VALIDATION AND VERIFICATION OF SAFETY-CRITICAL ASPECTS OF AUTONOMY IN ORBITAL ROBOTICS

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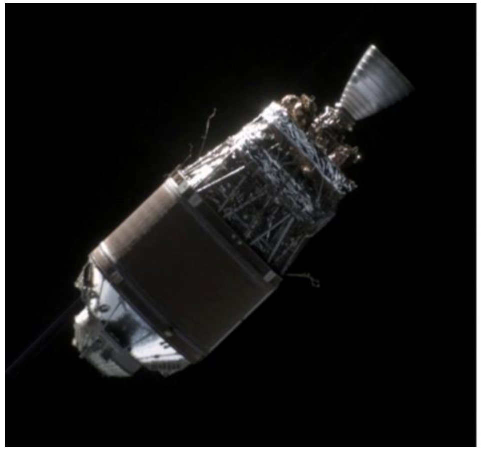
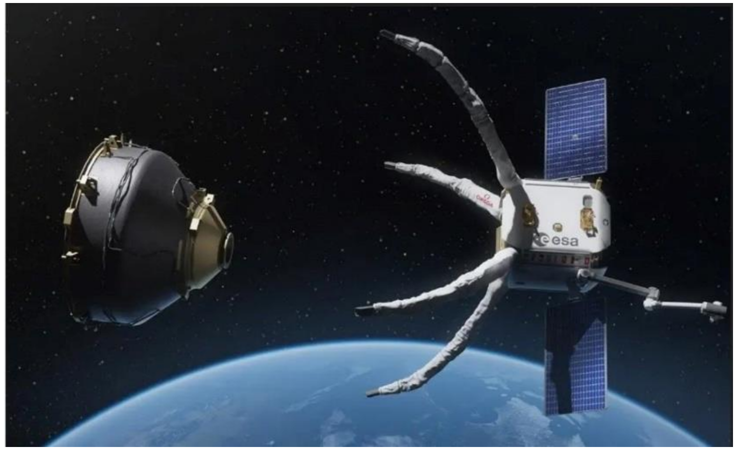
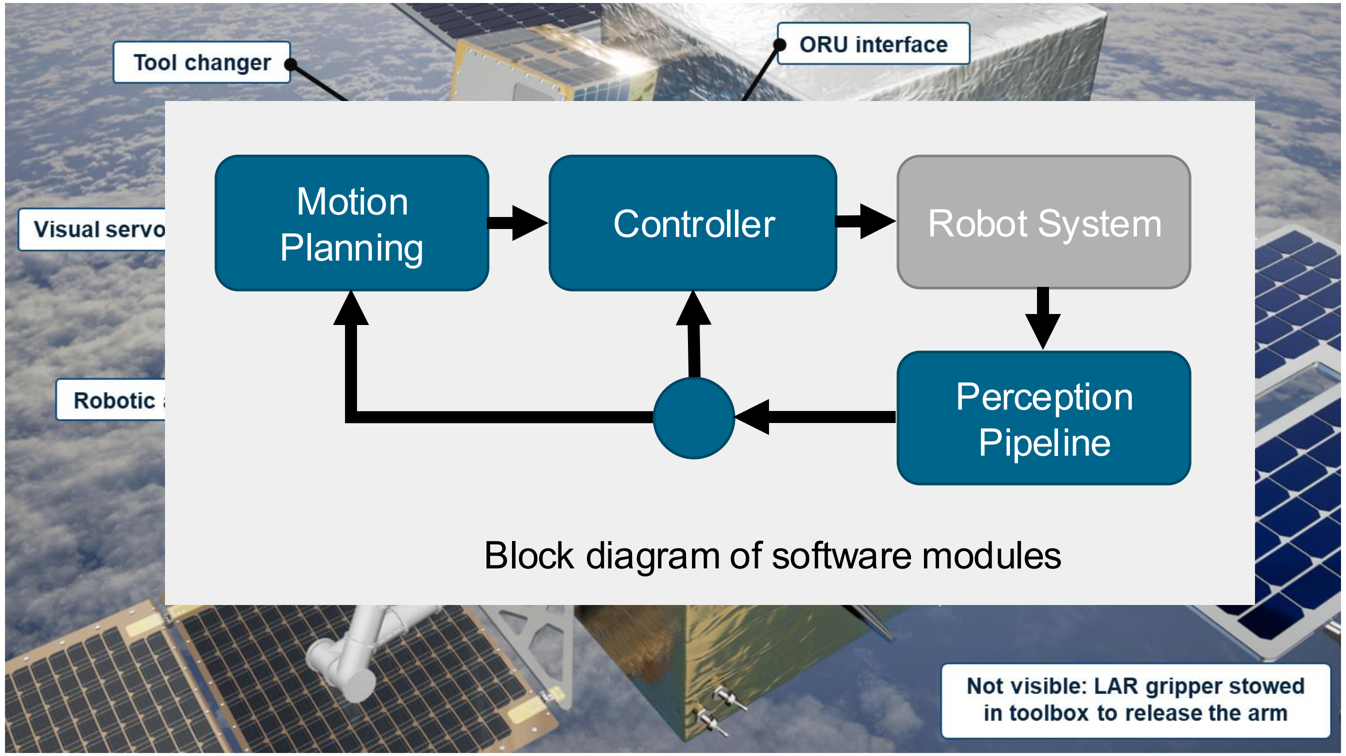
Orbital Robotics
Scenarios and Software Architecture

- In-Orbit Servicing
  - Life extension (MEV), Relocation
  - Upgrade, Repair (RSGS, EROSS SC)
- Active Debris Removal
  - Astroscale
  - ESA ADRIOS / Clearspace-1
- Assembly and Manufacturing
  - EU STARFAB automated orbitalwarehouse


ADRAS-J Mission (JAXA)



Clearspace-1 (ESA)

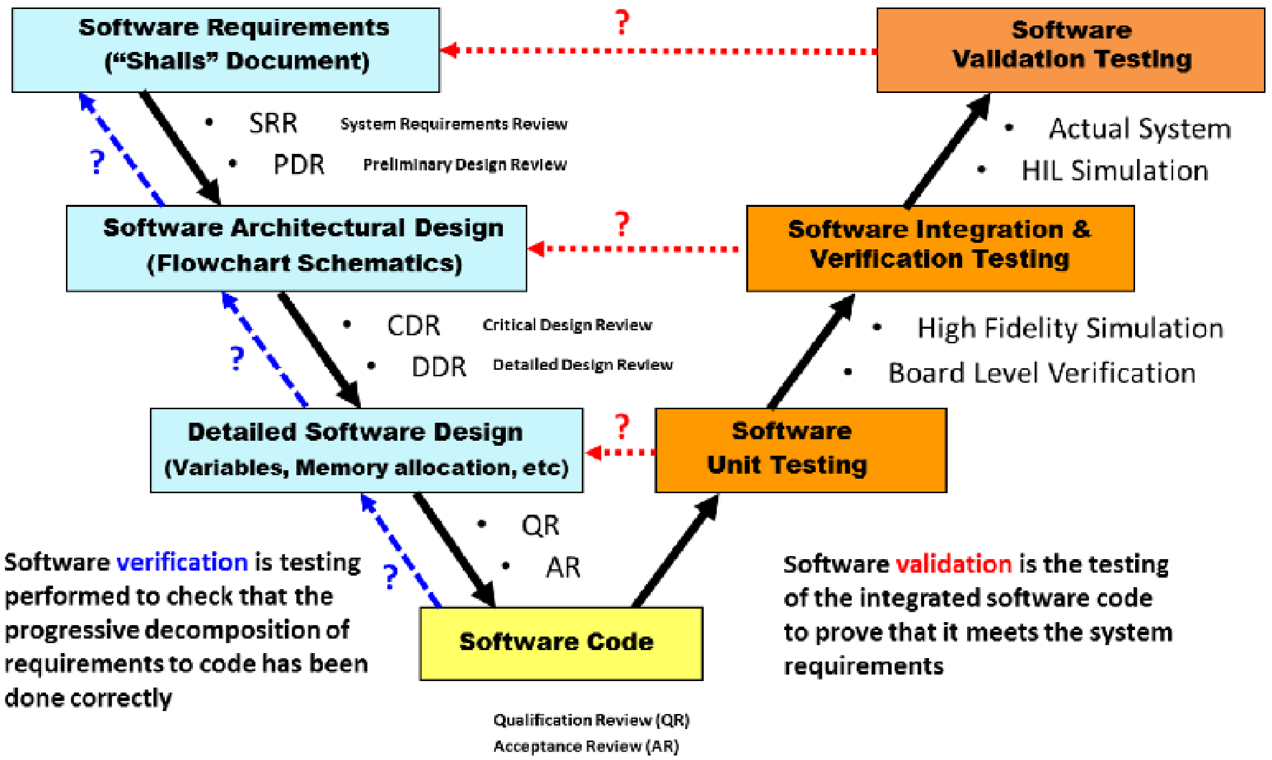


Block diagram of software modules

EROSS SC (EU)
European robotic orbital support services - servicing component

V&V for On-Orbit Tasks

- Verification: does the code perform as it was designed to?
- Validation: does the integrated code perform as it should in the target environment (e.g. PC/OBC, on-ground/on-orbit)?
- No formal standard for V&V of Optimal Control and DL-based Perception for on-orbit tasks



Waterfall software development lifecycle, verification, and validation. Credit: NASA Marshall Space Flight Center, ECSS-M-ST-10C

Optimal Control | Task

- Robots involved in highly complex tasks on-orbit
  - Highly nonlinear
  - Highly constrained
  - Often not suitable for convexification
- Formulate task as a parametric NLP($\boldsymbol{p}$):
  - $\boldsymbol{p} \in \mathbb{R}^{\mathrm{n_p}}$
  - $\mathrm{t_0} \leq t \leq \mathrm{t_f}$
  - $\delta t = \frac{\mathrm{t_f} - \mathrm{t_0}}{\mathrm{n} - 1}$

$$
\begin{aligned}
& \min_{\boldsymbol{z} \in \mathbb{R}^{\mathrm{n_z}}} J(\boldsymbol{z}, \boldsymbol{p}) \\
s.t. \quad & G_i(\boldsymbol{z}, \boldsymbol{p}) \leq 0, \qquad i = 0, \dots, \mathrm{n_G} \\
& H_j(\boldsymbol{z}, \boldsymbol{p}) = 0, \qquad j = 0, \dots, \mathrm{n_H}
\end{aligned}
$$

- V&V of non-convex optimal control-based methods
  - Not codified in literature
  - Can follow a similar procedure used in V&V of SW for small satellite
- Models are not perfect → uncertainty!

Optimal Control | Method

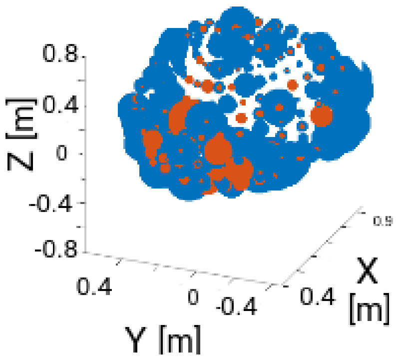
Task Workspace

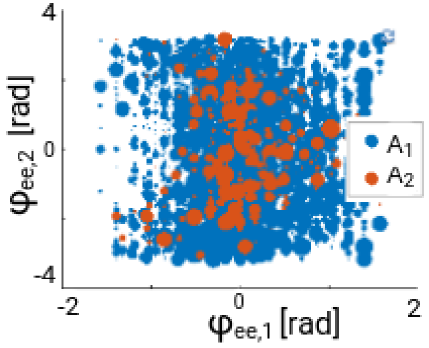
- A discrete grid on the task parameter space with:
  - Admissible solution on the grid points
  - Provable estimate of neighborhoods of validity of the sensitivity-based update for each grid point

$$\bar{\mathbf{z}}(\boldsymbol{p}) = \hat{\mathbf{z}}(\hat{\boldsymbol{p}}) + \frac{dz}{dp}(\boldsymbol{p} - \hat{\boldsymbol{p}})$$

- Result:
  - Indication of robustness distribution on the task parameter space
  - Simple onboard computation

Task workspace for robot arm approach task





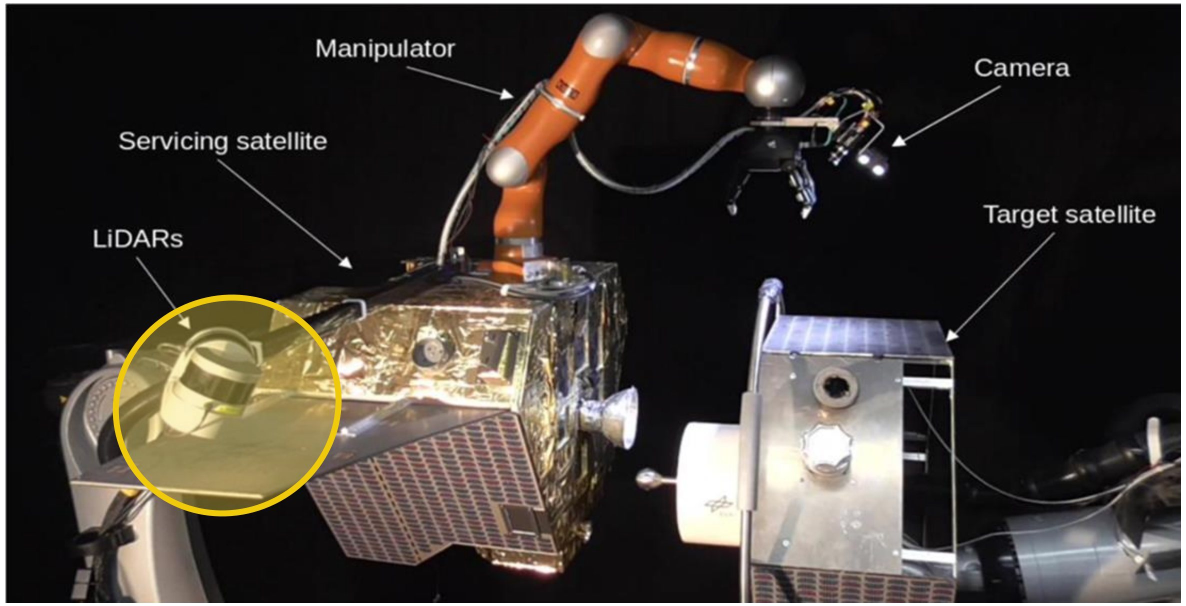
The Task Workspace in V&V

- Admissibility→ Satisfied mission operational requirements in the presence of uncertainty
- Mission planning:
  - Identify the safest corridors within which to operate
  - Targeted, early iteration on mission requirements
- Mission operations:
  - Assure robot operators that a generated or updated motion plan is feasible
  - Guide on whether another trajectory should be considered

DL-based Perception | Method

- We developed a DL method for **on-board 6D pose estimation** of a known target satellite

  - **Lightweight** architecture for Point cloud 2 Pose Regression (**P2PReg**), encoder based on PointNet layers
  - Provides **robust** initial pose estimate of a known client satellite, for initializing the visual tracker
  - Processes unordered point sets and regresses pose parameters **adapted to client object symmetry**



OOS-SIM (On Orbit Servicing – SIMulator), DLR

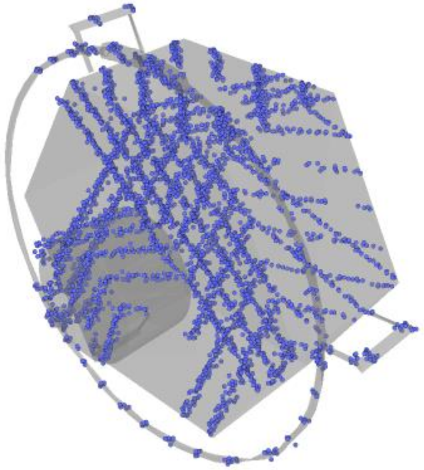
[M. Piccinin, U. Hillenbrand, "Deep Learning-based Pose Regression for Satellites: Handling Orientation Ambiguities in LiDAR Data". Journal Of Image and Graphics, Vol. 13, No. 2, 2025.]

DL-based Perception | V&V

- V&V for DL methods in space safety-critical applications → need of a W-shaped iterative process

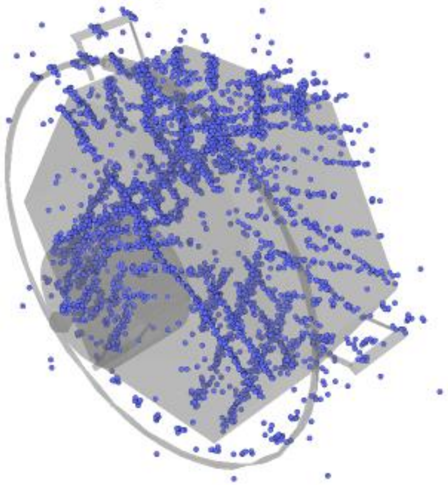
1. Data quality

simulated



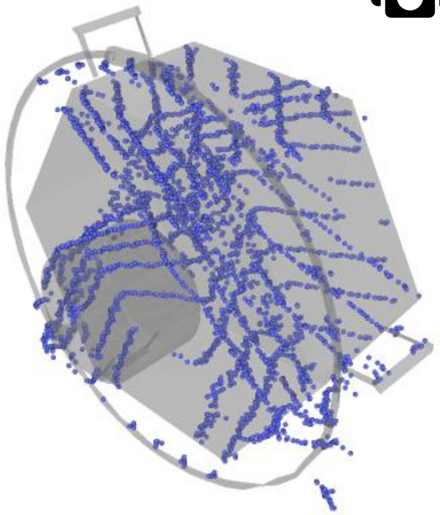
- Representativeness

augmented



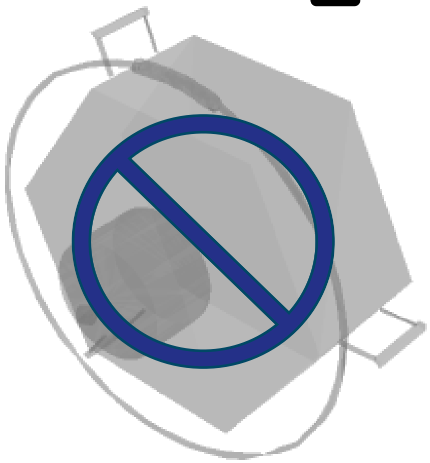
- Consistency

experimental



- Representativeness
- Fitness
- Metadata quality

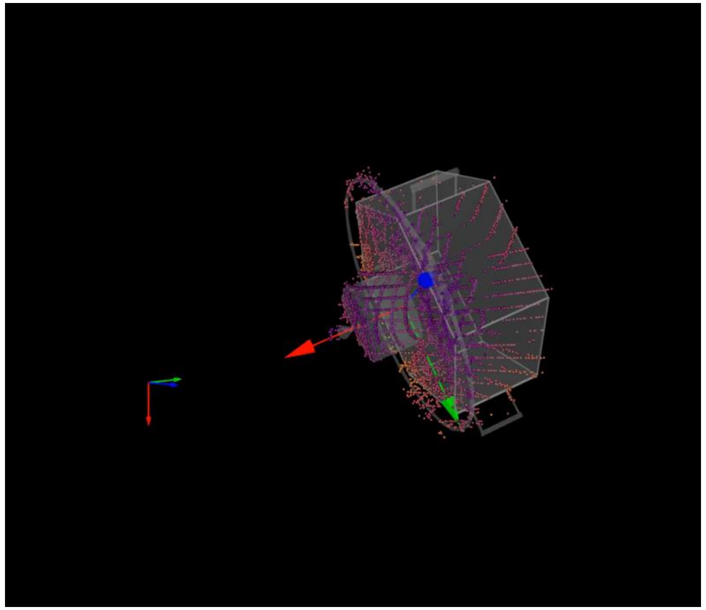
real



- Metadata quality

DL-based Perception | V&V

2. Model development and testing

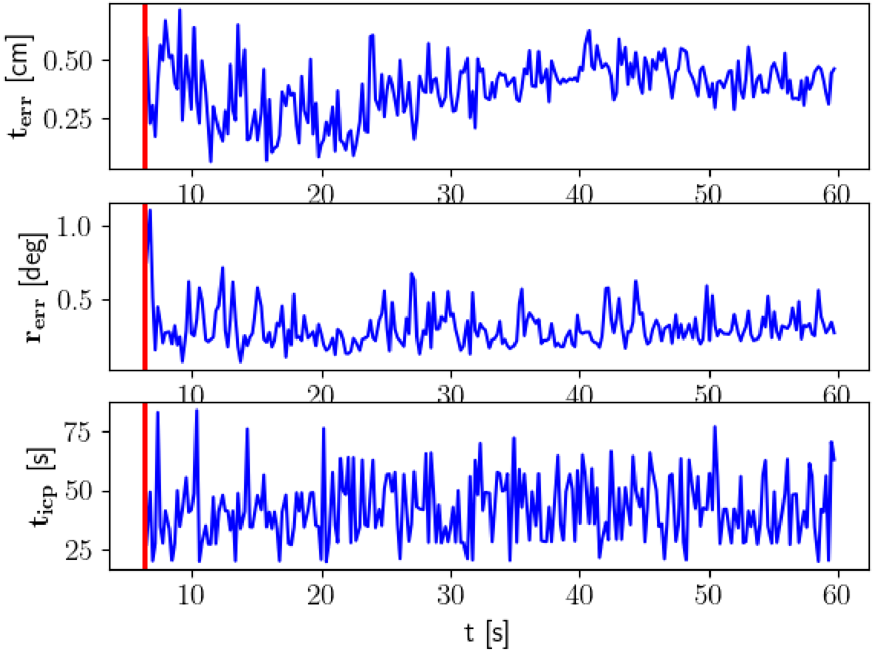


Evaluation of P2PReg pose initialization on single point clouds from on OOS-SIM.

- Outperforms classical and other DL methods
- Trained for **robustness** against data artifacts and model deviations
- Trained on solely synthetic data, it achieves excellent **sim2real transfer**

3. System testing

- Pose estimation running on space-relevant HW (ARM v7 processor)
- P2PReg successfully initializing the ICP tracker
- Requirements on translation error (t_{err}), rotation error (r_{err}) error and compute time (t_{icp}) are met

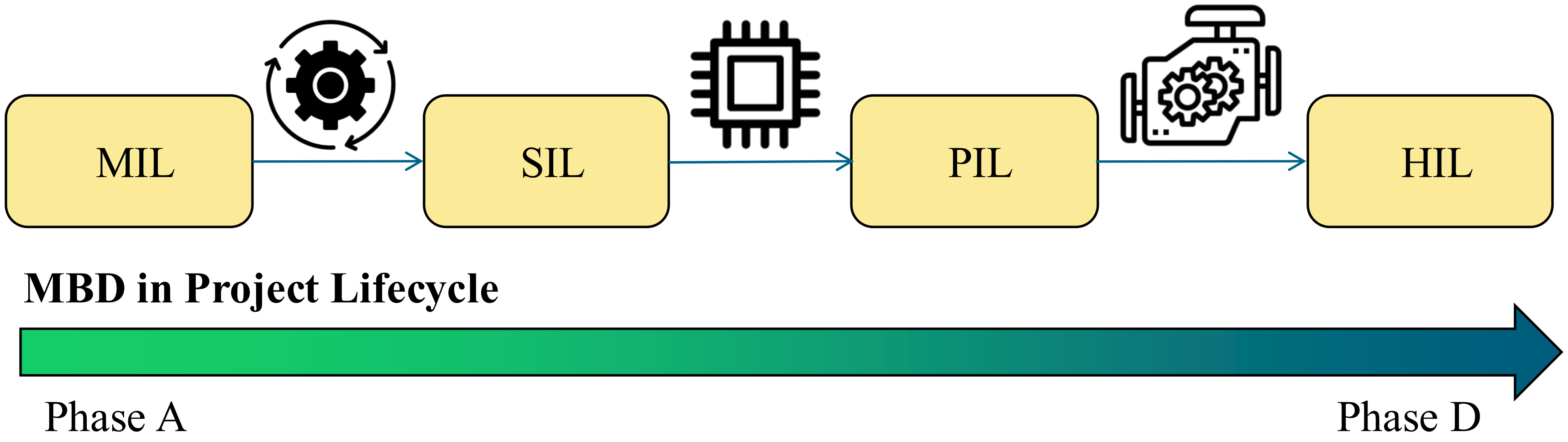


Pose estimation error and compute time for an example trajectory in open-loop PIL tests.

Model-based Design (MBD)

DDVV: *Design*, *Development*, ***Validation & Verification***

- From **Phase A/B1** to incremental **Phase C/D**
    - Incremental **TRL** improvement

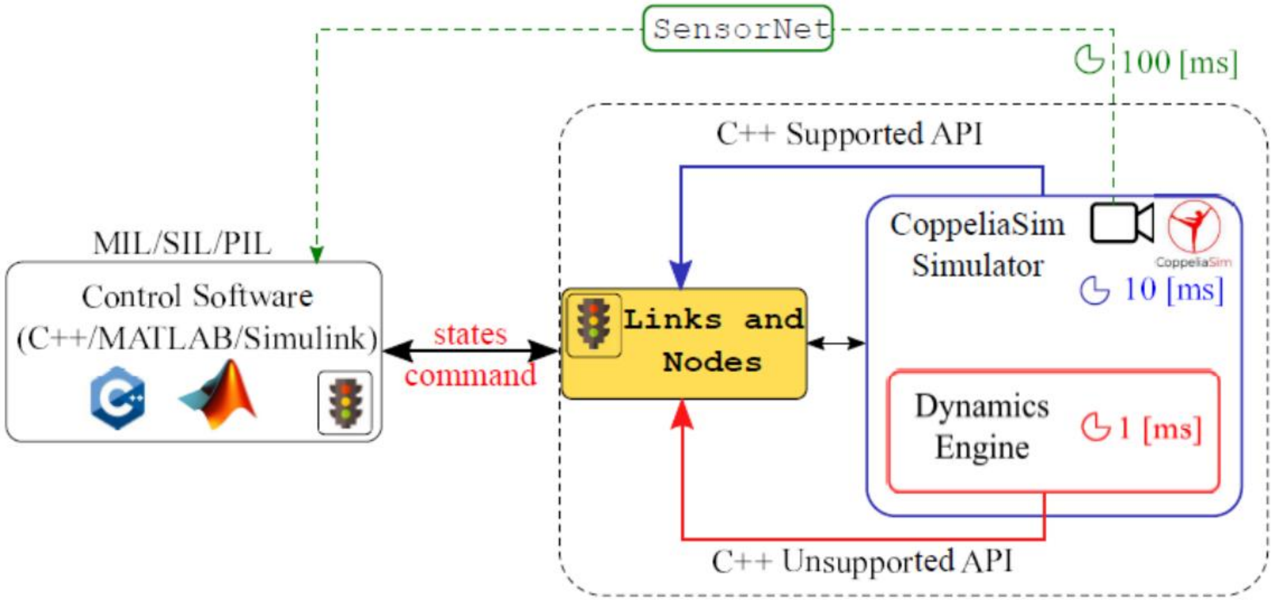


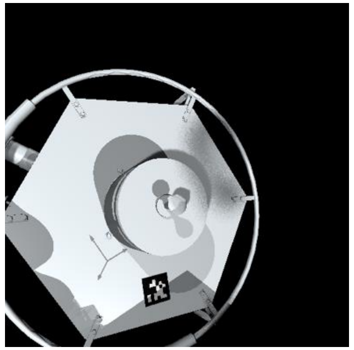
- **Different requirements**: Models, Sensors/Actuators, On-board computer, Math libraries

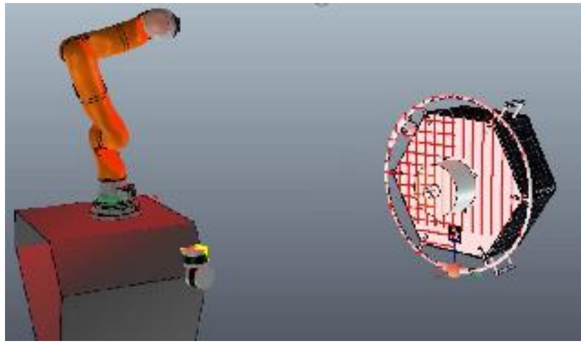
- **Key objective**: Provide a domain-specific DDVV implementation for Orbital Robotics

Model-in-the-Loop (MIL)

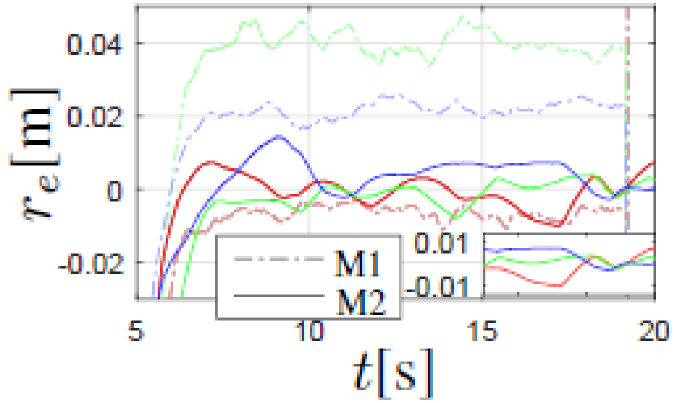
- Model-in-the-Loop:
  - Components:
    - Sensor Performance Models (Camera, LiDAR)
    - Actuator Performance Models (joint flexibility)
    - Disturbance models (e.g., sloshing, flexible appendages)







Perception: Synthetic Sensor data from MIL Framework



Control: Free-floating (M1) vs Free-flying (M2) End-effector controller (pos. error) in MIL Framework

Conclusion

- High-performance perception and control methods need dedicated V&V standards.
- In optimal control for space, common approaches include convexification, which is not suitable for robotics. New approaches are proposed for provable treatment of task uncertainty and for substantial reduction of V&V complexity.
- In ML-based pose estimation, some V&V guidelines are available. They were successfully implemented in our orbital scenario within MIL/SIL/HIL.
- The Model-based design approach was developed for rapid prototyping in orbital robotics.