Artificial Intelligence Tecnhologie at The Italian Space Agnecy

Artificial Intelligence

Speaker: Raffaele Votta– Italian Space Agency

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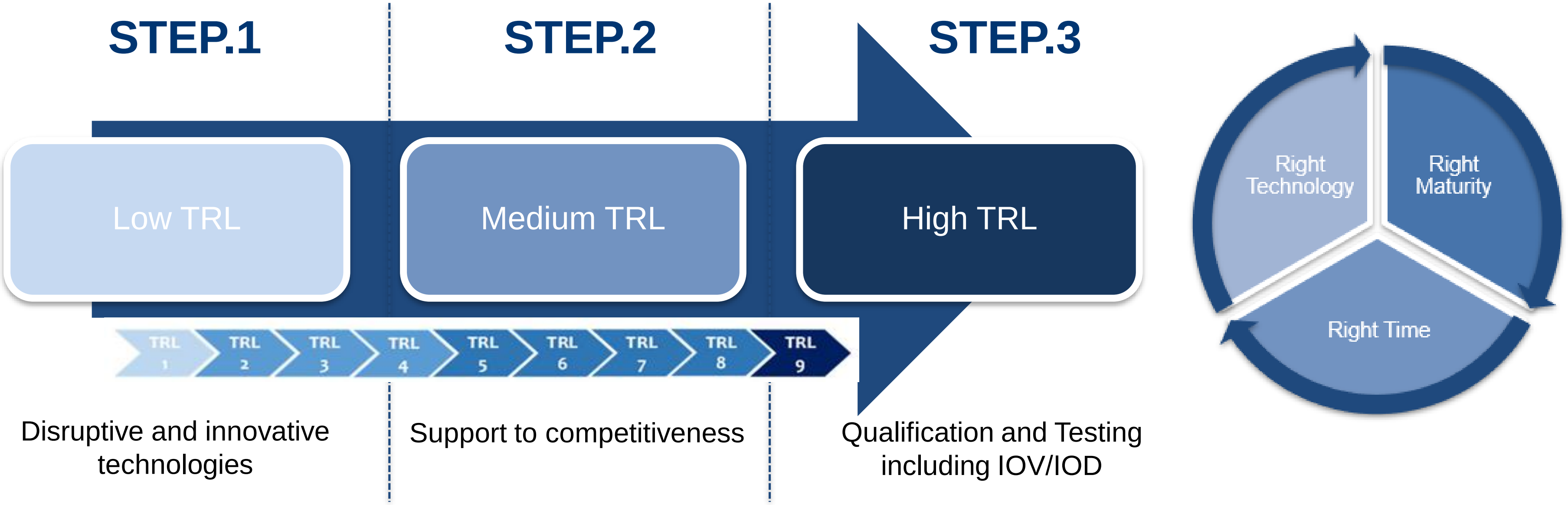
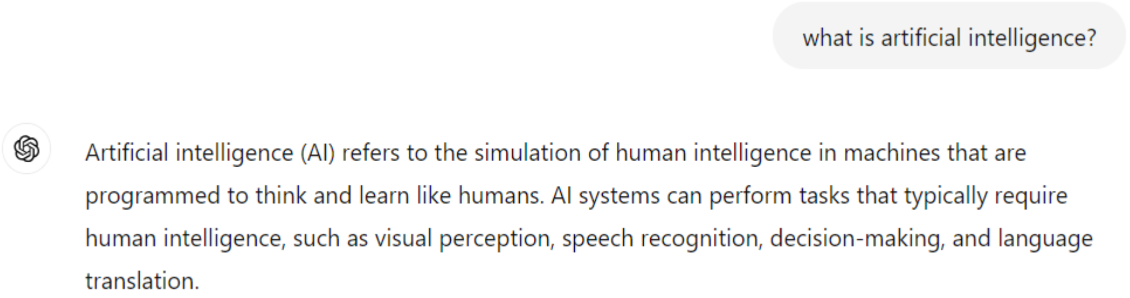
MULTI-STEP DEVELOPMENT



Artificial intelligence

What is artificial intelligence?

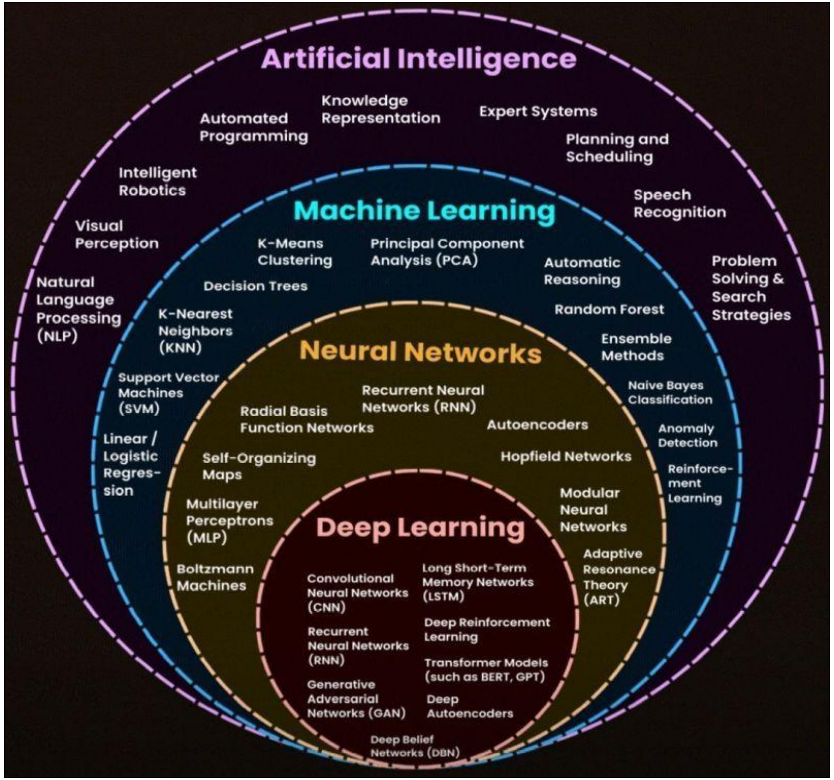


We are already beginning to see AI implemented into new space technologies. It is used to control large satellite constellations, to analyze the huge amounts of data that satellites collect, and to process data directly onboard satellites. **But there is potential to go further.**

Key words and concepts

- **Machine Learning (ML):** A subset of AI that involves training algorithms on data so they can learn and make decisions or predictions. Types of ML include:
  - **Supervised Learning**: The algorithm learns from labeled data.
  - **Unsupervised Learning**: The algorithm finds patterns in unlabeled data.
  - **Reinforcement Learning**: The algorithm learns by interacting with its environment and receiving rewards or penalties.
- **Natural Language Processing (NLP)**: A field of AI focused on the interaction between computers and humans through natural language. Examples include chatbots and language translation services.
- **Computer Vision**: This enables machines to interpret and make decisions based on visual data from the world. Applications include facial recognition and autonomous vehicles.
- **Robotics**: AI is used in robotics to enable robots to perform tasks autonomously or semi-autonomously.
- **Neural Networks**: A set of algorithms modeled loosely after the human brain that are designed to recognize patterns. They are the foundation for many ML models, particularly deep learning models.

Artificial Intelligence



Normative context

International level:

ISO/IEC 42001 / 2023 – International Standard for AI

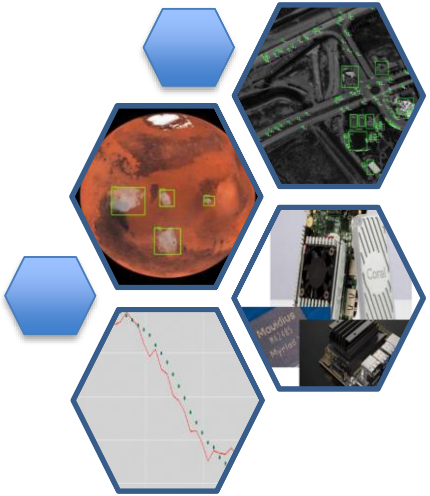
In Europe:

- **AI Act** approved by EU commission in march 2024
- **ECSS-E-HB-40** – guideline for the application of AI in space

Artificial Intelligence for space

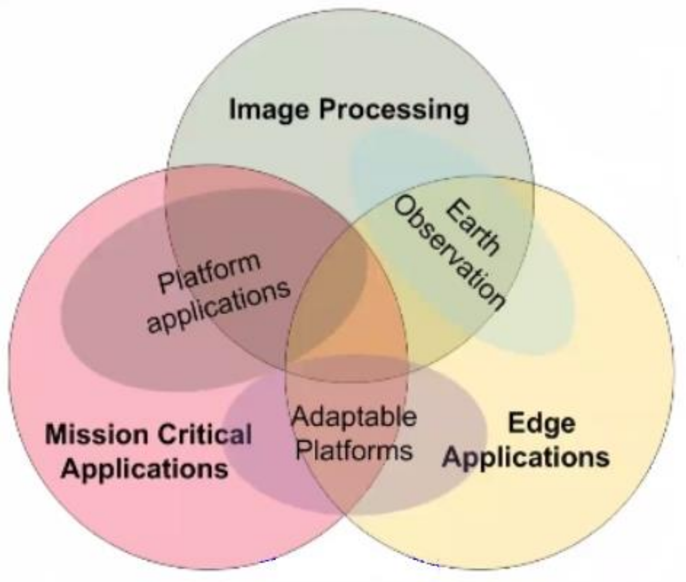
Many potential applications can benefit from AI capabilities at different levels:

- **Smart payload data:** on-board data processing
- **AI in operations:** reaction to failure, predictive maintenance, planning
- **Guidance Navigation and Control (GNC):** visual based navigation, in-orbit operations, autonomous exploration
- **AI in Data Exploitation:** features extraction, exploitation of scientific data, mining



AI represents a strong key enabling technology to increase autonomy in space missions

Artificial Intelligence for space



- **Debris removal, docking, In-orbit servicing**
  - Feature extraction
  - Identification vs. 3D mesh model
  - Obstacle avoidance
- **Landing, Robotic**
  - Camera/LIDAR processing
  - Identification of landing sites, craters, boulders
- **Payload Processing**
  - Cloud identification to increase compression
  - Vessel detection, identification of piratery
  - Open sea objects detection and monitoring
  - Identification of fast moving meteoroids
  - Fire/flares detection
- **Recofigurable platforms**
  - Autonomous failure prognostic and detection
  - Adapt platform to change in requirements of new standards
  - Autonomous safe mode management

Applications and current projects

On-board payload data processing

Failure Detection Isolation and Recovery

Advanced GNC

Robotics / Rovers

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On board data processing

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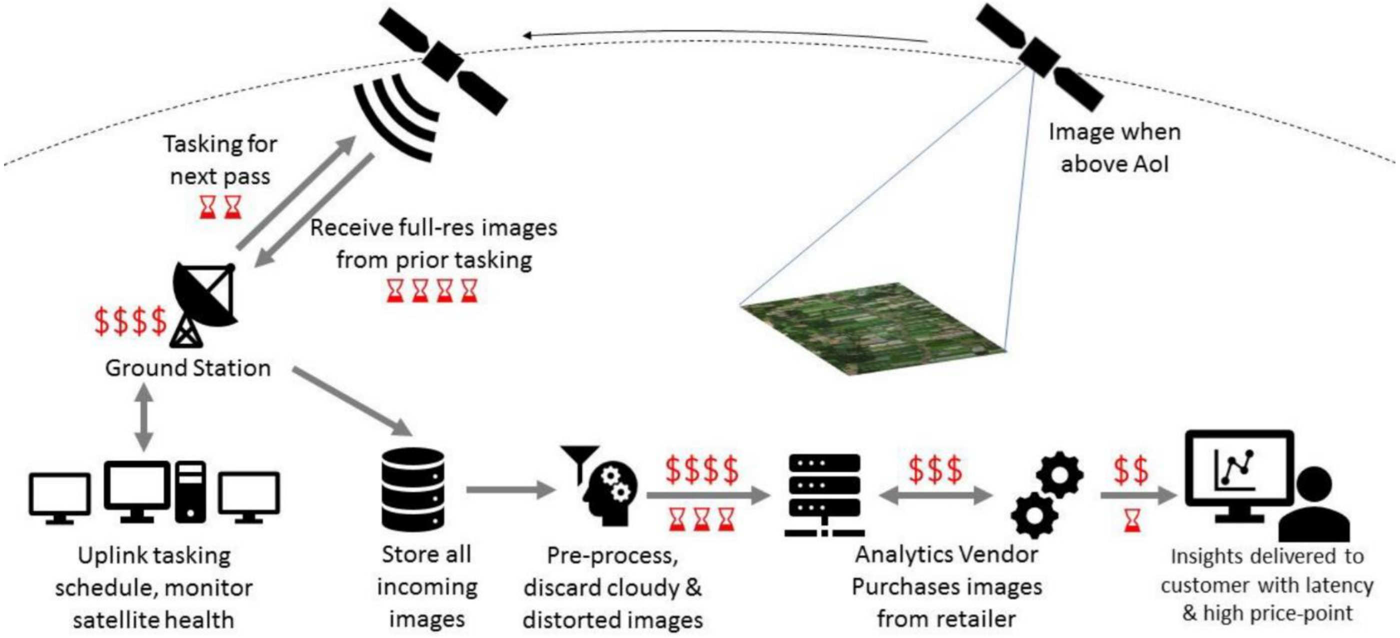
D-ORBIT NEW SPACE SOLUTIONS

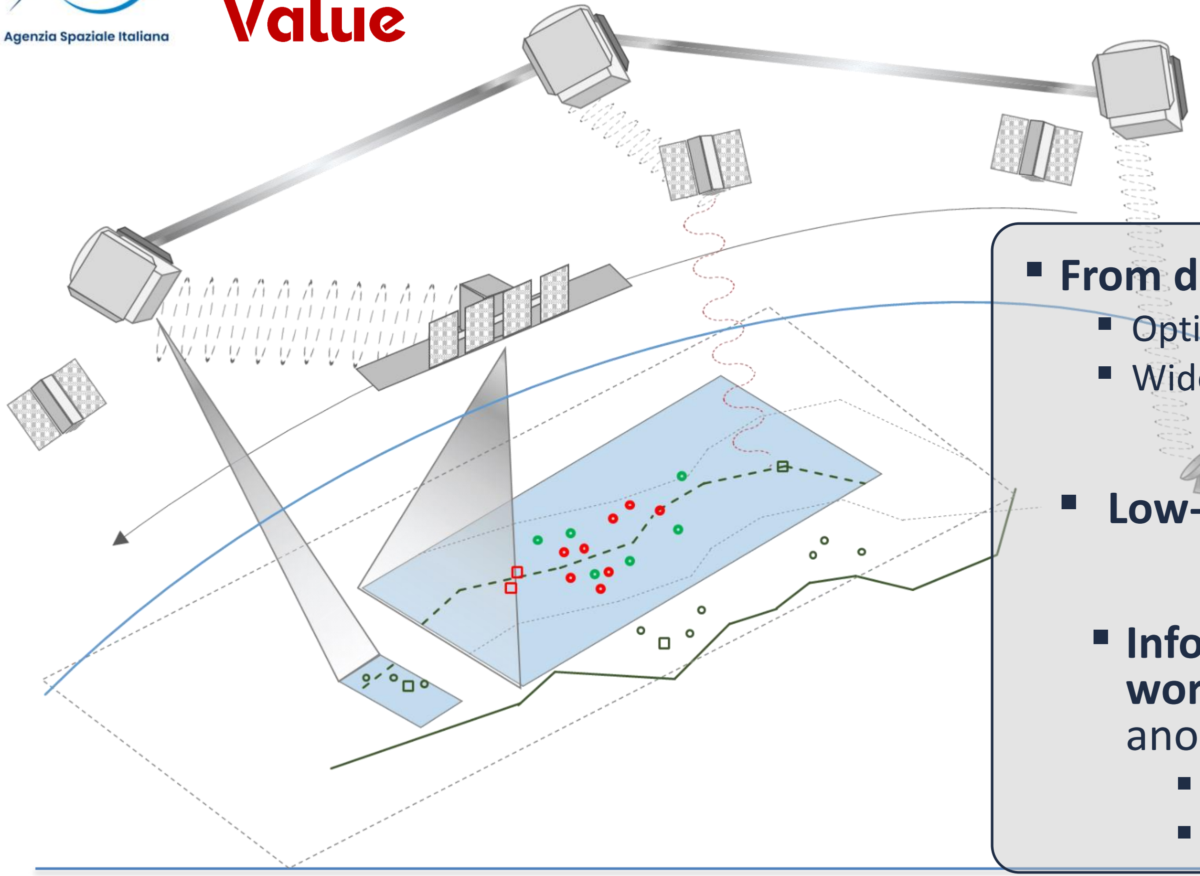
AIKO

EO Value Chain Today

This current model consists of ***multiple sequential activities, each adding costs and latency*** to servicing the needs of a customer.



3CS infrastructure: Improving Services' Key Value



- **From data to actionable** information
  - Optimization of the downlink channel usage
  - Wide area monitoring services
- **Low-latency alerting**
- **Information-driven autonomous workflow**: reaction to events or anomalies
  - sensors to sensor tasking
  - Multi-satellite coordinated acquisitions

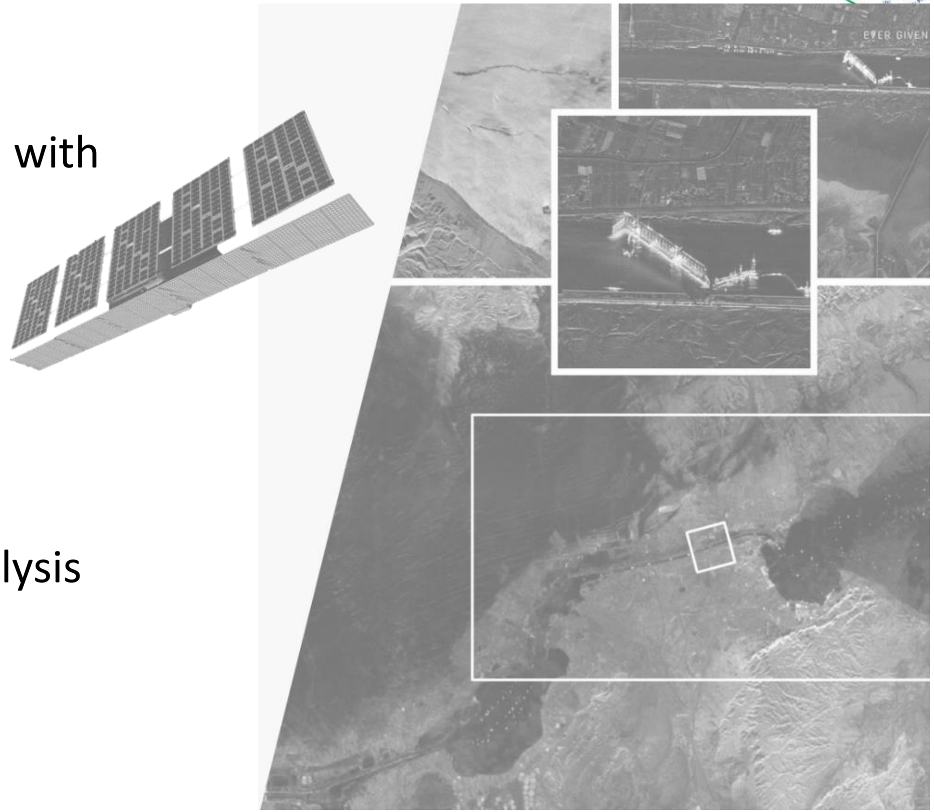
Observation node(s): EO

EO heterogeneous constellation equipped with

- Synthetic Aperture Radar and
- Optical sensors

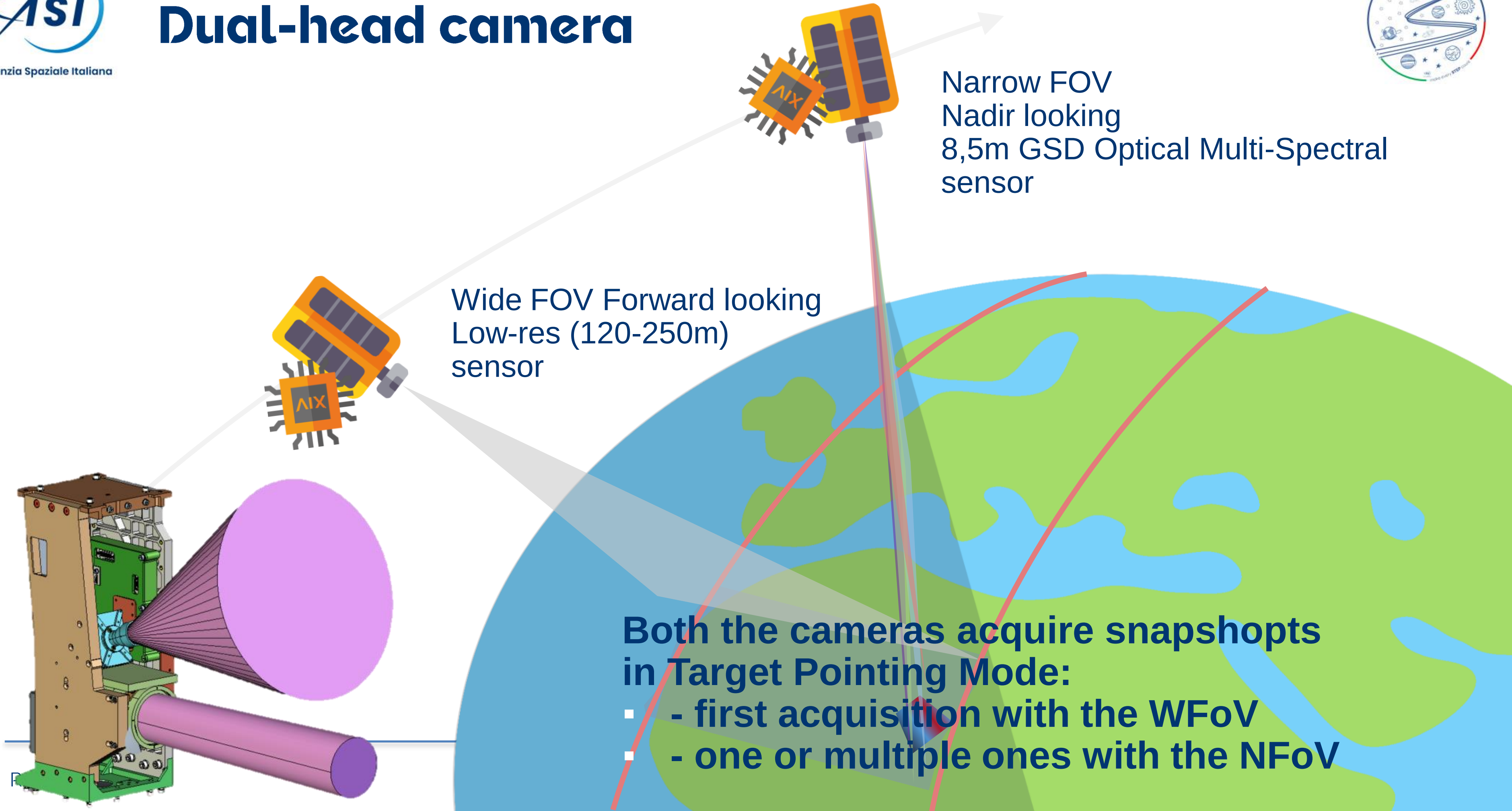
Provide data and actionable information

- Monitoring an area of interest or
- Reacting after a trigger for in-depth analysis



PoCs definition: a tip'n'cue scenario

Dual-head camera



Both the cameras acquire snapshopts in Target Pointing Mode:

- **- first acquisition with the WFoV**
- **- one or multiple ones with the NFoV**

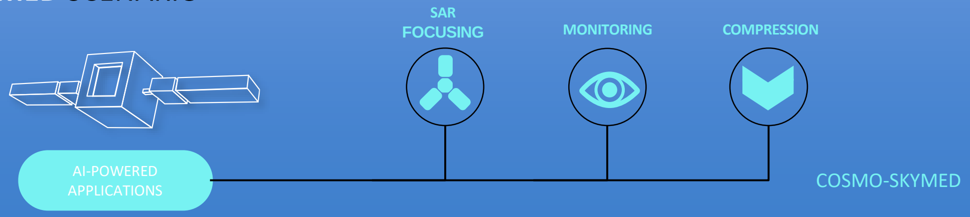
AISAR project

POWERED BY DESIGNED BY

AISAR

AIMS AND OBJECTIVES

- **TO PROVE FOCUSING CAPABILITIES ENABLING** REAL-TIME GROUND MONITORING.
- TO DEVELOP AN ON-BOARD **AI DATA COMPRESSION** PROTOTYPE – GEO-K
- TO ASSESS AI MODELS ON **REPRESENTATIVE HARDWARE**
- **COSMO-SKYMED** SCENARIO

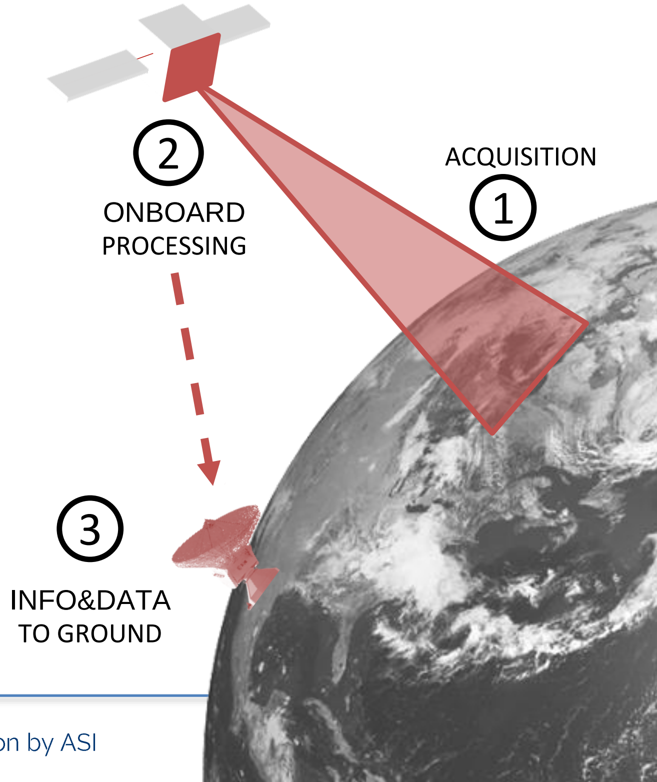


SAR with AI

+ **AI-Based Focusing**: Empowers efficient onboard SAR data processing, enabling satellites to operate with unprecedented autonomy and flexibility

+ **Real-Time Monitoring**: Leverages AI to enhance the accuracy and speed of surveillance, supporting new operational concepts

+ **Data Compression**: Addresses the critical challenge of data downlink bottlenecks, ensuring rapid and efficient data transmission



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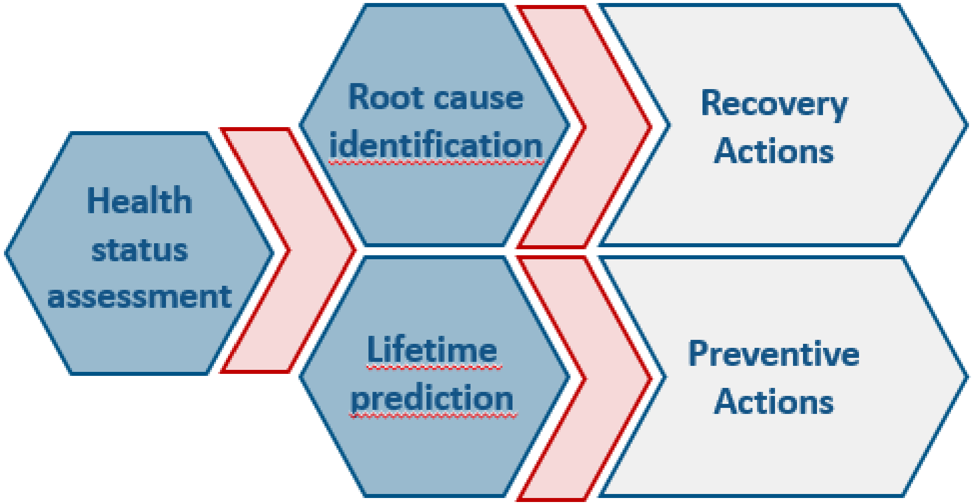
Advanced GNC

Robotics / Rovers

On-board / on-ground FDIR

Software modular solution to be deployed on-board or on-ground

AI based integrated with a general approach, rapid configuration and validation



Main advantes wrt current FDIR systems:

- early identification of anomalies
- identification of possible root caues
- Identification of correlated anomalies
- Prediction of Remaining Useful Life

SATE

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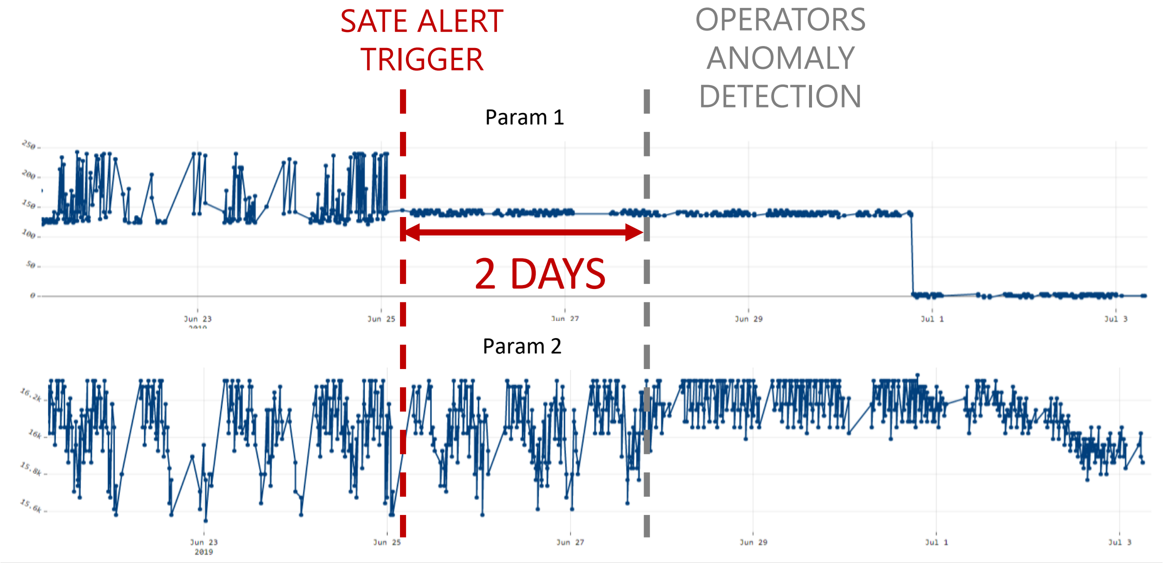
Technology maturity

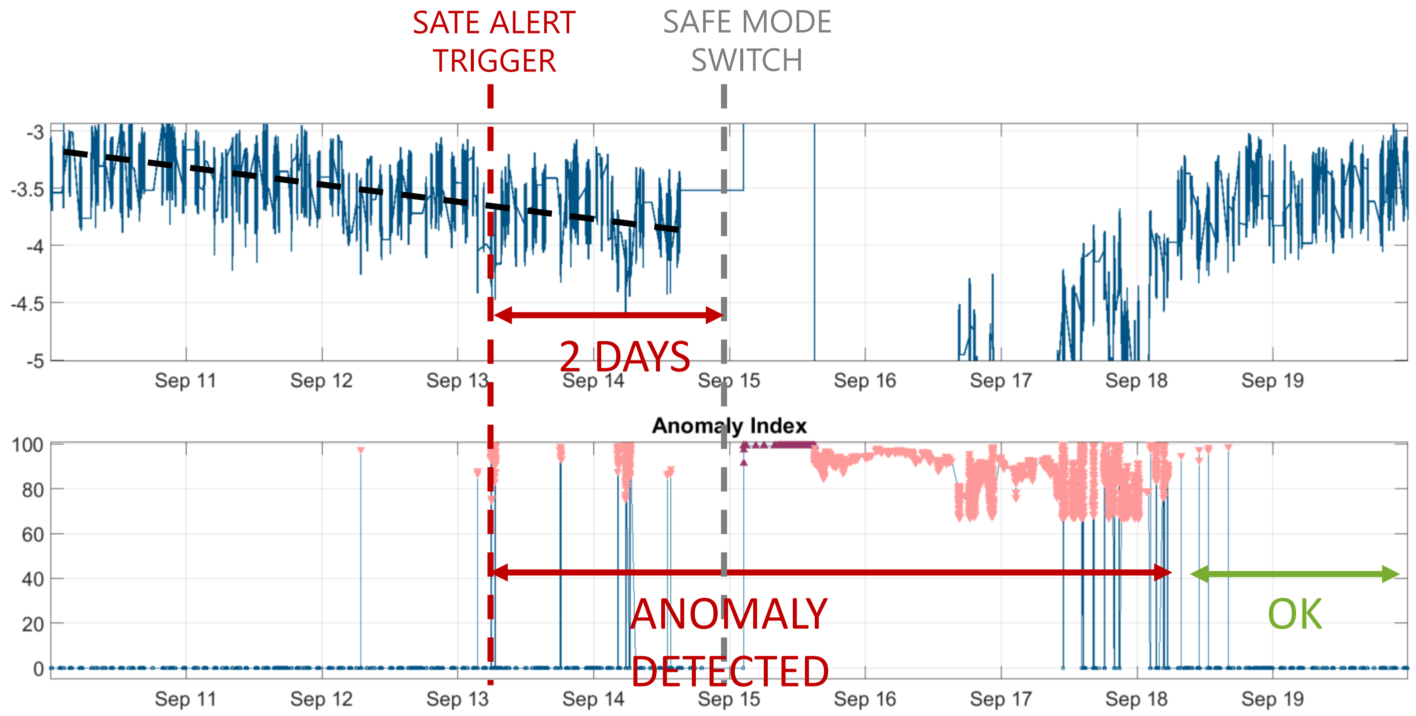
	On-Ground	On-Board
Space	TRL 8	TRL 3
Automotive	TRL 9	TRL 9
Energy	TRL 4	TRL 7

Success story: payload issue in flight



Even with parameters included in the expected nominal range, the anomaly is detected 2 days before respect the operators

Success story – reaction wheels



Even with parameters included in the expected nominal range, the anomaly is detected 2 days of safe mode transition

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Autonomous GNC - Motivation

POLITECNICO MILANO 1863

DIPARTIMENTO DI SCIENZE E TECNOLOGIE AEROSPAZIALI

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Leading space agencies increasingly investing in **gradual automation** of space missions.

Artificial Intelligence (AI) rapid developments start to influence the space research.

Autonomous flight operations crucial for variable and sustainable in-orbit servicing missions.

Flexibility, reactivity and **robustness**.

Goal: completely autonomous satellite.

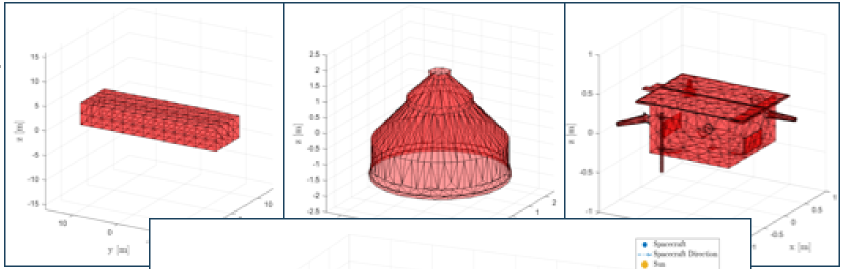
Research goal: assessment of reinforcement learning for adaptive guidance and control.

- Collision avoidance strategy
- **Image-based GNC**
- **Space Objects Inspection and Mapping**
- Autonomous Rendez-vous and Docking
- **Robotic Arm Grasping**

Non-cooperative target scenario

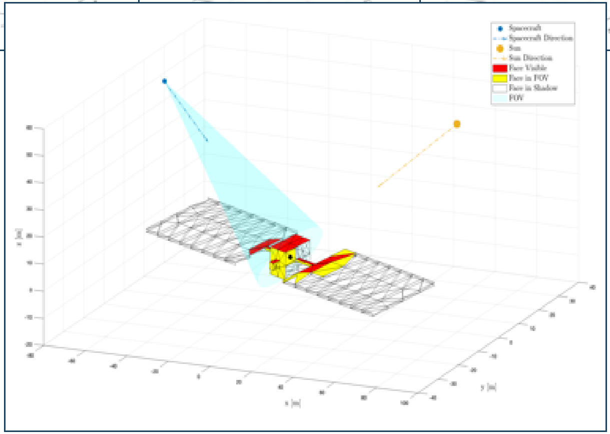
Problem: autonomous guidance and control for uncooperative and unknown space objects shape reconstruction.
→ Autonomy given by the AI/DRL trained agent.

State space:
Chaser-target relative pose (translational/rotational), Sun position.
- ❑ Perfect input state
- ❑ Noisy input state



Action space:
- ❑ Discrete (predefined and limited control vector choices)
- ❑ Continuous (control vector)

Main features and assumptions affecting the *reward function*:
- ❑ **VIS** (and TIR) **camera** → require Sun knowledge
- ❑ Camera always **pointed** towards object → avoid attitude control
- ❑ Object defined with **triangular mesh**



- ❖ **Relative Translational dynamics**: Eccentric Linearized 2° Order Differential Equations (target-centred LVLH)
- ❖ **Relative Rotational dynamics**: Euler's equations in LVLH frame, under small angles assumption.

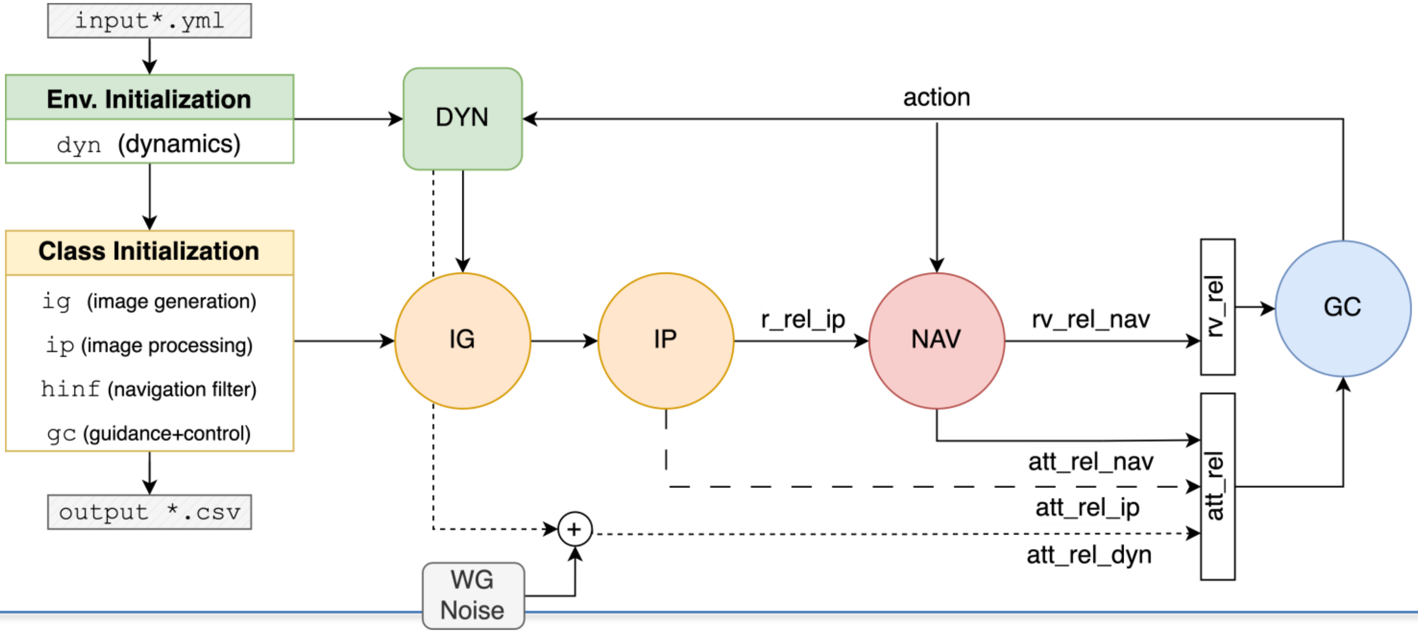
AI-based GNC Architecture

IMAGE GENERATION:
- **POV-Ray** generator which need.

IMAGE PROCESSING:
- Based on **YOLOv8s-pose** - CNN (convolutional neural network)

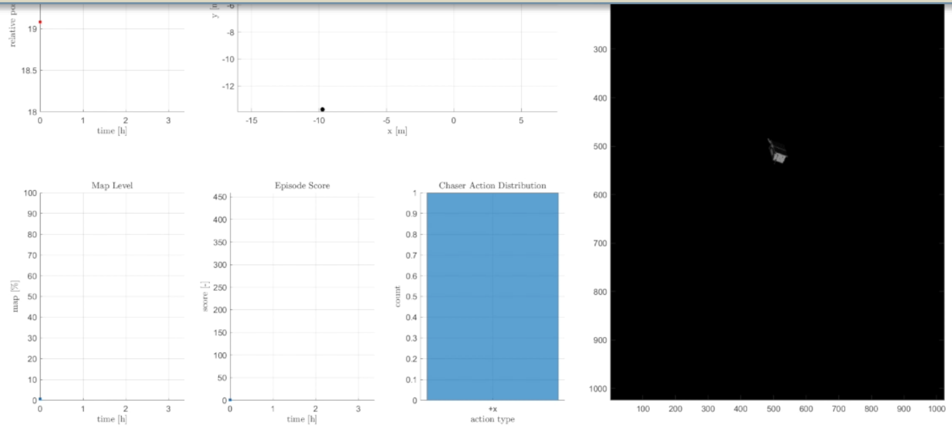
NAVIGATION FILTER:
- Relative Translational **H-infinity filter** based on **ROE** (relative orbit elements).

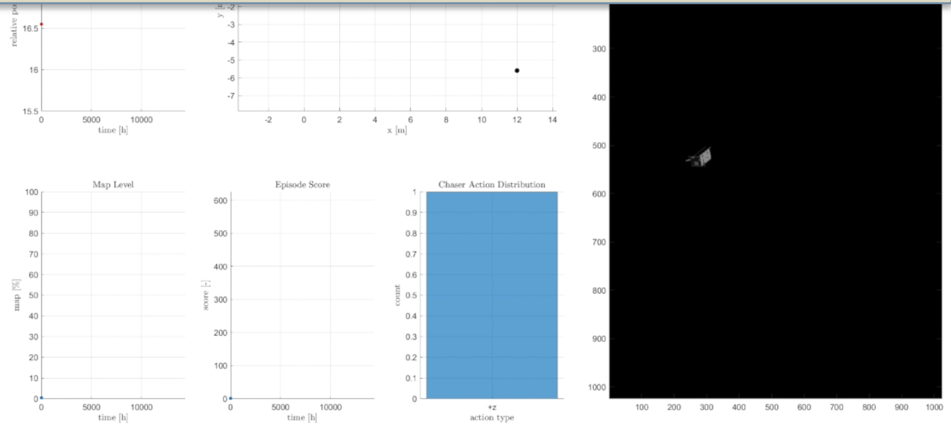
GUIDANCE & CONTROL:
- **Deep Reinforcement Learning** trained agent.



AI-based GNC: Performance

- **80%** of episodes reach a map level higher than **95%**.
- Less than **20%** of episodes **fails** because of the chaser has overcome the position limit range.
- All the episodes that overcome the position range, exit the maximum distance. **None** of them **crash** into the target object.
- The agent is **robust** to **input** coming from DYN, NAV or IP without any strong difference in forced target pointing.
- The agent is robust also to **attitude control** assumption relaxation.





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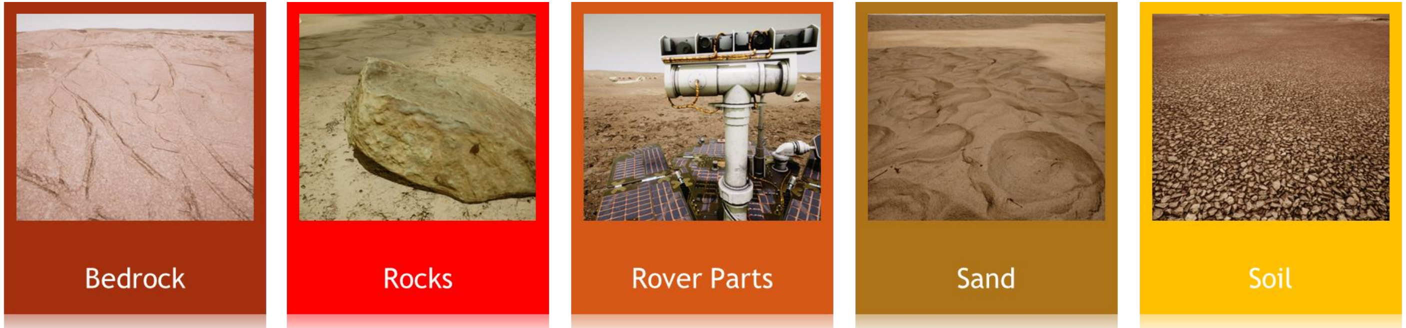
Recognition of Martian surface images

Synthetic Dataset



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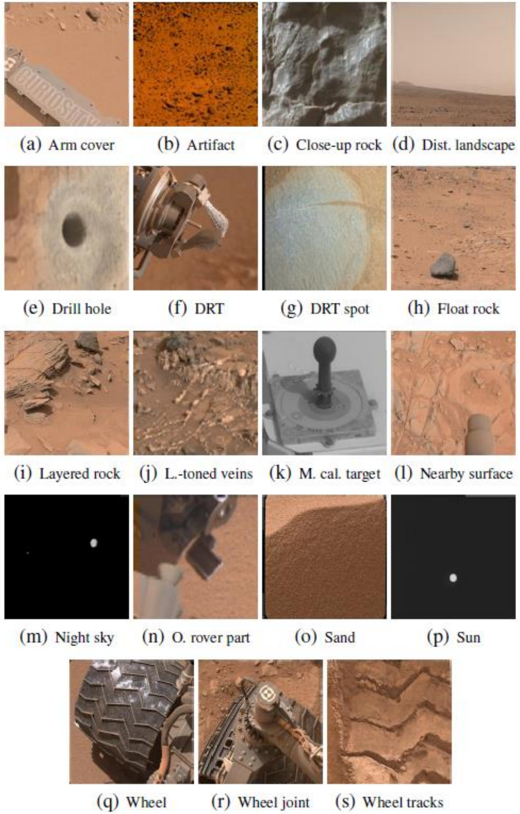
Recognition of Martian surface images

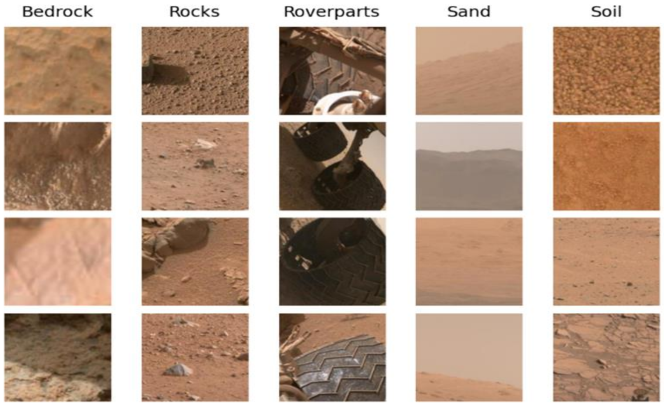


Dataset MSL Curiosity Rover Images with Science and Engineering Classes

- ***Bedrock***
- ***Rocks***
- ***Rover parts***
- ***Sand***
- ***Soil***

Recognition of Martian surface images

Support set 5-way 4-shot



Query images

Conclusions

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Key factors for AI adoption in space

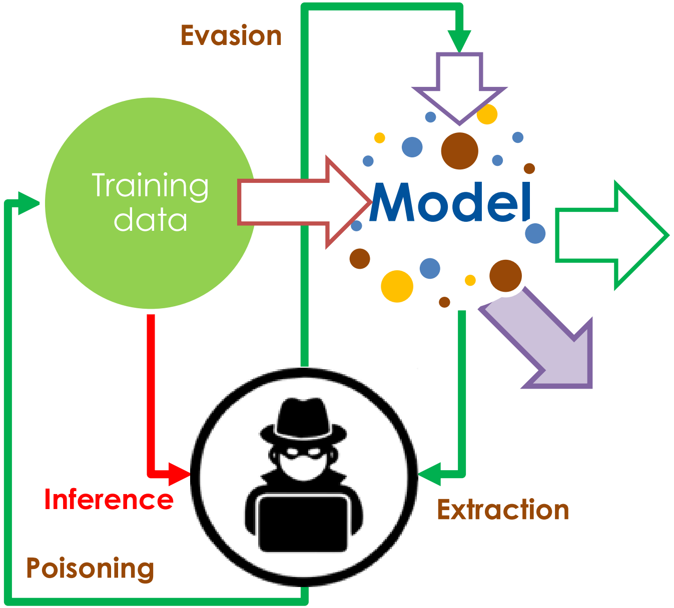
Massive use of AI in space market is related to **two key factors**:

Security: Lsecurity of models and data is fundamental for space missions applications, due to the intrinsic nature of space activities and potential consequences in case of violation or compromission

Trustworthiness: The opacity of ML models is seen as a significant limitation for their development and widespread adoption, especially for systems that make high-risk decisions.

Security in AI models

Objective: mitigate new attack vectors introduced by AI techniques, protecting AI systems from unauthorized access and manipulation.



INFERENCE ATTACKS

To determine the information used to train a model

ADVERSARIAL ATTACKS

POISONING: aim to corrupt a model and its performance during the training phase.

EXTRACTION: reconstruct part of the model's structure.

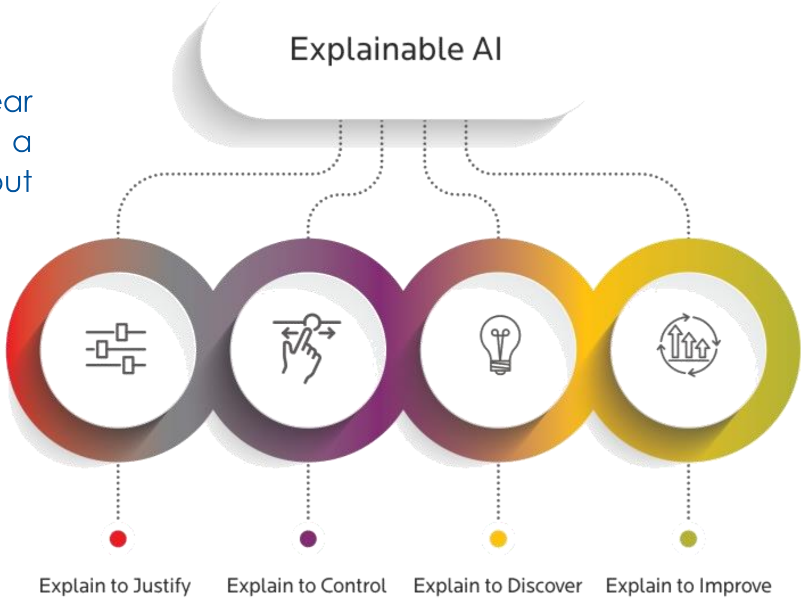
EVASION: aim to manipulate inputs to alter the results of AI models in deployment.

Trustworthiness of AI models

Objective: make explicit the internal functions, correlations, and parameters that determine predictions in order to understand the connections between the inputs and outputs of the AI.

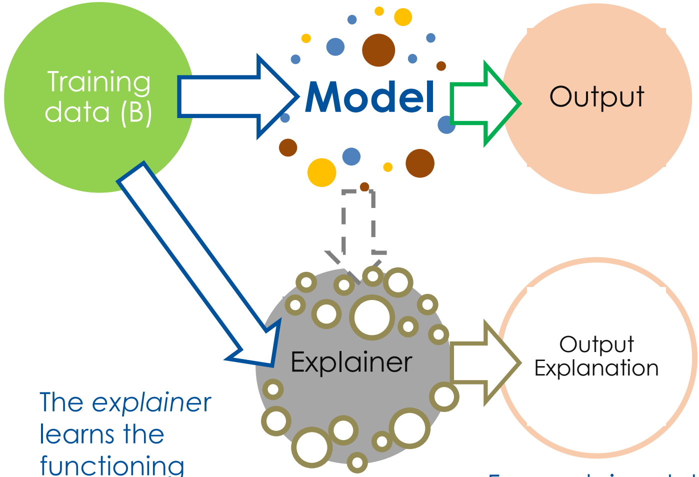
An AI model learns and exploits complex and nonlinear correlations between input variables to describe an output in a (typically) **Black Box mode**: we know the inputs and outputs, but not the process that connects them

The operational limitations in applying the model's guidance stem from the lack of **trust** and **understanding**, which impact the assumption of responsibility:



eXplainable AI

eXplainable AI (XAI) models can an provide a clear, concise, comprehensive, and valid explanation of the reasoning behind a model's suggestion and its validity.

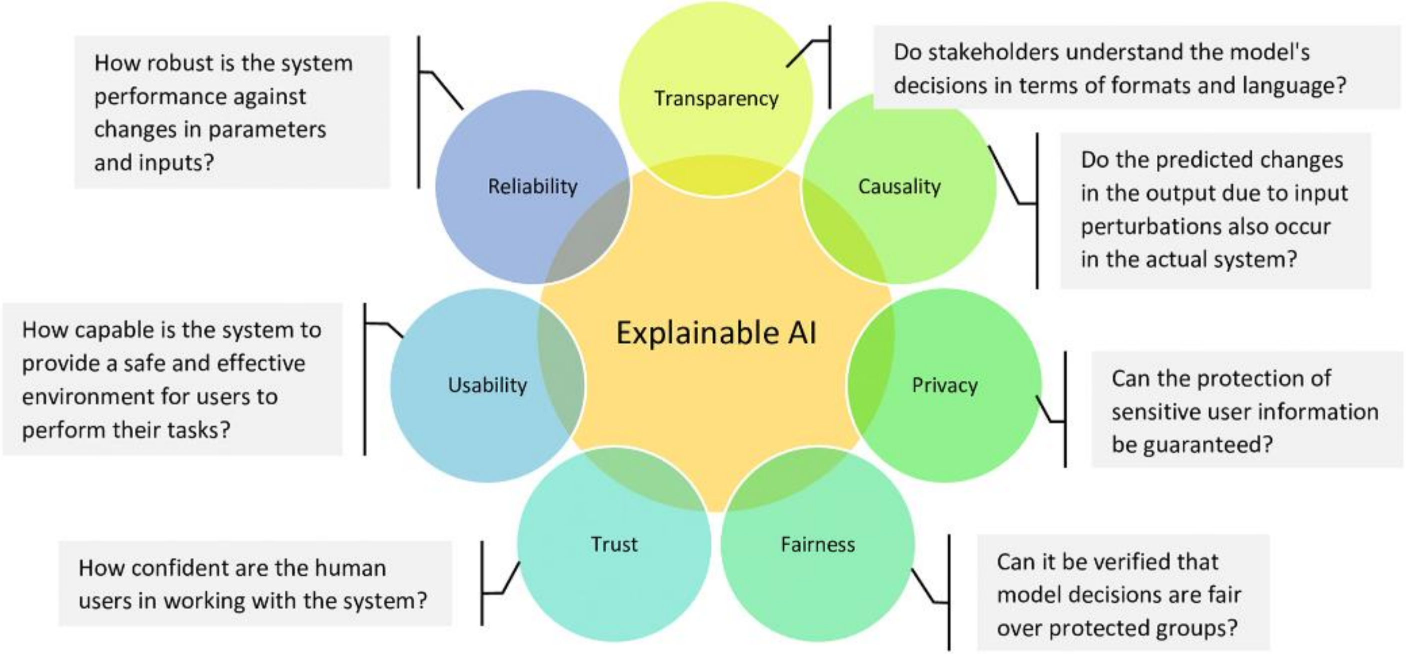


The *explainer* learns the functioning of the model.

For each input, the *explainer* provides an explanation of how the model operates.

- XAI does not modify the performances of the model
- XAI can be applied to existing models in a general approach
- The *explainer* inherits the validity and quality of the model to which it is associated

Explainable Artificial Intelligence (xAI)



Conclusions

ASI, among the main contributors to the European Space Agency, can leverage the advantage of being a "first mover" in the development of AI based models in a number of different domains, and can be among the first agencies in the world to create AI applications that are secure and reliable "by design", specifically designed for mission-critical applications.