Current and future developments of on-board autonomy in GNC systems at ESA

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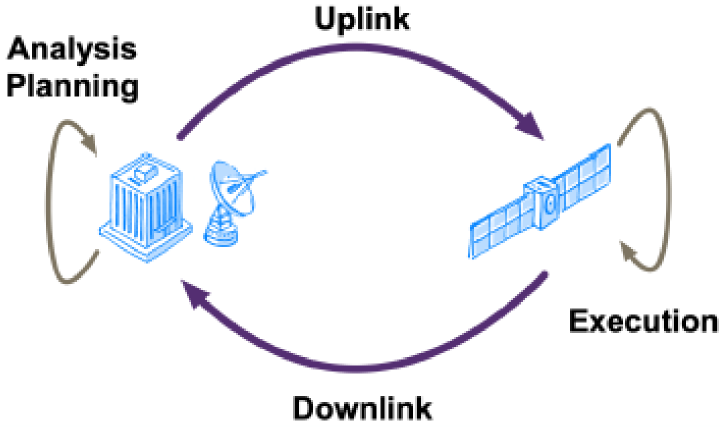
Autonomy: definition, need, mission applications, autonomy on ESA missions

Autonomy: definition and need (1/2)

Autonomy is "**the ability of a system to achieve goals while operating independently of external control**" (2015 NASA Technology Roadmap).

Autonomy initially introduced in tasks/missions where the ground commanding control loop has a characteristic **timescale** that may be greater than the timescale needed to exercise control. Autonomy moves analysis and planning functions from ground to on-board.



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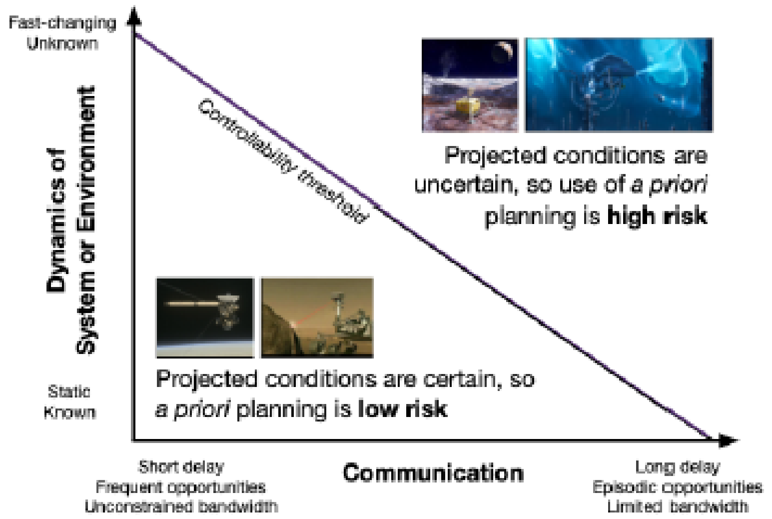
Historically, the response to this need has materialised into use of time-driven command sequences, critical sequences retries, autonomous control and navigation functions, FDIR and fail-safe functions.

Autonomy: definition and need (2/2)

Autonomy is also necessary when a spacecraft has to **react to changes** in the environment or within the spacecraft itself at a shorter time-scale than afforded by communication constraints.



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When the **dynamics** of the system or environment **is fast-changing or unknown** or the **communication is constrained** by limited data rates, restricted link availability, long delays, especially if large data products are required for ground-based planning (e.g. contextual maps for path planning), using a priori planning for control increases mission risk.

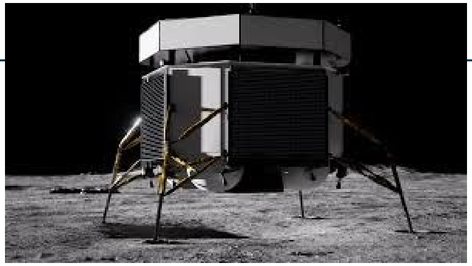
Autonomy: mission applications (1/2)

Mission / mission phase	Drivers	Enabling/enhancing autonomous functions
Entry, descent and landing	- Short dynamic timescales - Limited or no a priori atmosphere/surface characterization - Communication delays/gaps	- Absolute and relative navigation (terrain-relative) - Hazard detection and avoidance - Autonomous planning / re-planning - Real-time guidance
Opportunistic science (e.g. comet flyby, but also astrophysical transient events observation)	- Limited communication and time to perform critical targeting - Optimise science return	- Autonomous navigation - Autonomous planning / re-planning - Real-time guidance - Science planning
Multi-spacecraft missions	- Limited time to coordinate observations with ground in the loop - Optimise science return / coverage	- Autonomous navigation - Autonomous planning / re-planning - Science planning
Missions to unexplored small bodies (asteroids, comets,…)	- Uncertain relative spacecraft/body position - Unknown body shape and gravity - Unknown surface properties	- Autonomous navigation - Autonomous mapping / inspection - Absolute and relative navigation (terrain-relative) - Hazard detection and avoidance - Real-time guidance
Aerobraking	- Potential high operational workload	- Autonomous navigation - Autonomous planning / re-planning
Interplanetary cruise with EP	- Mitigating impact of thrust interruptions on trajectory	- Autonomous navigation - Autonomous planning / re-planning - Real-time guidance

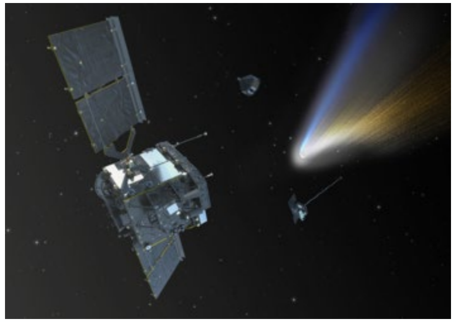
Autonomy: mission applications (2/2)

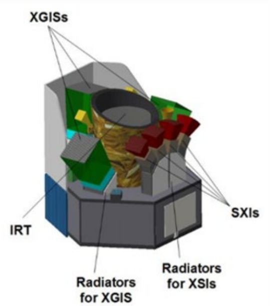
Mission / mission phase	Drivers	Enabling/enhancing autonomous functions
Rendezvous and proximity operations, robotic missions (e.g. debris removal, ISAM, etc.)	- Short dynamic timescales - Communication gaps - Safety of space assets - Potentially uncooperative targets - Potentially uncertain target optical properties - Robotic elements coordination - Highly variable configurations and MCI properties	- Autonomous navigation - Autonomous mapping / inspection - Autonomous planning / re-planning - Real-time guidance - Combined control and operation of platform and robotic elements
Controlled de-orbitation	- Limited knowledge of atmospheric properties - Increase autonomy in the manoeuvring for increased de-orbitation accuracy - Maintain controllability in presence of high drag	- Autonomous navigation - Autonomous planning / re-planning - Specific control algorithms for high drag
Collision avoidance in LEO	- Short reaction time	- Autonomous navigation - Autonomous planning / re-planning - Autonomous Collision Avoidance Manoeuvre (CAM)
Generic	- Cost reduction - Reliability increase - Operations simplification	- STR-based safe-mode

Autonomy in ESA missions



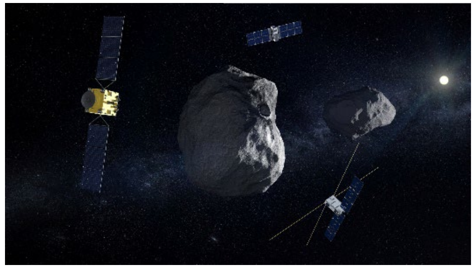
EDL: RFM, Argonaut, L4-Enceladus, MEDAL





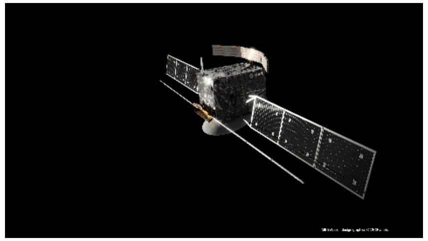
Opportunistic science: Comet-Interceptor, Theseus

Multi-spacecraft missions: HERA, Comet-Interceptor, Ramses



Small-body missions to unexplored bodies: HERA, Comet-Interceptor, Ramses

Robotic missions with close proximity operations: ClearSpace-1, RISE



Aerobraking: EnVision

Interplanetary cruise with EP: M-Argo

Controlled de-orbitation: Copernicus HPCM

Review of enabling autonomy functions

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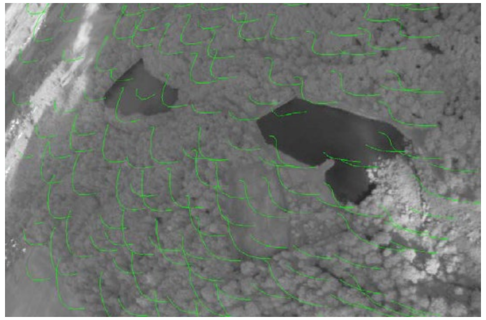
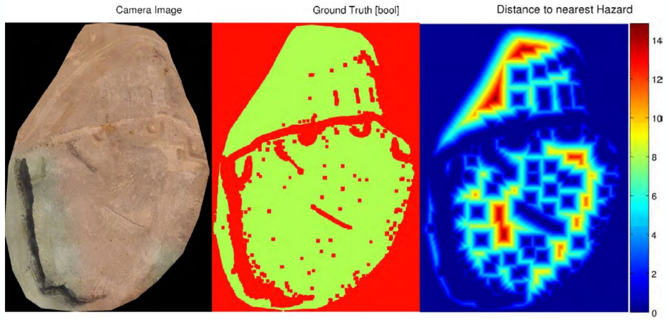
Absolute and relative navigation

Absolute and relative navigation (terrain-relative), HDA

Relative navigation and HDA state-of-the-art already at **high level of autonomy** based on past developments for Lunar Resource lander, NEXT Lunar Lander and PILOT, and current developments for Argonaut and corresponding preparatory activities (e.g. ANPLE, SAGE, ATB-MOON, GENEVIS, Advanced Navigation Techniques for Pinpoint Landing, VisNavEM, GENEVIS-2, …)

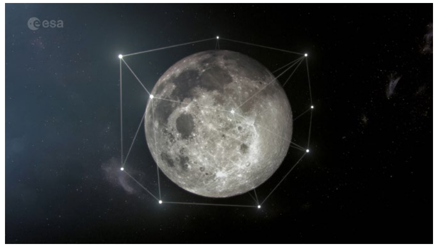




Absolute navigation needs initialization from ground and possibly monitoring from ground based on tracking to cross-check absolute navigation performance.

Feasibility of assisting initialization from ground investigated in co-sponsored PhD “Autonomous Optical Navigation and Orbit Estimation for Exploration Missions” (ESA/DLR co-sponsoring).

For Moon and Mars scenarios, **use of dedicated navigation aids** (e.g. Moonlight constellation) may lead to new navigation solutions, which could potentially also result in increased autonomy.



Review of enabling autonomy functions

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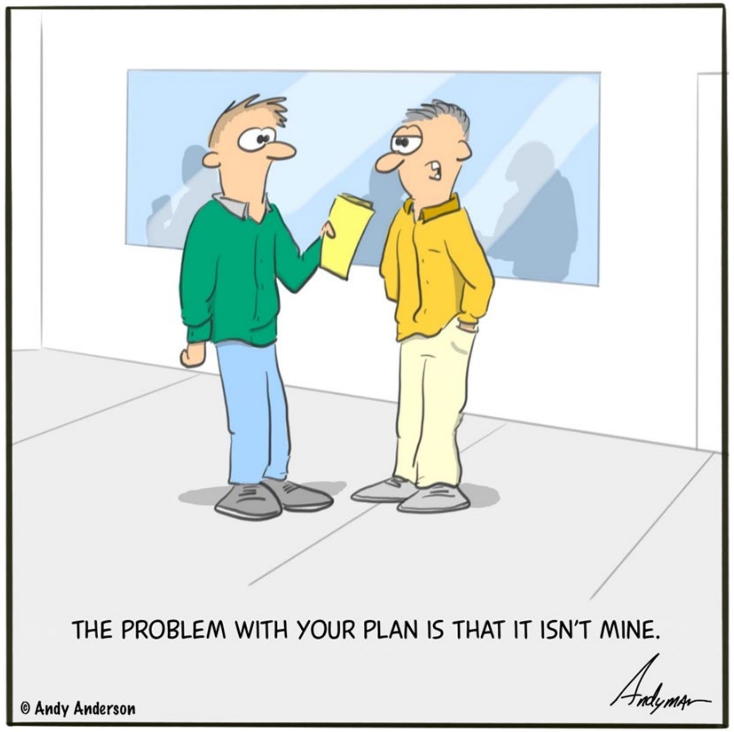
Autonomous planning / re-planning



Autonomous planning / re-planning (introduction)

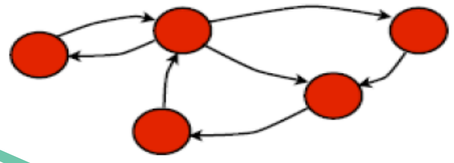
Multi-layered autonomous systems

1 – **supervisory layer** (networked architecture combining finite state machines with continuous dynamics)

2 – intermediate **optimisation layer generating the reference behavior** (e.g. trajectories, guidance) as triggered by the supervisory layer

3 – bottom layer executing **stabilization and reference tracking** according to inputs from the intermediate layer

Credits R. Murray: Optimization-Based Control

Level	Model	Specification
Decision-Making		$(\phi_{\text{init}} \wedge \Box\phi_{\text{env}}) \implies (\Box\phi_{\text{safe}} \wedge \Box\Diamond_{\leq T}\phi_{\text{live}})$
Optimization	$\dot{x} = f_\alpha(x,u)$ $g_\alpha(x,u,z) \leq 0$	$\min J = \int_0^T L_\alpha(x,u)\,dt + V(x(T))$
Regulation	$y = P_{yu}(s)\,u + P_{yd}(s)\,d$ $\lVert W(s)d(s) \rVert \leq 1$	$\lVert W_1 S + W_2 T \rVert_\infty < \gamma$

Classical AOCS/GNC regulation

Tactical autonomy, based on complex dynamical models, reactivity and fast execution

Strategic autonomy, based on macroscopic abstract models, slow execution, could need MIP

Autonomous planning / re-planning (introduction)

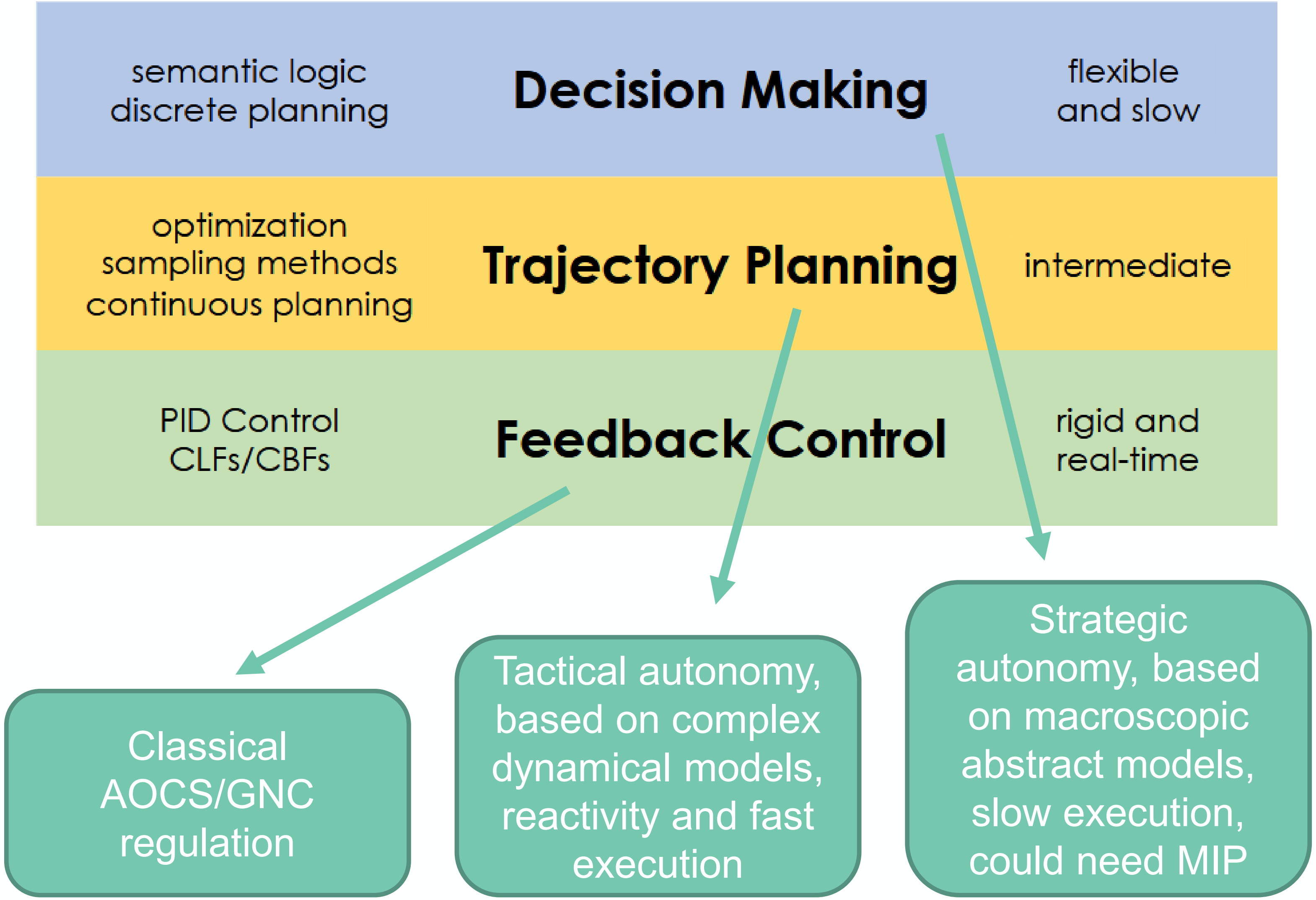
Multi-layered autonomous systems

1 – **supervisory layer** (networked architecture combining finite state machines with continuous dynamics)

2 – intermediate **optimisation layer generating the reference behavior** (e.g. trajectories, guidance) as triggered by the supervisory layer

3 – bottom layer executing **stabilization and reference tracking** according to inputs from the intermediate layer

Credits N. Matni et al.: Towards a Theory of Control Architecture



Autonomous planning / re-planning (enablers)

Enablers (not exhaustive)

1 – In supervisory layer

- Reduced order models for long-term planning

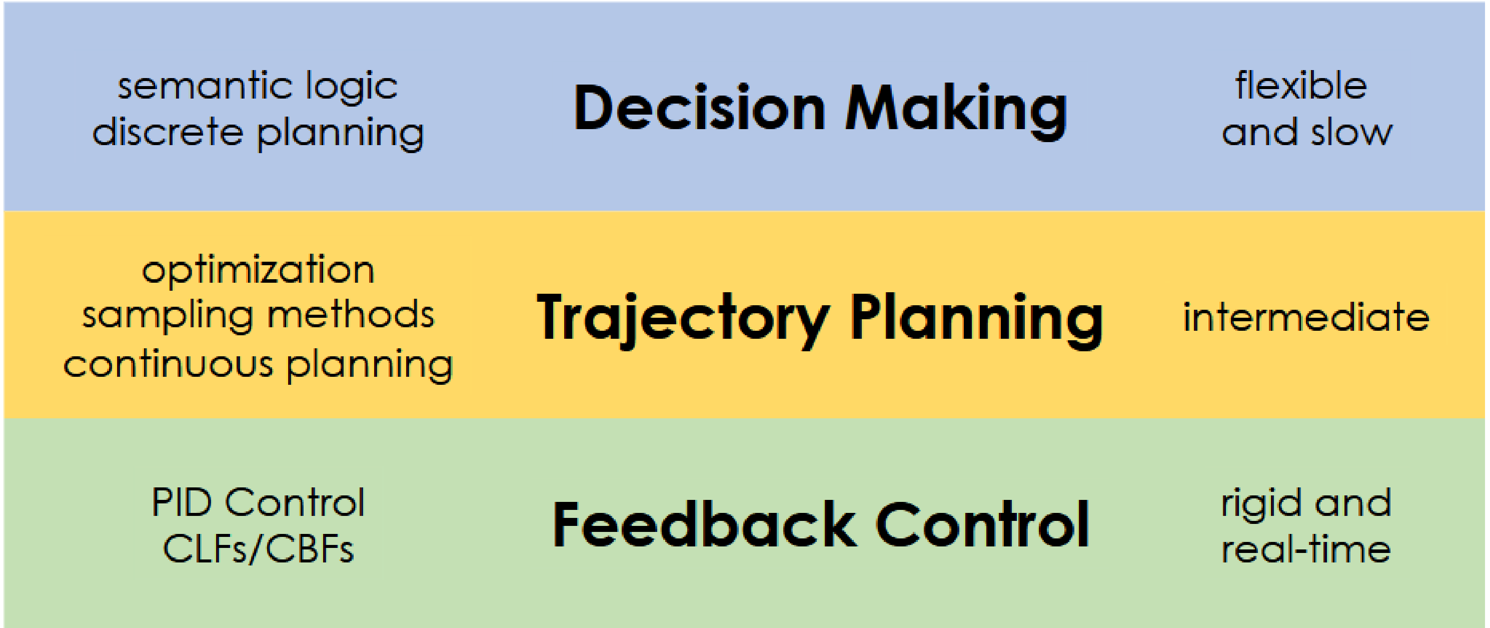
2 – In intermediate optimisation layer

- Robust Differential Dynamic Programming (Robust DDP)
- Fault-tolerant control
- (Data-learning) MPC
- Control Barrier Functions (CBFs) – discrete

3 – In regulation layer:

- Control Barrier Functions (CBFs) – continuous
- On-line SysID

Credits N. Matni et al.: Towards a Theory of Control Architecture



Key observation: **global GNC performance can be improved by synergistically leveraging the strengths at each layer!**

Autonomous planning / re-planning in EDL

In context of Moon and planetary EDL, strategic planning is **limited today to pre-allocated divert manoeuvres**.

In the future, **autonomous divert** can be based on on-board evaluation of HDA output, resource monitoring, FDIR state, etc.

For the current Moon missions (Argonaut), priority is on securing basic divert capabilities (low autonomy).

Building blocks for higher autonomy are being developed in the context of MEDAL and reusable launchers.

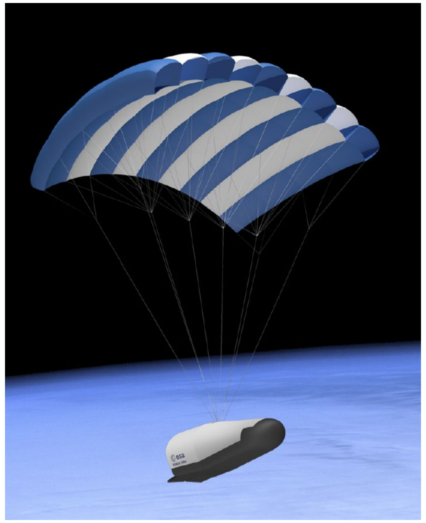
Autonomous planning functional architectures is provided by the **Mission Vehicle Management (MVM) function** developed as supervisory layer, relying on reduced-order models, composed of:

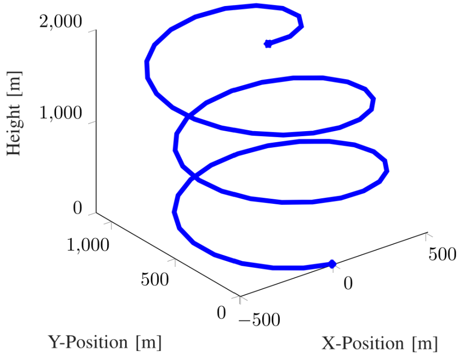
- **Flight mode selector**, in charge of tracking and regulating the transitions between flight phases, and driving the configuration of other MVM functions and lower layers (Guidance & Control)
- **Target manager**, in charge of providing boundary conditions for real-time optimisation / re-optimisation during flight
- **Exception manager**, in charge of handling off-nominal conditions, including not only failures but also loss of performance or to recover from unforeseen dynamics (e.g. larger than expected external disturbances)

Robust DDP as enabler for autonomous planning / re-planning in EDL (and space transportation)

"Artificial Intelligence Techniques for GNC Design, Implementation and Verification" activity completed in 2023:

- A **robust differential dynamic programming (DDP)** approach jointly optimizes both reference trajectories and tracking controllers, aiming to reduce sensitivity to model uncertainties and enhance overall system robustness and performance.
- **Robust trajectory planning**: the proposed method generates trajectories that actively avoid regions of high uncertainty in the state space.
- The robust trajectories autonomously implement energy management strategies, such as spiraling over a landing point to dissipate excess altitude (**implicit TAEM**)
- Benchmarking of the Robust DDP method against nominal (non-robust) trajectories underscores the **superior landing accuracy and robustness** of Robust DDP, particularly in the presence of model uncertainties





(Data-learning) MPC as enabler for autonomous planning / re-planning in EDL (and space transportation)

"**Data learning model predictive control**" activity in ESA GSTP Compendium 2026-28:

- Context: **Model Predictive Control (MPC)** enhanced by data-learning techniques (e.g., Gaussian Process-based MPC or reinforcement learning) shows promise for space applications where simple parametric models are insufficient to meet requirements.
- Relevance: Particularly useful for scenarios like highly flexible dynamics, sloshing effects, atmospheric effects during landing, or in-orbit servicing/manufacturing.
- Current State: Prototypes exist, but implementation and validation on space hardware are needed.
- Objective: Develop a data-learning MPC (e.g., Gaussian Process-based MPC or reinforcement learning) based on **on-board training of predictive models**.
- Challenge: **Key importance of capturing uncertainty in these predictive models** just like we use uncertainties (covariances) on physics-based parametric models.
- Adoption: Ensure compatibility with automatic code generation and real-time performance on flight HW

Fault-tolerant control as enabler for autonomous planning / re-planning in EDL (and space transportation)

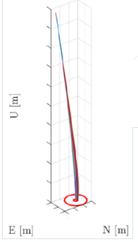
“**Fault-tolerant control of clusters of rocket engines**” activity completed in 2023:

- Designed and verified G&C laws for a reusable first stage with a cluster of engines, for the ascent, propelled re-entry flight and landing burn.
- Application of **successive convexification** to create a 6-DoF trajectory optimizer algorithm, for re-entry and landing burn trajectory optimization.
- Development of recovery functions, such as **dynamic thrust allocation, fault-tolerant control and controller reconfiguration**, and characterization of application domains of each function.
- Definition of **fault-tolerant G&C functions** for the most common launcher failures, considering numerical efficiency, convergence, and scalability.

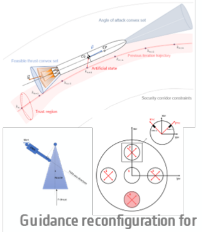
“**Maturation of onboard fault-tolerant control techniques**” in GSTP Compendium 2026-28:

- Develop fault-tolerant control techniques that can seamlessly employ actuators of potentially very different types and characteristics (e.g. multiple thrusters and aerodynamic surfaces on a launcher or re-entry vehicle).

Mission phases for ascent and descent



Landing trajectories under engine failure


Guidance reconfiguration for a cluster of 5 engines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GSTP Element 1
Develop
Compendia 2026 - 2028

Generic Technologies
Artificial Intelligence
Quantum Technologies
Innovative Propulsion
Sustainable Space
(Cyber)security
Serialisation (Standardised Sub-Systems)
Technologies for VLEO (Very Low Earth Orbit)

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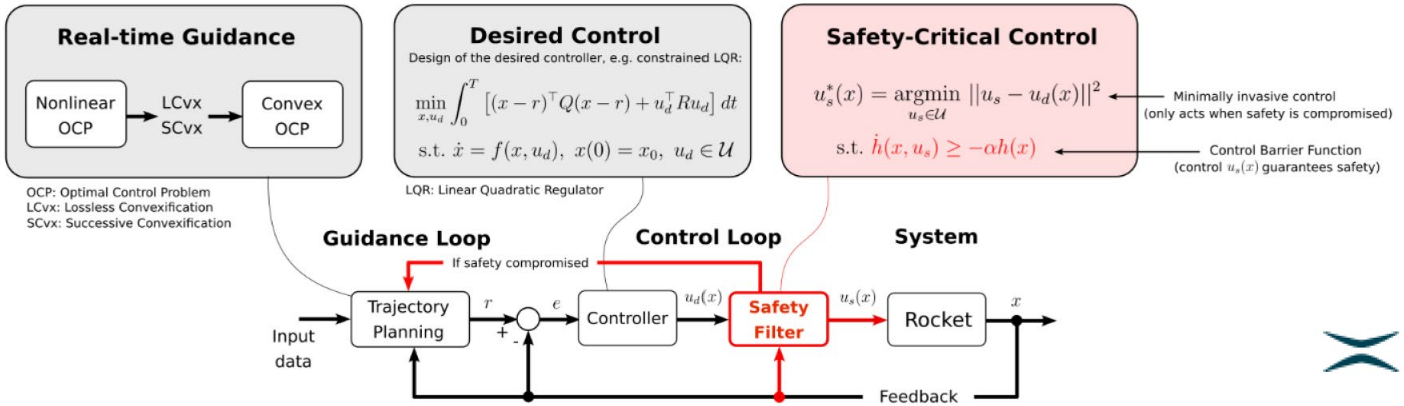
CBFs as enabler for autonomous planning / re-planning in EDL (and space transportation)

“Smart Launcher - Autonomous MVM and Monitoring Systems for Safe and Adaptable GNC Systems” activity completed in 2025:

- **Shift Authority to Control Loop**: Integrating CBFs reduces the guidance loop’s burden by giving the controller more authority, especially in fault-tolerant scenarios.
- **Reduce Guidance Complexity**: Transfers responsibility from guidance to control, minimizing design and verification efforts for guidance algorithms and cutting missionization costs.
- **Expand Flight Capabilities**: Enables broader flight envelopes and landing conditions, increasing launch windows and **improving mission flexibility**.
- Enhance Robustness & Safety: Provides **stronger robustness and safety guarantees** for rocket landing operations, even amid environmental and system uncertainties.



On-line system-identification as enabler for autonomous planning / re-planning in ISAM

"**On-board System Identification for Uncertainty Modelling and Characterisation**" activity completed in 2023:

- Addressing an in-orbit servicing scenario, achieved identification of inertia parameters of a satellite base and of its manipulator appendages, of the modal parameters of flexible appendages, and of the sloshing parameters for the fuel tanks, despite unmeasurable states and significant measurement noise.

"**Real-time system identification for complex system modelling and autonomy operations**" completed in 2026:

- Detailed design and development of SAGE, a toolbox allowing sparse identification of nonlinear dynamics (SINDy), alongside a baseline Extended Kalman Filter
- Validation done on 2 use cases (propellant sloshing and nonlinear SADM disturbance) using simulated data, and also flight data from Airbus' fleet
- Embeddability ensured through a Processor in the Loop (PIL) test on a LEON4 target

"**Orbital Maneuvering Enabled by Gauging Aggregate properties (OMEGA)**" kicked-off in 2026:

- Objective of this activity is to develop robust time-varying guidance and control algorithms for in-orbit servicing & assembly using model-based and predictive dynamical models

Autonomous planning / re-planning for opportunistic science

Existing flight experience in US with "**Autonomous Sciencecraft Experiment**" on Earth Observing-1 (EO-1), enabling the spacecraft to **autonomously detect dynamic science events** (e.g. volcanic eruptions, flooding, ice break-up, etc.) by several autonomy components:

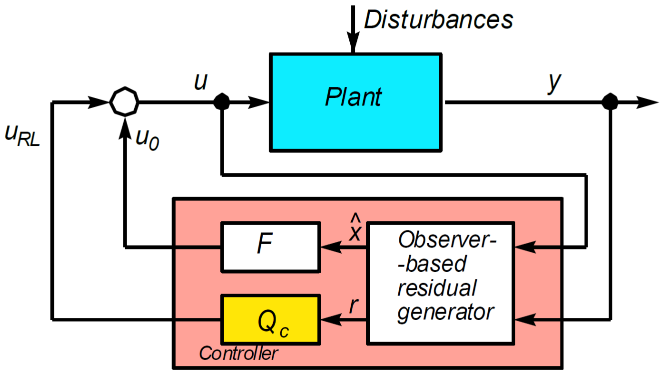
- **On-board science processing algorithms**, processing on-board payload data to detect science events
- **On-board planning and scheduling software**, providing response actions in different operational scenarios based on models of spacecraft constraints
- **Executive software**, generating detailed commanding sequences

Autonomous mission planning / re-planning

Several past and on-going studies are **looking into model-based as well as model-free techniques** as means to provide autonomous on-board planning and execution capabilities for spacecraft:

- **Markov Decision Processes**
- **Approximate Dynamic Programming**
- **Q-learning**

Potential to address planning and execution problems that satisfy temporal logic specifications, e.g. using Q-learning preliminarily investigated in technology studies with wide scope ("**Artificial Intelligence Techniques for GNC Design, Implementation and Verification**")



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TRL still low: **gap to be closed in Europe!**

Layered MVM as enabler for autonomous planning / re-planning in ISAM

“**Layered mission-vehicle management for autonomy enhancement of rendezvous and proximity operations**” activity in ESA GSTP Compendium 2026-28:

- **Autonomous vehicle management** is believed to be a key functionality in future rendezvous and proximity operations to ensure **fast reactivity in the event of non-nominal conditions and to relieve ground from the intensive monitoring** of possibly a large number of spacecrafts in operation.
- In order to achieve this goal, it is essential to achieve a **higher integration of spacecraft functions**, and especially of the various decision layers (i.e. lower level control tasks such as attitude control or thermal control, mid-level planning tasks, such as path planning or trajectory guidance, and higher level management of on-board resources including the system FDIR) that execute the mission plan.
- The goal is to **combine the two domains of mission and path planning with collision risk assessment and anomaly detection** to achieve a versatile mission and ensure a seamless continuation in the event of failures


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Date of issue: 19/09/2025 Issue: 1 Revision: 0

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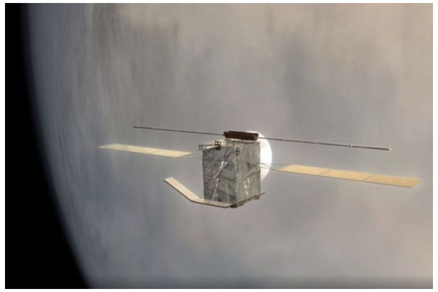
Autonomous planning / re-planning for aerobraking

State-of-the-art **semi-autonomous techniques** for aerobraking (e.g. Pericentre Time Estimator – PTE) add mission robustness but **ground segment's effort** for planning, commanding and monitoring aerobraking operations remains high (TGO experience).

Means to increase autonomy horizon and decrease operational workload investigated in technology activities with EnVision as target mission.



Main conclusions:

- **Mixed (predictive-reactive) corridor control strategy** using surrogate variables for decision making
- Weight on prediction or reaction could be **adapted based on level of confidence on atmospheric model**
- Autonomy functions (performing **navigation updates on-board for all orbital parameters** – enhanced PTE - **and for time of the next pericenter**, carrying out **autonomous corridor control** and manoeuvers to maintain the pericenter altitude within a pre-defined range and generating **on-board TC sequences** to complete the aerobraking operations during the autonomy target) allow an **autonomy horizon of 7 to 9 days**
- Reduction in deltaV and/or aerobraking duration enabled

Review of enabling autonomy functions

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AI / machine learning

"We've got a problem. I've turned it on
but I can't turn it off again."

Autonomy and AI / machine learning: current vision at ESA

AUTONOMY ≠ AI

AUTONOMY ≠ MACHINE LEARNING

- The foundation of **GNC** systems has **traditionally relied on model-based techniques**, which in turn, have their foundations on a solid body of **mathematical proofs** (guarantees of stability, robustness, etc.)
- The emergence of **data-driven techniques** (broadly speaking grouped under the name Machine Learning or even more generally AI) represents an **alternative paradigm, with high potential** in cases where traditional methods are less effective
- AI has the potential to **complement** traditional model-based techniques with data-driven methods, to **enhance the robustness and performance** of GNC, **mainly for those problems/applications** that are affected by **large uncertainties (e.g. uncertain dynamics)** or **even lack of mathematical models** that are a challenge for the traditional GNC design/verification techniques.

Data-driven techniques complementary to model-based ones

Autonomy and machine learning - What we learned so far: main outcomes from completed activities

Main outcomes from completed activities:

- Consider machine learning **only where it brings an added value compared to the state-of-the-art** (e.g., either better performance or more flexibility/adaptation, etc.)
- Integration of **machine learning into GNC systems to be based on hybridization** with existing solutions (as opposed to fully AI-based GNC)
- **High potential for application of machine learning to image processing applications**
- **Interest in machine learning for modelling/system identification** (especially for highly uncertain systems)
- **In the long term, on-board training will be an enabler for adaptability to new/unknown environments** (calls for new techniques not explored so far for on-board use)

Issues for deployment of machine learning into mission-critical systems:

- **Explainability/verifiability** (including metrics to specify performance/robustness) at different levels, based on ad-hoc validation and qualification processes:
    - Hard problem, probably breakthroughs will be in automotive/civil aviation and space will follow
    - The scalability of proposed methods is still to be demonstrated
- **Ensuring safety and FDIR management for AI-based GNC systems**
- Public availability of (labelled/unlabelled) **data for training**

Autonomy and machine learning - Short-term needs and recommendations

Short-term needs for maturation of integration of machine learning within GNC/AOCS systems:

- **Validation & verification**: develop tools and techniques as well as adapt the industrial V&V process to account for machine learning elements within the GNC systems architecture
- **Fault-detection, Isolation, and Recovery**: GNC FDIR enhancement (fast reaction times, fail-safe/fail-ops strategies, impacts on system availability, etc.)
- Use of **machine learning techniques for design and tuning of control systems**
- **Robustification of image processing techniques**
- **Leverage machine learning methods** (e.g. guided policy search and imitation learning) **to ensure computational efficiency and to enable enhanced performance of real-time optimal control methods**
- Assess data-driven techniques for **on-ground and on-board system identification**
- Assess **deployment of machine learning to enhance platform autonomy**

Recommendations:

- **In-orbit experiment** recommended to accelerate adoption (more than for other technologies)
- **Find synergies across applications and domains** (e.g. AI applied to image processing for navigation/optical payloads or for automotive)

Review of enabling autonomy functions

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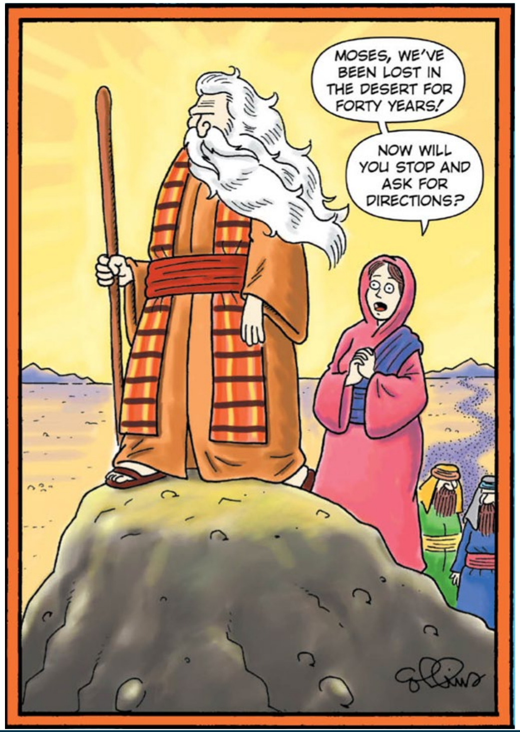
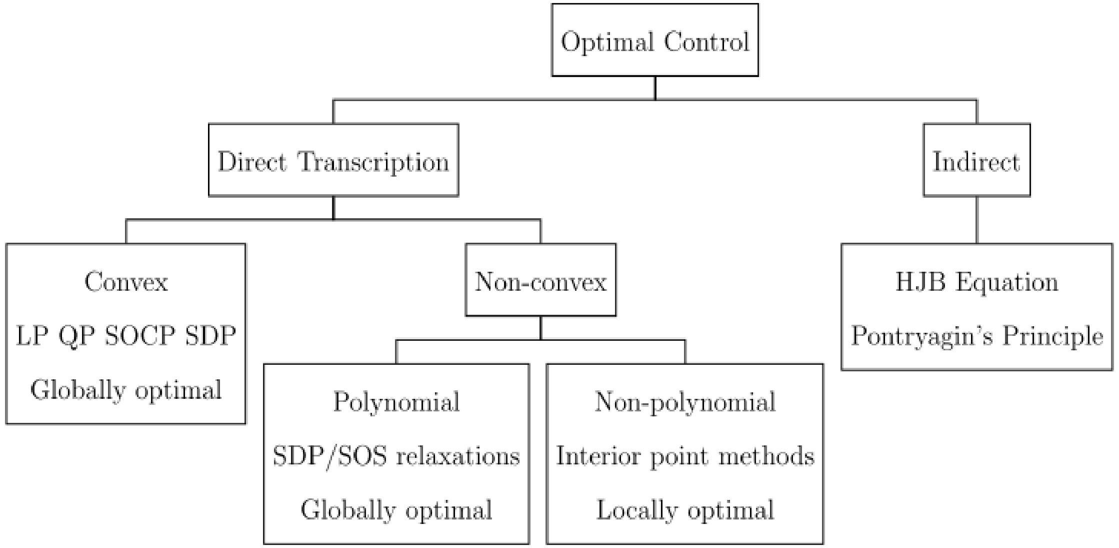
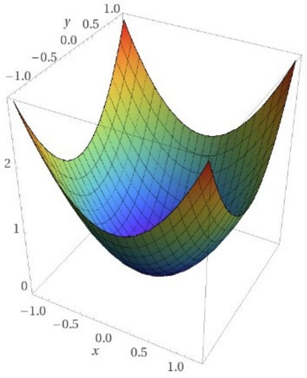
Real-time guidance



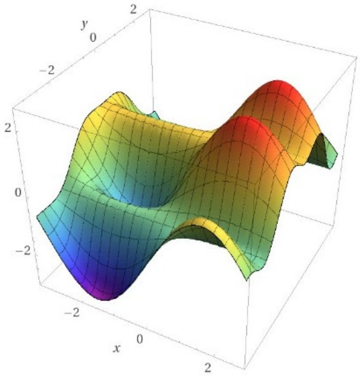
Real-time guidance - introduction (1/2)

Trajectory optimisation problems that arise in the context of EDL (and re-usable rockets) can be cast as **optimal control problems** and solved by direct transcription or indirect methods.



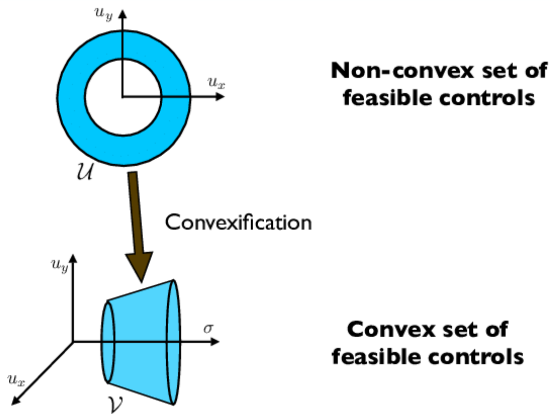


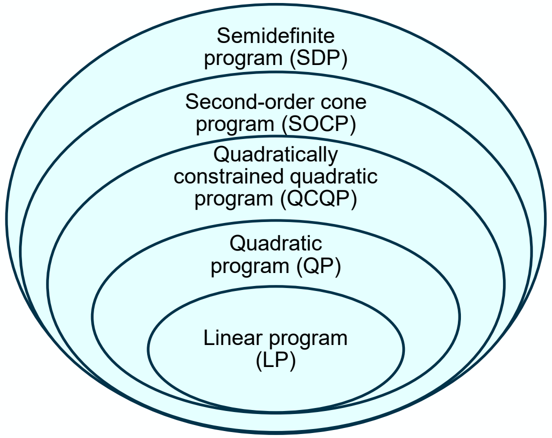
Convex optimisation algorithms are numerically solid thanks to the convexity properties that they exploit and can achieve real time performance.

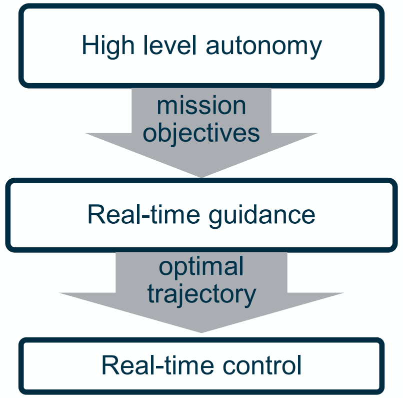


Real-time guidance - introduction (2/2)

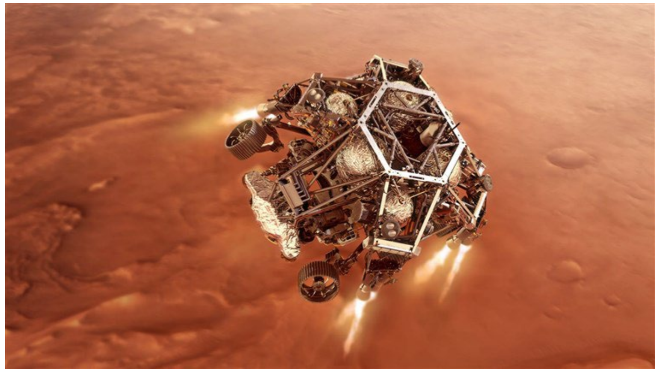
Even in presence of significant constraints in the optimisation problem that make the problem non-convex, **convexification techniques** can be used to convert the original non-convex formulation in a type of convex optimisation problem







Concept flight proven in NASA Mars landers and SpaceX rocket stage landings



Real-time guidance - applications

Application	Completed/on-going developments at ESA	Notes
Planetary or Moon landing	2 large (> 1 Meuro) parallel contracts for GNC TRL maturation in the frame of Argonaut	One of the 2 parallel activities favoured a solution with pre-computed trajectories, the other favoured a complete on-board re-optimisation
Reusable rocket stages	Studies funded by TDE (Technology Development Element) and FLPP (Future Launchers Preparatory Programme)	Close cooperation with demonstration platforms developments DTV and ADAMP, which will be used to de-risk real-time guidance technology Several other similar efforts in Europe under H2020 or other programmes
Rendezvous & proximity operations (including robotic manipulation)	Study funded by GSTP (General Support Technology Programme)	
Low-thrust trajectory	Study funded by GSTP (General Support Technology Programme)	Addressing low-thrust Earth-Moon transfer scenario. Study concluded in 2020
Attitude guidance & control	Study funded by TDE (Technology Development Element)	Addressing the Comet-Interceptor and THESEUS scenarios
Descent and landing using parafoil	Study funded by GSTP (General Support Technology Programme)	Application to Space Rider project

Aiding adoption: the V&V question

Adoption of real-time guidance in safety-critical and mission-critical systems requires **increasing the trust** in optimisation-based guidance and control software, through sound verification and validation procedures.

"**Verification and validation of real-time optimised safety-critical GNC SW systems**" completed in 2024:

- Informed by **formal verification methods** and resulting in a **mixed testing-proof approach**, **guidelines for V&V were defined**.
- The use of a **clear mapping** from high-level requirements to optimisation elements (cost function, constraints) **transfers the burden of verification** to the verification of the **underlying optimisation solver**.
- This last step is achieved starting with a formal review of the algorithm description and mathematical specifications, which feed the creation of a new set of requirements that can be enforced through review, executable formal specification, and formal proof
- This V&V approach was employed using Frama-C on a toy optimisation problem, and at MIL-SIL-PIL level in MATLAB/Simulink on a set of benchmark problems

Aiding adoption: white-box efficient solvers

Adoption of real-time guidance in safety-critical and mission-critical systems hinges on **efficient solvers** that are fully white-box in nature.

"**Efficient embedded solver for optimal guidance and control on spacecraft processors**" in ESA GSTP Compendium 2026-28:

- Deploying optimisation-based guidance and control algorithms directly onboard spacecraft is limited by existing solvers, which are often not designed with the limited hardware resources of spacecraft in mind, leading to **challenges in meeting real-time performance and robustness**.
- The activity will develop a modular software package to allow users to quickly specify the constraints and objectives for their particular use case and **ensure that their structure (e.g., sparsity, constraint types, and discretization) is aligned with the** capabilities of the targeted **solver** implementation.
- The tool will leverage modern optimization toolchains that support symbolic modelling, automatic differentiation, and efficient code generation.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Compendia 2026 - 2028

Generic Technologies
Artificial Intelligence
Quantum Technologies
Innovative Propulsion
Sustainable Space
(Cyber)security
Serialisation (Standardised Sub-Systems)
Technologies for VLEO (Very Low Earth Orbit)

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→ THE EUROPEAN SPACE AGENCY

Review of enabling autonomy functions

-

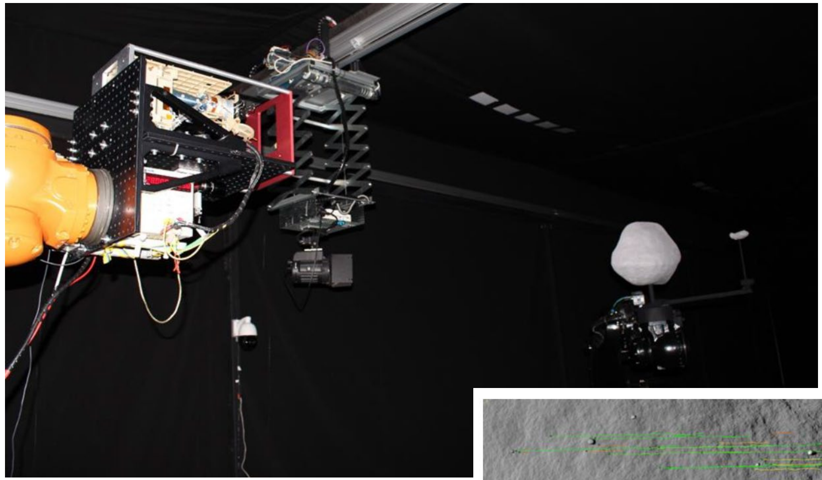
Autonomous navigation: vision-based, multispectral, and event-based

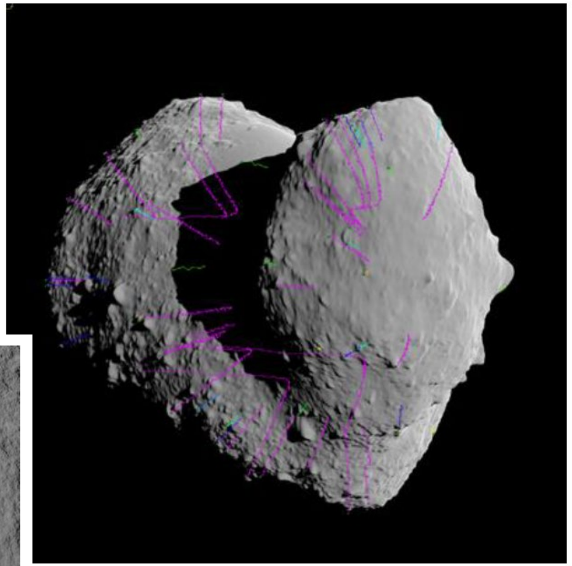
"What traffic lights, officer?"

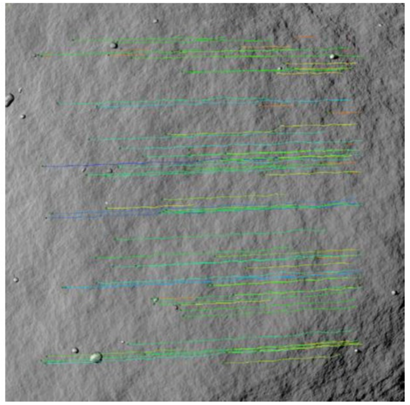
Autonomous navigation – vision-based

Autonomous vision-based navigation capability being deployed in several ESA projects:

- JUICE
- HERA
- Comet-Interceptor
- Argonaut
- L4 Enceladus mission
- ClearSpace-1
- RISE
- ELSA-M
- Several Cubesat initiatives (e.Inspector, M-ARGO, etc.)





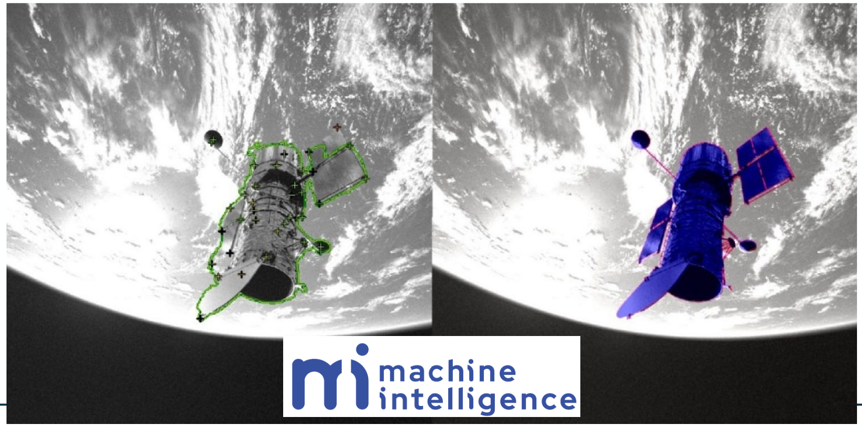


Challenges remain to optimize solutions in area of image-processing, navigation filters, data fusion, avionics architectures, verification & validation, interface with ground-based navigation, how to phase in the autonomous navigation, etc…

Autonomous navigation – robustness challenge in vision-based

"**Deep Neural Network for Robust Satellite Model Matching**" activity completed in 2025 (further work on-going):

- Developed a **deep learning-based onboard** system for real-time, robust satellite **pose estimation**, targeting applications like autonomous rendezvous, in-orbit servicing, and space debris removal.
- The development tackles key space-based vision **challenges**, including dynamic backgrounds, variable illumination, hardware limitations of space processors, and the scarcity of annotated real space imagery
- The technical approach is based on a **modular CNN architecture** with synthetic data generation (via Houdini and USD), **keypoint-based pose estimation**, and **semantic segmentation** to enable accurate, real-time pose estimation from monocular camera input.
- Performance Highlights: Achieves **sub-metric positional error and angular accuracy better than 1.5 deg**, with over 99% valid solutions in standard scenarios and real-time inference (up to 68.94 FPS) on embedded hardware like NVIDIA Jetson and HAILO



Autonomous navigation – multi-spectral navigation & event-based navigation

Several on-going and planned HW developments towards **multi-spectral navigation**, with inclusion of near-IR and/or thermal-IR channels together with visible spectrum, bring relaxation of illumination constraints and hence of operational constraints.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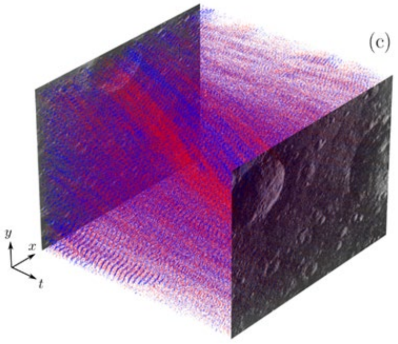
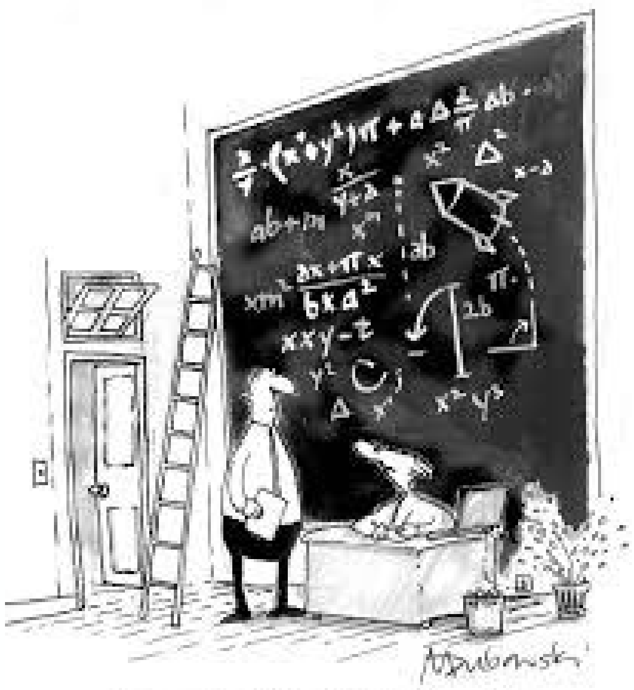
"Event-Based Vision for Advanced Navigation and Space Sustainability" in TDE Work Plan 2027:

- Traditional frame-based vision systems face **limitations** in space due to **motion blur, low dynamic range, and high latency**, particularly in scenarios with fast manoeuvres and extreme lighting.
- **Event cameras** provide **asynchronous, high-speed, and energy-efficient vision** capabilities, making them well-suited for space applications requiring precise and real-time perception.
- Objective to **develop and validate a modular perception stack** for event-based nav.



Examples of advanced autonomy deployment in ESA missions

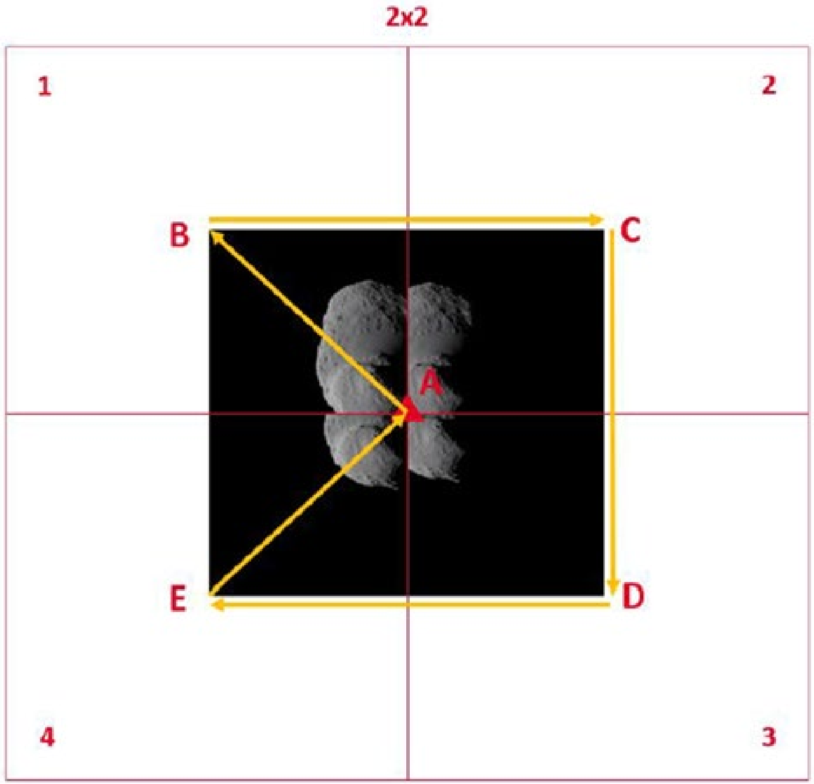


As a matter of fact, it IS rocket science.

Autonomous guidance on HERA

Different options available for **attitude guidance** during proximity operations

- Ground-based attitude profile (Chebyshev polynomials)
- Autonomous guidance
    - Point payload to asteroid using autonomous navigation and keep solar arrays perpendicular to Sun
    - Smooth transition towards ground profile for Earth comms
- MOSAIC: perform raster of images around estimated asteroid centre

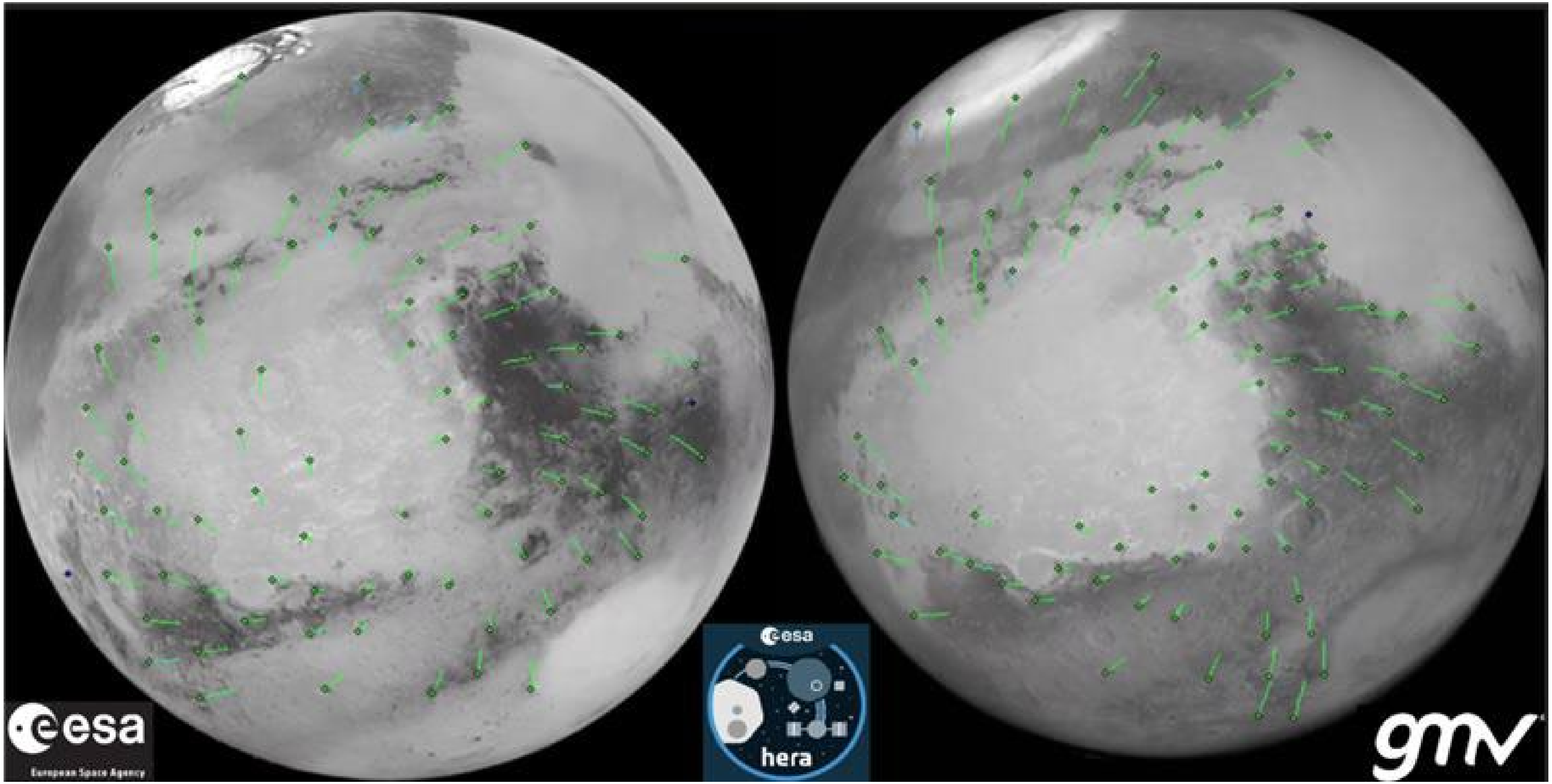


MOSAIC example
Credits GMV

Autonomous **translational guidance**

- Corrects ground-commanded delta-V based on autonomous navigation to minimize trajectory dispersion
- Extra trajectory correction maneuvers (nominally zero delta-V) introduced in arcs heavily perturbed

In-flight verification of unknown feature tracking at Mars



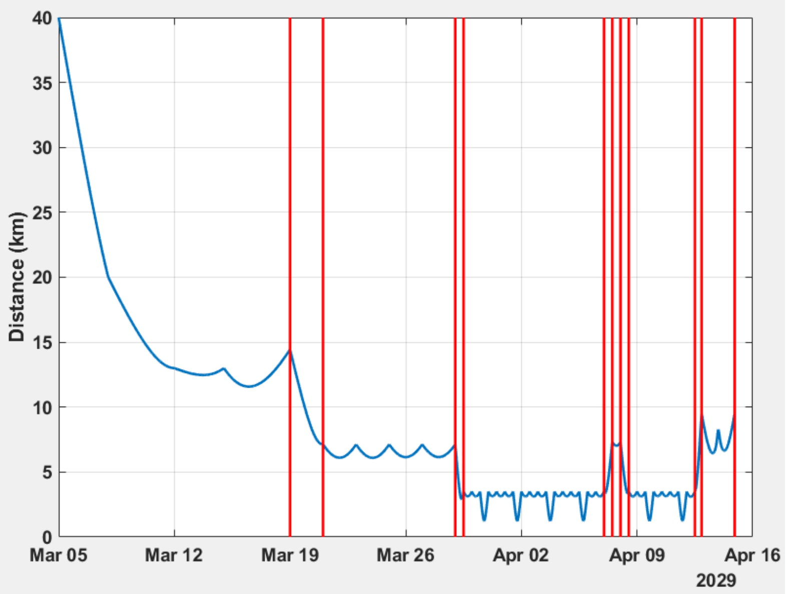
Autonomy requirements in RAMSES

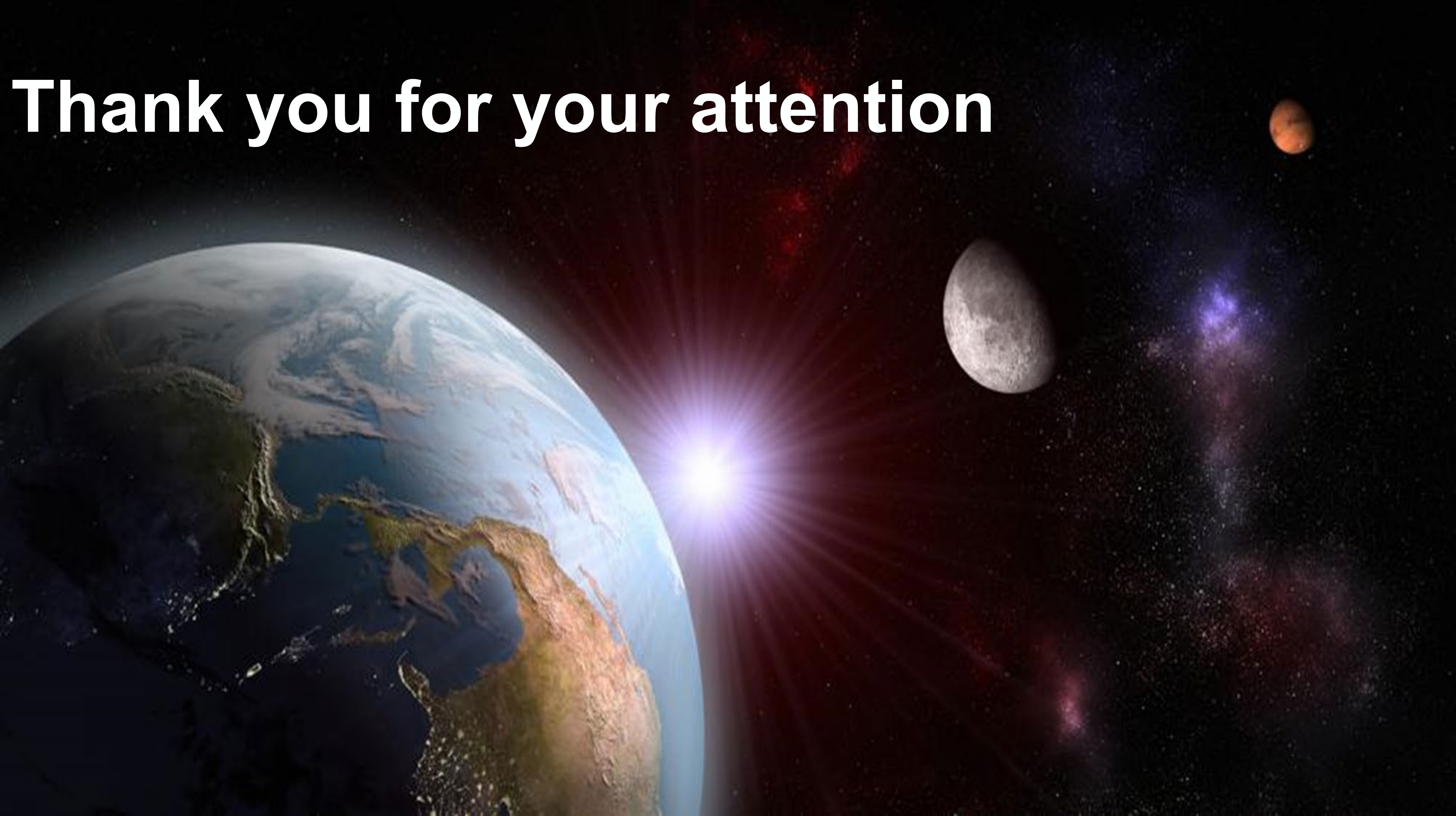
Autonomous attitude and translational navigation needed 1 week after arrival (assumes 1 week of commissioning while SC is ground controlled)

- **Very short time** from arrival to Apophis closest approach to Earth.
- Delta-V frequency too high to have ground in the loop

Relies on HERA autonomous technologies but **extended capabilities**

- **Autonomous solar array guidance** by default in all modes
- **Autonomous translational guidance** by default in all prox ops
- **Hovering** if altimeter working (no extra a priori ground information needed)




Thank you for your attention