13th ESA Workshop on Avionics, Data, Control and Software Systems (ADCSS2019)

IOA-GNC: AUTONOMOUS ON-ORBIT ASSEMBLY

INNOVATING SOLUTIONS

IOA-GNC: OBJECTIVES AND INNOVATION

Background:

- Mastering autonomous in-orbit assembly technologies is crucial in order to enable future missions such as human exploration missions (requiring large in-orbit habitable structures) or scientific missions (requiring large reflectors).

High-level Objective:

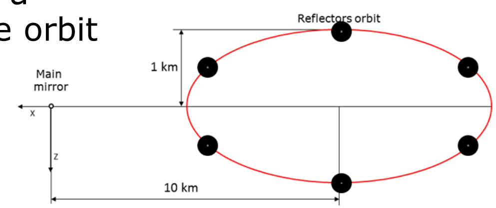
- IOA-GNC (Advanced GNC for In-Orbit Assembly of flexible vehicles) activity is devoted to the design, prototyping, verification and validation (till Model-in-The-Loop level) of an on-board control system aimed at controlling vehicle(s) of different in-orbit assembly scenarios.

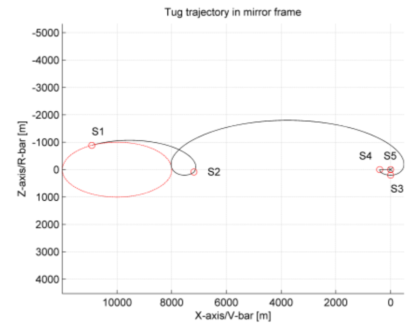
Specific Lower-level Objectives, Challenges and Innovative Aspects/Paradigms:

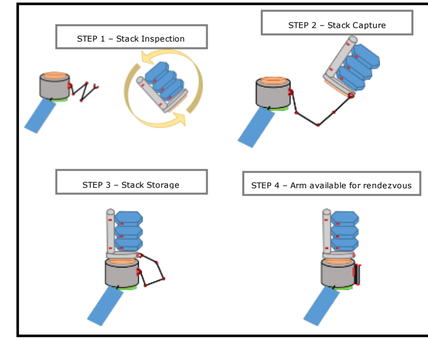
- **Three realistic** and challenging in-orbit assembly scenarios
- **Advanced multivariable GNC** systems for autonomous in orbit assembly (applied to the three reference scenarios).
- **Robust control techniques** (large MCI variations, growing structures and dynamic flexible systems, e.g. robotic manipulators)
- **Advanced FDA** (Failure, Detection and Accommodation) techniques for sensors and thrusters.
- **Full goal-oriented (level E4) autonomy system for on-board re-planning** in case of mission-level failures (nominal plan is no more achievable) with no ground intervention.

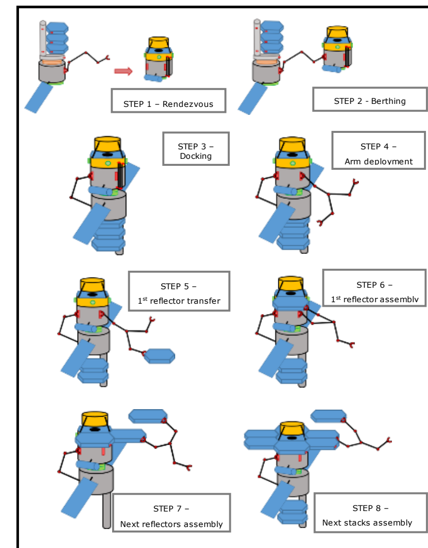
TUG-BASED TELESCOPE ASSEMBLY (LTT)

- Assembly of a telescope around a Central Module in a LLO, using a tug that retrieves reflectors from a safe orbit and transports them to the CM
- Three elements in the rendezvous
  - Tug
  - Central Module
  - Reflectors, in 6 stacks of 3 (**18 total**), in a non-drifting orbit of 2x1 km, 10 km behind the telescope with an out of plane component (safety)
- Assembly operations description
  - Tug separates from CM and transfers from CM orbit to reflector orbit.
  - Tug deploys robotic arm and captures reflectors in the same manoeuvre, while the platform performs station keeping.
  - Tug secures stack of reflectors and returns to CM, performing opposite set of manoeuvres.
  - Tug deploys robotic arm and attaches to CM in the same manoeuvre, while the platform performs station keeping. Tug and CM are assembled into a "combo".
  - Combo assembles reflectors from storage point to structure through the CM robotic arm.
- **Autonomy level**
  - **E3 (event-driven timeline)** with major **on-board re-planning capabilities at guidance/trajectory/manoeuvres level**



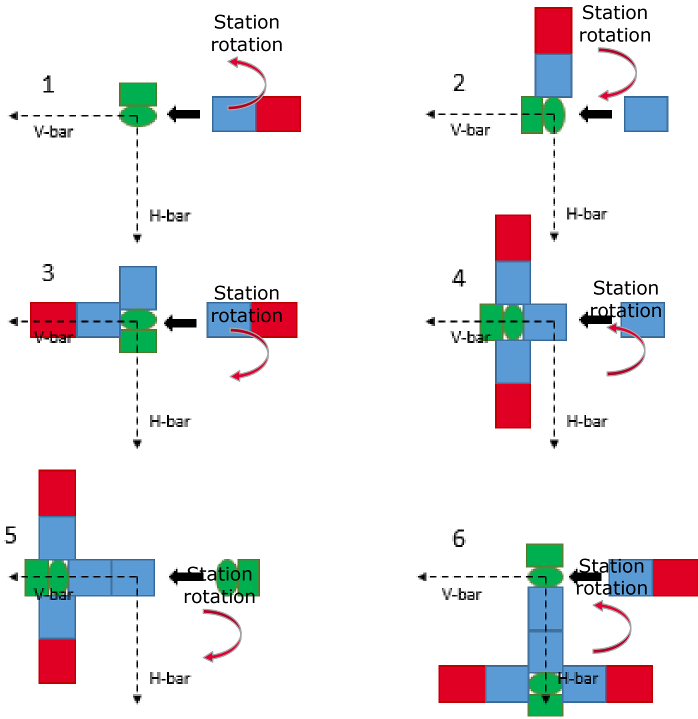


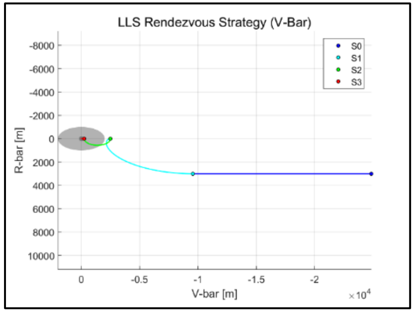


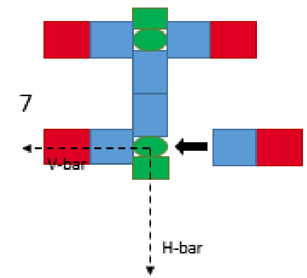


LUNAR SPACE STATION (LSS)

- The assembly is performed by repeating a series of steps, changing the properties of the target (station, including angular momentum transfer during docking) and the chaser (Pressurized, Service and Combo modules).
- The modules are separated in a point far from the station to avoid complex operations near the station, then are sent into a drifting trajectory.
- One module approaches at a time on each assembly step.
- The proposed assembly strategy favours a V-bar approach due to the passive safety added with this approach.
- A total of **12 modules** comprise the nominal station, using 4 stacks transported from LEO. In total, 7 assembly operations (steps).
- **Autonomy level**
  - **E3 (event-driven timeline)** with major **on-board re-planning capabilities at guidance/trajectory/manoeuvres level**

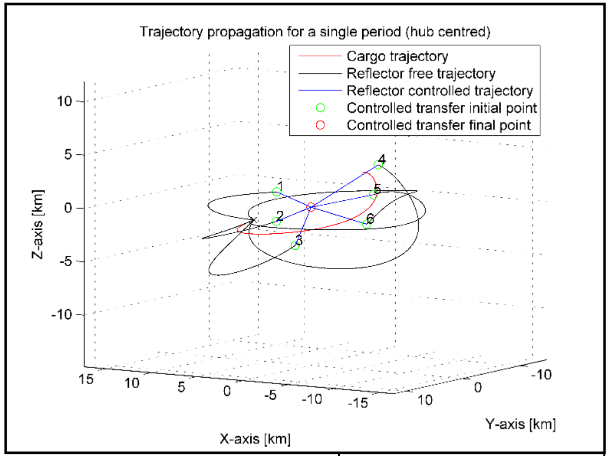


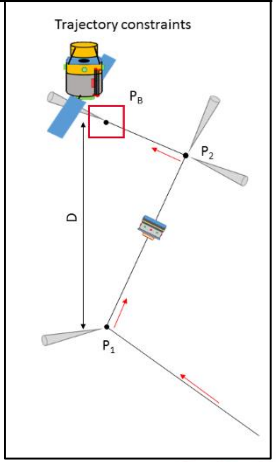




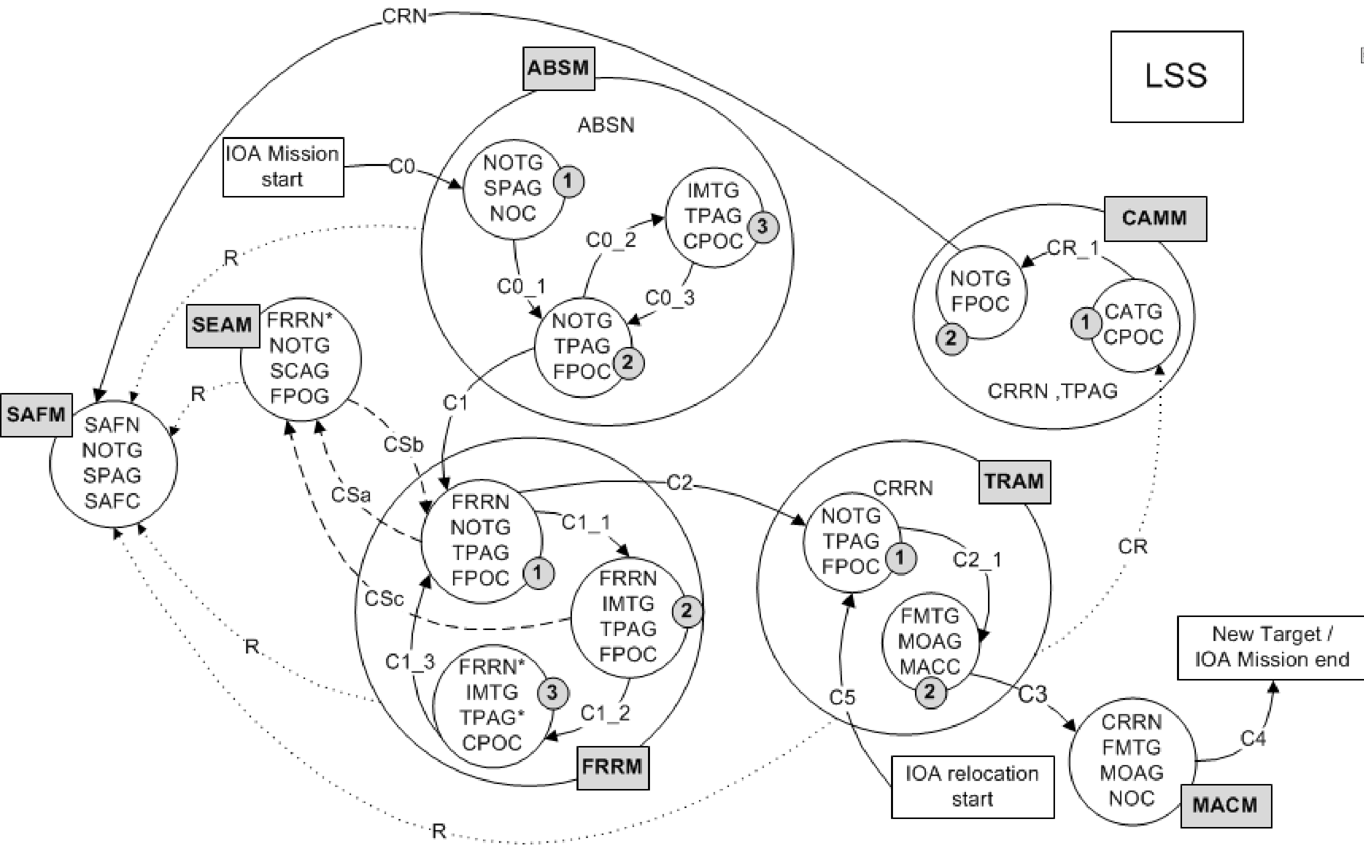
SELF-SUFFICIENT TELESCOPE ASSEMBLY (HST)

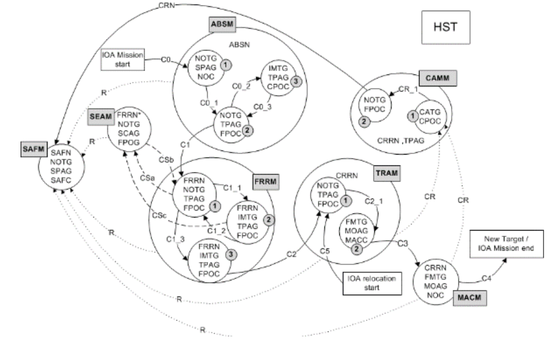
- Scenario:
  - Assembly of a telescope around a Hub in a Halo orbit, using a swarm of reflectors that are assembled by means of a robotic arm
  - Cargo vehicle transporting reflectors is already in a hold point in the same halo orbit 10 km away from the hub
  - Six reflectors are released from the cargo with 0.3 m/s, in six different stable equally spaced directions.
  - 3 cargos are considered for a total of **18 reflectors**
- Approaching trajectories designed as diagonal steps:
  - Minimization of plume impingement
  - Additional passive safety
- Assembly operations description
  - A single leg starts with a single reflector after commissioning.
  - The reflector performs rendezvous operations and stays in the berthing box.
  - Deployment of the robotic arm and capture of the reflector, by robotic arm motion.
- Advanced FDA techniques included/validated in this scenario
- **Autonomy level**:
  - **Full autonomy (level E4, goal-oriented) included/validated in this scenario**

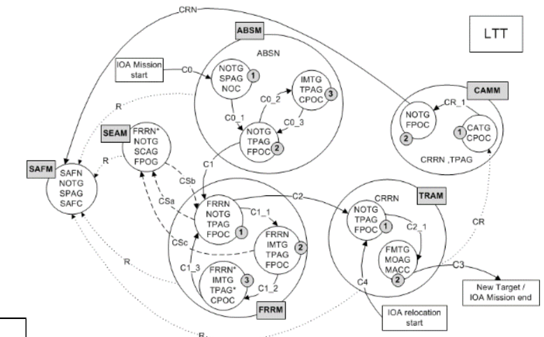




GNC SUBMODES







GUIDANCE DESIGN OVERVIEW

- Guidance definition focused on intermediate to close rendezvous, including impulsive and forced motion trajectories
- **Low Lunar Orbit** guidance based on LEO strategies for keplerian orbits
  - State propagation performed using Yamanaka-Ankersen equations
  - Main differences wrt LEO
    - Longer reference orbital period (2 h vs 1.5 h)
    - Smaller curvature radius (~1900 km ~6800 km)
    - Different disturbances (gravity, drag…)
- **Halo** guidance newly developed for this activity
  - Halo dynamics are much slower than the typical LEO dynamics (14 days compared to 1.5 hours)
  - Rendezvous strategies based on exploitation of orbital dynamics are unfeasible, as they require transfers that are of the order of magnitudes of the reference orbit -> a rendezvous would last months
  - Approaching trajectories present very small curvatures over long periods of time. Manoeuvres can be considered straight lines for several hours ➔ development of "tacking strategy"
  - Conclusions from IOA-GNC halo guidance design used as a starting point for NRO-GNC (HERACLES)

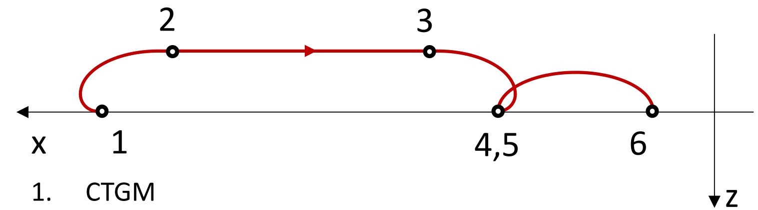
LLO MANOEUVRES

Impulsive guidance uses the **following manoeuvres**:

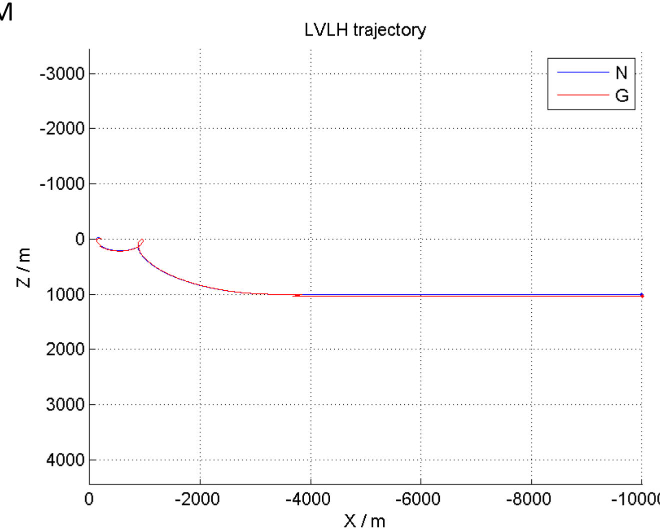
- **CTGM**: cotangential transfer, analogous to Hohmann transfer, and used to transfer to higher / lower orbit
- **NDTM**: non-drifting transfer, analogous to radial hop, and used to perform drift-free hops between hold points on V-bar
- **XING**: manoeuvre at crossing point. Algorithm detects crossing between two trajectories and calculates manoeuvre required to pass from one trajectory to the next
- **YCTR**: out-of-plane control. Adjusts out-of-plane manoeuvre at node.
- **TPTR**: two-point transfer. Calculates two ΔV's based on initial state, terminal state and transfer time

Guidance plan contains sequence of manoeuvres, plus parameters that define desired relative state

Relative state is propagated using the **Yamanaka-Ankersen** equations



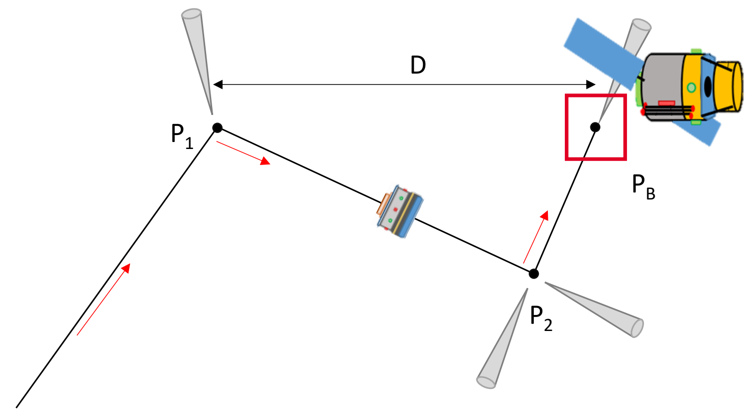
1. CTGM
2. XING
3. CTGM
4. XING
5. NDTM
6. XING

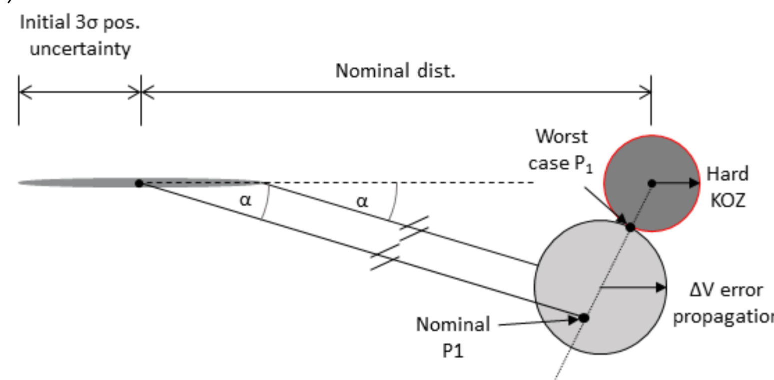


HALO IMPULSIVE MANOEUVRES

- Approach in zig-zag: “**Tacking**”
  - Straight line approach exploiting (lack of) halo dynamics
  - Increased safety by not approaching target directly
  - Improved navigation by approaching at an angle
  - Allows to get relatively close to target without thrusting towards target, allowing reduced plume impingement
- Safety considerations
  - Trajectory defined as an angle with respect to target LOS
  - Angle of approach defined assuming
    - Large errors in radial direction due to navigation estimation
    - Control errors in manoeuvre application
    - Guidance error due to non-modelled dynamics
- Guidance performs the following functions
  - Calculate approach angle for next tack
  - Calculate approach direction, taking Sun direction into consideration
  - Calculate approach ΔV, based on estimated distance and transfer time
  - Monitor current approach angle obtained from navigation and determine time of next manoeuvre
  - Monitor current distance

Trajectory constraints

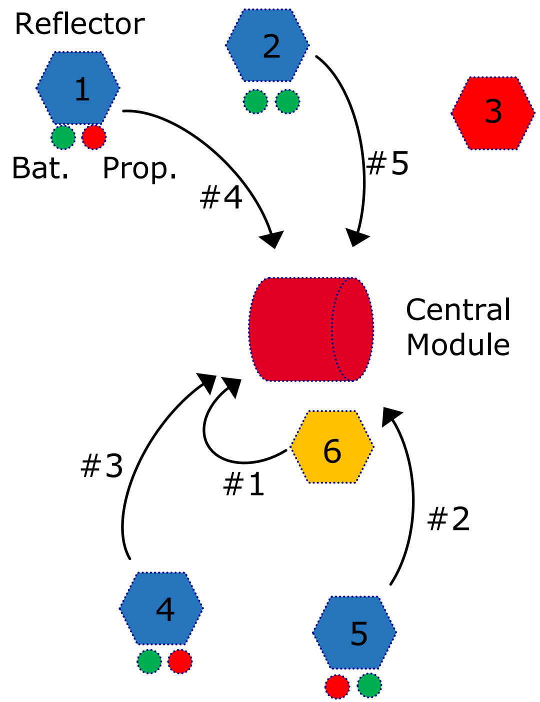




AUTONOMY SYSTEM OVERVIEW

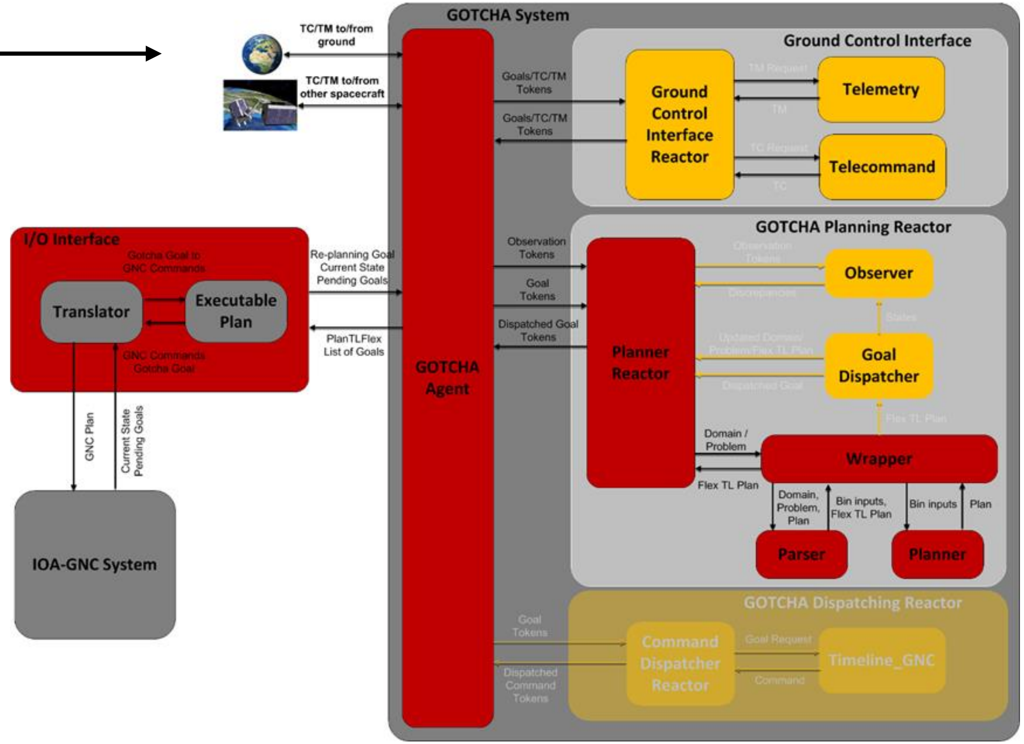
- Scenario:
  - Assembly of a telescope around a Hub in a Halo orbit
  - Six reflectors are released from the cargo for docking with the central module.

- **Objectives** of the Autonomy subsystem:
  - Generate a **new temporal plan** for completing the docking of all operative reflectors **after a fault** (re-planning)
  - Decide the **sequence and parameters** for assembling the reflectors to comply with resource (propellant and battery) restrictions
  - Determine the desired **transference time** for each reflector (among N predefined transfer times)
  - Model the **battery** and **propellant** consumption as linear functions
  - Generate an optimal plan (wrt. time, time/propellant)



AUTONOMY SYSTEM ARCHITECTURE

- Based on **GOTCHA** (from Robotics Planetary Exploration) generic Architecture:

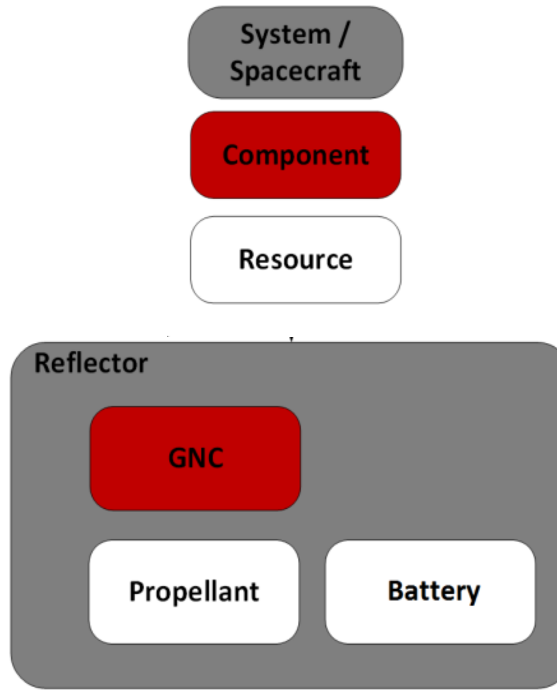


- **Tailoring** of GOTCHA to IOA-GNC:
  - GOTCHA **designed for Surface Robots,** complex environments with high level of uncertainty
  - **Adapted for orbital scenarios**. First application known by GMV
  - Autonomy for **contingency** not solvable by GNC, without ground intervention
  - Possibility of scaling to more complex scenarios

- **Mission** autonomy vs **GNC** autonomy
  - **Mission level** parameters (order of assembly, duration of assembly) treated by **GOTCHA**
  - **Lower level** information (**trajectories**, “path planning” of surface operations) treated at **GNC**
  - **GOTCHA** in IOA uses **estimated costs** of different operations, but does not duplicate entirely GNC functions

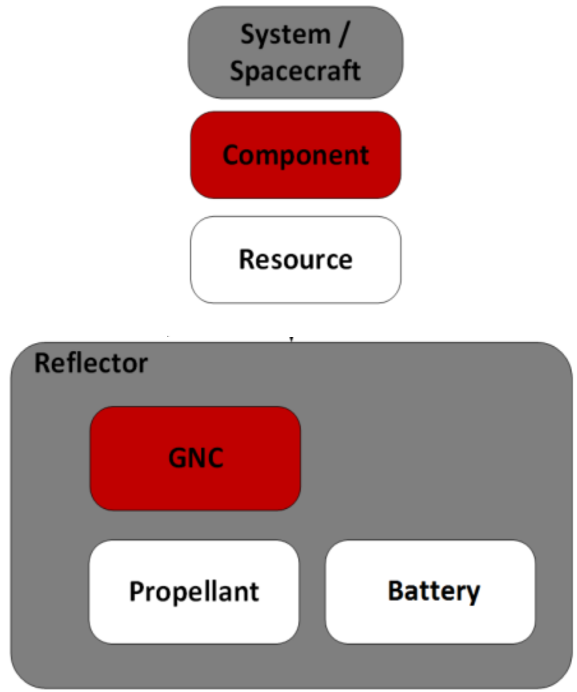
AUTONOMY SYSTEM OVERVIEW

- Autonomy Level:
  - Overall level of Autonomy is **E4**:
    - Goal oriented mission replanning
    - Takes into account the available resources
    - Generation of temporal plans with temporal flexibility (flexible starting/duration)
    - The need to promptly react to changes
  - Level of Autonomy of individual reflectors is **E3**:
    - Event-based autonomous operations (Adaptive)
- Centralized system:
  - Autonomy capabilities centered on Hub using information of reflectors states
  - Mission stops when re-planning is required, reflector parameters re-initialized with updated values
- Modelled using PDDL:
  - Reflectors modelled as GNC objects with properties
  - PDDL properties can be
    - Numerical (**functions**)
    - Logical (**predicates**)
  - Properties can change by means of **actions** with flexible **conditions** and **effects**
  - PDDL coded in two files:
    - **Domain** contains a definition of the predicates, functions and actions
    - **Problem** contains state of the mission at re-planning, and the **goal** states



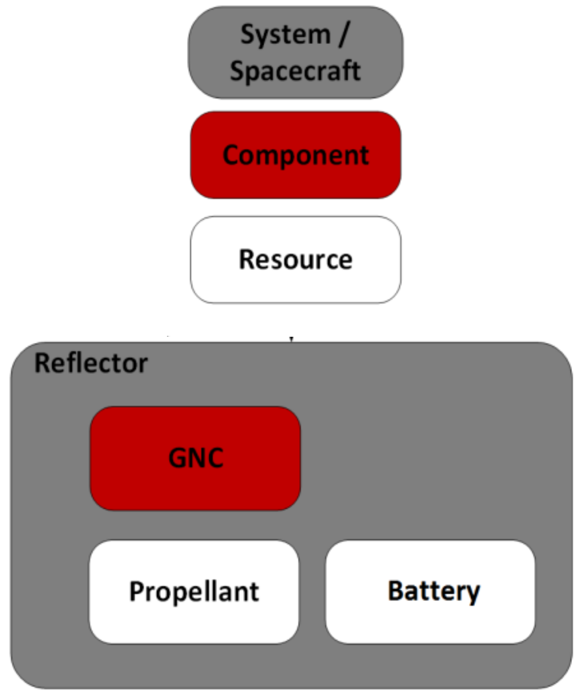
AUTONOMY SYSTEM RESOURCES

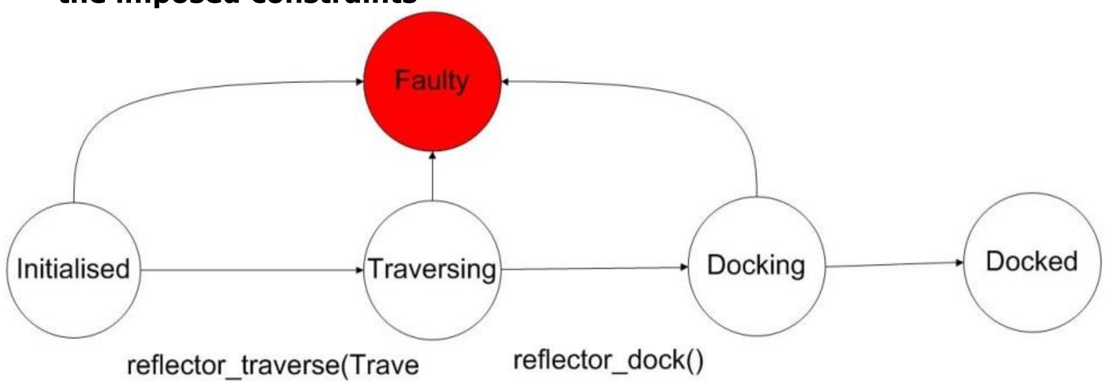
- **Reflector Battery resource**:
  - Relevant to **limit** the possible manoeuvers due to limited **operating time**.
  - Resource model:
    - Battery consumption is **proportional to time** elapsed since the start of the plan
    - Battery consumption can **vary depending on the state** of the reflector
    - Could be replaced in the future by higher fidelity battery models if needed
- **Reflector Propellant resource**:
  - Relevant to **limit** the possible **manoeuvers** to be undertaken regarding the transference times.
  - Resource model:
    - Propellant consumption **inversely proportional** to the transference **time** (Halo rendezvous dynamics).
    - Given a propellant cost for a nominal traverse time, it is possible to linearly compute the cost for any other traverse times.



AUTONOMY SYSTEM COMPONENTS & STATES

- **Reflector GNC component**: The status of the reflector is modelled according to the possible states/phases and transitions.
  - **Initialized**: A reflector is ready to start its traverse towards the Hub
  - **Traversing**: A reflector has started the traverse towards the central module
  - **Docking**: A reflector has reached the berthing box and starts the docking
  - **Docked**: The reflector is correctly assembled after completing the docking.
  - **Faulty**: At any time a reflector can be declared faulty and be discarded
  - **The replanning is successful if all reflectors end docked or faulty under the imposed constraints**

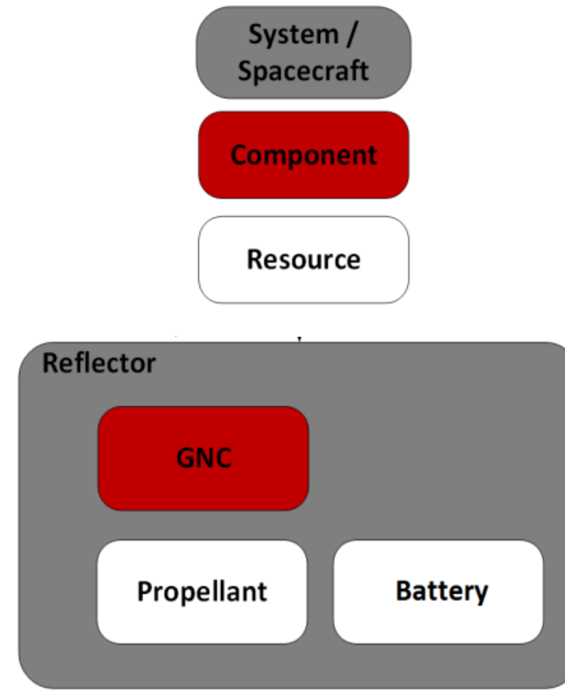


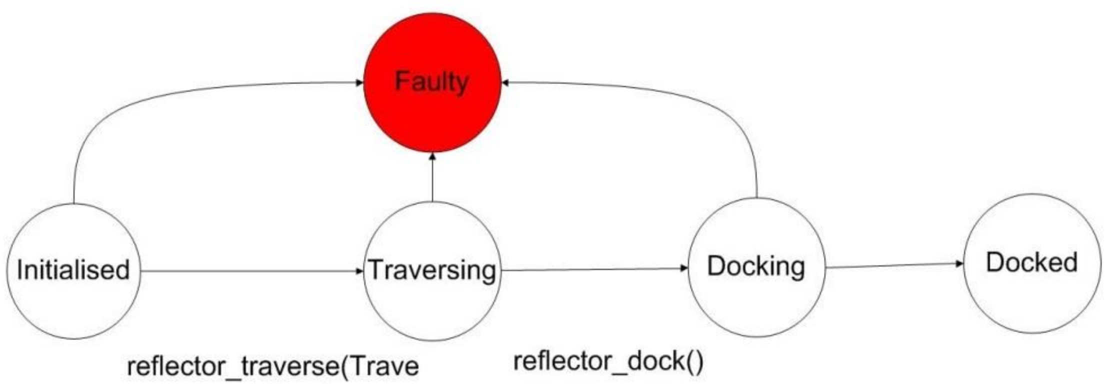


AUTONOMY SYSTEM ACTIONS

- **Traverse_reflector (traverse_time)**: execute the traverse phase
  - Duration: The reflector traverse time (parameter): **Nominal** Traverse Time multiplied by one of the **possible traverse time multipliers**.
  - Precondition: Enough battery to complete the Traversing and Docking phases.
  - Precondition: Enough propellant to complete the traverse in the specified time.
  - Effect: The reflector passes to Docking state.

- **Dock Reflector()**: execute the docking phase for a reflector
  - Duration: duration of the docking phase (fixed).
  - Conditions: the reflector is in Docking state.
  - Effects: The reflector passes to Docked state.





AUTONOMY SYSTEM TEST CASES

- Test cases
  - **Single failure:** A single reflector is compromised during the assembly sequence. The fault can be detected in any reflector during the assembly of another reflector, of during the assembly of the faulty reflector itself. Two test per failure modelled. Modelled cases are:
    - **Propellant depletion**: Propellant level of one reflector not enough to complete whole assembly. Modelled as lower ΔV available
    - **Robotic Arm Grasping Point/Docking Site failure:** Need to try a different assembly point or grappling point. Modelled as increased duration of berthing/docking phase.
    - **Battery depletion:** Battery available not enough to complete whole assembly. Modelled as lower battery level.
    - **Reflector loss:** Reflector declared faulty and non-recoverable. Modelled as reflector in state faulty.
  - **Double failure:** Two reflectors with combinations of single failure cases:
    - **Propellant depletion + GP/DS failure**
    - **Propellant depletion + Battery depletion**
    - **Propellant depletion + Reflector loss**
    - **GP/DS failure + Battery depletion**
    - **GP/DS failure + Reflector loss**
    - **Battery depletion + Reflector loss**
  - **Irrecoverable failure:** Injected failure is so severe that no solution exists with all reflectors in the sequence. The objective is to go for the closest mission success possible:
    - **Propellant depletion**
    - **Battery depletion**
    - **Propellant + battery depletion**

AUTONOMY SYSTEM RESULTS

- Single failure: Propellant loss/reduction in Ref#6 during assembly of Ref#4

Reflector	Status	Nominal ΔV (m/s)	Available ΔV (m/s)	Time of flight (s)	Battery available (s)
1	Assembled	-	-	-	-
2	Assembled	-	-	-	-
3	Assembled	-	-	-	-
4	Initialized	6.3	16.5	15000 (Transfer) 1000 (Assembly)	84800
5	Initialized	14	29.4	20000 (Transfer) 1000 (Assembly)	84800
6	**Initialized**	**14**	**4.7**	**20000 (Transfer) 1000 (Assembly)**	**84800**

	Nominal	Solution
Order	[-, -, -, 4, 5, 6]	[-, -, -, 6, 4, 5]
Velocity	[-, -, -, n, n, n]	[-, -, -, v, f, f]
Cost (m/s)	[-, -, -, 6.3, 14, 14] **34.3**	[-, -, -, 4.7, 12.6, 28] **45.3**
Duration (s)	[-, -, -, 16000, 21000, 21000] **58000**	[-, -, -, 61000, 11000, 8600] **80600**
Cost fun	**93.308**	**125.782**

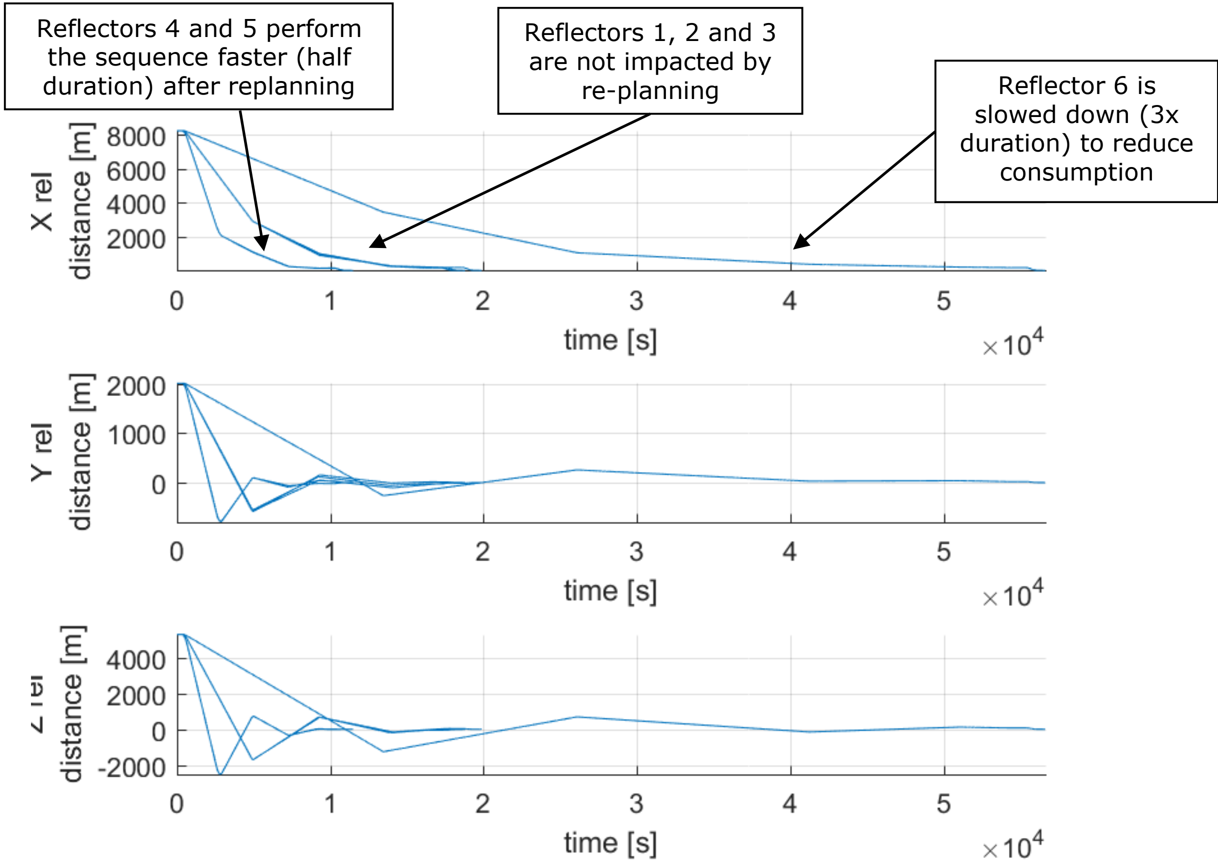
- Double failure: Berthing partial failure in Ref#1 + propellant loss/reduction in Ref#3

Reflector	Status	Nominal ΔV (m/s)	Available ΔV (m/s)	Time of flight (s)	Battery available (s)
1	**Berthing**	**-**	**-**	**- (Transfer) 5000 (Assembly)**	**128000**
2	Initialized	14	29.5	20000 (Transfer) 1000 (Assembly)	128000
3	**Initialized**	**14**	**4.7**	**20000 (Transfer) 1000 (Assembly)**	**128000**
4	Initialized	14	29.5	20000 (Transfer) 1000 (Assembly)	128000
5	Initialized	14	29.5	20000 (Transfer) 1000 (Assembly)	128000
6	Initialized	14	29.5	20000 (Transfer) 1000 (Assembly)	128000

	Nominal	Solution
Order	[1, 2, 3, 4, 5, 6]	[1, 3, 6, 2, 4, 5]
Velocity	[n, n, n, n, n, n]	[n, v, n, f, f, f]
Cost (m/s)	[-, 14, 14, 14, 14, 14] **70**	[-, 4.7, 14, 28, 28, 28] **102.7**
Duration (s)	[1000, 21000, 21000, 21000, 21000, 21000] **106000**	[1000, 61000, 21000, 11000, 11000, 11000] **116000**
Cost fun	**177.298**	**218.7**

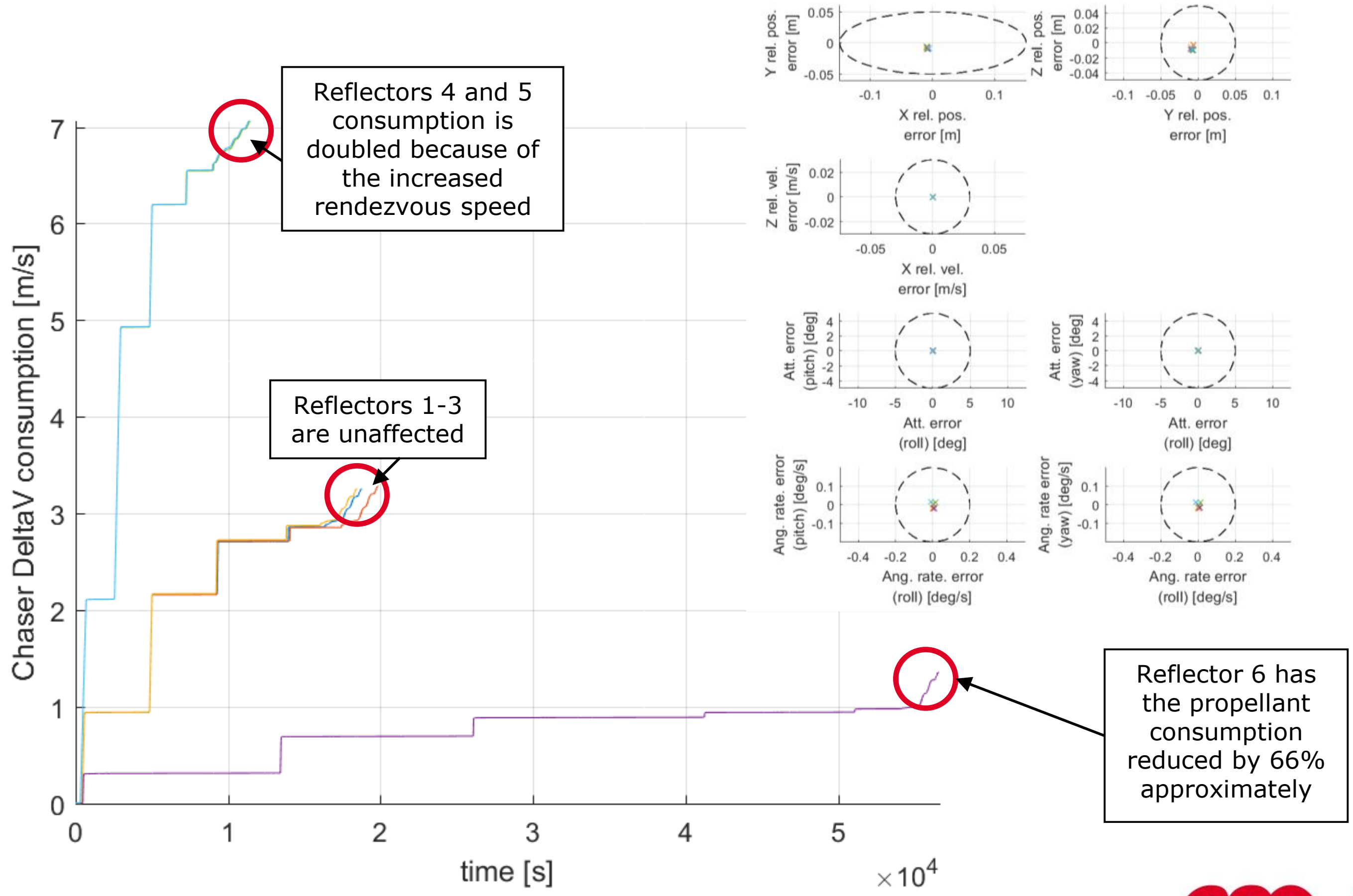
AUTONOMY SYSTEM TEST RESULTS

- Example with propellant failure in reflector 6 during assembly of reflector 4
  - Reflectors 1, 2 and 3 perform nominal assembly (nominal speed/deltaV) before the failure
  - After Ref#6 propellant loss, on-board replanning is launched. As result, Ref#6 is given priority and assembled next at 0.33x the nominal speed (to decrease the required delta-V)
  - After Ref#6 assembly, Ref#4 and Ref#5 are assembled at 2x the nominal speed (recovery of mission timeline by expending additional deltaV available at Ref#4 and Ref#5)



AUTONOMY SYSTEM TEST RESULTS

- Example with propellant failure in Ref#6 during assembly of Ref#4
- Reflectors 1, 2 and 3 assemble at nominal speeds
- Reflectors 4 and 5 assemble at 2x the nominal speed
- Reflector 6 assembles at 0.33x the nominal speed



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THANK YOU

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