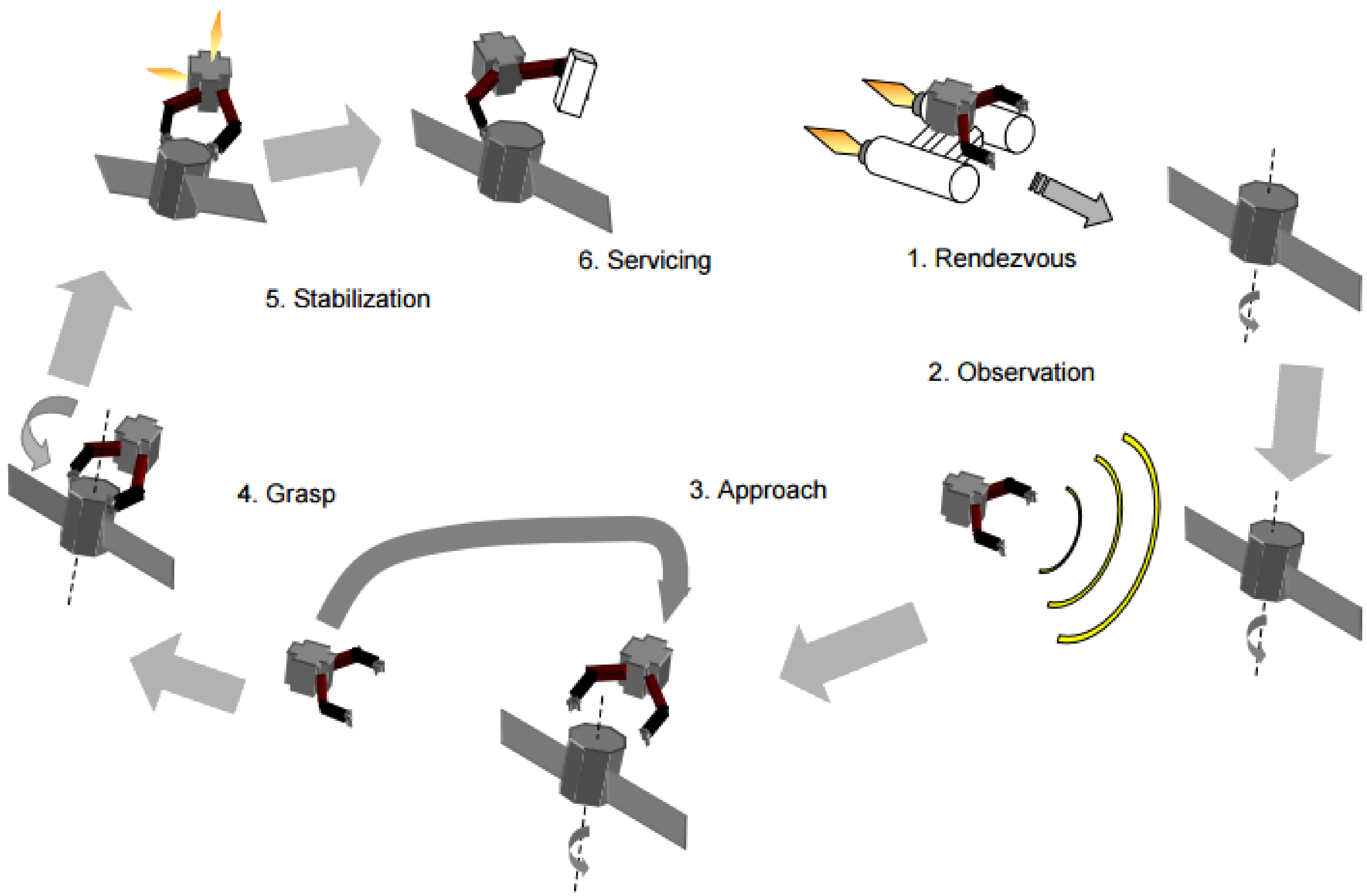


Chaser spacecraft:

  - 7 DoF robotic manipulator
  - GNC activated during all phases
  - Grasping point is known
  - X= -3 Km Z= 500 m in LVLH frame



d.Deorbit mission

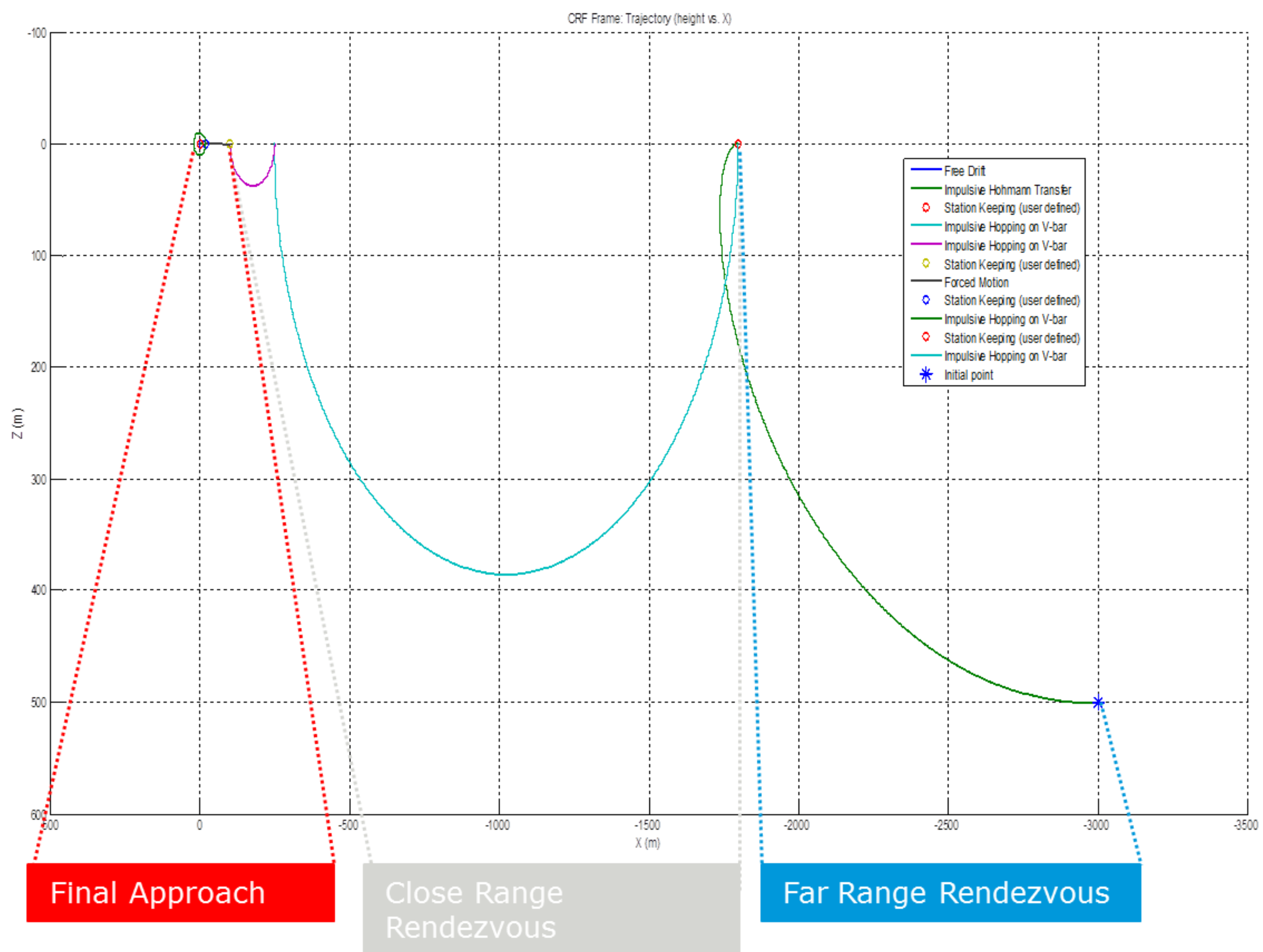


[source: Jacobsen, S. et. al., *Planning of safe kinematic trajectories for free flying robots approaching an uncontrolled spinning satellite, ASME DETC 2002]*

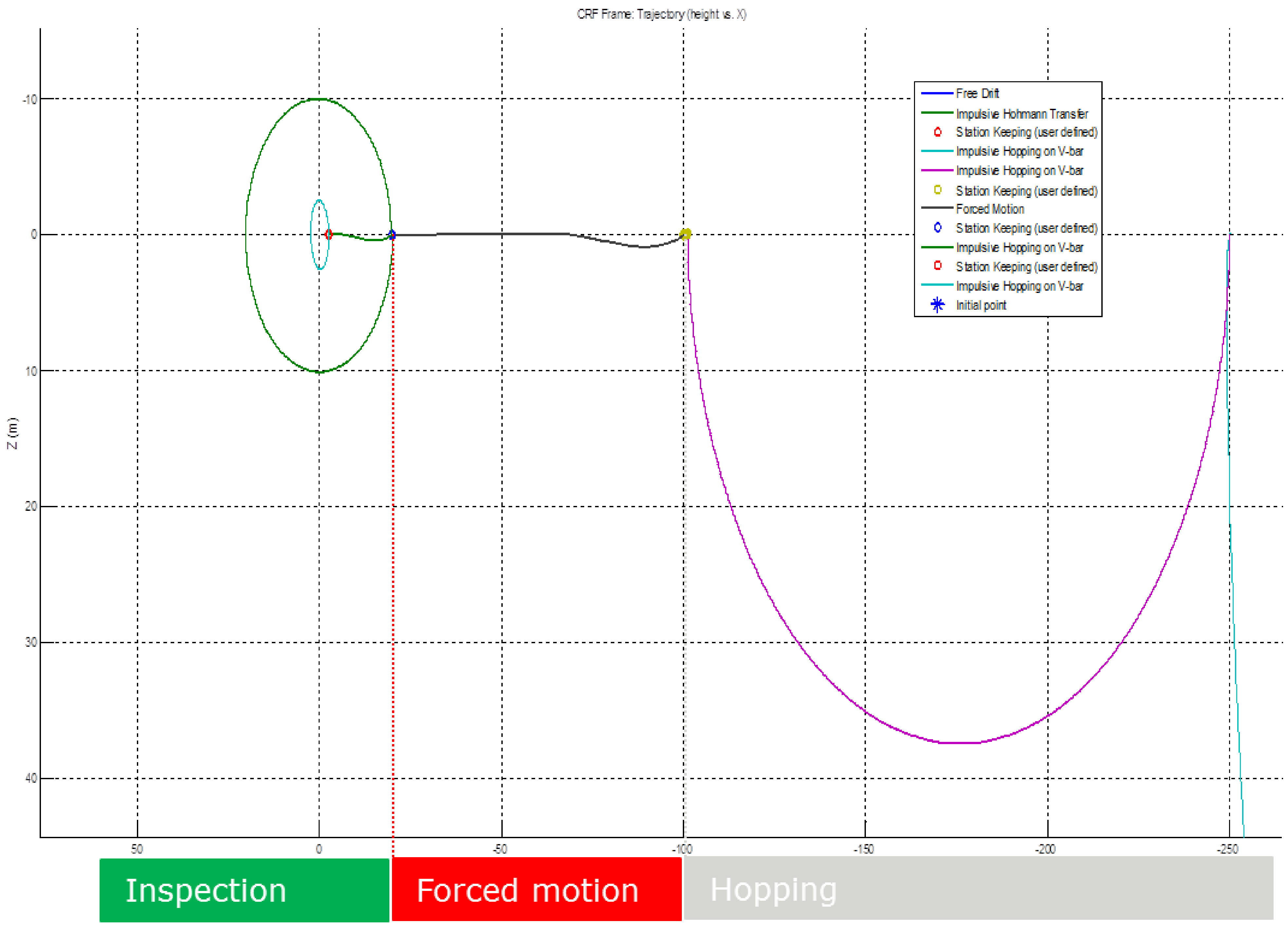
d.Deorbit mission

The rendezvous and capture sequence consist of five phases, divided by holding points:

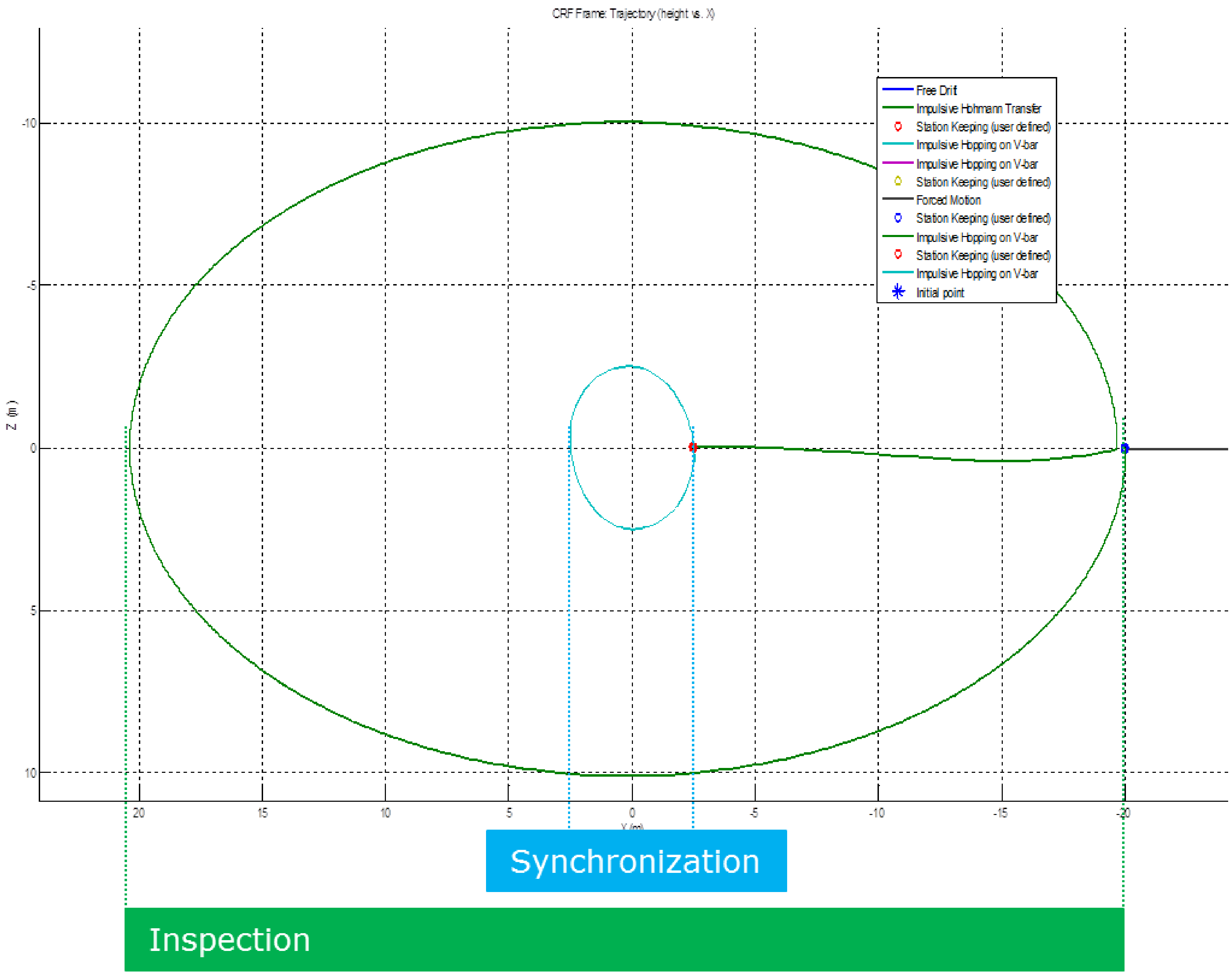
- Far range rendezvous -> Orbit transfer
- Close range rendezvous -> Hopping phase
- Final approach
- Inspection:
  - Forced Motion
  - Inspection
  - Synchronised motion
- Capture phase
- Target stabilisation phase
- De-orbiting phase



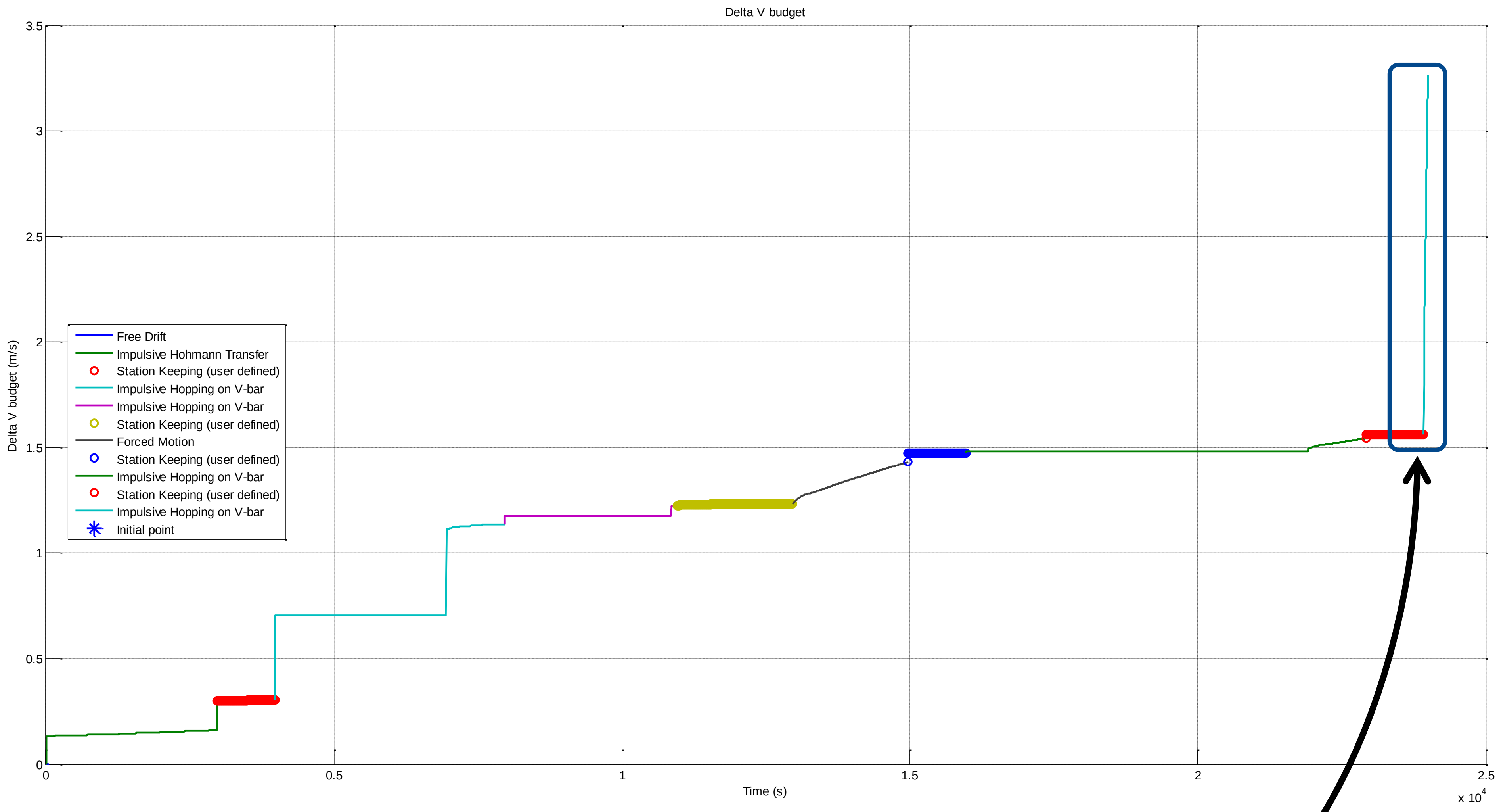
d.Deorbit mission



d.Deorbit mission

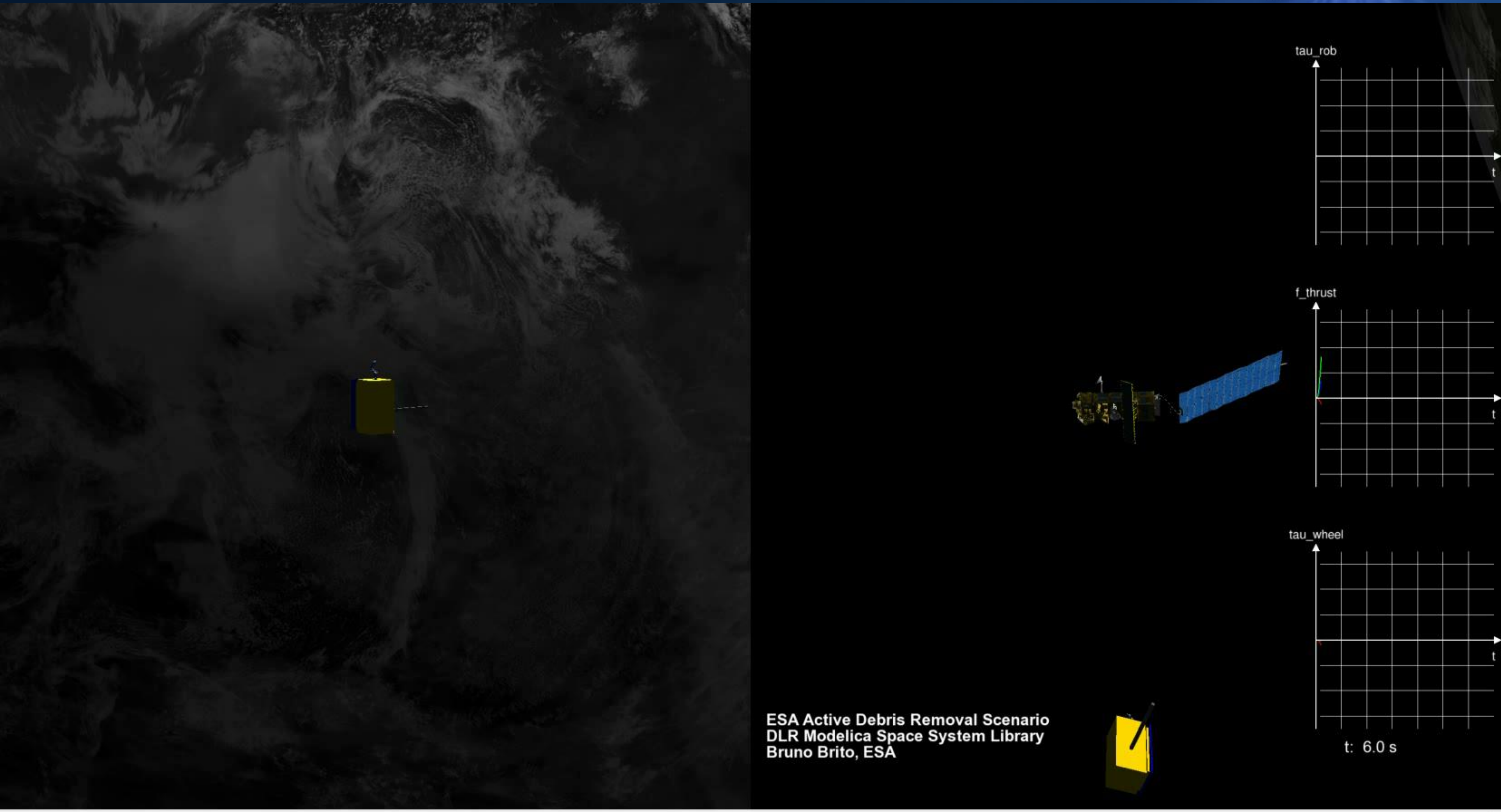


d.Deorbit mission



50% of the fuel is spent only in the synchronisation!

Simulation results



Conclusions

- We need:

1. Optimal control to improve the system performance;
2. Optimal estimators to reduce the noise effect in the sensor measurements;
3. Optimal path planning for the success of the mission.

The optimisation is needed to solve the problem!

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Thank you for your attention!

Questions?

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