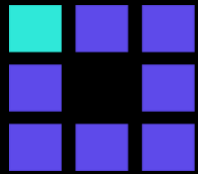


PHD IN AEROSPACE ENGINEERING

Thesis: Planning of operations and propulsion maneuvers in satellites based on digital twins and multidisciplinary optimization



IE NAI



uc3m
PHD

Candidate: Gianni Pecora

Supervisor: Daniel González Arribas

Advisor : Hodei Urrutxua Cereijo

Advisor : Manuel Sanjurjo Rivo



IVENAI SPACE

PROBLEM
MOTIVATION

METHODOLOGY

RESULTS

FUTURE STEPS

EVENTS &
TALKS



A software suite for Mission & Space Mobility Analysis, simulated environments & spacecraft Digital Twins.

360™ is a mission analysis tool with a **cutting-edge space mobility analysis capability**. It's based on a high fidelity flight dynamics propagator, coupled to a **heuristic optimization algorithm** which enables a wide range of concurrent engineering and design functionalities.

IENAI SPACE

PROBLEM
MOTIVATION

METHODOLOGY

RESULTS

FUTURE STEPS

EVENTS &
TALKS

Current low-thrust trajectory design approaches are limited by key simplifications:

- No integration of power constraints — often assume ideal or unlimited power
- Neglect of attitude dynamics
- Lack of ADCS modeling — omits actuator limitations and environmental disturbances

RESULT: Inaccurate, overly optimistic mission profiles unsuitable for real small satellite operations

THE GAP

To enable reliable mission planning for small satellites with electric propulsion, we need:

- An accurate digital twin that integrates trajectory, power generation, and attitude management
- A system that considers actuator performance, external disturbances, and energy-conscious decision-making

IENAI SPACE

PROBLEM
MOTIVATION

METHODOLOGY

RESULTS

FUTURE STEPS

EVENTS &
TALKS

To create a high-fidelity digital twin that integrates low-thrust trajectory planning, power management, and complete 6-DoF attitude dynamics.

Literature Review

Literature survey of **six-degree-of-freedom ADCS** digital twins, low-thrust guidance (**Q-Law**), and **power-aware mission** planning.

Identify gaps in power–attitude coupling

BIBLIOGRAPHY:

- Morante, D. Hybrid multi-objective trajectory optimization of low-thrust space mission design. Diss. Universidad Carlos III de Madrid, 2019
- Varga Gábor I., and JM Sánchez Pérez. "Many-revolution low-thrust orbit transfer computation using equinoctial Q-law including J2 and eclipse effects." 6th International Conference on Astrodynamics Tools and Techniques. Vol. 1. Darmstadt Germany, 2016.
- Petropoulos, A. E. "Refinements to the Q-law for low-thrust orbit transfers, 15th AAS." AIAA Space Flight Mechanics Conference. 2005.
- Quinsac, G., et al. "Attitude control: A key factor during the design of low-thrust propulsion for CubeSats." Acta Astronautica 176 (2020): 40-51.
- Di Pasquale, G., Sanjurjo Rivo, M., Perez-Grande, D.. "Space mobility optimization and concurrent engineering for modular micro-propulsion systems with 360 by IENAI SPACE." 73rd International Astronautical Congress (IAC). 2022.

IENAI SPACE

PROBLEM
MOTIVATION

METHODOLOGY

RESULTS

FUTURE STEPS

EVENTS &
TALKS

To create a high-fidelity digital twin that integrates low-thrust trajectory planning, power management, and complete 6-DoF attitude dynamics.

ADCS, Actuator & Disturbance Modeling

Attitude Control Laws

Controllers like PID for each main axis that feature **gain scheduling**, as well as the capability to utilize a genetic algorithm to find the **optimal gains**.

Disturbance Torque Modeling

- **Magnetic Torque**: computed via the International Geomagnetic Reference Field (IGRF) model
- **Gravity-Gradient Torque**: derived from spacecraft inertia tensor and local gravity vector
- **Thruster-Induced Torques**: off-center thrust and misalignment effects when used in attitude mode

IENAI SPACE

PROBLEM
MOTIVATION

METHODOLOGY

RESULTS

FUTURE STEPS

EVENTS &
TALKS

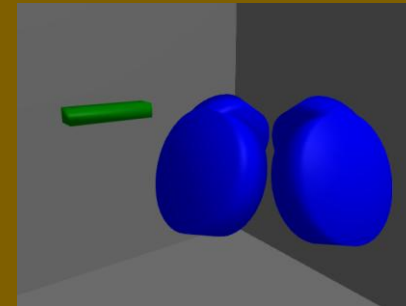
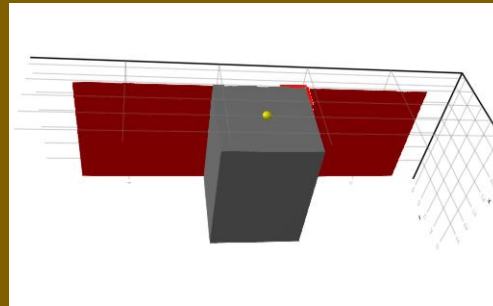
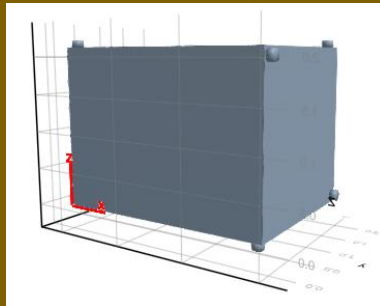
To create a high-fidelity digital twin that integrates low-thrust trajectory planning, power management, and complete 6-DoF attitude dynamics.

ADCS, Actuator & Disturbance Modeling

Creating a Digital Twin

Actuators Suite

- Reaction Wheels & Magnetorquer-based desaturation logic
- Magnetorquers
- Dual-Use Thrusters: modeled for both orbital positioning and attitude torque generation



IENAI SPACE

PROBLEM
MOTIVATION

METHODOLOGY

RESULTS

FUTURE STEPS

EVENTS &
TALKS

To create a high-fidelity digital twin that integrates low-thrust trajectory planning, power management, and complete 6-DoF attitude dynamics.

Adaptive Power-Integrated Trajectory Control

Adaptive ADCS Fidelity

- **High-Fidelity 6-DoF** during critical thrust/power phases to capture misalignment effects
- **Efficient 3-DoF** in non-critical operations to minimize computational load

Power-Aware Guidance

- Align thrust windows with the battery's state of charge and the availability of sunlight.
- Automatically switch to a sun-pointing orientation when the state of charge is low to facilitate quick recharging.

IENTAI SPACE

PROBLEM
MOTIVATION

METHODOLOGY

RESULTS

FUTURE STEPS

EVENTS &
TALKS

To create a high-fidelity digital twin that integrates low-thrust trajectory planning, power management, and complete 6-DoF attitude dynamics.

Case Study

GTO–GEO Transfer

Objective: validate digital twin under real-world constraints: low-thrust propulsion, limited power, and full ADCS integration.

Adaptive ADCS & Power-Aware Guidance

IENTAI SPACE

PROBLEM
MOTIVATION

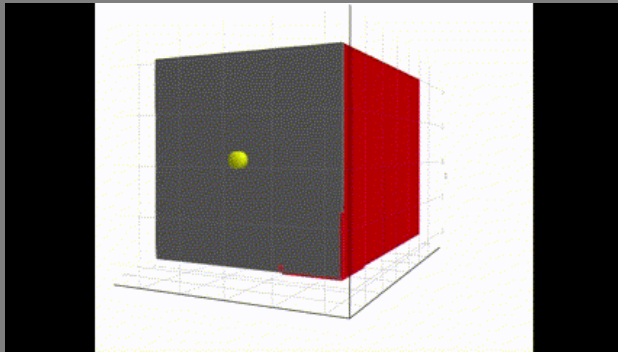
METHODOLOGY

RESULTS

FUTURE STEPS

EVENTS &
TALKS

SPACECRAFT

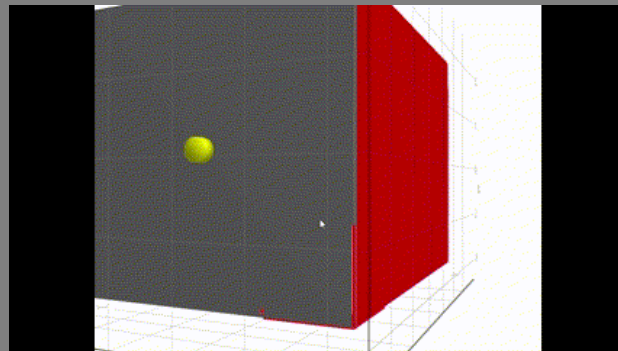


Hall Effect
Thruster

4 Bradford
Space RW
Unit W45E



Ibeos
B50-1237 50V
Battery



GENETIC ALGORITHM PROBLEM

OPTIONS FOR NSGA-II SOLVER

Variable	Meaning	Lb	Ub
W_{ecc}	Q-law eccentricity weight factor	0.01	100
W_{incl}	Q-law inclination weigh factor	0.01	100
$\eta_{r,th}$	Thrust effectivity coefficient	0	0.98
$SOC_{H,th}$	Battery SOC High threshold	0.4	0.5
$SOC_{L,th}$	Battery SOC Low threshold	0.51	0.99

OBJECTIVES

- Minimize mission phase duration
- Maximize leftover propellant
- Minimize total energy draw

IENAI SPACE

PROBLEM
MOTIVATION

METHODOLOGY

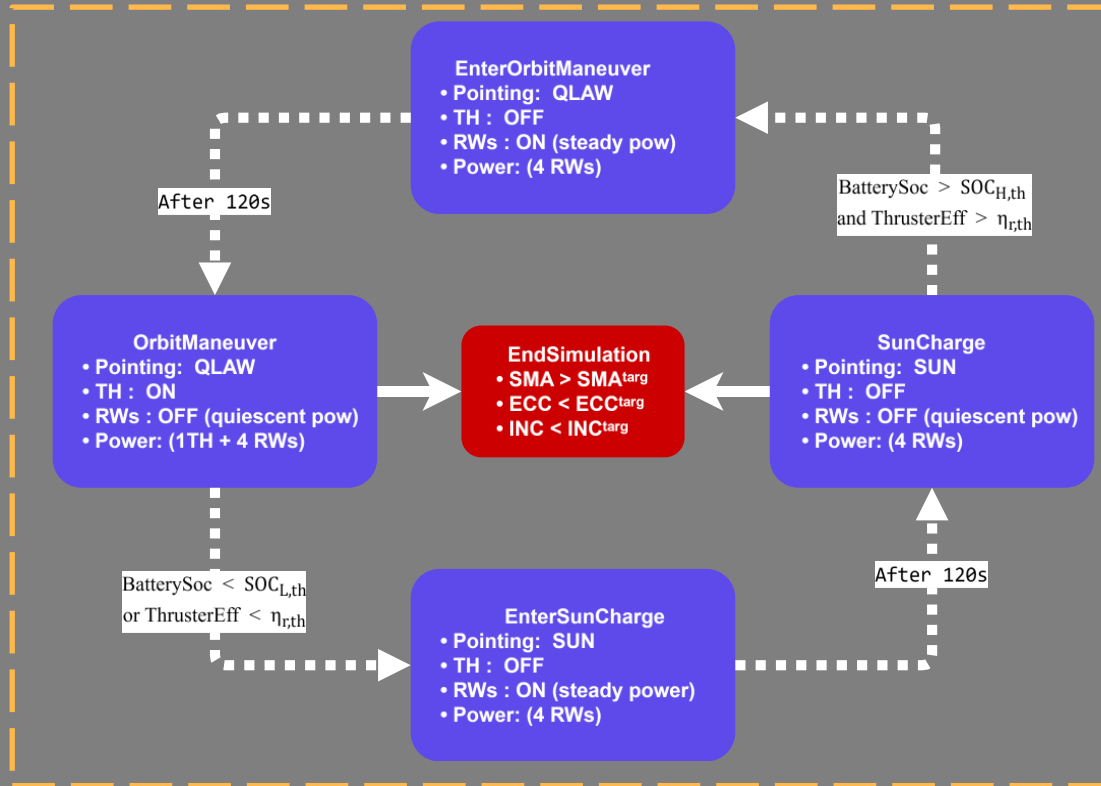
RESULTS

FUTURE STEPS

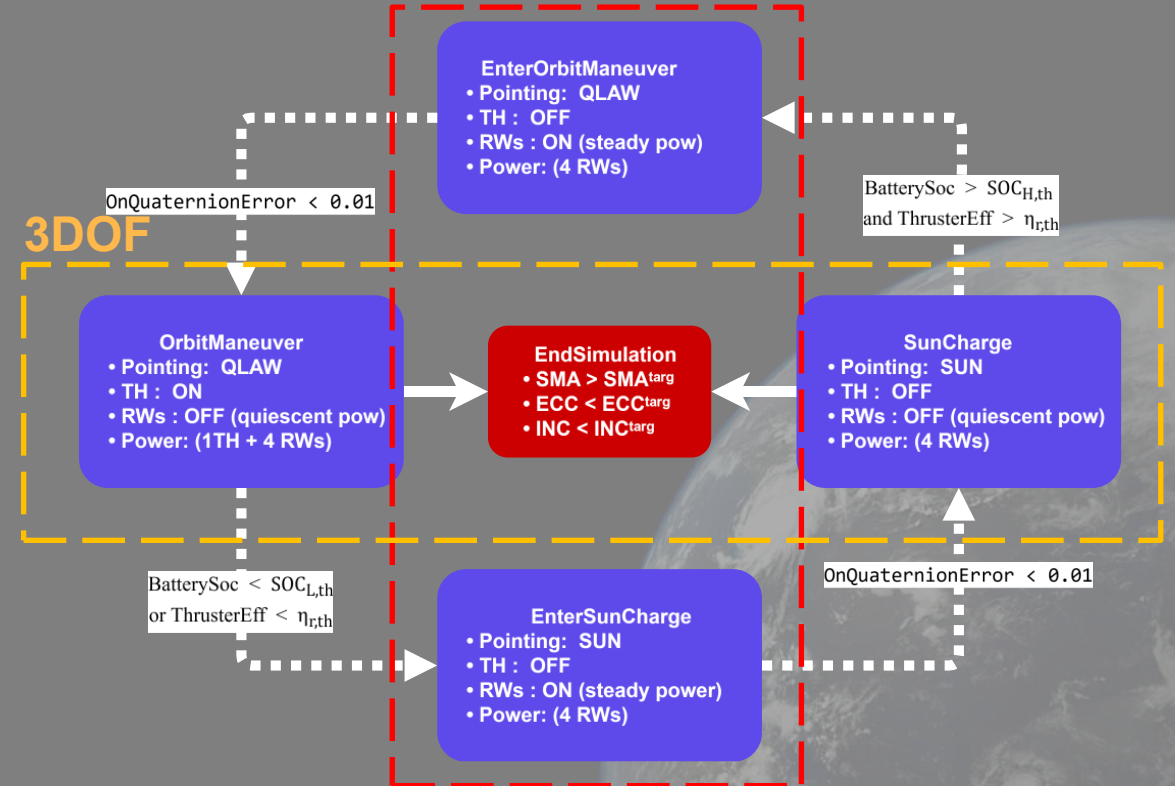
EVENTS &
TALKS

OPERATION MACHINE

3DOF



6DOF



IENAI SPACE

PROBLEM
MOTIVATION

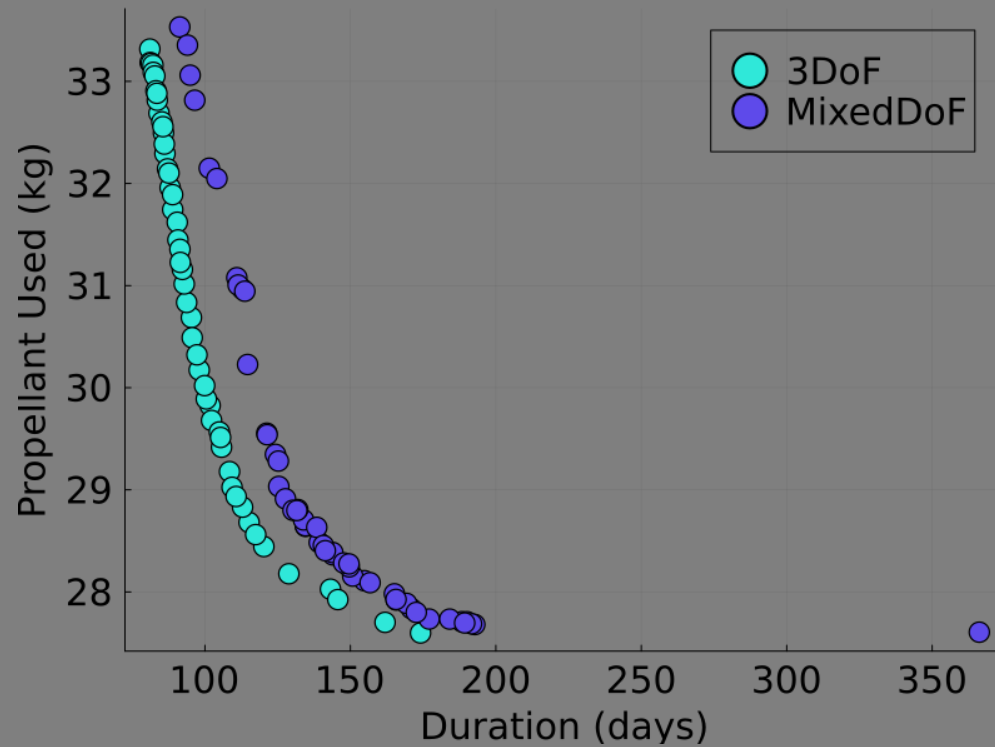
METHODOLOGY

RESULTS

FUTURE STEPS

EVENTS &
TALKS

OUTPUTS



SIMULATION TIME	
6 DOF	at least 300s
Mixed DOF	33.6 s
3 DOF	11.2 s

[IENAI SPACE](#)

[PROBLEM
MOTIVATION](#)

[METHODOLOGY](#)

[RESULTS](#)

[FUTURE STEPS](#)

[EVENTS &
TALKS](#)

Reinforcement Learning & QLaw Parameters Adaptation (Work in Progress)

Objective:

Dynamically adapt QLaw parameters over time using Reinforcement Learning (RL) to optimize trajectory.

Current status:

Literature review on RL applied to QLaw parameters completed.

Initial model implemented with early results — promising but not yet mature

Methodology:

RL agent selects optimal QLaw parameters

Parameters evolve dynamically throughout the simulation.

Next step for validation:

Benchmarking vs. Genetic Algorithm (GA) by splitting the simulation and optimizing each segment independently (computationally expensive, but valuable for comparison).

IENTAI SPACE

PROBLEM
MOTIVATION

METHODOLOGY

RESULTS

FUTURE STEPS

EVENTS &
TALKS

Next In Line

New Operation Machine Concept

Goal:

Refine the operation logic by introducing a **more realistic** and mission-aligned scenario.
Adapt the current model to better reflect operational constraints and real mission dynamics.

Application to a Real Mission

Selected Case Study:

ESA's SMART-1 lunar mission

IENTAI SPACE

PROBLEM
MOTIVATION

METHODOLOGY

RESULTS

FUTURE STEPS

EVENTS &
TALKS

Conference Participation & Upcoming Presentation

Attended:

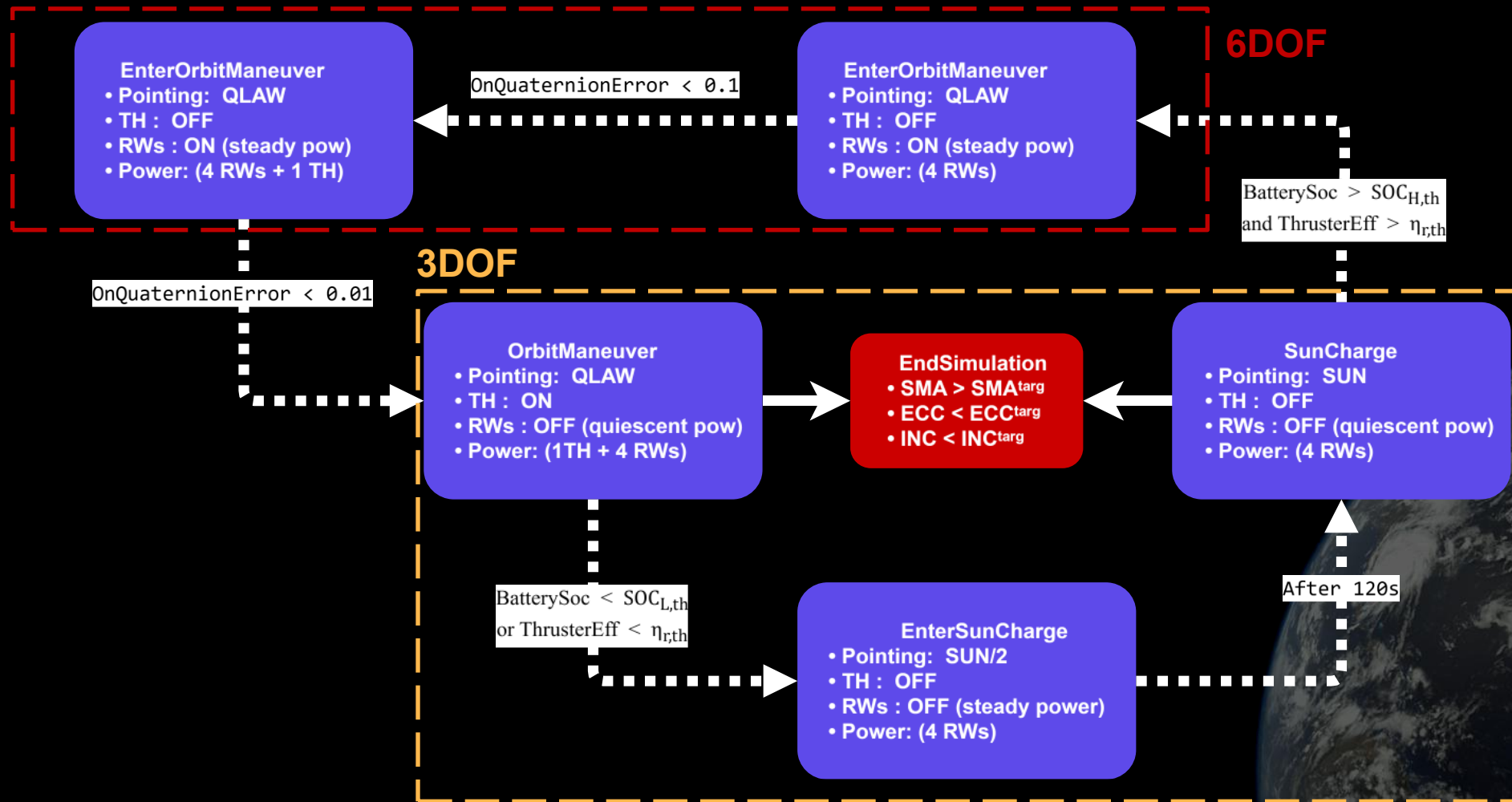
- ✓ **MBSE 2024 Workshop** – Bremen, May 28–29, 2024
Model-Based Space Systems and Software Engineering
- ✓ **JuliaCon 2024** – July 9–13, 2024
Conference on scientific computing with Julia
- ✓ **IAC 2024** – Milan
International Astronautical Congress – Attendee

Upcoming Presentation:

- 🎯 **IAC 2025 :**
 - Title: **Low-Thrust Trajectory Design with Power Constraints and Attitude Dynamics Integration**
Abstract accepted → Journal paper forthcoming
 - Title: **Efficient Mission Analysis for Small Satellites: Maneuver Planning, Constellation Deployment, and Propulsion Optimization**

THANK YOU!
QUESTIONS?

New Operation Machine Concept



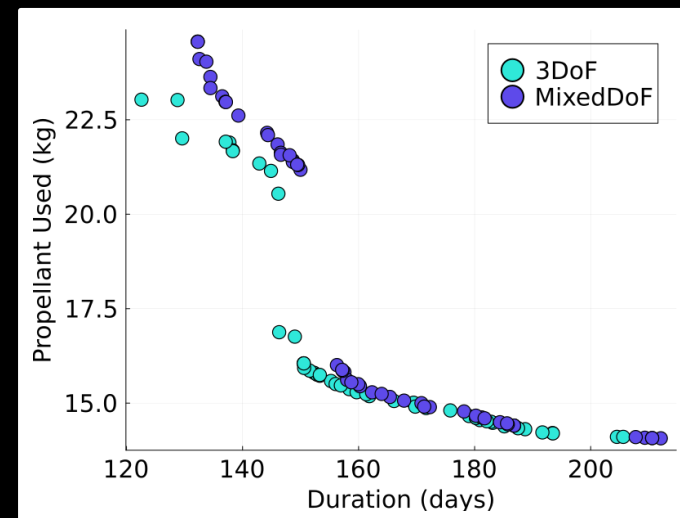
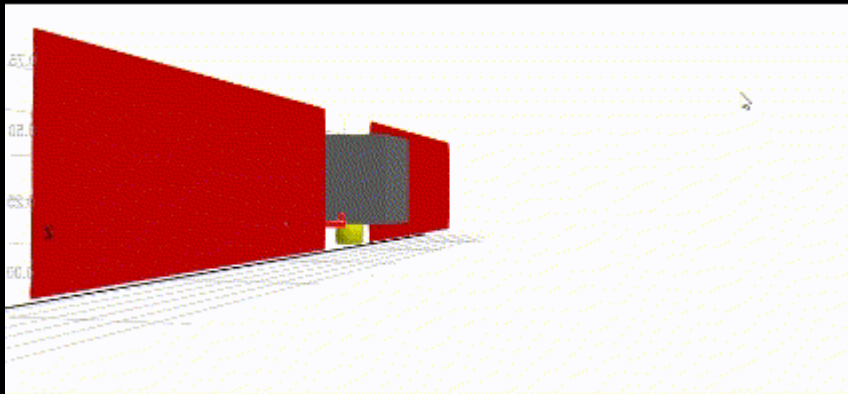
ESA'S SMART-1 MISSION

Objective:

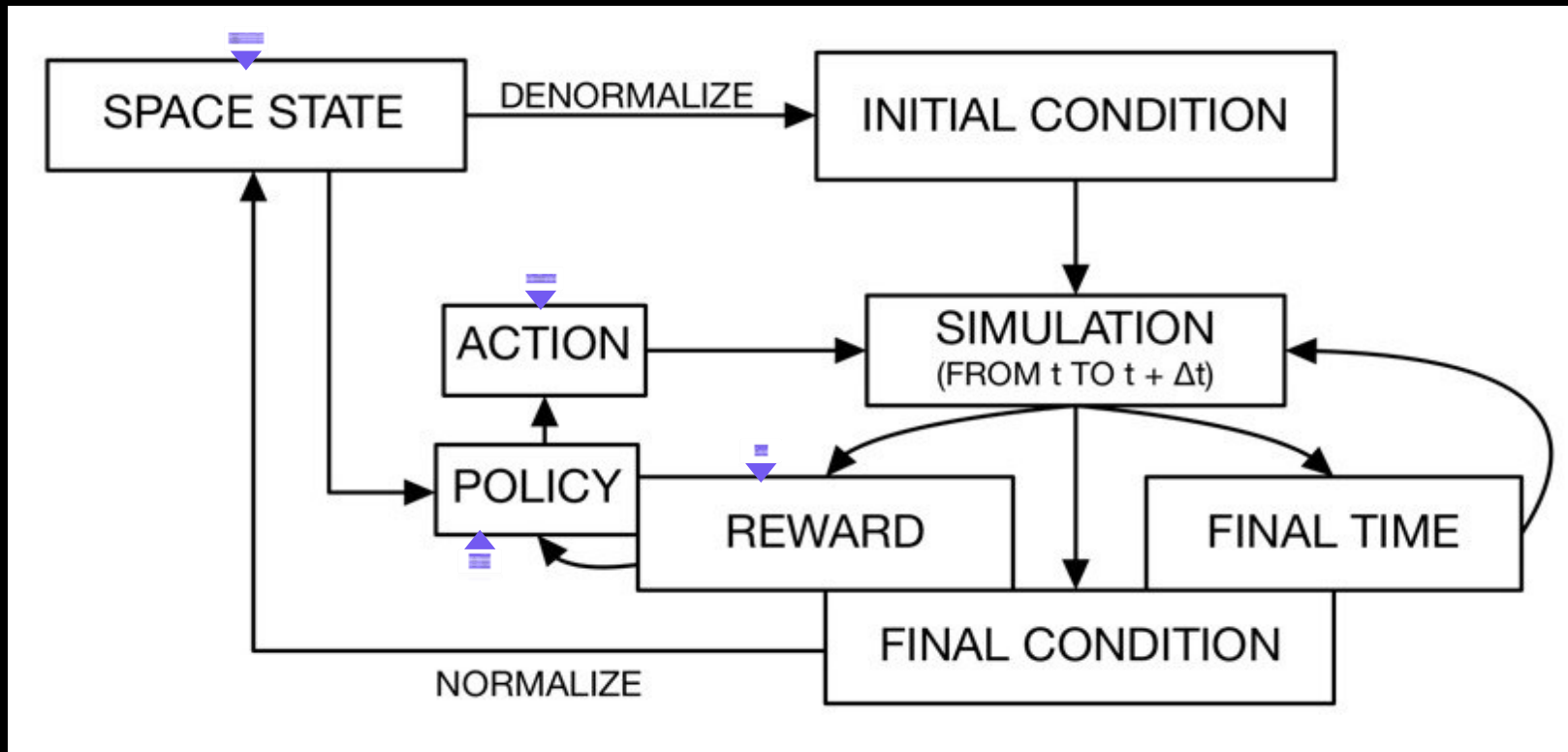
Qualify solar electric propulsion for deep-space operations.

Why it fits:

Demonstrated low-thrust transfer over long durations
Included complex orbital maneuvers and attitude control
Offers a validated framework for GTO to GEO transfer simulation



REINFORCEMENT LEARNING



BIBLIOGRAPHY:

- Holt, Harry, et al. "Optimal Q-laws via reinforcement learning with guaranteed stability." *Acta Astronautica* 187 (2021): 511-528
- Silvestrini, Stefano, and Michèle Lavagna. "Deep learning and artificial neural networks for spacecraft dynamics, navigation and control." *Drones* 6.10 (2022): 270.

	Space State	Normalized
Semimajor axis [m]	a	$\frac{a - a_{min}}{a_{max} - a_{min}}$
Eccentricity [-]	e	e
Inclination [rad]	i	i/π
Right Ascension of the Ascending Node [rad]	Ω	$\Omega/2\pi$
Argument of Perigee [rad]	ω	$\omega/2\pi$
True Anomaly [rad]	v	$v/2\pi$

A and **B** are weighting factors that should be selected based on the desired balance between mass conservation and time optimization

Simulation Condition	Reward Calculation
Single Step End	$-B \cdot t_{step}$
Episode End	$A \cdot \frac{m_f}{m_{initial}}$
$t_{step} = \frac{time}{86400}$	

Variable	Meaning	Lb	Ub
$\eta_{r,th}$	Q-law effectivity coefficient	0	0.98
W_e	Q-law a weighting factor	0.01	100.0
W_i	Q-law e weighting factor	0.01	100.0

PPO (Proximal Policy Optimization)	
Type	Off-policy, Model-Free, Actor-Critic
Action Space	Discrete & Continuous
Exploration Method	Stochastic policy (learns a probability distribution)
Policy Type	Stochastic (outputs action probabilities)
Optimization	Uses clipped objective function to prevent large policy updates