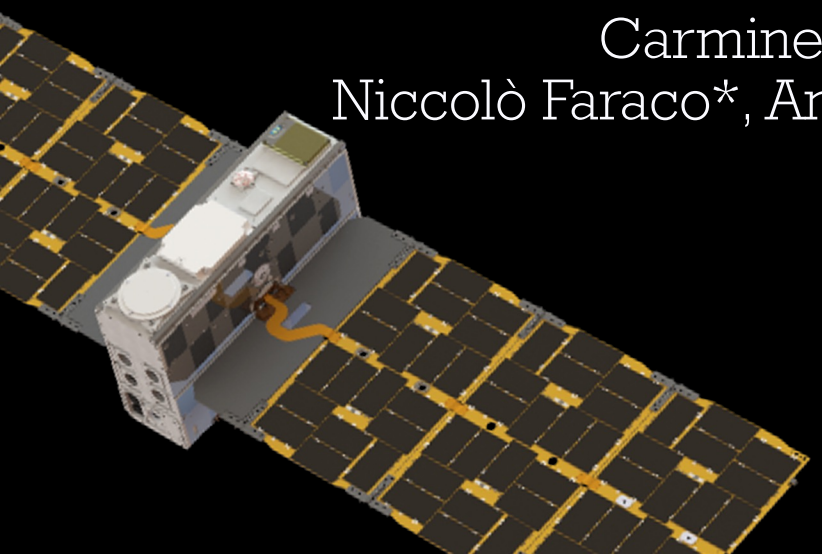
https://github.com/MattiaPugliatti/corto

CORTO: a Collaborative Rendering Library for Space Applications

Carmine Buonagura*, Mattia Pugliatti†, Dario Pisanti‡,
Niccolò Faraco*, Andrea Pizzetti*, Michele Maestrini*, Francesco Topputo*



23 October 2024

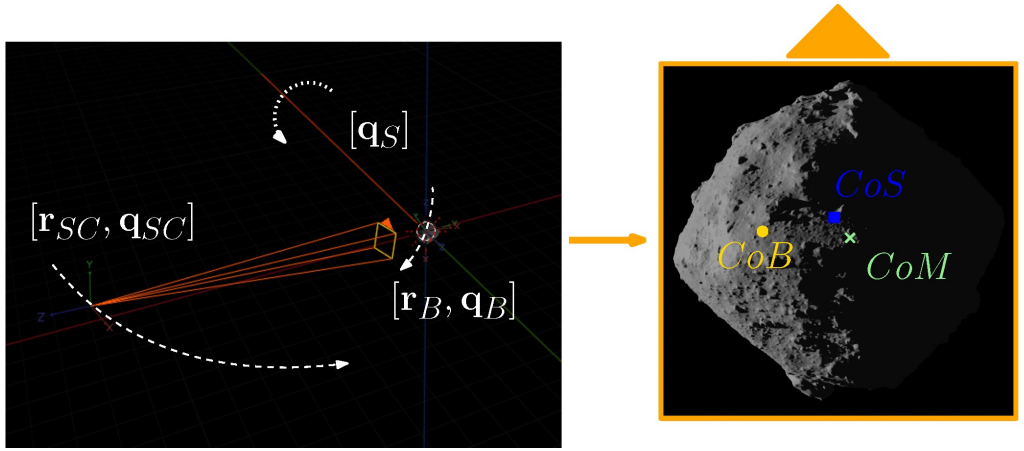
*Politecnico di Milano
†CU Boulder
‡Scuola Superiore Meridionale

Outline

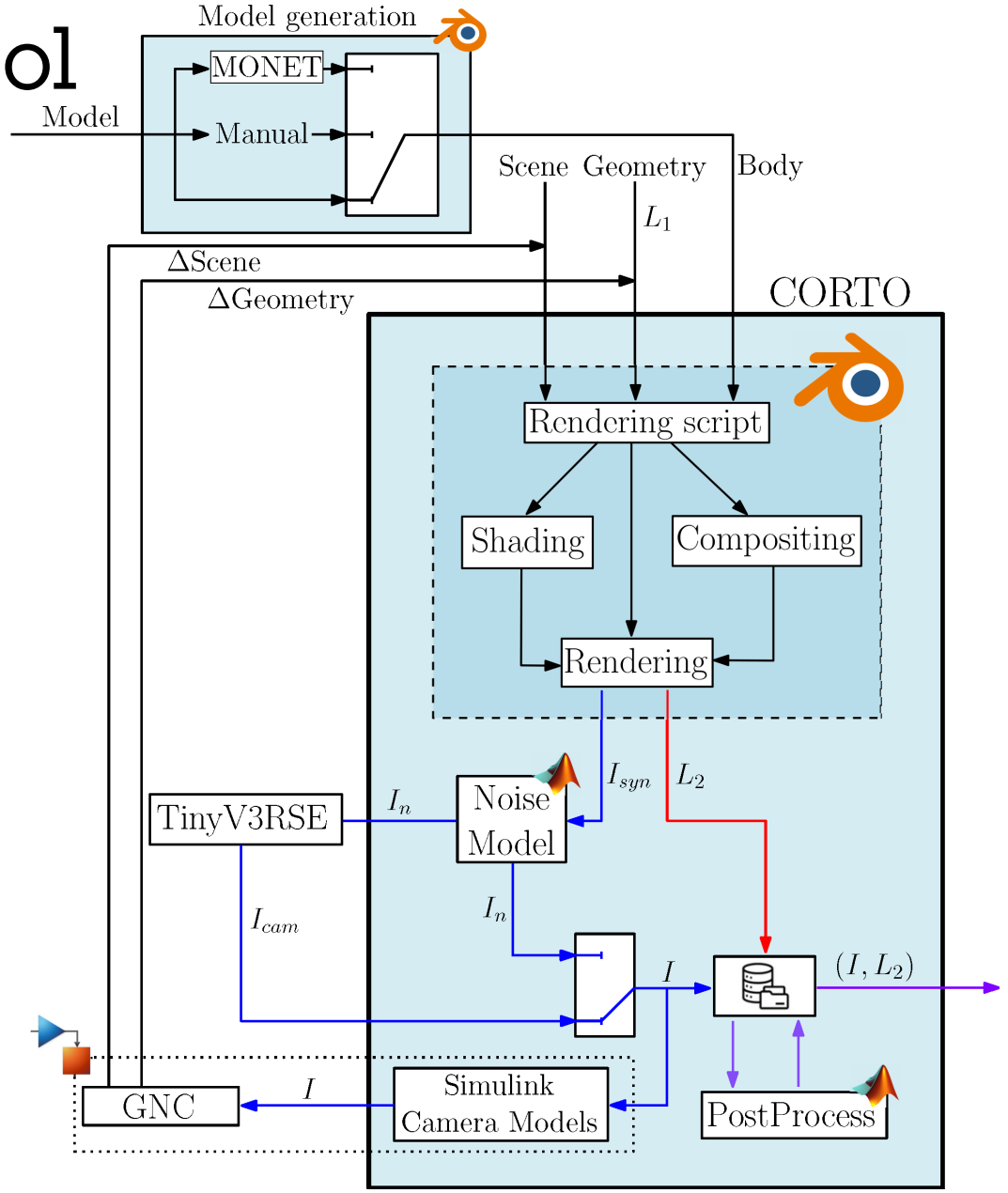
- CORTO
- Case Studies
- Validation
- Publications

Celestial Object Rendering TOol

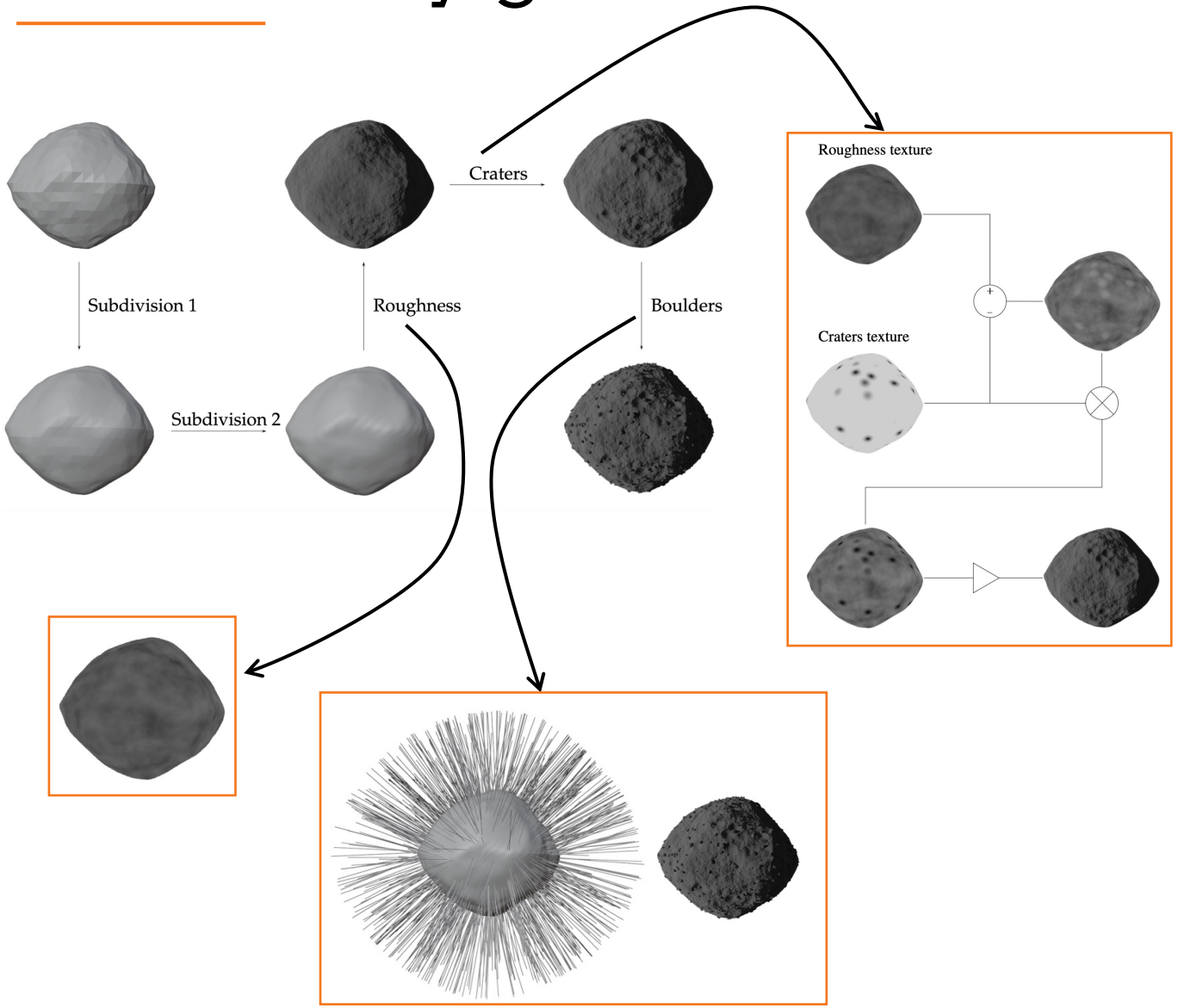
- In an artificial environment the user is in control
- Capability to generate arbitrary views with different geometric and illumination conditions
- Generation of large datasets of high-fidelity image-label pairs
- Closed-loop capabilities
- **Blender** (other options: PANGU, SurRender, SISPO, SpyRender, etc.) :
  - **PROs**: Open source, well documented and supported, supports Python scripting, easy to interface, easy to learn and use
  - **CONs**: Not designed for scientific applications, path-tracing, it often requires inventive solutions, validation is always an open point

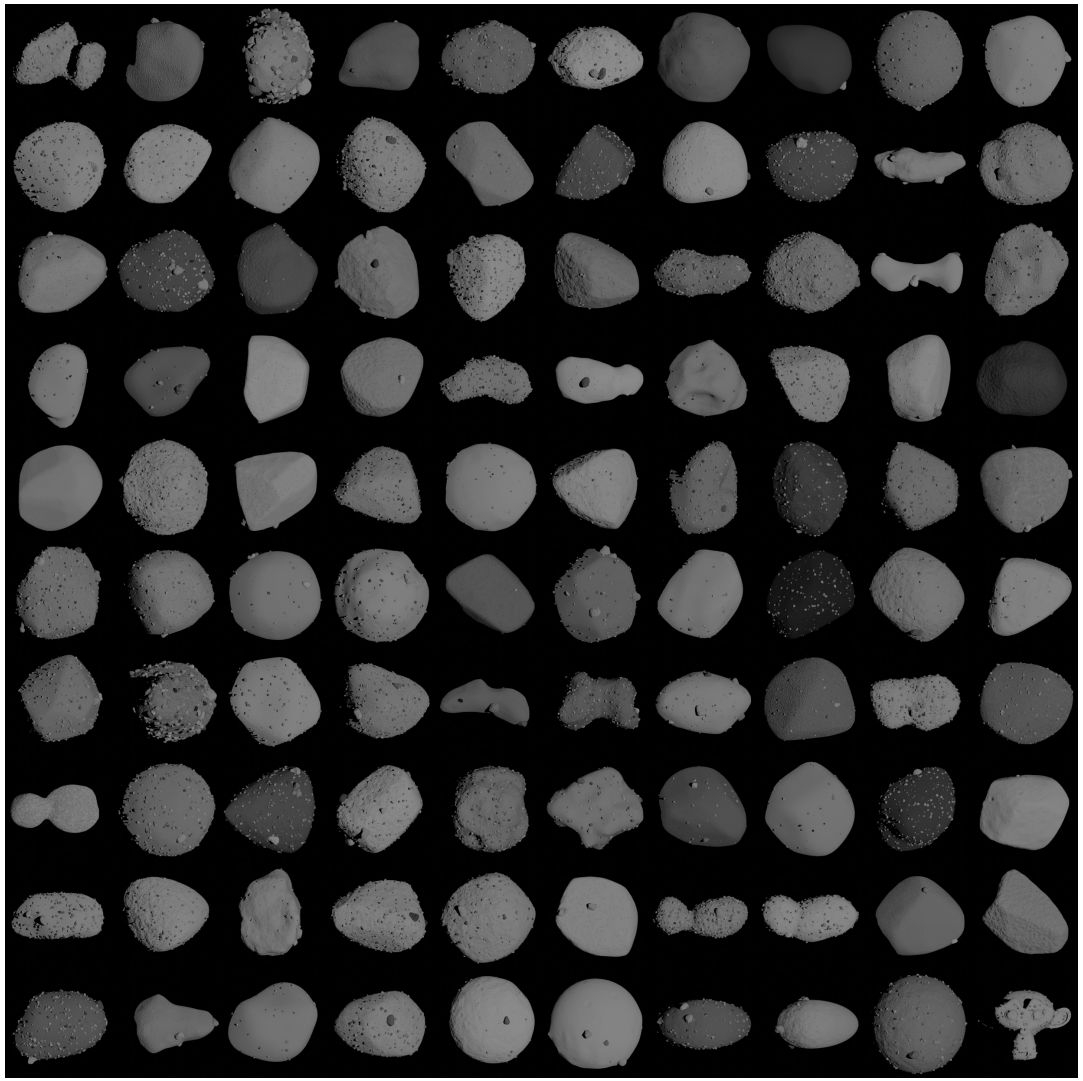


$$L_1 = [r_{SC}, q_{sc}, r_b, q_b, q_s, CoM, CoS, \rho_{sc}, \Psi, \dots]$$



Minor bOdy geNErator Tool - MONET

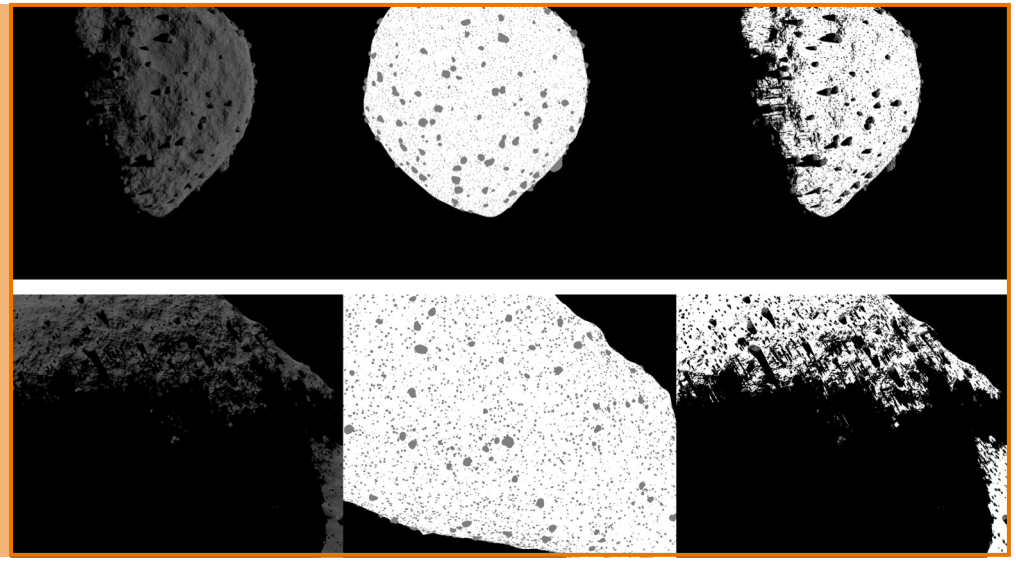


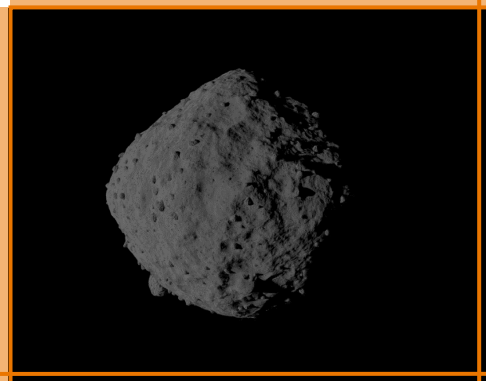


DeepNav

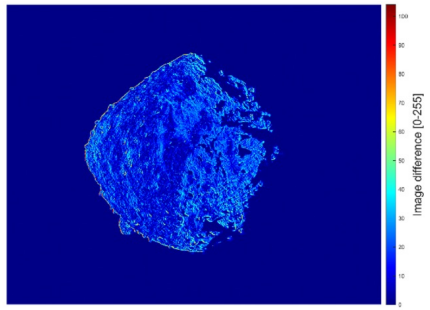
- Dataset for orbit determination with deep learning
- 13,000 images per body
- Different spacecraft trajectories, morphological conditions, rotational rates, attitude errors, and noises.
- Domain gap assessment

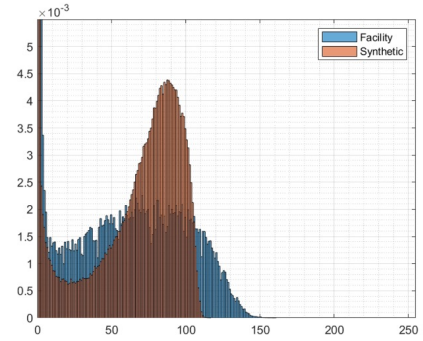
Segmentation masks

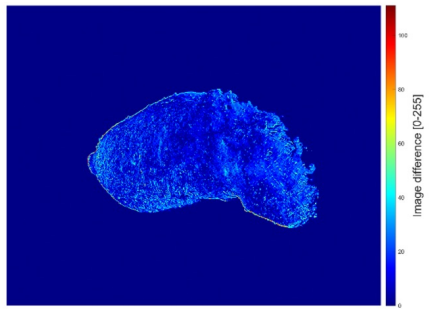


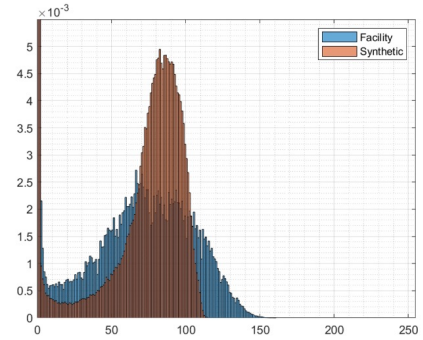
	Synthetic	Optical facility
Bennu		
Itokawa		

Domain gap



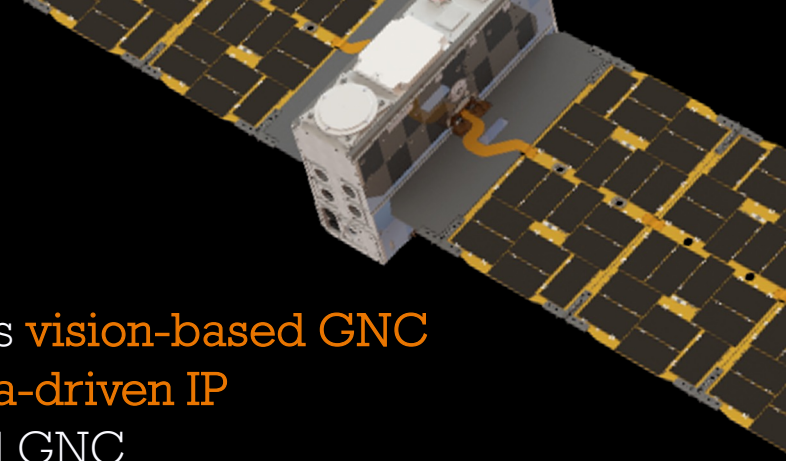




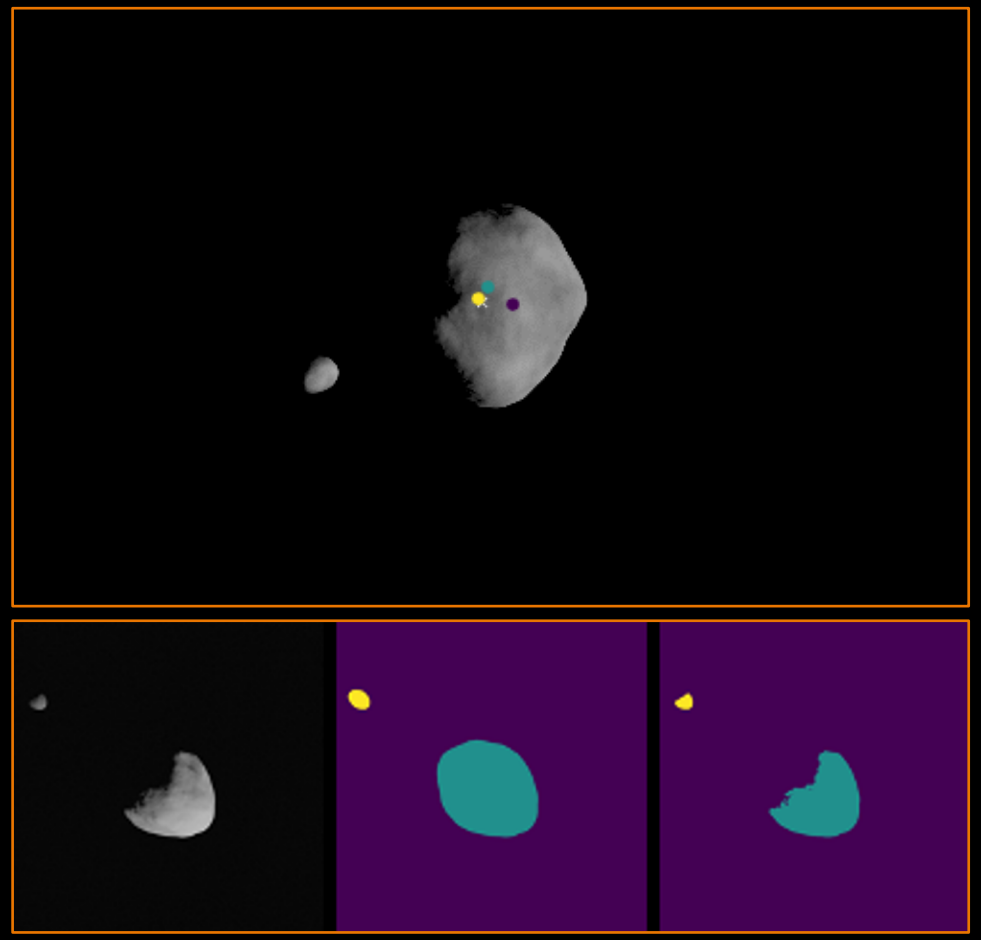


Attitude errors

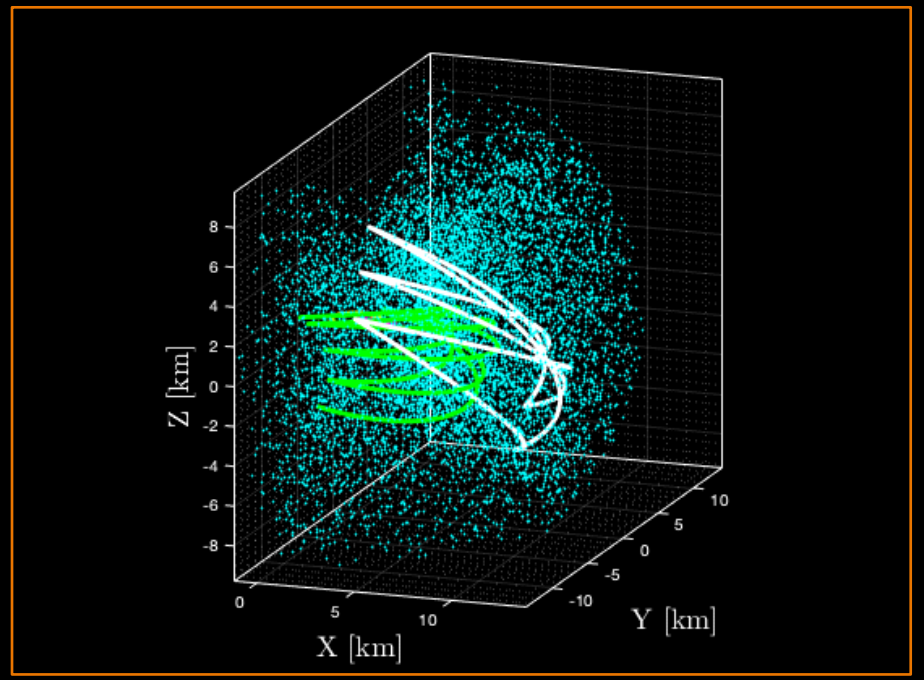
Milani



Didymos binary system



- Semi-autonomous vision-based GNC
- Design of the data-driven IP
- V&V of the IP and GNC
- Object recognition, centroid, phase angles, and range regression

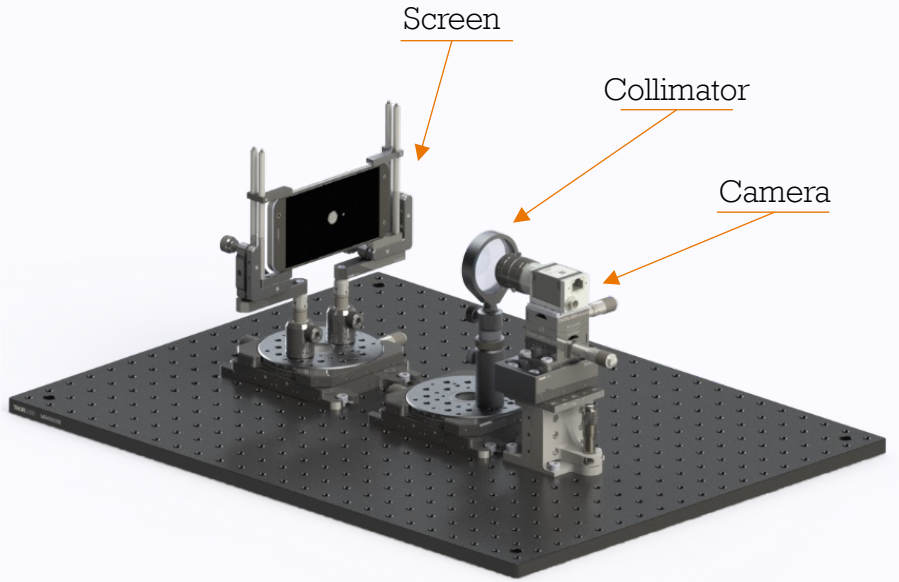


Moon exploration

Samples of renderings of the Moon with a Lambertian reflectance model

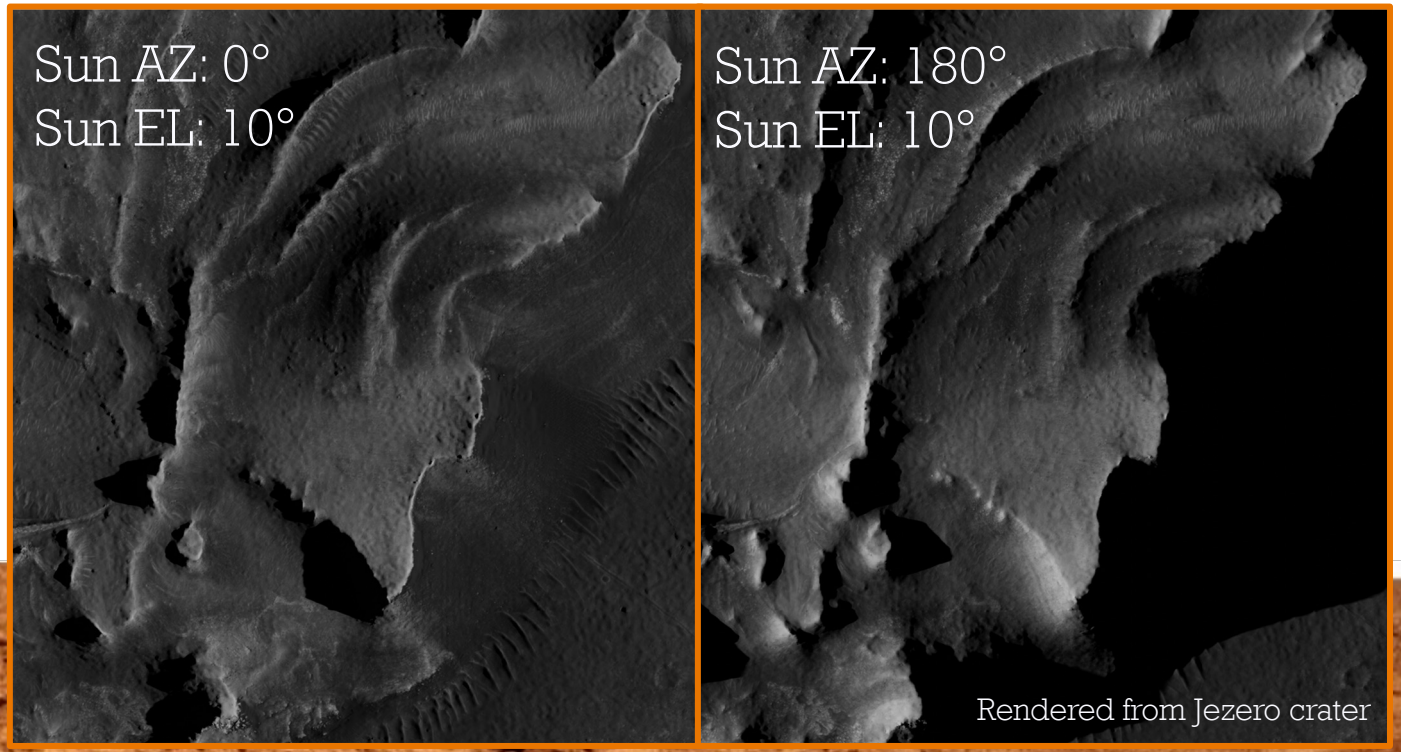
Star-Nav

- Assess the feasibility of using a space-proven TRL 9 star tracker to perform autonomous horizon-based Optical Navigation on the Moon limb.
- Generated a dataset of 1000 images at different phase angles and distances.
- Algorithms successfully tested with Processor-In-the-Loop (PIL) and Hardware-In-the-Loop (HIL) campaigns.



TinyV3RSE optical facility

Planetary – Mars Surface Exploration

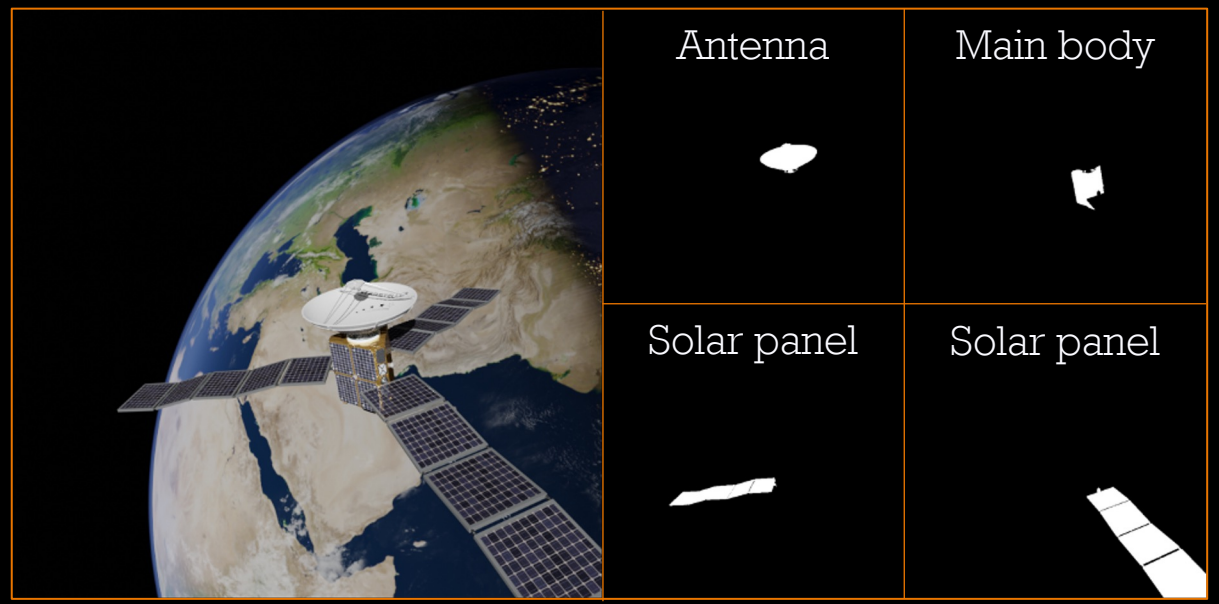


The next generation of Mars rotorcrafts: the Mars Science Helicopter

- Synthetic image terrain dataset with wide range of illumination conditions and terrain morphologies
- Support the validation of map-based localization pipelines for long-range navigation in challenging lighting
- Support the validation of autonomous landing site detection and hazard avoidance pipelines

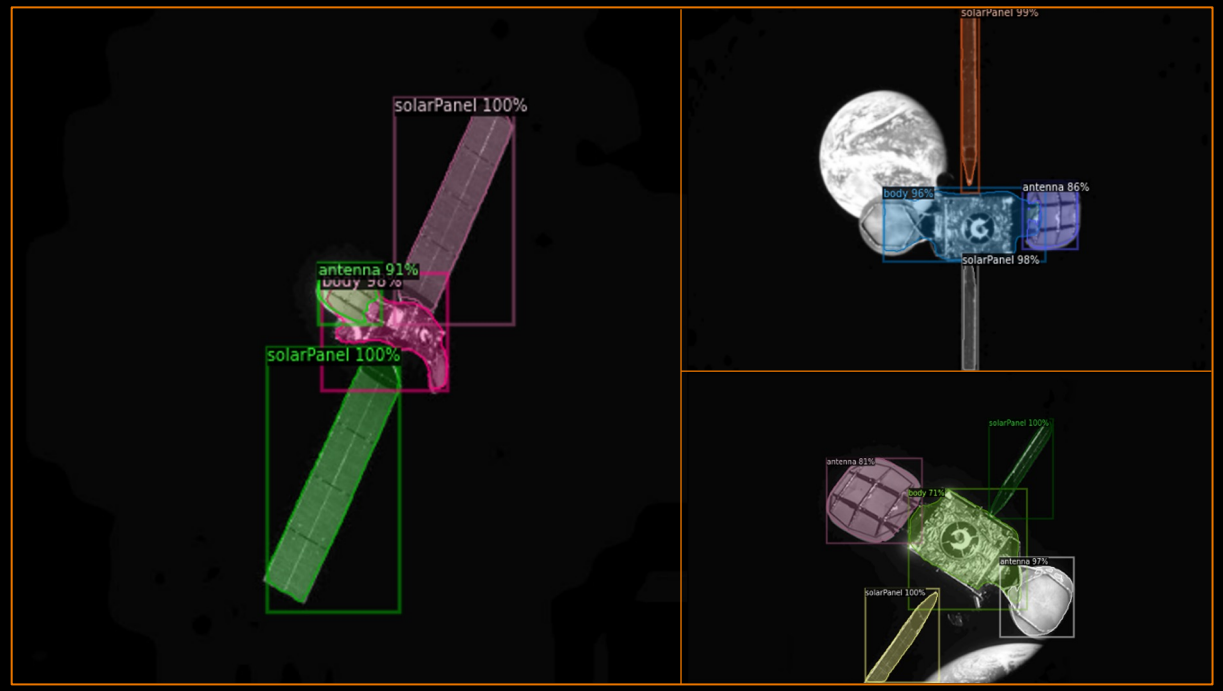
Bapst J, et al. Mars Science Helicopter: Compelling Science Enabled by an Aerial Platform. Bulletin of the AAS, 2021, 53(4), https://baas.aas.org/pub/2021n4i361

Artificial bodies

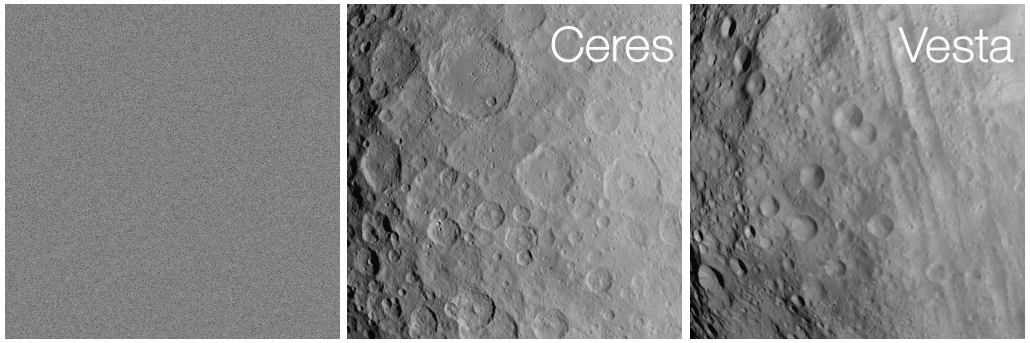


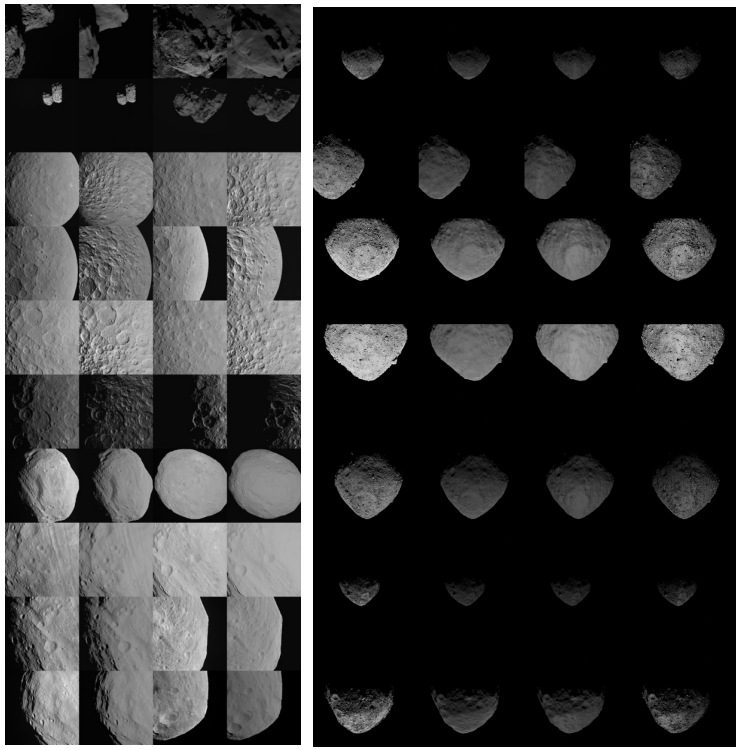
- **Binary masks** are generated for each component of the spacecraft using Blender's compositor nodes.
- These can be used as the **ground truth** for the training of ML algorithms.

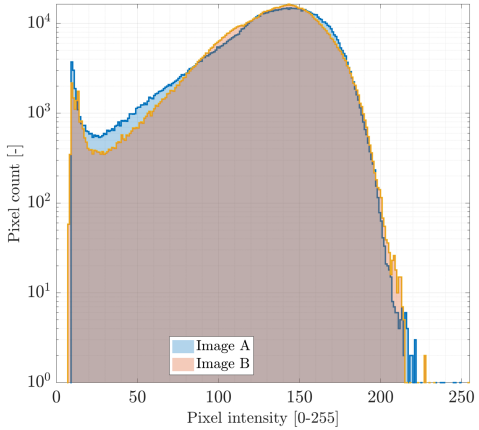
- **Inference on real** space imagery from the MEV-1 mission showed promising results.

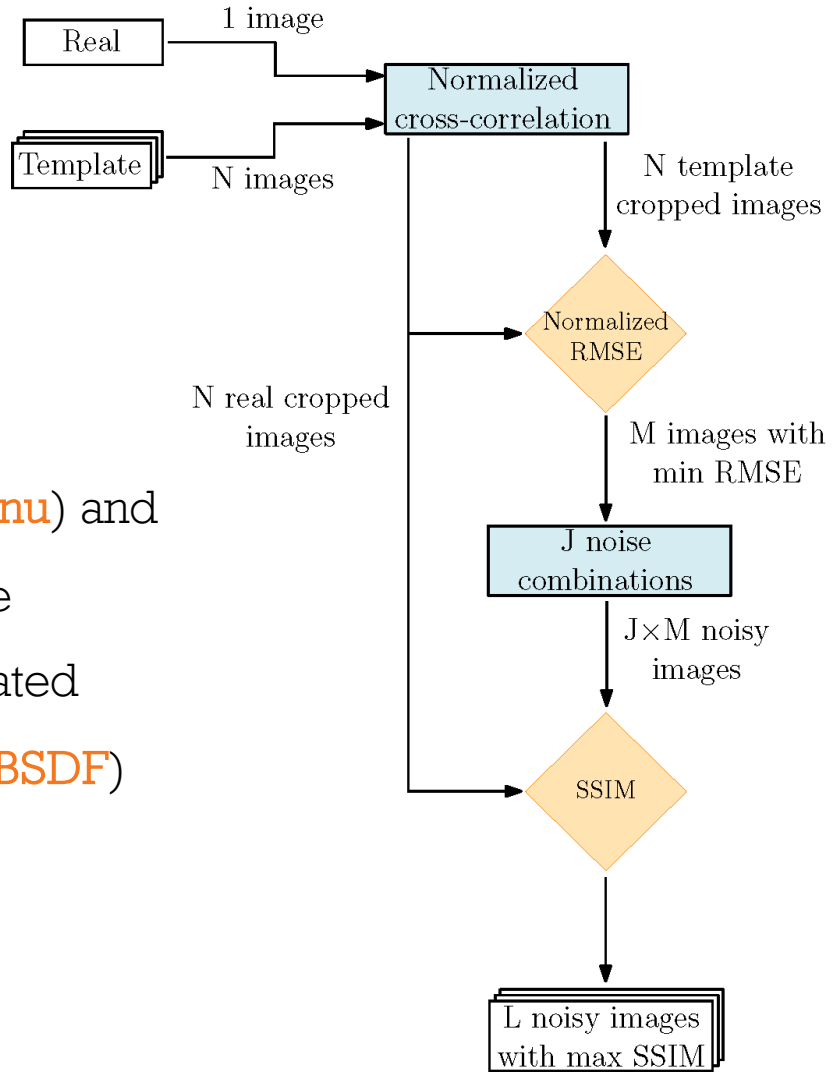


Validation







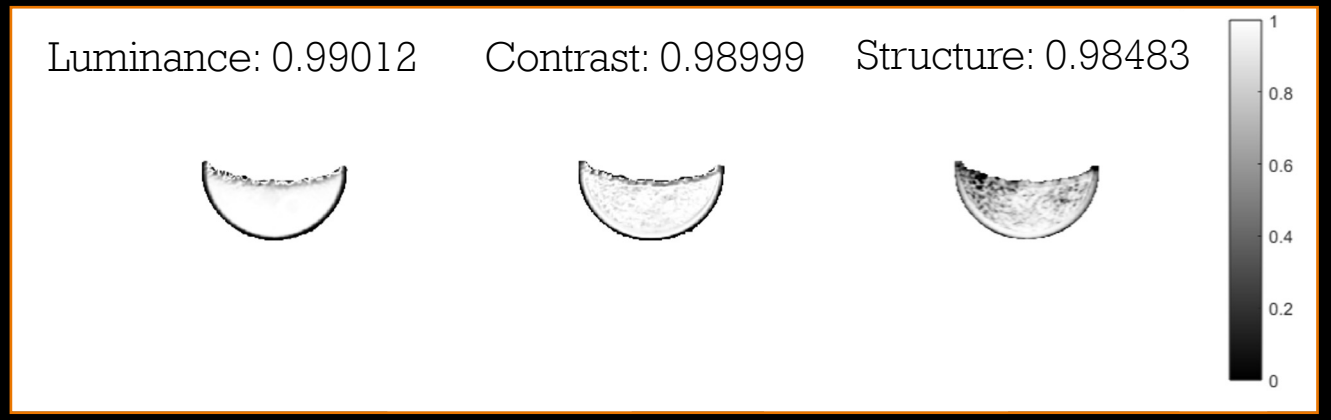


- Automatic (67P, Ceres, Vesta, Bennu) and manual (Moon) validation pipeline
- Different shading options investigated (Textures, Principled BSDF, OSL-BSDF)
- Combining different metrics and assessments: NCC, histogram comparison, SSIM and RMSE

Radiometric calibration

- A radiometric calibration pipeline tunes the Blender solar strength parameter so to deliver the correct radiometric content
- After calibration, CORTO renderings against real space images (SMART-1 mission) matches the radiometry at the same exposure time
- Differences expected due to kernel inaccuracies and absence of noise/diffraction effects

CORTO rendering (left) vs real image (right) at 30 ms exposure time



Quantitative analysis of image matching using SSIM. 1 = best score

Publications

GIT REPOSITORY

https://github.com/MattiaPugliatti/corto

JOURNAL PAPERS

Buonagura, C. and Pugliatti, M. and Topputo, F. MONET: The Minor bOdy geNErator Tool at DART lab. MDPI Sensors 24 (11), 3658 (2024). https://doi.org/10.3390/s24113658.

Pugliatti, M. and Buonagura, C. and Topputo, F. CORTO: The Celestial Object Rendering TOol at DART Lab. MDPI Sensors 23 (23), 9595 (2023). https://doi.org/10.3390/s23239595

CONFERENCE PAPERS

Pugliatti, M. and Buonagura, C. and Pisanti, D. and Faraco, N. and Pizzetti, A. and Meastrini, M. and Topputo, F. DESIGN AND CASES STUDIES OF CORTO, AN OPEN ACCESS RENDERING TOOL FOR CELESTIAL AND ARTIFICIAL BODIES. 75th International Astronautical Congress, Oct 2024.

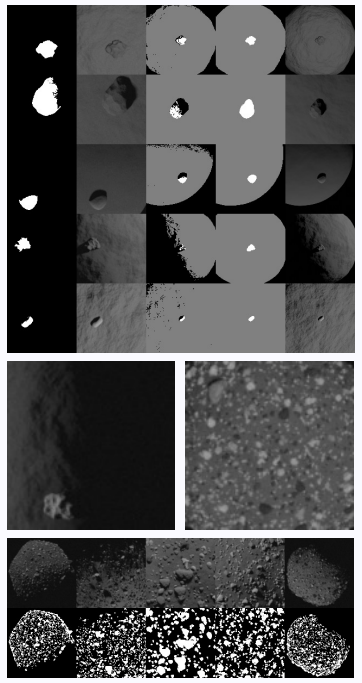
Buonagura C., Pugliatti M., Franzese V., Topputo F., Zeqaj A., Zannoni M., Varile M., Bloise I., Fontana F., Rossi F., Feruglio L. and Cardone M.; Deep Learning for Navigation of Small Satellites About Asteroids: an Introduction to the Deepnav Project. 2nd International Conference on Applied Intelligence and Informatics (AII2022), Sep 2022.

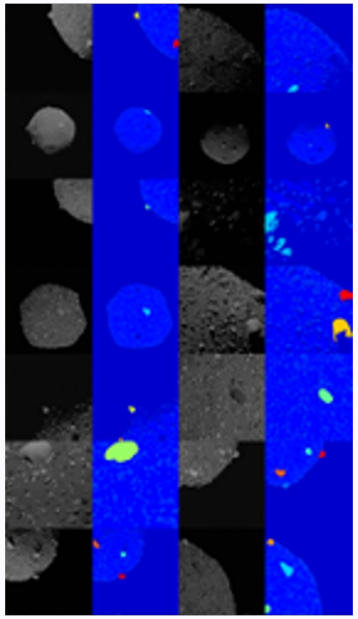
Datasets

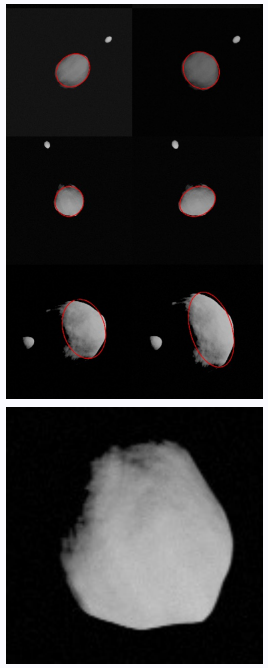
DOORS: Dataset fOr bOuldeRs Segmentation, Pugliatti, M. and Topputo, F.(https://zenodo.org/records/7107409). October 2022. [Size 2.7 GB, 791 views, 178 downloads] {Regression, Segmentation }

The image processing of Milani: challenges after DART impact, Pugliatti, M., Giordano, C. and Topputo, F. (https://zenodo.org/records/7962714). May 2023. [Size 7.3 Gb, 357 views, 30 downloads] {Regression, Object recognition}

A multi-scale labeled dataset for boulder segmentation and navigation on small bodies, Pugliatti, M., Maestrini, M. (https://zenodo.org/records/8406581). October 2023. [Size 7.3 Gb, 275 views, 15 downloads] {Regression, Segmentation}

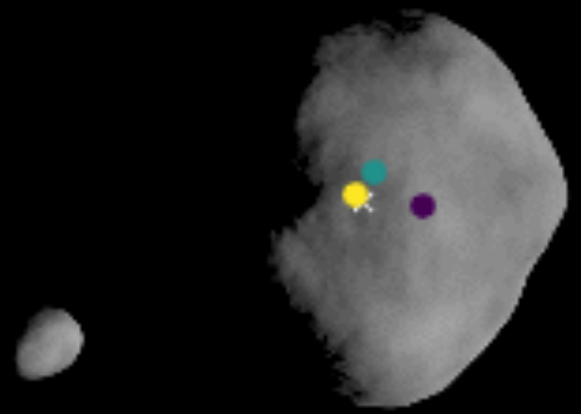






Thank you for the attention!

https://github.com/MattiaPugliatti/corto



POLITECNICO MILANO 1863

European Research Council
Established by the European Commission

EXTREMA

Overview of testing and simulation capabilities of the EXTREMA Simulation Hub

Di Domenico Gianfranco

DIPARTIMENTO DI SCIENZE E TECNOLOGIE AEROSPAZIALI

DART Group

October 23, 2024

esa

EXTREMA

To what extent can we navigate the solar system free of human supervision?

The Engineering Extremely Rare Events in Astrodynamics for Deep-Space Missions in Autonomy (EXTREMA) project wants to challenge and revolutionize the current paradigm under which spacecraft are piloted in the interplanetary space.

EXTREMA

European Research Council
Established by the European Commission

Pillar 1
Autonomous Navigation

Pillar 2
Autonomous Guidance

Pillar 3
Autonomous Ballistic Capture

Experiment 1
EXTREMA Optical Facility

Experiment 2
EXTREMA Thrust Test Bench

Experiment 3
Ballistic Capture Corridors

EXTREMA Simulation Hub (ESH)

IMPACT

The EXTREMA Simulation Hub

RETINA Optical Facility

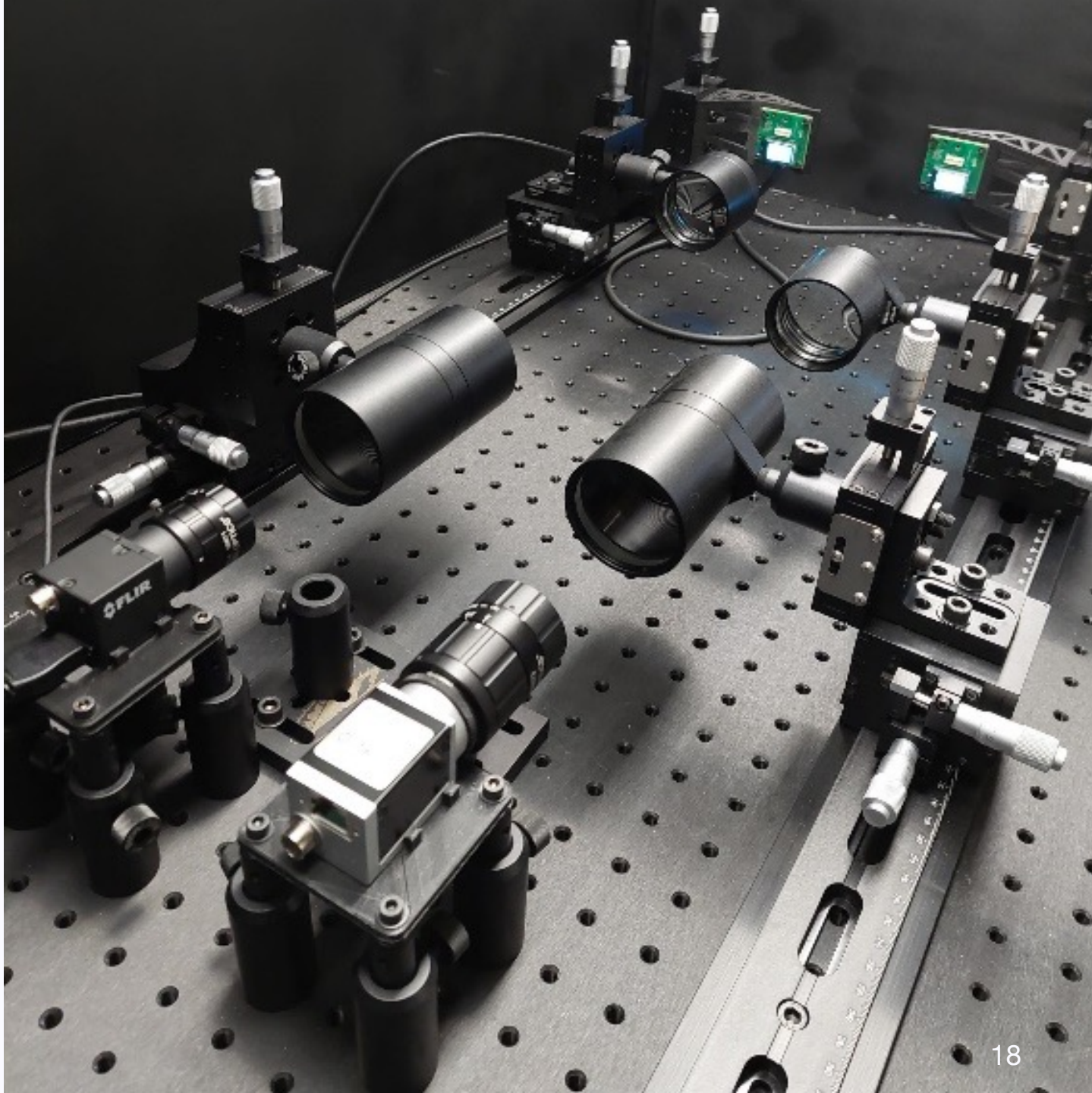
Geometrically and **radiometrically** calibrated (photon-count calibration)

Dual-line optics for advanced image processing pipelines

Covers a **wide range of camera FOVs**

Can host CubeSats **cameras** and **star trackers**

Integrated **rendering system**



ETHILE Thrust Test Bench

- Configurable with **multiple electrical engines profiles**
- **Throttling** can be commanded or set by external conditions (i.e., reduced power from solar array)
- Thruster-in-the-loop procedure takes into account **unmodeled variations** of the thrust vector

European Research Council
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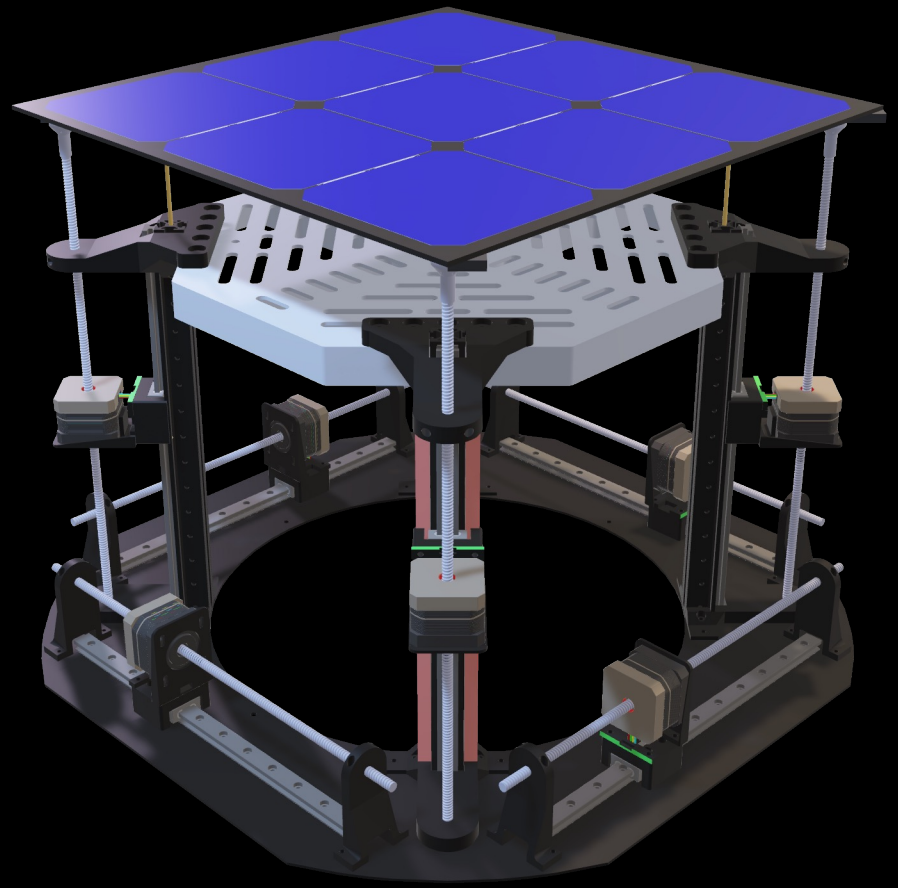
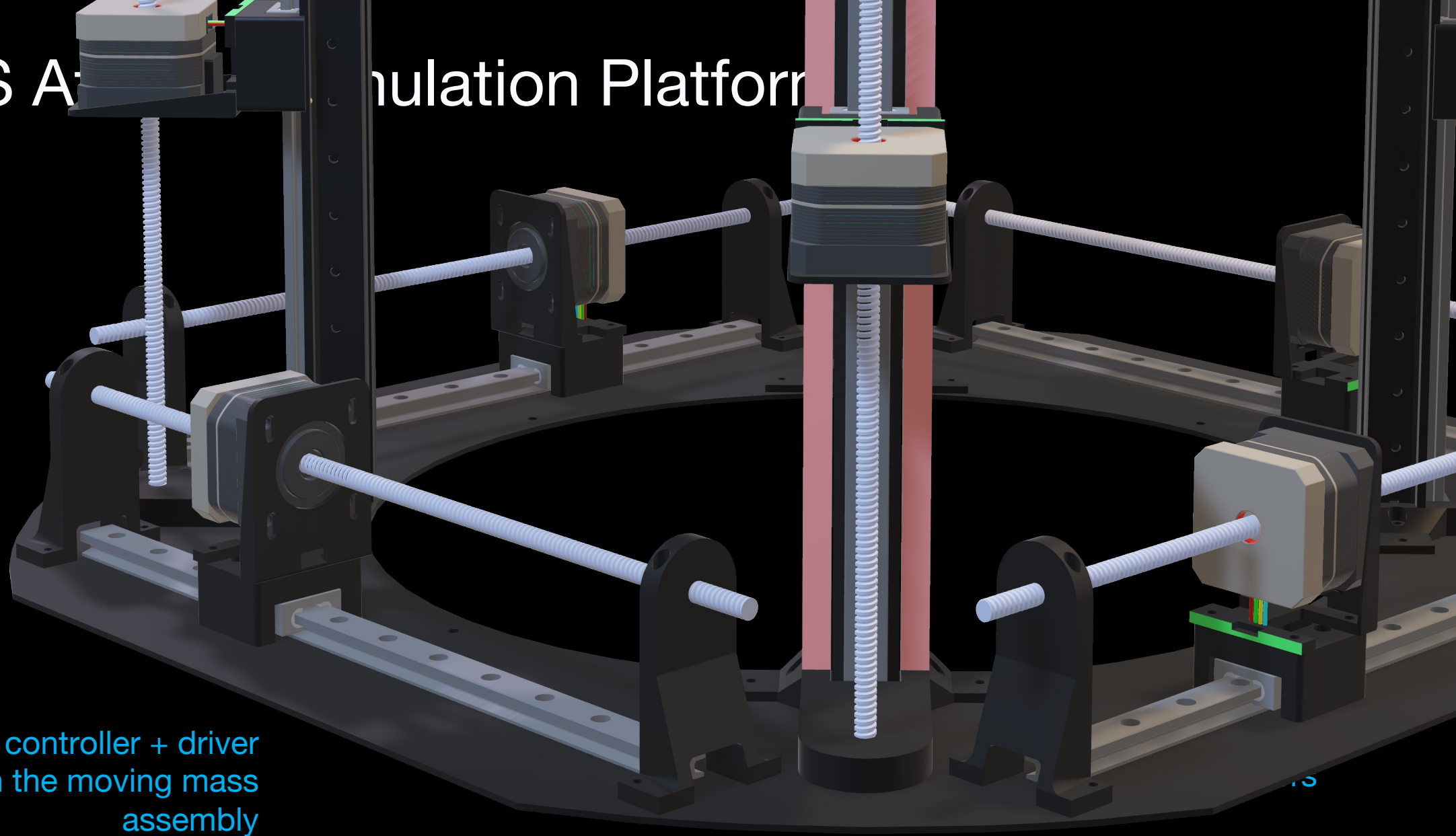
EXTREMIA

STASIS Attitude Simulation Platform

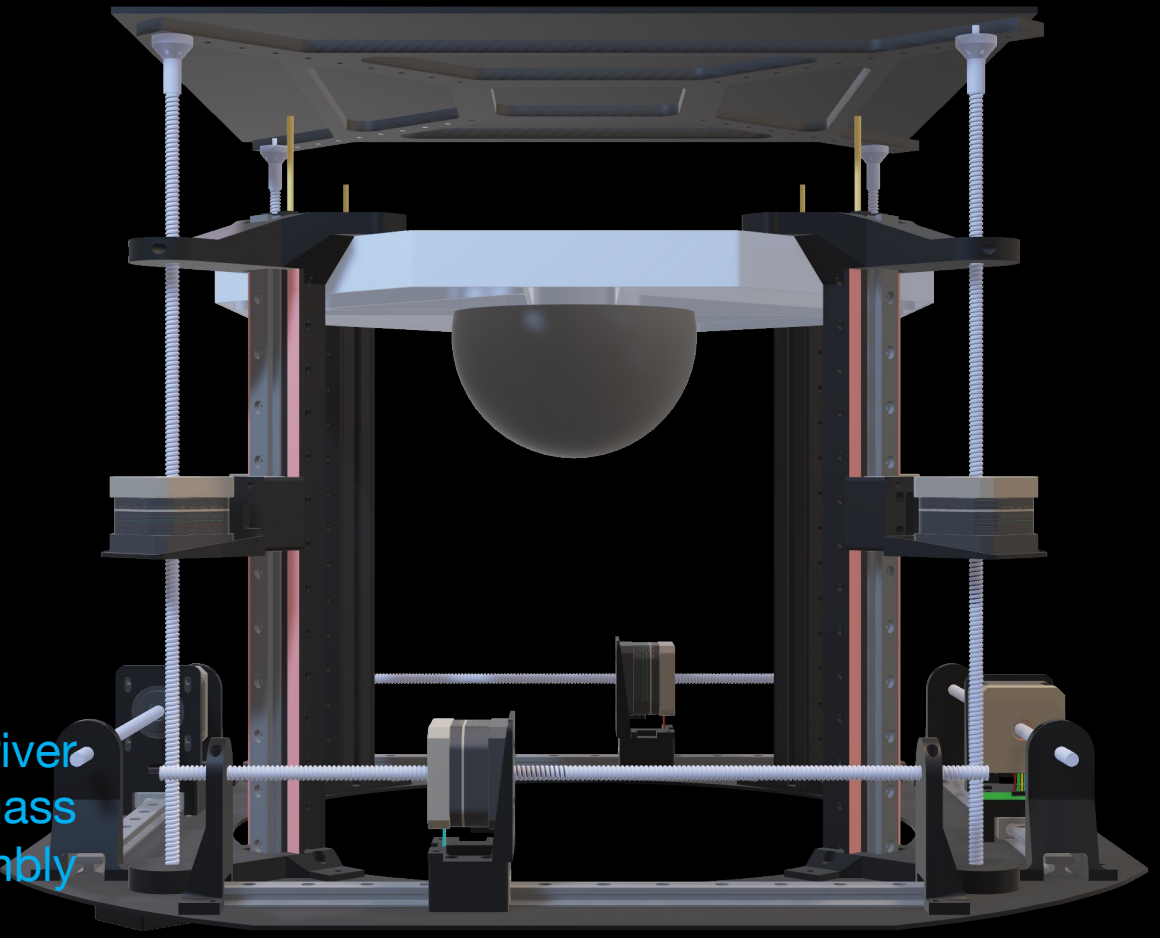


STASIS A nulation Platform



Stepper motor controller + driver integrated in the moving mass assembly

STASIS Attitude Simulation Platform

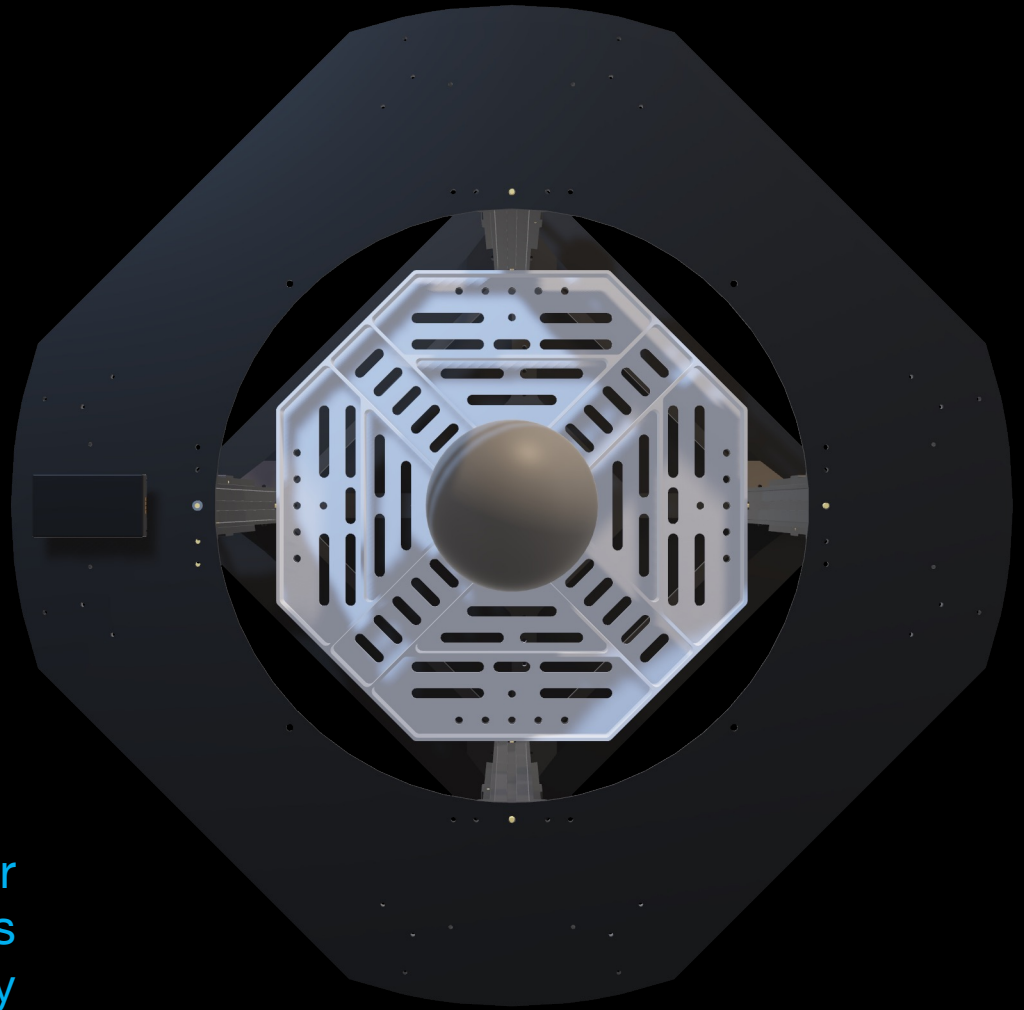


Rigid brass rod connections for power distribution

Stepper motor controller + driver integrated in the moving mass assembly

STASIS Attitude Simulation Platform

Bottom board as structural and power management unit



Rigid brass rod connections for power distribution

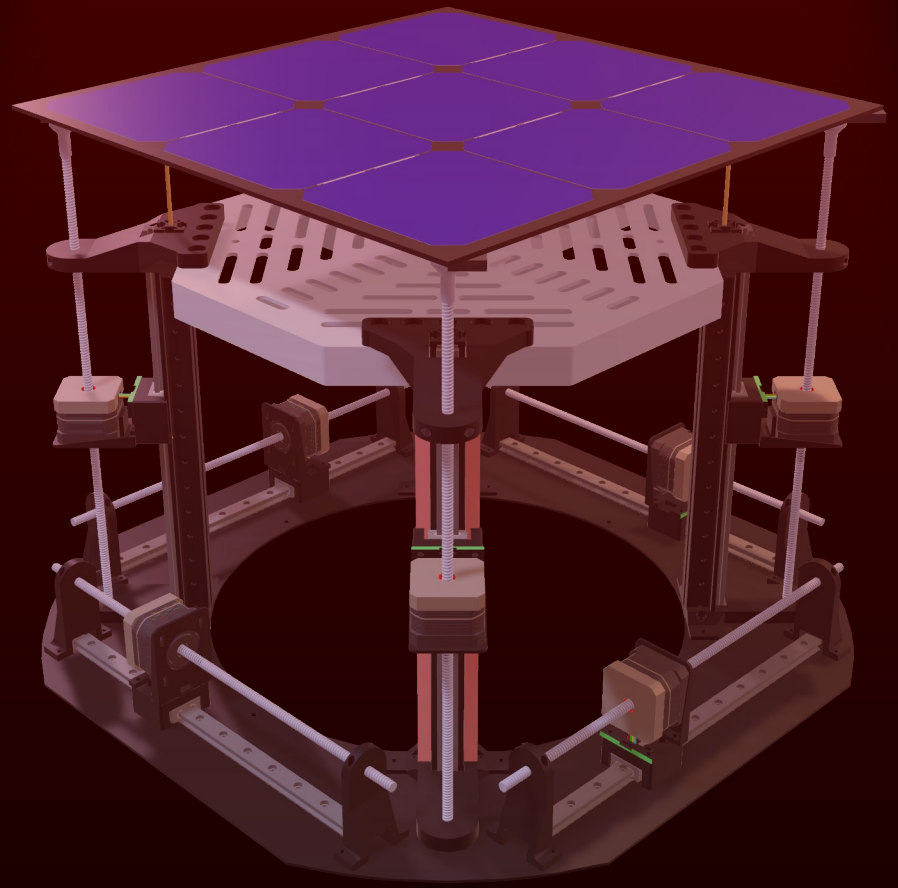
Stepper motor controller + driver integrated in the moving mass assembly

Sliding contact surfaces for wireless power to motors

STASIS Attitude Simulation Platform

Wireless power beaming system

Bottom board as structural and power management unit



Rigid brass rod connections for power distribution

Stepper motor controller + driver integrated in the moving mass assembly

Sliding contact surfaces for wireless power to motors

STASIS Attitude Ground Truth System

ACCURACY

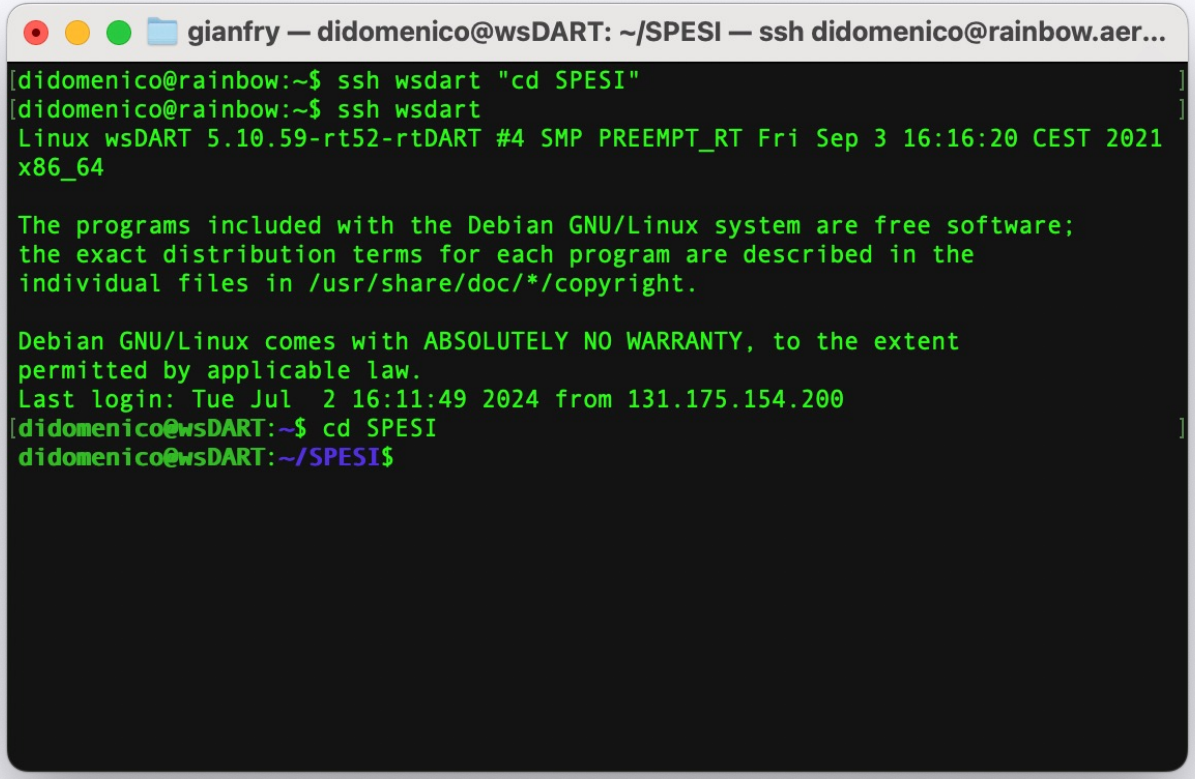
45 arcsec

RATE

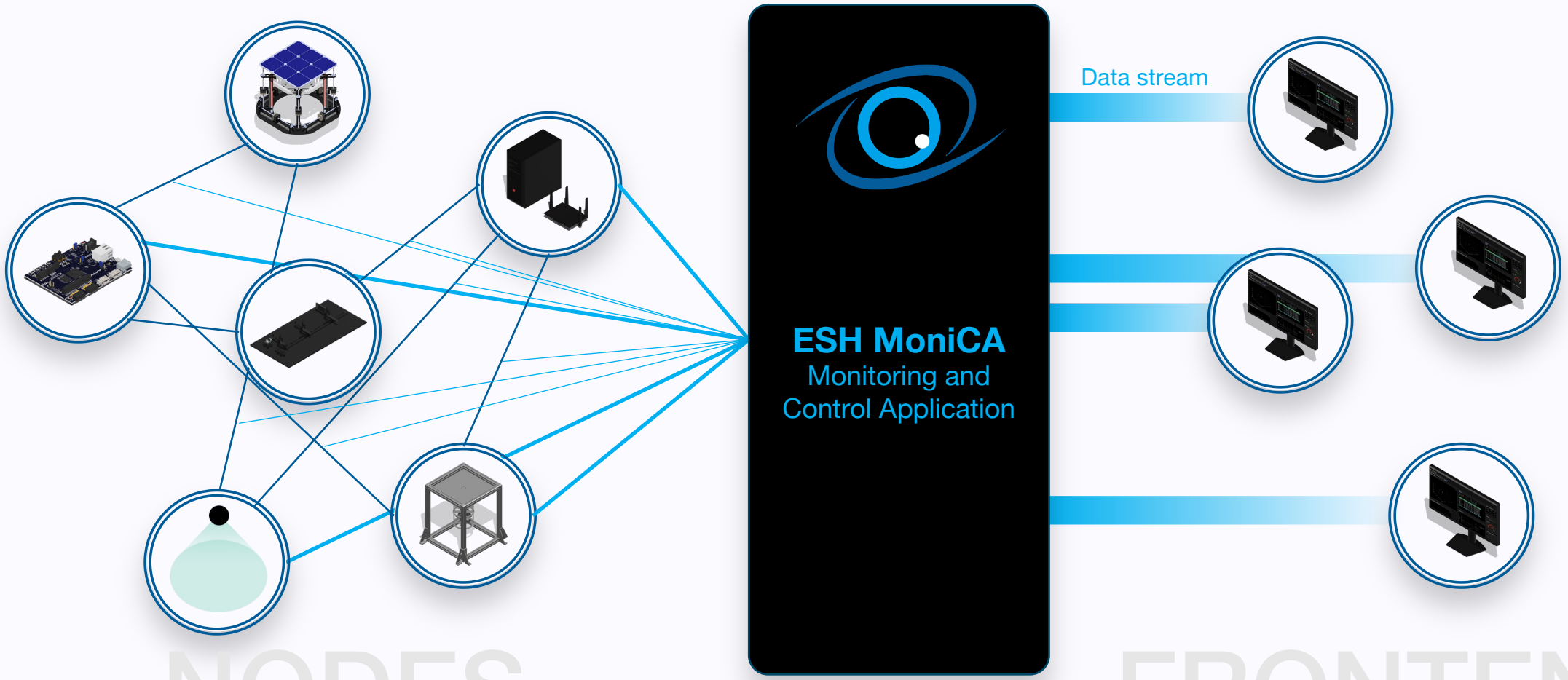
55 Hz

SPESI – the Space Environment Simulator

- Based on **RT-Linux**
- **Stochastic numerical propagator** with real-time integration with existing facilities
- **SIMD-based computations** for minimal latency and maximum fidelity
- Propagates the **virtualized degrees of freedom** with numerically and physically accurate environmental models



MoniCA (Monitoring and Control Application)

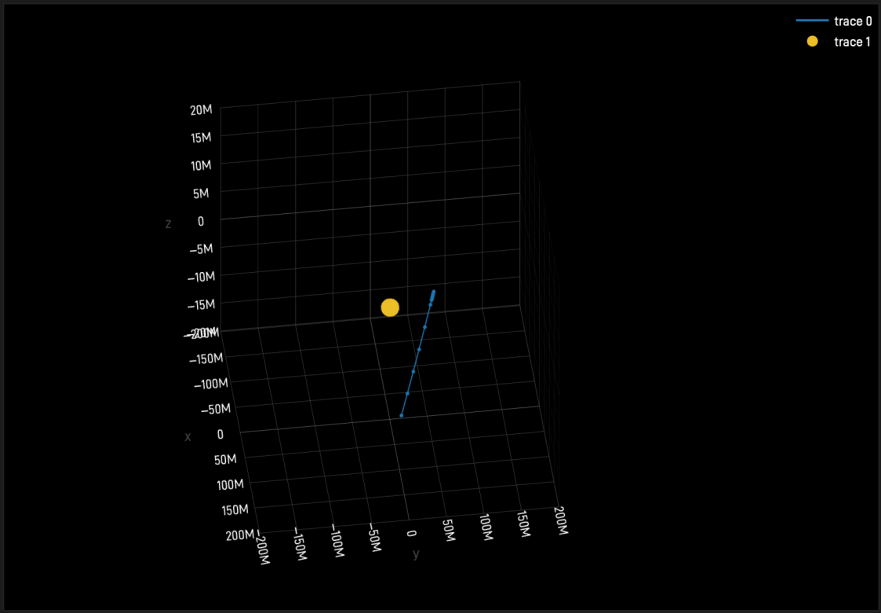


MoniCA Demo

Fork and modify me to demonstrate your issue when creating an issue for gridstack.js

STASIS Balancing | Scenario Generator Start session

SPESI integrator



Terminal2

Disconnect

```
  0[|                        0.6%]   Tasks: 57, 118 thr; 1 running
  1[                         0.0%]   Load average: 0.06 0.03 0.00
  2[||                       3.2%]   Uptime: 10 days, 23:24:46
  3[                         0.0%]
Mem[||||||||||||||||1.09G/3.71G]
Swp[|||||||              25.5M/100.0M]

    PID USER      PRI  NI  VIRT   RES   SHR S CPU%▽MEM%   TIME+  Command
 100752 pi         20   0  825M 51312 36544 S  0.0  1.3  0:00.00
 100758 pi         20   0  825M 51312 36544 S  0.0  1.3  0:00.00
 100759 pi         20   0  825M 51312 36544 S  0.0  1.3  0:00.61
 100761 pi         20   0 5439M  511M 47468 S  0.0 13.5  1:08.84
 100762 pi         20   0 5439M  511M 47468 S  0.0 13.5  0:00.02
 100763 pi         20   0 5439M  511M 47468 S  0.0 13.5  0:03.23
 100764 pi         20   0 5439M  511M 47468 S  0.0 13.5  0:03.58
 100765 pi         20   0 5439M  511M 47468 S  0.0 13.5  0:03.48
 100766 pi         20   0 5439M  511M 47468 S  0.0 13.5  0:03.70
 100767 pi         20   0 5439M  511M 47468 S  0.0 13.5  0:00.00
 100768 pi         20   0 5439M  511M 47468 S  0.0 13.5  0:00.85
 100769 pi         20   0 5439M  511M 47468 S  0.0 13.5  0:00.84
 100770 pi         20   0 5439M  511M 47468 S  0.0 13.5  0:00.84
 100771 pi         20   0 5439M  511M 47468 S  0.0 13.5  0:00.84
F1Help  F2Setup F3SearchF4FilterF5List  F6SortByF7Nice -F8Nice +F9Kill  F10Quit
```

Estimated attitude DCM

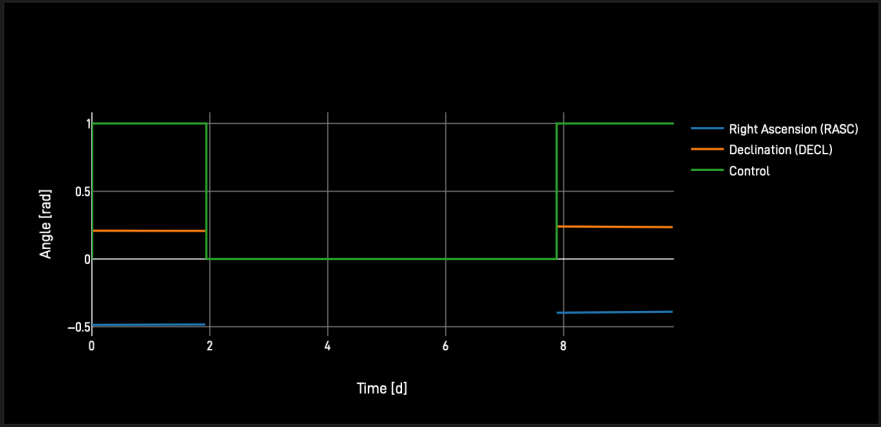
0.229	0.973	0.000
-0.118	0.028	-0.993
-0.966	0.227	0.121

FlatSat Status

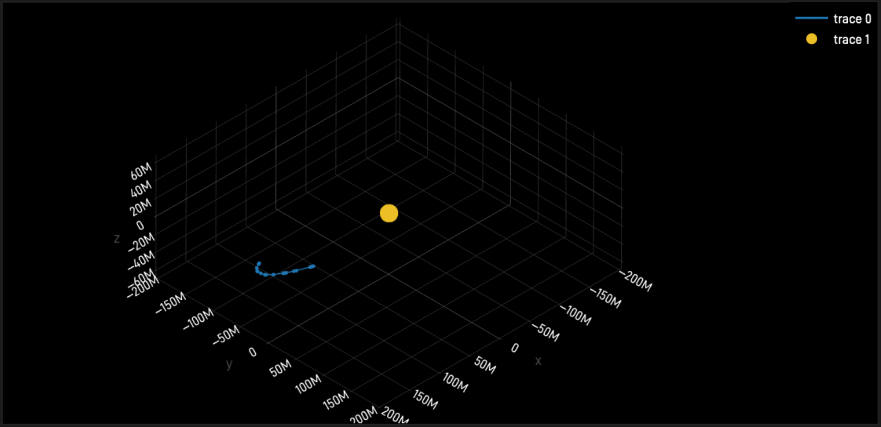
EXDIRGCU

Solar Lamp

Guidance Solution



Estimated Spacecraft Trajectory



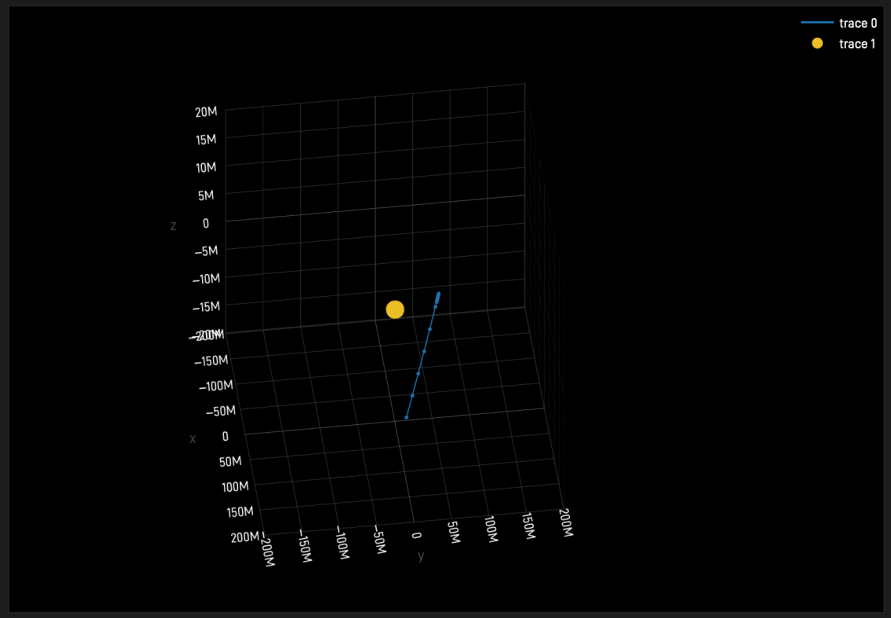
MoniCA Demo

Fork and modify me to demonstrate your issue when creating an issue for gridstack.js

STASIS Balancing | Scenario Generator Start session

Real spacecraft Trajectory

SPESI integrator



Fully-functional sandboxed web terminal

Terminal2

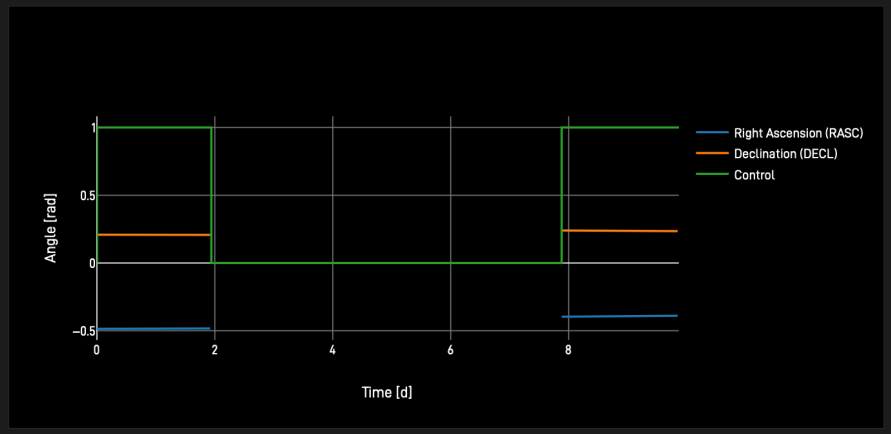
Disconnect

```
  0[|                        0.6%]   Tasks: 57, 118 thr; 1 running
  1[                         0.0%]   Load average: 0.06 0.03 0.00
  2[||                       3.2%]   Uptime: 10 days, 23:24:46
  3[                         0.0%]
Mem[||||||||||||||||1.09G/3.71G]
Swp[|||||||           25.5M/100.0M]

    PID USER      PRI  NI  VIRT   RES   SHR S CPU%▽MEM%   TIME+  Command
 100752 pi         20   0  825M 51312 36544 S  0.0  1.3  0:00.00
 100758 pi         20   0  825M 51312 36544 S  0.0  1.3  0:00.00
 100759 pi         20   0  825M 51312 36544 S  0.0  1.3  0:00.61
 100761 pi         20   0 5439M  511M 47468 S  0.0 13.5  1:08.84
 100762 pi         20   0 5439M  511M 47468 S  0.0 13.5  0:00.02
 100763 pi         20   0 5439M  511M 47468 S  0.0 13.5  0:03.23
 100764 pi         20   0 5439M  511M 47468 S  0.0 13.5  0:03.58
 100765 pi         20   0 5439M  511M 47468 S  0.0 13.5  0:03.48
 100766 pi         20   0 5439M  511M 47468 S  0.0 13.5  0:03.70
 100767 pi         20   0 5439M  511M 47468 S  0.0 13.5  0:00.00
 100768 pi         20   0 5439M  511M 47468 S  0.0 13.5  0:00.85
 100769 pi         20   0 5439M  511M 47468 S  0.0 13.5  0:00.84
 100770 pi         20   0 5439M  511M 47468 S  0.0 13.5  0:00.84
 100771 pi         20   0 5439M  511M 47468 S  0.0 13.5  0:00.84
F1Help  F2Setup F3Search F4Filter F5List  F6SortBy F7Nice -F8Nice +F9Kill  F10Quit
```

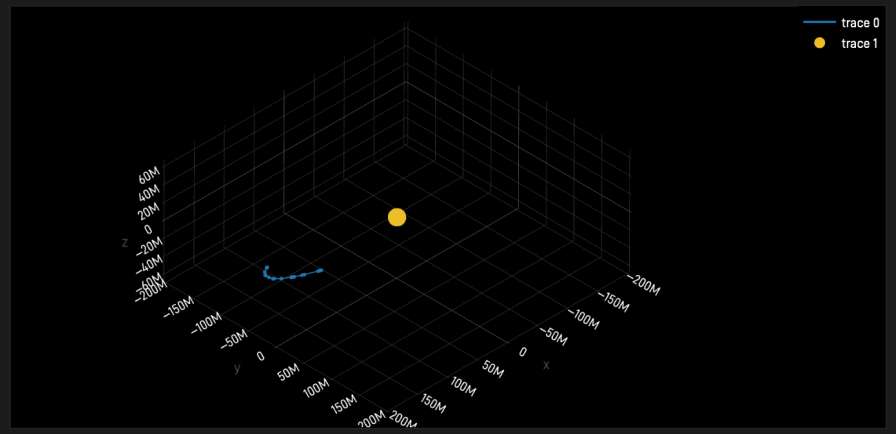
Last Computed Guidance Solution

Guidance Solution



Spacecraft Estimated State

Estimated Spacecraft Trajectory



Spacecraft Telemetry

Estimated attitude DCM

0.229	0.973	0.000
-0.118	0.028	-0.993
-0.966	0.227	0.121

FlatSat Status

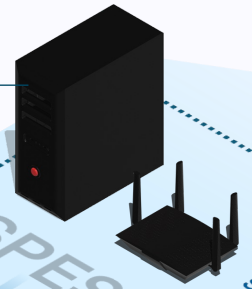
EXDIRGCU

Solar Lamp

Control widgets

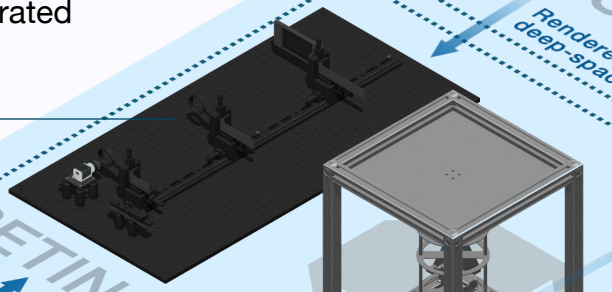
ESH

Real-time stochastic integrator
Integrated deep-space scene renderer

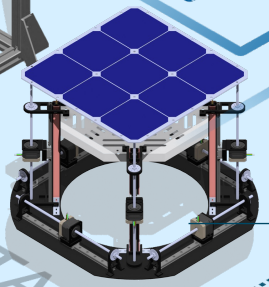


Allows operators to monitor variables of interest
Control capabilities at both simulation and device level

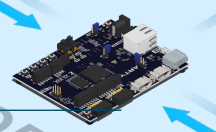
Radiometrically and geometrically calibrated
Hosts the spacecraft camera
Captures the image when commanded



Senses the real executed thrust value
Estimates the actual platform orientation



Replicates spacecraft attitude in space
Hosts OBC and ADCS suite

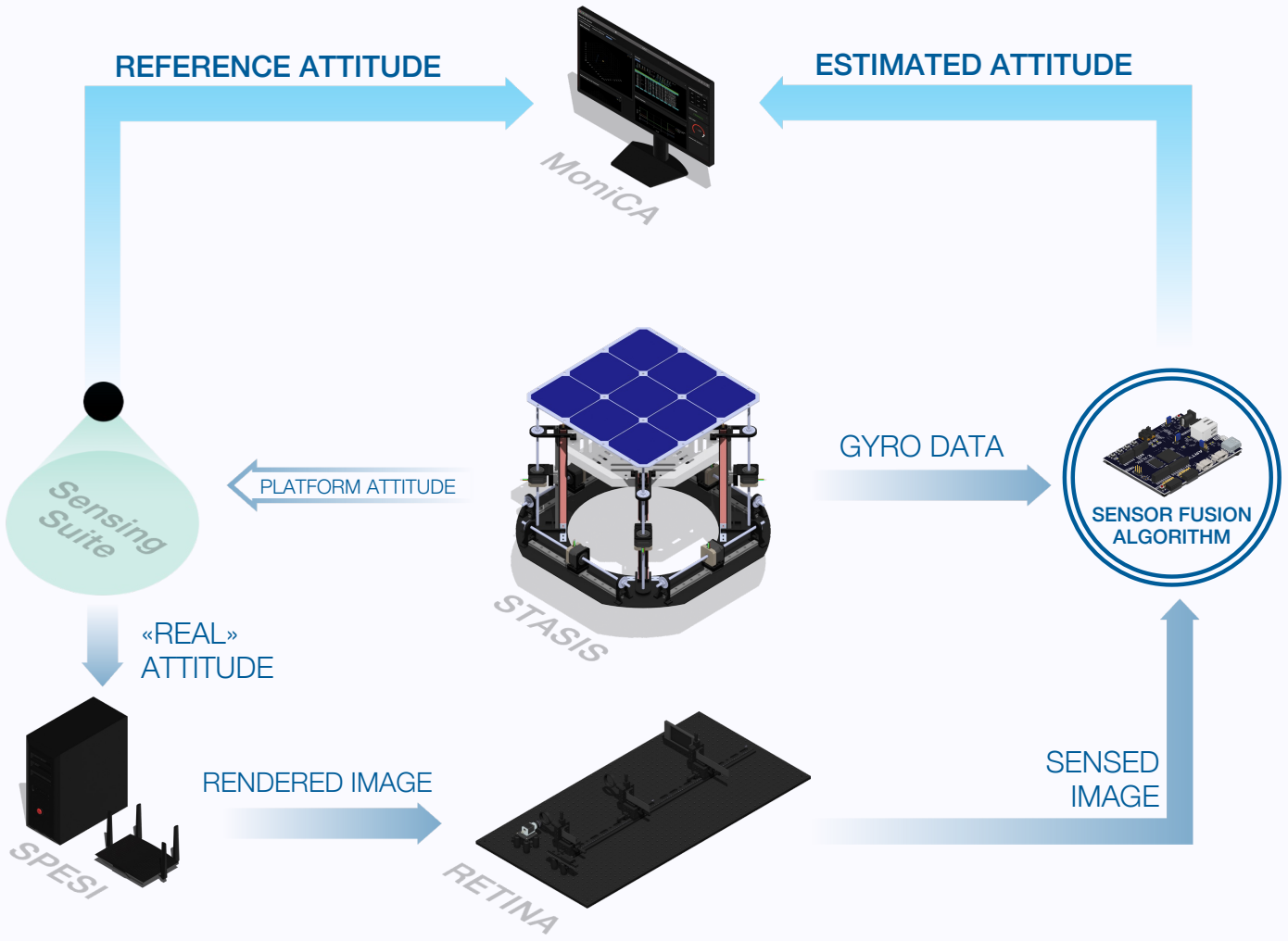


Representative processor
Runs autonomous GNC algorithms
Controls and commands HW facilities

Executes thrust command outputs
Simulates low-thrust electrical engines

Use cases

Use case. Hardware-in-the-loop attitude determination.

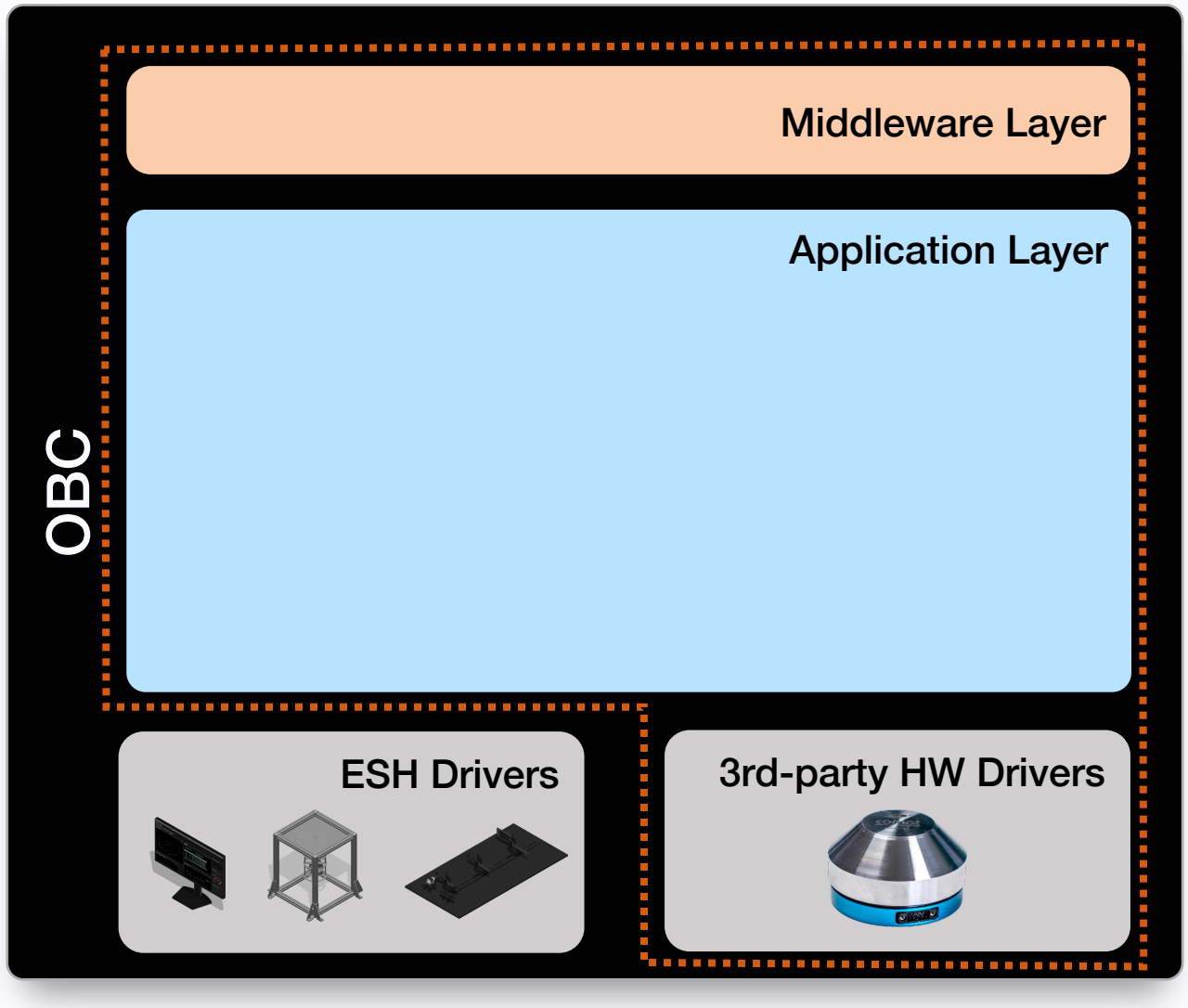


This setup allows V&V procedures for **attitude estimation algorithms** combining both gyroscope data (mounted on STASIS) and star trackers (mounted inside RETINA).

Both estimations and reference quantities can be monitored directly from the MoniCA interface.

The same setup can be further employed for **characterizing** the hardware.

Use case. On-board FSW V&V (down to driver level).

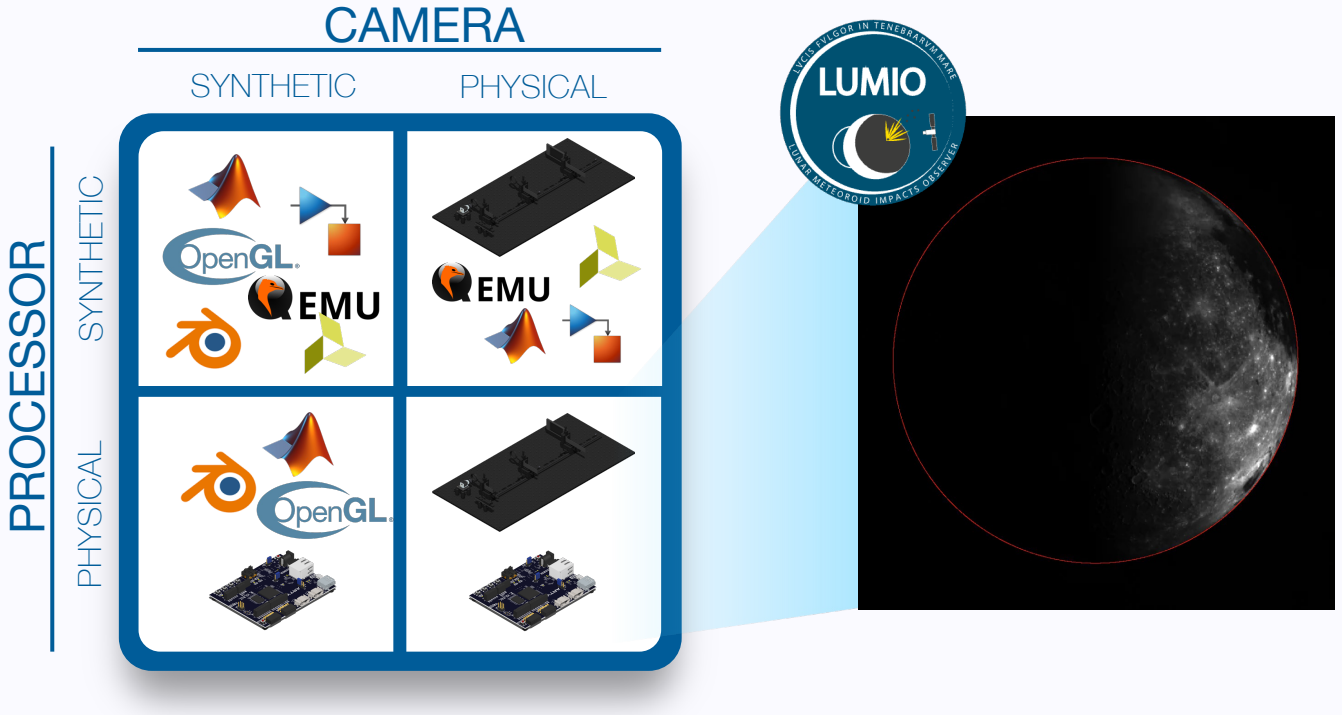


The possibility of employing custom hardware in an integrated simulation settings allows testing on-board flight software down to the driver level.

As an example, in the case of GNC systems, this approach allows testing system without abstraction levels, integrating low-level states with goal-oriented algorithms in configurable mission scenarios.

In 2023, we received a RW40 reaction wheel from COMAT, and succesfully wrote and tested drivers for the wheel, validating its datasheet performances.

Use case. P/C/PC-in-the-loop navigation V&V.

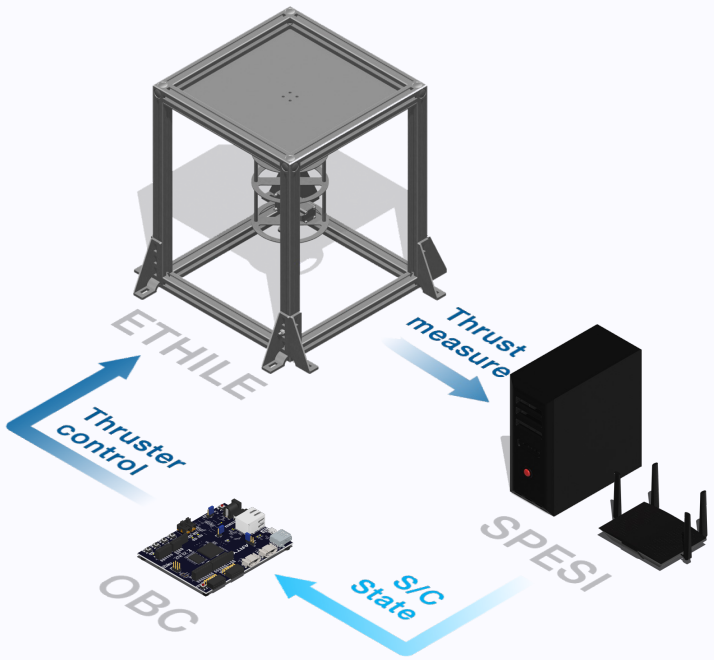


A configurable optical facility allows to complement existing V&V procedures for navigation algorithms, starting from synthetic models **for both the camera and the on-board processor/IPU.**

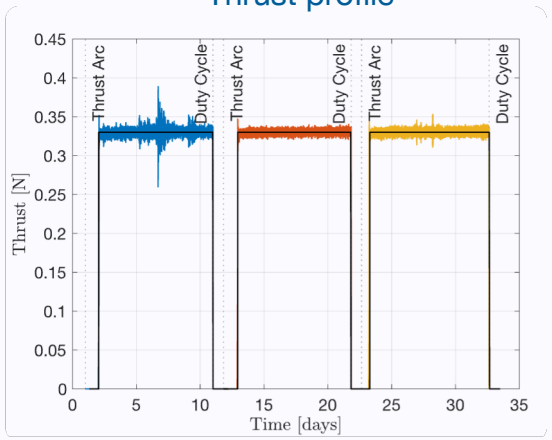
It is possible to progress from a full synthetic simulation to a **full physical one**, keeping the existing image processing pipelines, additionally accounting for unmodeled effects of the camera.

This is the approach followed for the validation of the **LUMIO Image Processing Pipeline.**

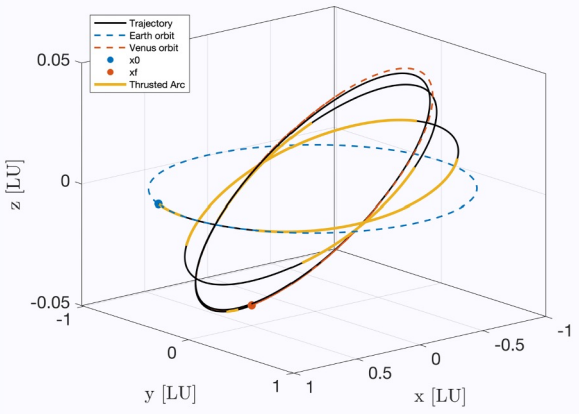
Use case. Closed-loop guidance algorithm with physical thruster.



Thrust profile



Trajectory



The thruster-in-the-loop setup allows to validate **closed-loop guidance approaches** in a real-time simulation framework, accounting for variable thrust profiles.

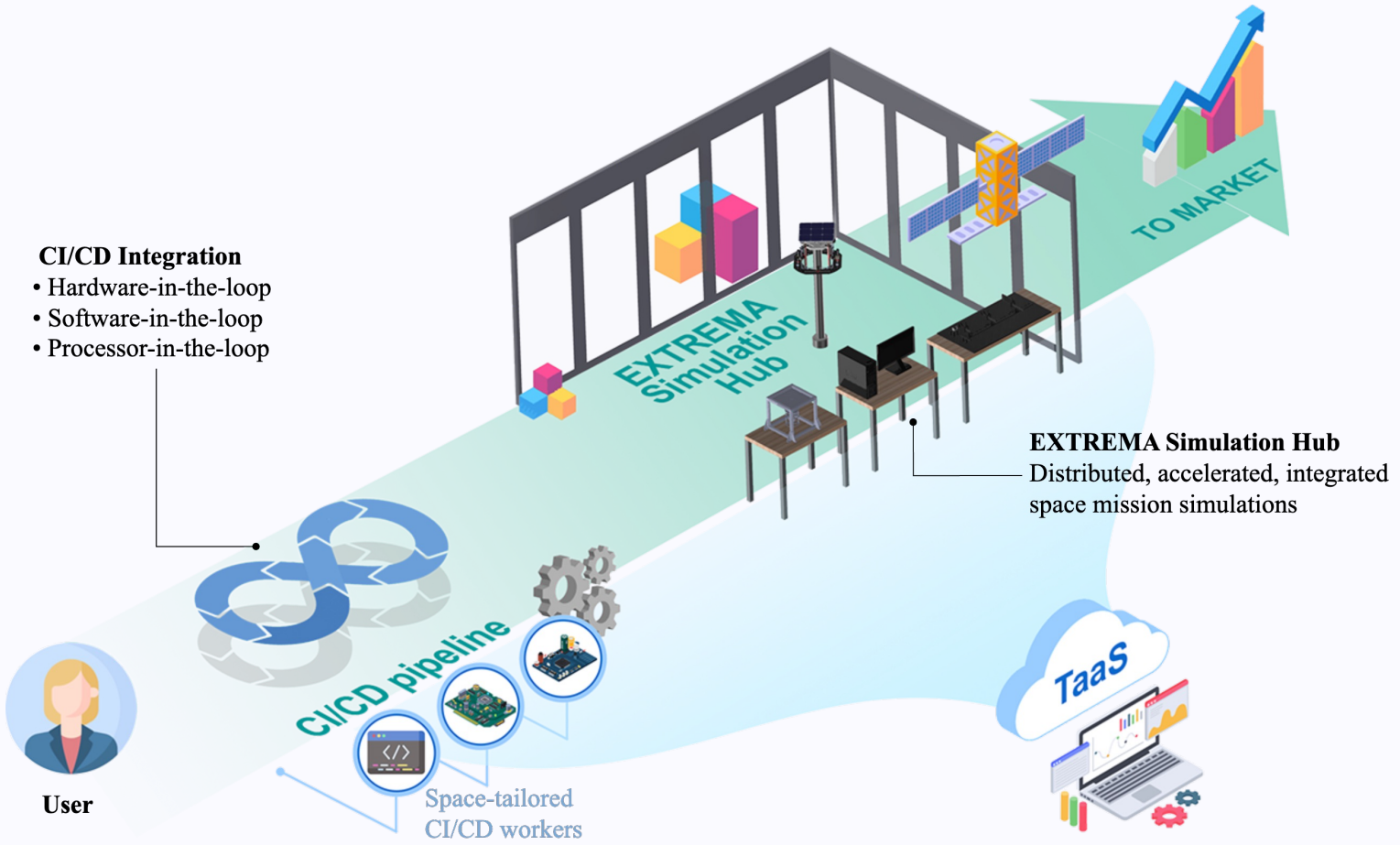
Moreover, the thrust measurement system allows accounting for unmodeled variations in the thrust profile, such as thruster beam-out phenomena.

Such an approach allows to validate the **convergence and performance** of the optimization algorithms with initial conditions within expected operative conditions.

ERC-2024-PoC

AXESS

Accelerated X-in-the-loop Environment for Spacecraft Systems Testing



AXESS

CI/CD Integration

- **Dedicated workers** for space applications
- Integration with existing **versioning and CI/CD tools**
- Allows code validation at **instruction level**
- Permits performance-based **hardware trade-offs**

On-demand ESH

- Integration of **custom hardware** in ESH facilities
- **Test automation** with real hardware feedback
- **Accelerated framework** allows faster HiL simulations
- **On-demand format** lowers entry bar for smaller players

AXESS

European Research Council
Established by the European Commission

Summing up

ESH Stack

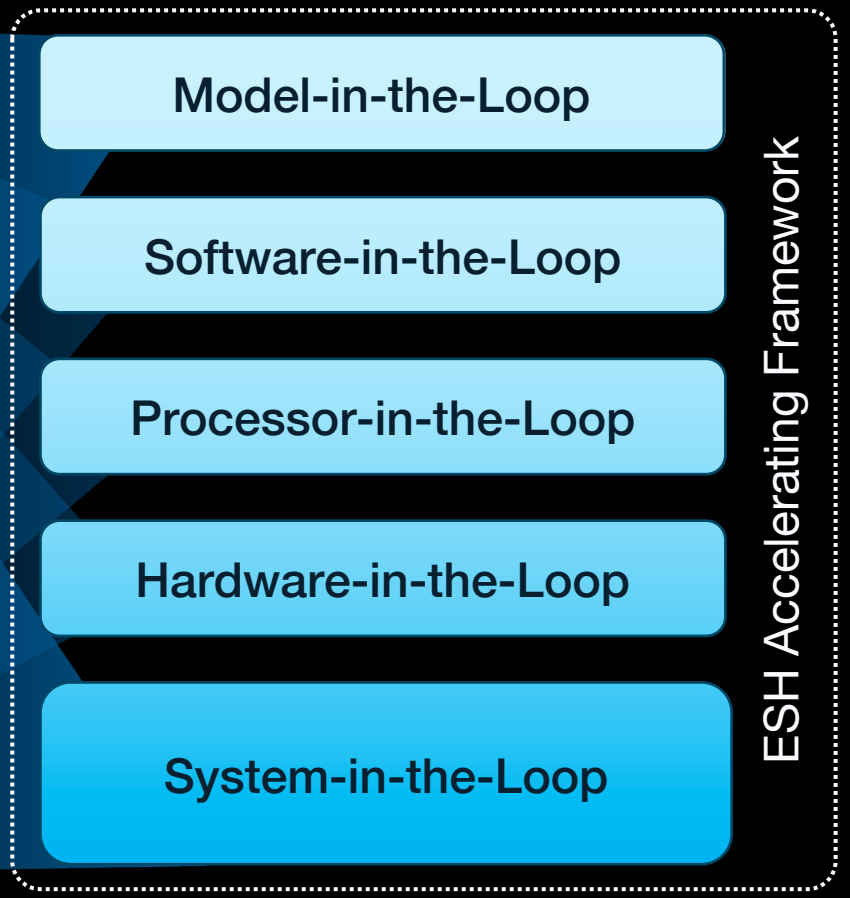
- RETINA Optical Facility
- ETHILE Thrust Test Bench
- STASIS Attitude Simulator
- ELAPSE On-board RT Software
- SPESI Propagator and Renderer
- ESH Sensing Suite
- MoniCA Monitoring & Control

Workflows

ESH Accelerating Framework

- Model-in-the-Loop
- Software-in-the-Loop
- Processor-in-the-Loop
- Hardware-in-the-Loop
- System-in-the-Loop

Workflows



The ESH is open to third parties to demonstrate its testing and V&V capabilities on small spacecraft subsystems and components.

POLITECNICO
MILANO 1863

European Research Council
Established by the European Commission

EXTREMIA

This project has received funding from the European Research Council (ERC) under the European Union's Horizon 2020 research and innovation programme (grant agreement No. 864697)

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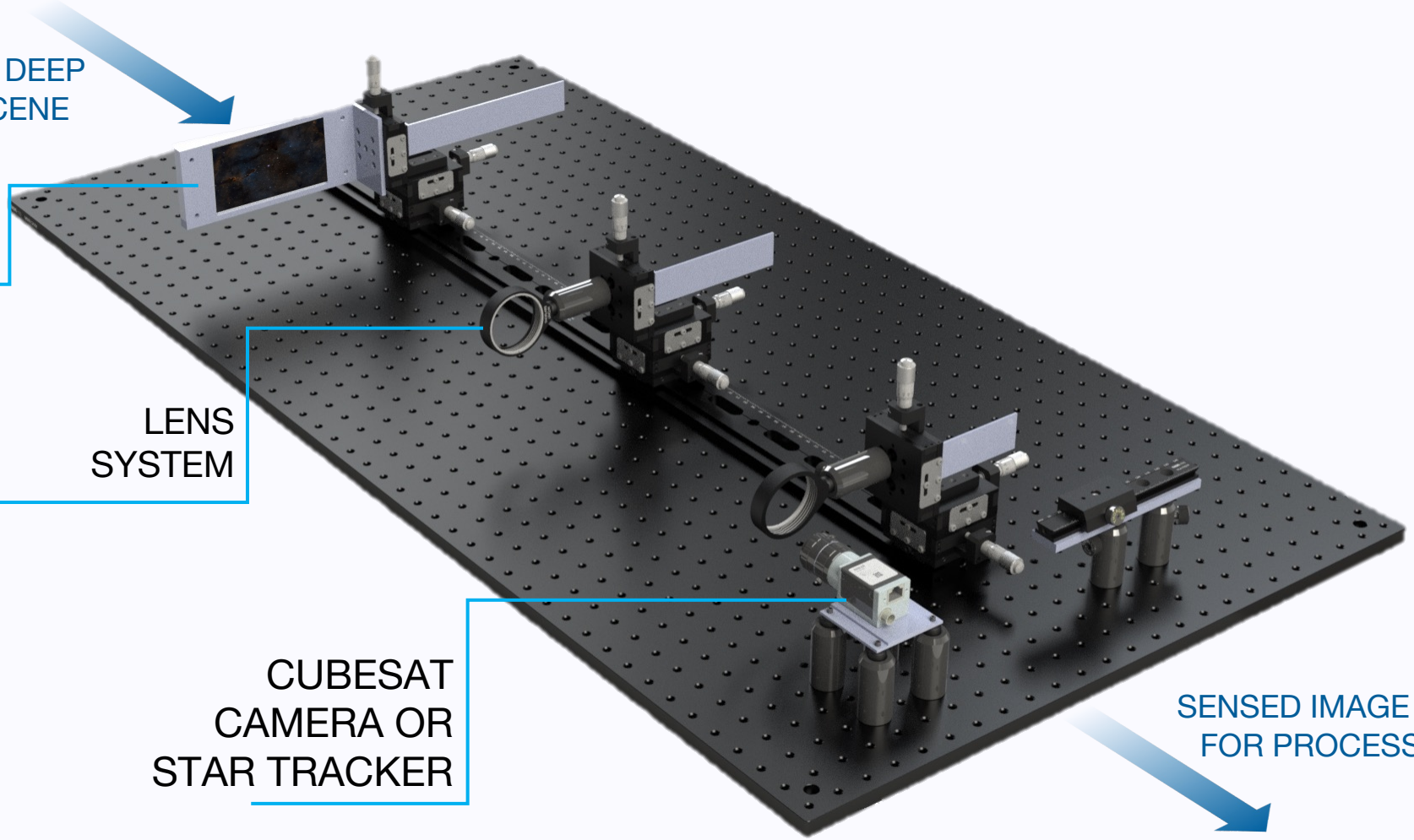
DIPARTIMENTO DI
SCIENZE E TECNOLOGIE
AEROSPAZIALI

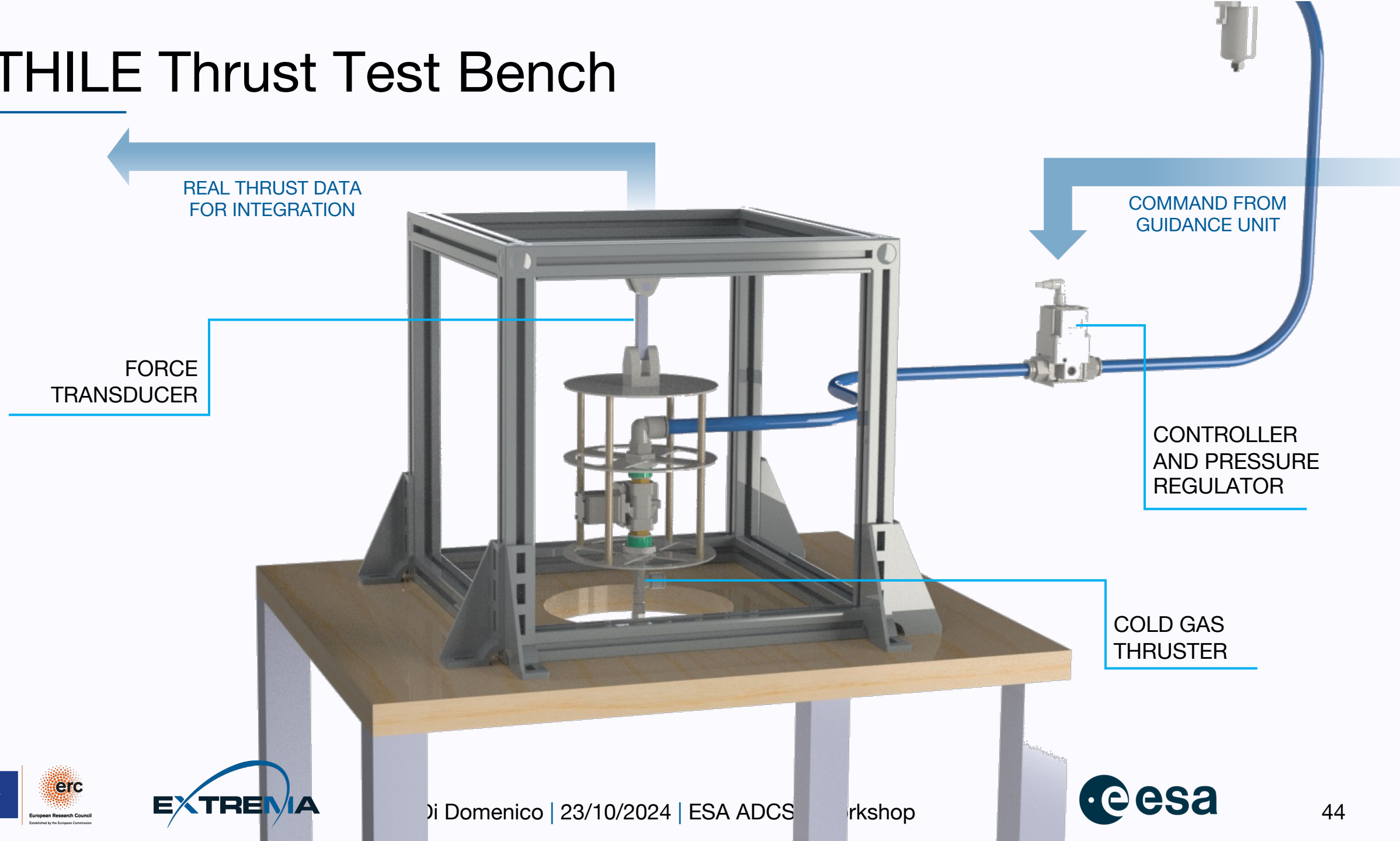
esa

Backup slides

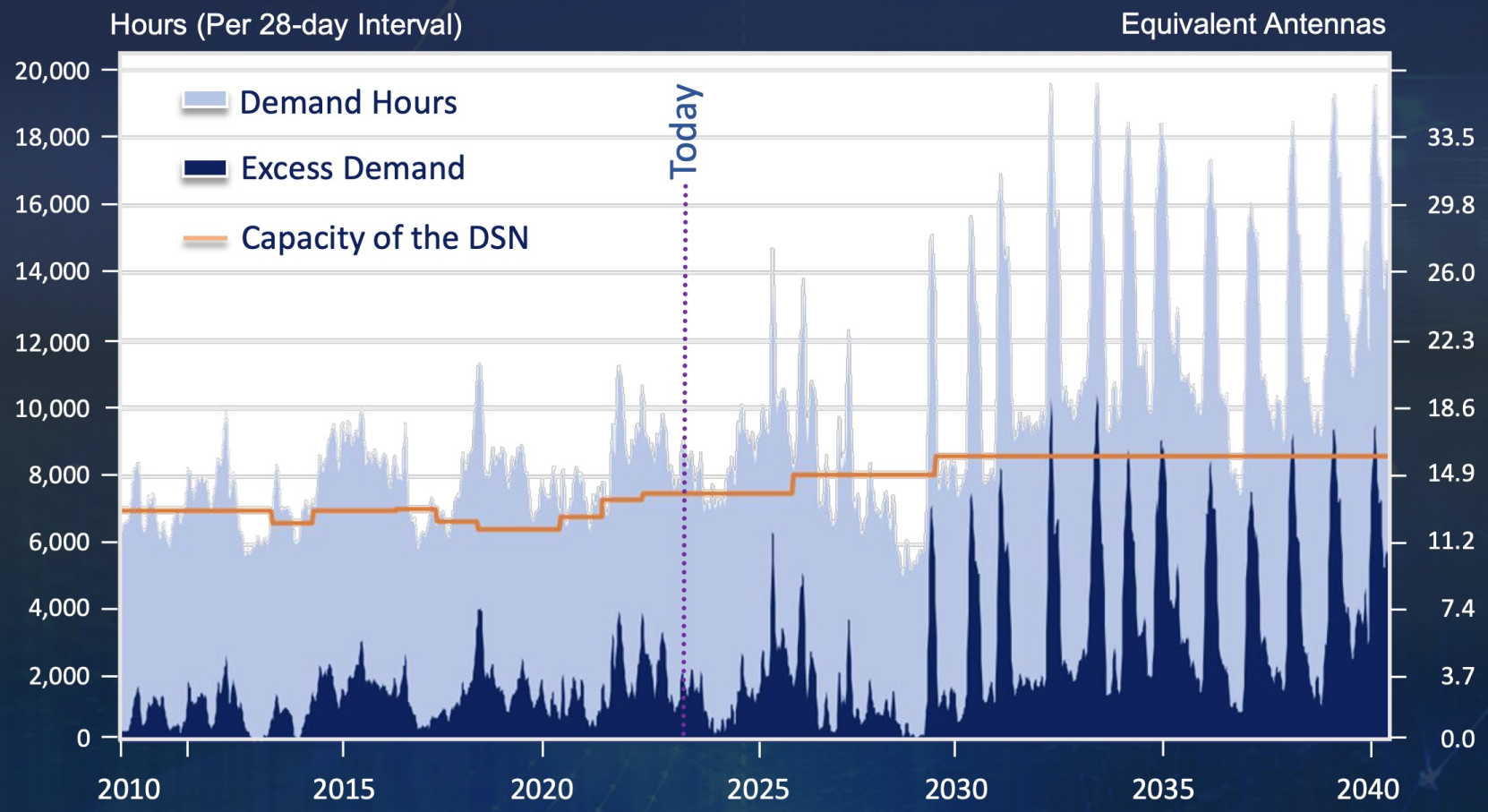
RETINA Optical Facility



ETHILE Thrust Test Bench



Deep Space Network Alone **Cannot Meet Lunar User Needs**



Supply and Demand Challenge

- Growth in deep space and future Mars missions is an already significant demand on the Deep Space Network (DSN)
- NASA and International partners have planned lunar missions that will create a new level of network demand
- Resolution will rely on combination of international partners and leveraging commercial industry

NASA Office of the Inspector General, 7/12/23

Unified Communication Framework

Message schemas

Wrapper

```
syntax="proto2"
import "nanopb.proto"

message estimatedState {
    required float t;
    repeated float r [max_count=3, fixed_count=3];
    repeated float v [max_count=3, fixed_count=3];
}

message acquiredImage {
    ...
}


message calculatedTrajectory {
    ...
}

message flatsatMessage {
    required uid = 1 [default = 2406];
    oneof msg {
        estimatedState state = 2;
        estimatedState image = 3;
        estimatedState trajectory = 4;
    };
}
```

nanopb compiler

protoc compiler

Static type definitions for embedded devices

MoniCA C++ macros and metaprogramming

Bindings for high-level application/MoniCA frontend

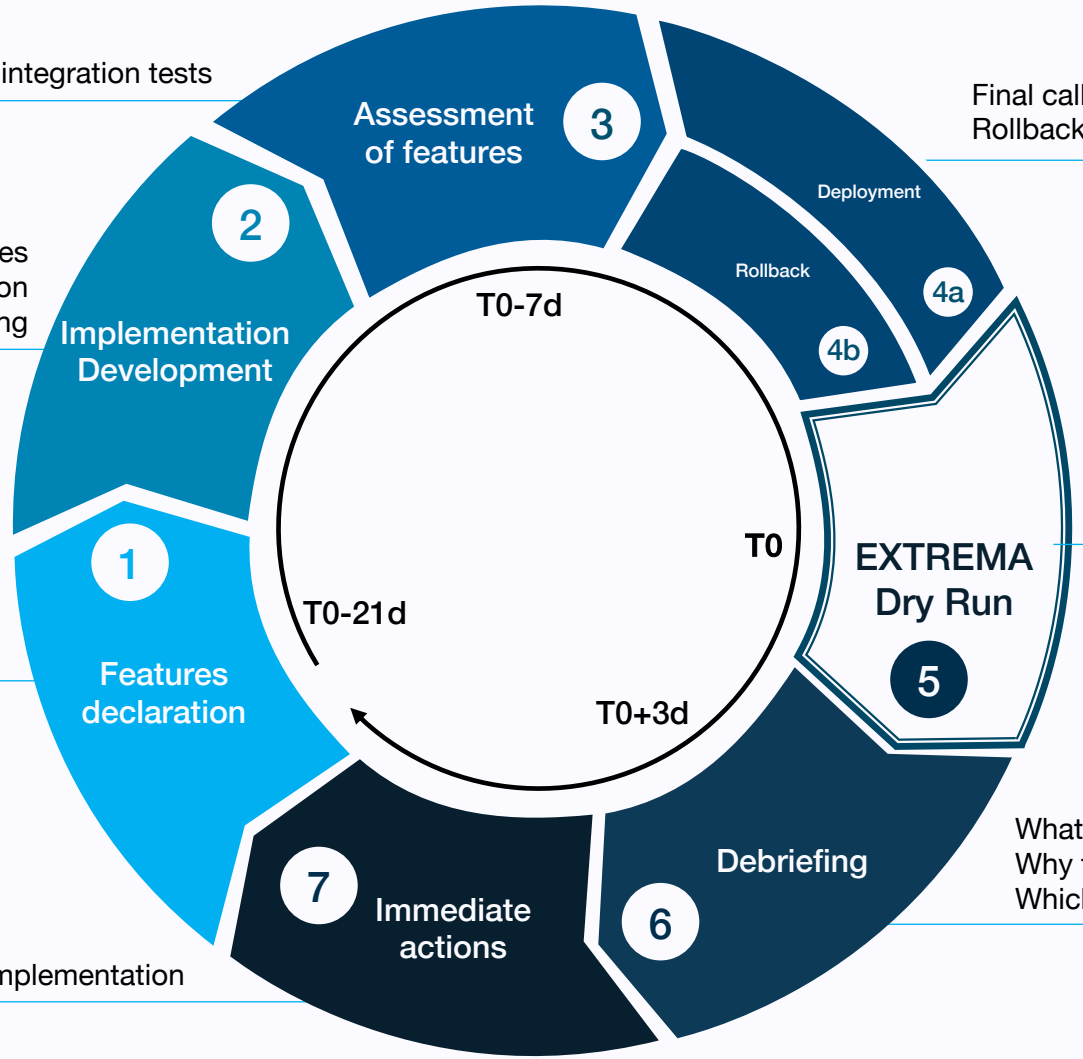
The EXTREMA Development Approach

Development of autonomous software and algorithms

Development of testing and validation facilities (ESH)

In EXTREMA, both the facilities for testing and validating the autonomous technologies and the autonomous technologies themselves are developed **concurrently**.

The EXTREMA Dry Run Development Approach



Preliminary integration tests

Final call on feature readiness
Rollback to older version(s) if needed

Development of stated features
Design space exploration and implementation
Unit testing

Random scenario simulation execution
Live monitoring and debugging
Live issue tracking
Simulation report generation
Log collection

Which features will be implemented in the next Dry Run?
Which improvements do I aim to develop?

What went good, what went wrong?
Why things went good, why things went wrong?
Which are the lesson learned?

Immediate bug fixes implementation

ELAPSE

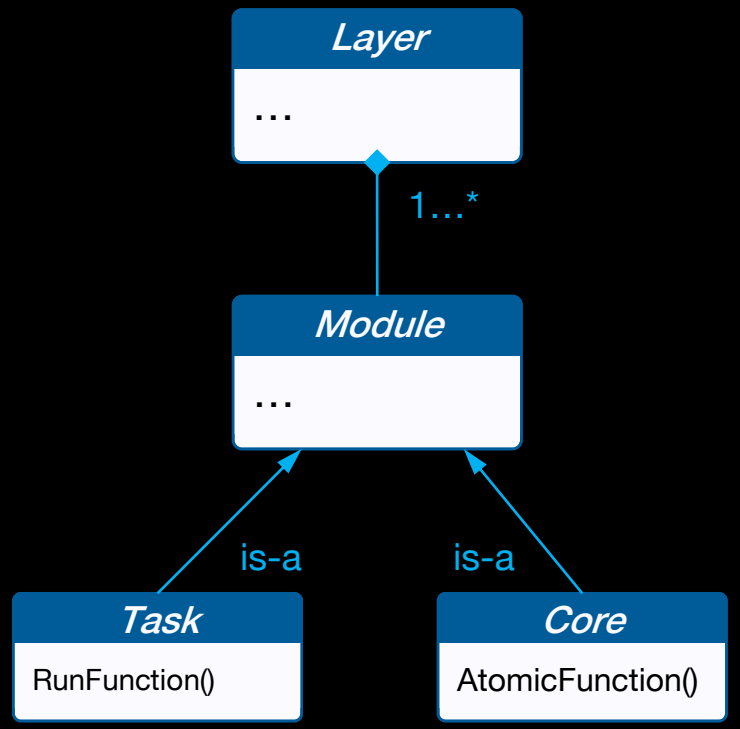
DESIGN PRINCIPLES

- Modularity
- Configurability
- Event-based

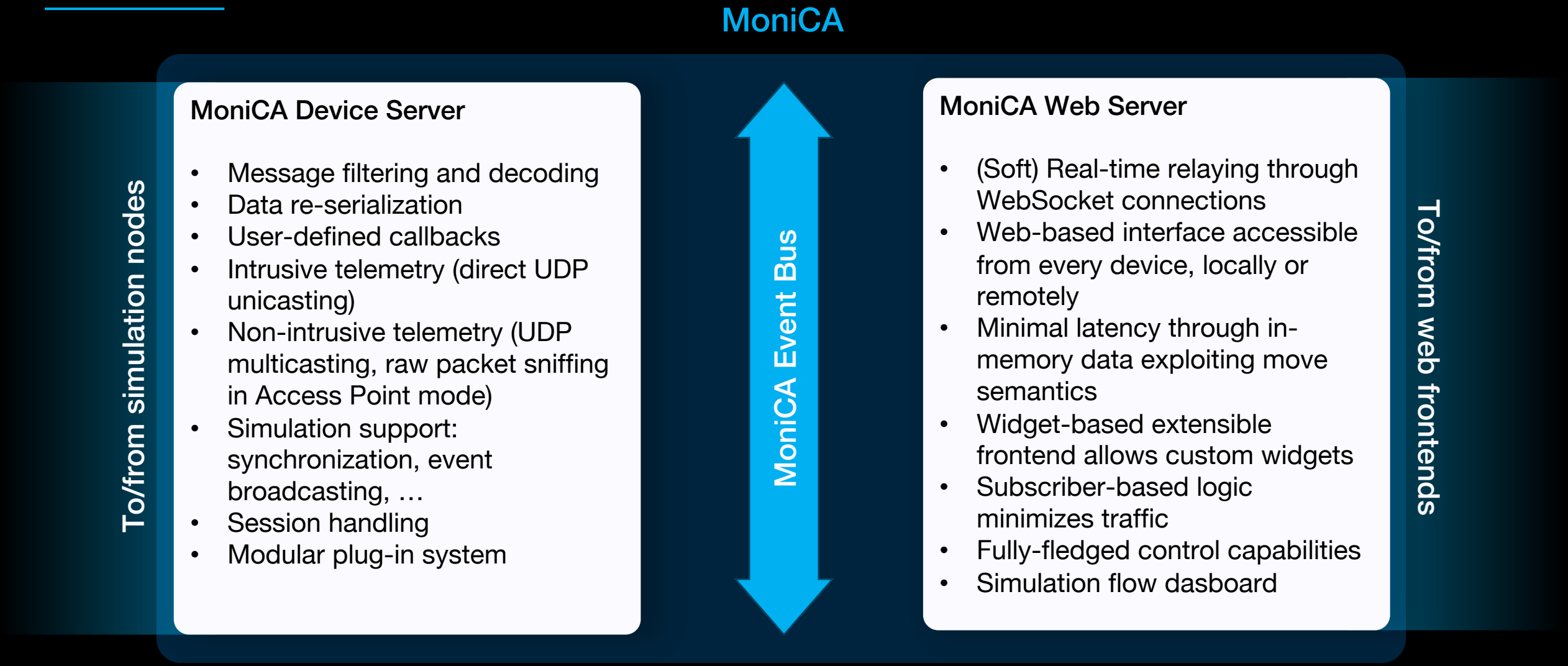
PARADIGMS

- Object-oriented
- Multi-threading
- (Soft) Real-timeness

ABSTRACTION



ESH MoniCA


MoniCA
To/from simulation nodes
MoniCA Device Server
• Message filtering and decoding
• Data re-serialization
• User-defined callbacks
• Intrusive telemetry (direct UDP unicasting)
• Non-intrusive telemetry (UDP multicasting, raw packet sniffing in Access Point mode)
• Simulation support: synchronization, event broadcasting, …
• Session handling
• Modular plug-in system
MoniCA Event Bus
MoniCA Web Server
• (Soft) Real-time relaying through WebSocket connections
• Web-based interface accessible from every device, locally or remotely
• Minimal latency through in-memory data exploiting move semantics
• Widget-based extensible frontend allows custom widgets
• Subscriber-based logic minimizes traffic
• Fully-fledged control capabilities
• Simulation flow dasboard
To/from web frontends

Accelerating the simulation

An accelerating framework based on dynamic similarity and formalized through a dimensional DEV&DESS approach is used to reduce simulation times while keeping physical meaningfulness.