Iowa State University

Multidisciplinary Design Optimization of a Low-Thrust Asteroid Orbit Insertion Using Electric Propulsion

Authors: Yacob Medhin, Tushar Sial, Dr. Simone Servadio

AIAA Region V Student Conference, 2026

Outline

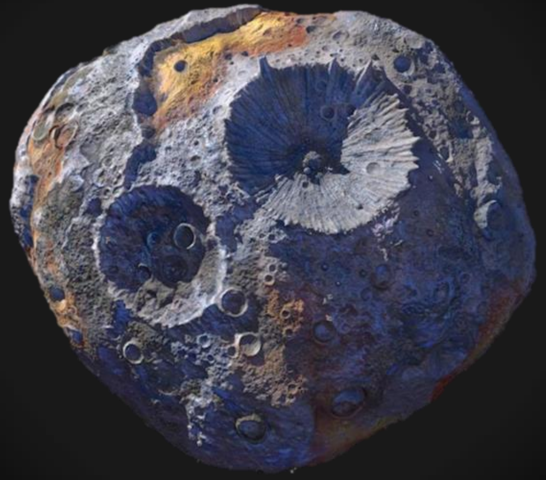
1. Motivation & Literature Review
2. Mission Architecture
3. Physics & Subsystem Models (Power, Propulsion, Mass-Coupling)
4. MDO Framework Formulation (OpenMDAO/Dymos)
5. Numerical Challenges: Collocation Defects
6. Results: Baseline vs. Fully Coupled MDO
7. Conclusion
8. Next Steps
9. References

Purpose

Design a time-optimal, low-thrust spiral descent from a 750 km to a 200 km orbit around 16-Psyche.

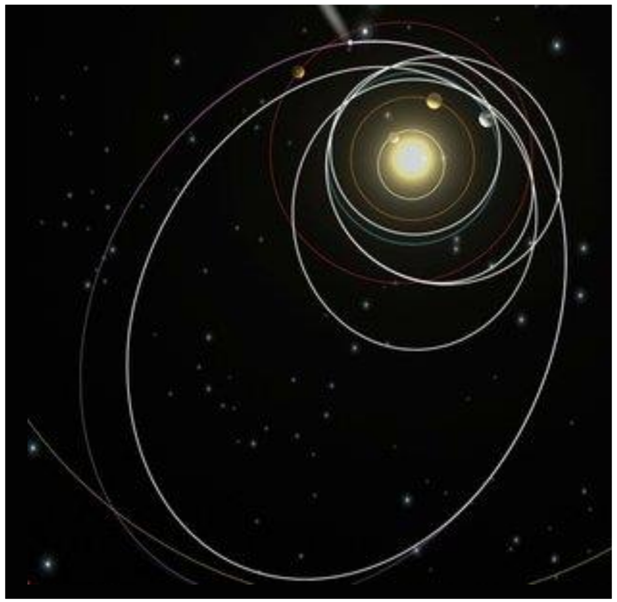
Fully couple solar power generation, VSI electric propulsion, and dynamic mass-area penalties.

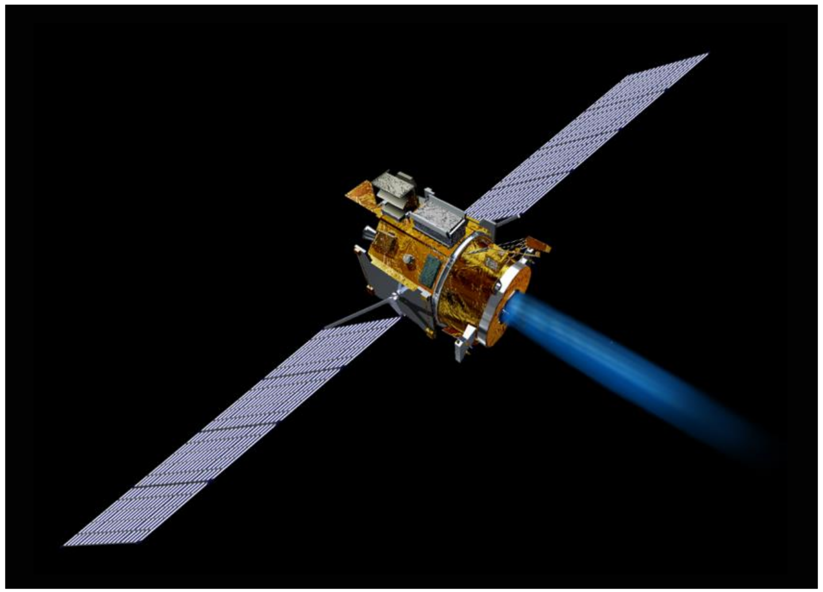
Quantify the multidisciplinary trade-off between solar array sizing, spacecraft mass, and time of flight in a power-starved environment.



Significance & Novelty

- Low gravity enables effective continuous low-thrust
- Weak sunlight at 2.9 AU forces power–trajectory coupling
- Mission is power-limited due to realistic solar & thruster models
- Includes solar degradation, PPU limits, and thrust smoothing
- The Problem: Traditional decoupled design assumes infinite power availability or fixed spacecraft mass, yielding physically infeasible trajectories in deep space.



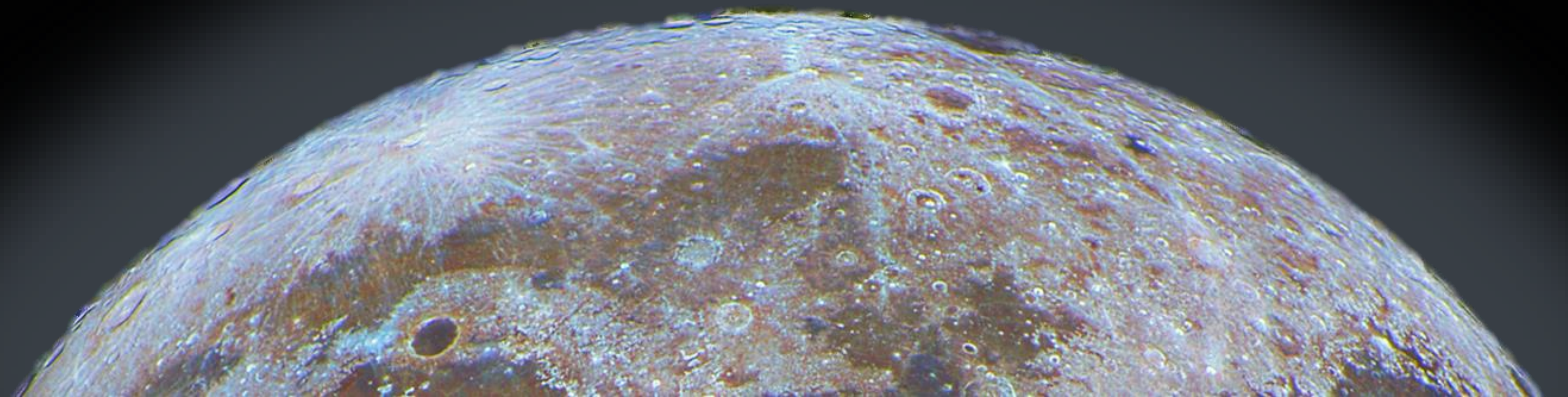


Literature Review

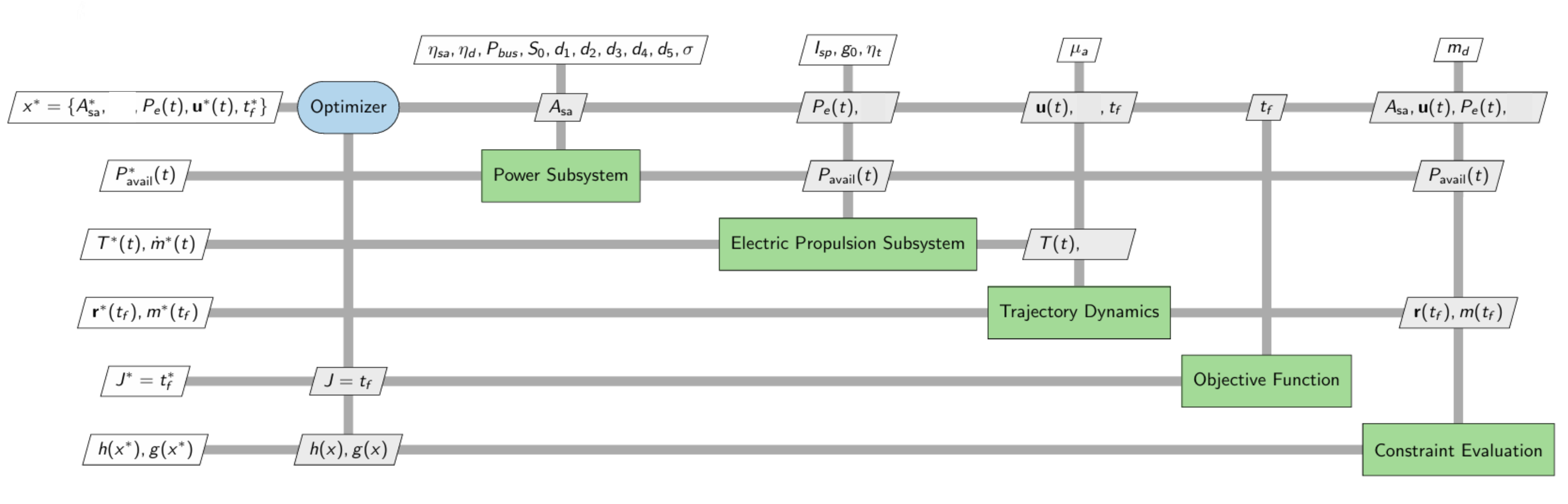
- Low-thrust spacecraft–trajectory co-optimization with direct methods and coupled design variables [1]
- Integrated SEP vehicle models linking solar power, propulsion performance, and long-duration orbit transfers [2]
- Trajectory and energy-management simulator coupling EP performance, power allocation, and guidance [3]
- Dymos/OpenMDAO-based low-thrust trajectory optimization with gravity-assist capability [4]

Methodology

Trajectory Model → Power Model → Thruster Model → Coupled Dynamics → Optimization



XDSM Diagram



Physics-Based Power & Propulsion Models

- Solar Power Generation ($P_{SA}(t)$)
  - Modeled using high-fidelity polynomial data for the asteroid belt regime ($r \approx 2.9AU$)
  - Includes Time-Based Degradation:
    - Power drops by ~3% per year due to radiation exposure.
    - $P_{SA}(t) \propto \frac{1}{r^2} * (1 - \sigma t)$
- Power Budgeting:
  - Bus Power (P_{bus}): 590 W reserved for spacecraft operations.
  - PPU Limit: Power constrained by the Power Processing Unit's max capacity (4863 W).
  - Result: $P_{avail} = \eta_d * \min(P_{SA} - P_{bus}, P_{max})$
- Variable Specific Impulse (VSI) Engine:
  - Utilizes SPT-140 Hall Thruster data.
  - Thrust (T) and Mass Flow ($\dot{m}$) are interpolated functions of input power (P_E) not constants.
  - Allows the optimizer to throttle the engine as power degrades.

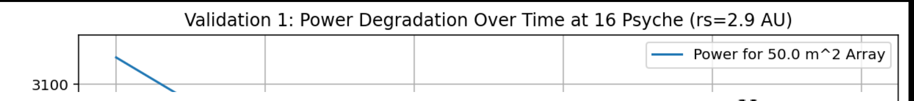
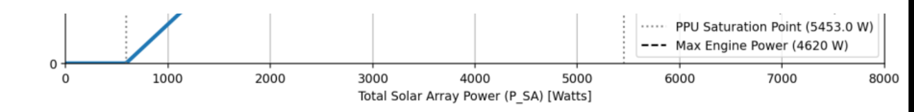


Table 1: Throttle table for SPT-140 Hall thruster.[32]

Mode #	Power (Watts)	T (mN)	$\dot{m}$ (mg/s)	I_{sp} (sec)	η
1	4989	263	13.9	1929	0.5
2	4620	270	16.5	1670	0.48
3	4589	287	17.8	1647	0.5
4	4561	264	16.4	1645	0.47
5	4502	260	16.2	1641	0.46
6	4375	246	14	1790	0.49
7	3937	251	17.5	1461	0.46
8	3894	251	17.5	1464	0.46
9	3850	251	17.5	1464	0.47
10	3758	217	13.9	1597	0.45
11	3752	221	13.9	1617	0.47
12	3750	215	13.6	1614	0.45
13	3460	184	17.1	1099	0.29
14	3446	185	20.4	925	0.24
15	3402	189	16.3	1181	0.32
16	3377	201	15.8	1302	0.38
17	3376	175	18.2	979	0.25
18	3360	198	14.7	1371	0.4
19	3142	191	13.8	1409	0.42
20	3008	177	11.4	1579	0.46
21	1514	87	6.1	1449	0.41



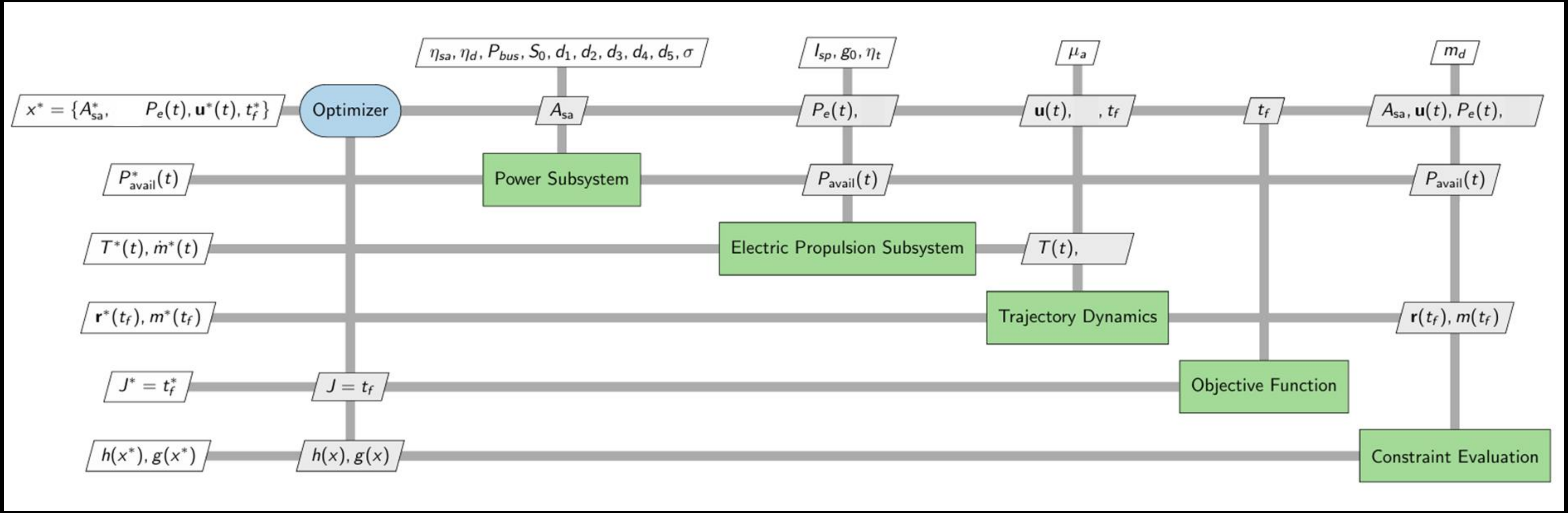
Dynamic Spacecraft Mass-Area Coupling

- The MDO Trade-Off:
  - Power generation is assumed independent of spacecraft mass.
- Physical Realism:
  - The optimizer cannot grow the solar array area (A_{SA}) without penalizing the spacecraft's kinetic performance ($a = F/m$).
- The Coupling Logic:
  - The initial wet mass is dynamically calculated based on the hardware sizing.
  - The solver balances electrical power gains against structural "dead weight."

- **Equations:**
  - $M_{initial} = M_{dry} + M_{propellant}$
  - $M_{dry} = M_{bus} + (N_{eng} * M_{eng}) + (\rho_{SA} * A_{SA})$
- ***Hardware Constants:***
  - **Core Bus (M_{bus}): 200 kg**
  - **Propellant ($M_{propellant}$): 100 kg**
  - **SPT-140 Engine (M_{eng}): 4.5 kg**
  - **Array Areal Density (ρ_{SA}): 2.0 kg/m^2**

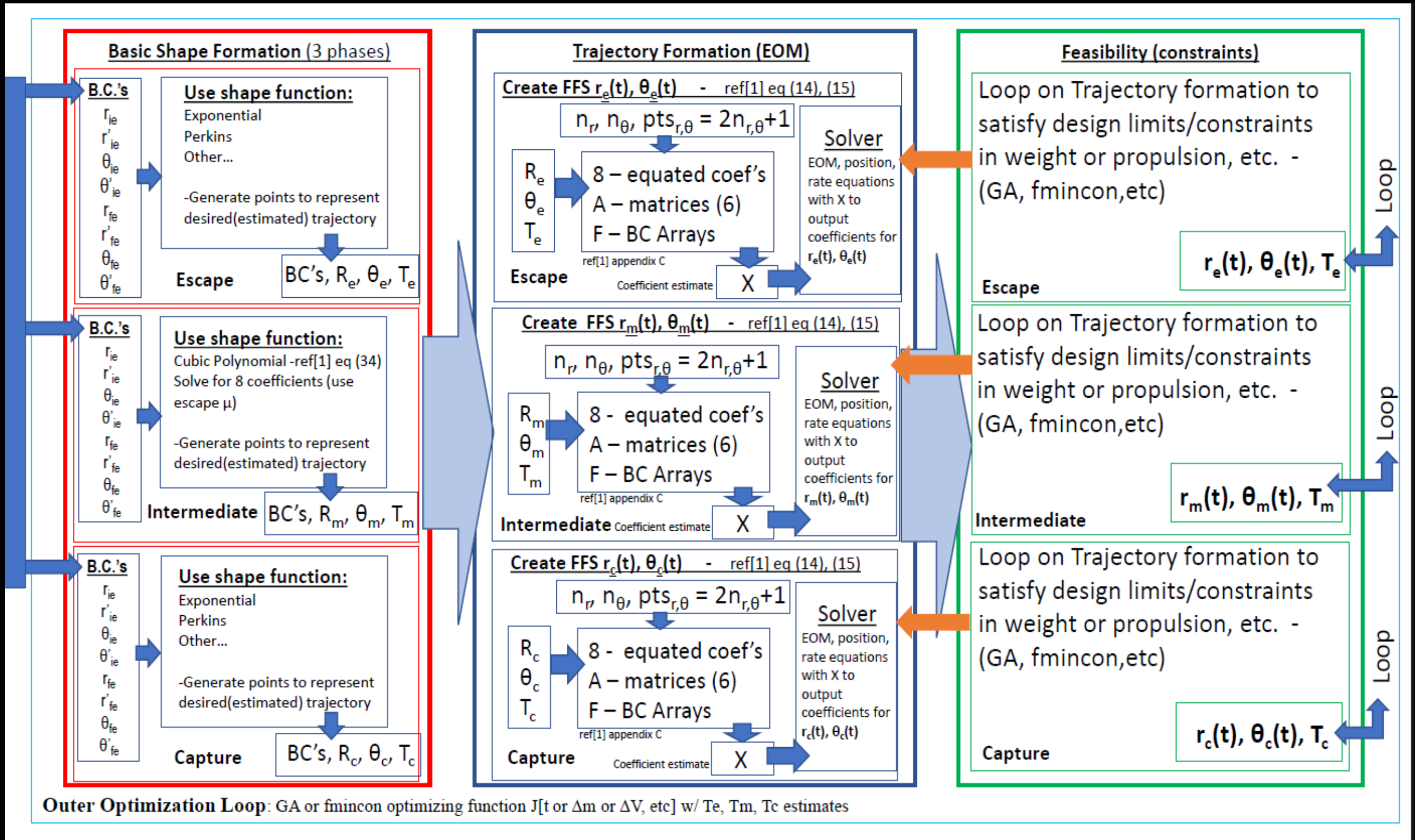
Coupled Dynamics

- Merges trajectory, power, and thrust models.
- Thrust limited by available power.
- Mass decreases over time.
- Produces valid spiral descent.



Initial Guess Trajectory

- Fast Fourier Series (FFS) method to generate a smooth initial trajectory.
- Produces radius, velocity, angle, mass, thrust, and direction profiles.
- Ensures the optimizer starts from a feasible trajectory.
- Reduces convergence failures and improves solver stability.



Optimal Control with Dymos

- Uses direct collocation to transcribe the ODE.
- IPOPT solves the resulting nonlinear program.
- OpenMDAO manages derivatives.
- Couples power, thrust, and trajectory inside the optimization framework.

Optimization Problem Formulation

Objective is to minimize time of flight.

$$
\begin{aligned}
\min_{\mathbf{u}(t), P_e(t), A_{sa}, t_f} \quad & t_f \\
\text{s.t.} \quad & \dot{\mathbf{r}}_{\mathbf{a}} = \mathbf{v}_{\mathbf{a}}, \\
& \dot{\mathbf{v}}_{\mathbf{a}} = -\frac{\mu_a}{r_a^3}\mathbf{r}_{\mathbf{a}} + \frac{T}{m}\mathbf{u}(t), \\
& \dot{m} = -\frac{T}{I_{sp} g_0}, \\
& T = \frac{2\eta_t P_e}{I_{sp} g_0}, \\
& \mathbf{r}(0) = \mathbf{r}_0, \ \mathbf{r}(t_f) = \mathbf{r}_f, \\
& m(0) = m_0 = m_p(0) + m_d, \ m(t_f) = m_p(t_f) + m_d \geq m_d \geq 0, \\
& 0 \leq P_{\text{avail}} \leq P_{SA}, P_e \leq P_{\text{avail}}, \quad \|\mathbf{u}(t)\| = 1, \quad A_{sa_{LB}} \leq A_{sa} \leq A_{sa_{UB}}
\end{aligned}
$$

Design Variables

- $u(t)$; Thrust direction vector
- A_{SA}; Solar array area
- t_f; Final time
- $P_e(t)$; Engine Power Command

Optimization Constraints

Boundary Constraints

$r(0) = R_{Psyche} + 750km$

$r(t_f) = R_{Psyche} + 200km$

$v_{radial}(t_f) = 0$

$m(t_f) \geq m_d$

Path Constraints

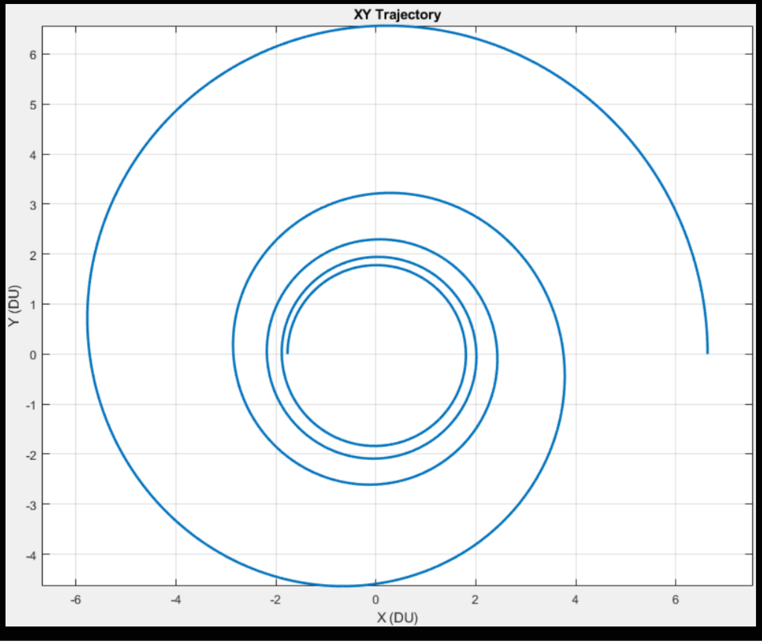
$\| u \| = 1$

$P_E(t) \leq P_{avail}(t)$

$m(t) \geq m_d$

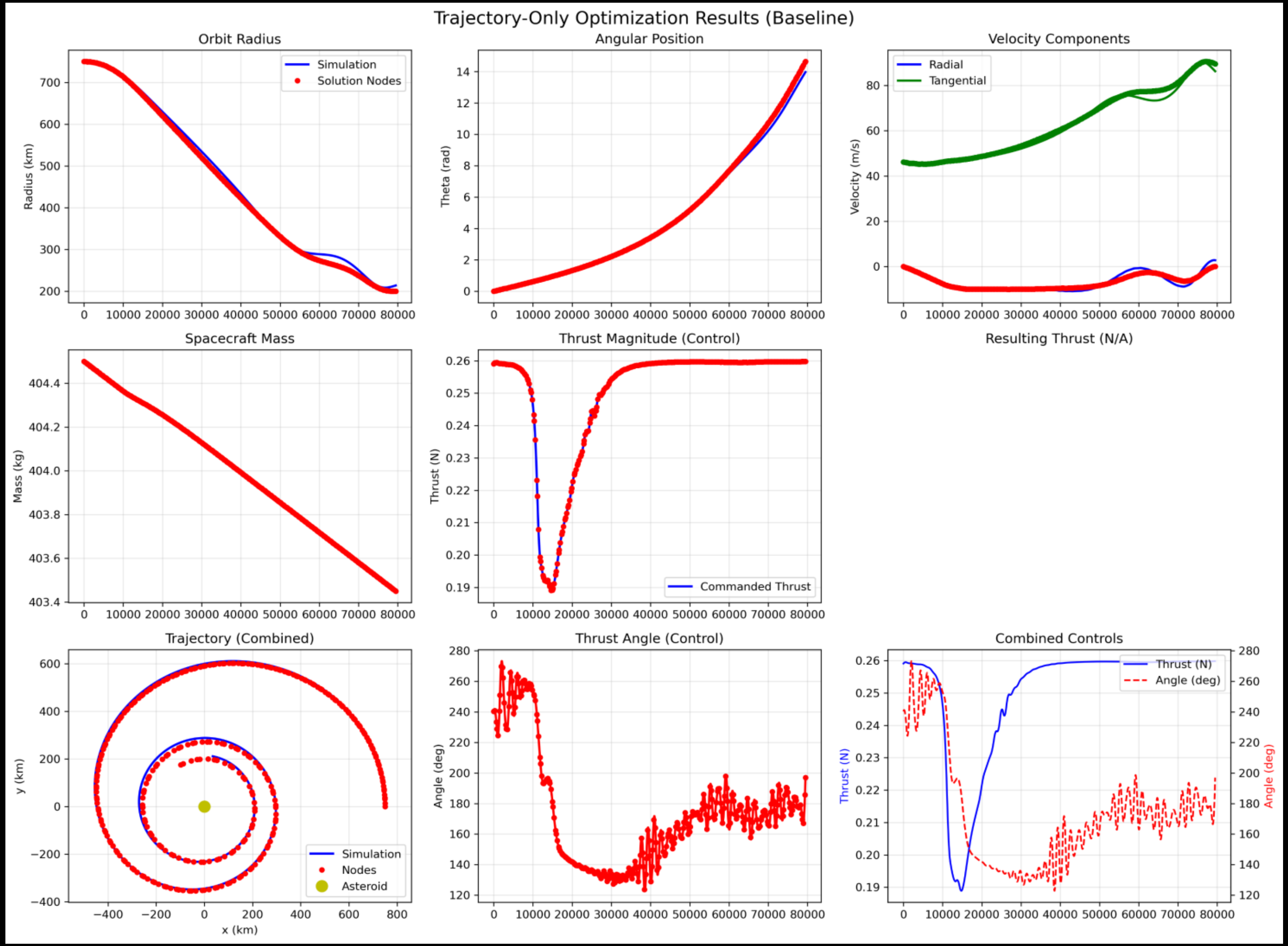
Simulation Results (Initial Guess)

- Low-thrust spiral descent from 750 km → 200 km.
- Assumption of Constant Specific Impulse: 1800s.
- Thrust direction slowly rotates inward.
- Final arc circularizes the 200 km orbit.



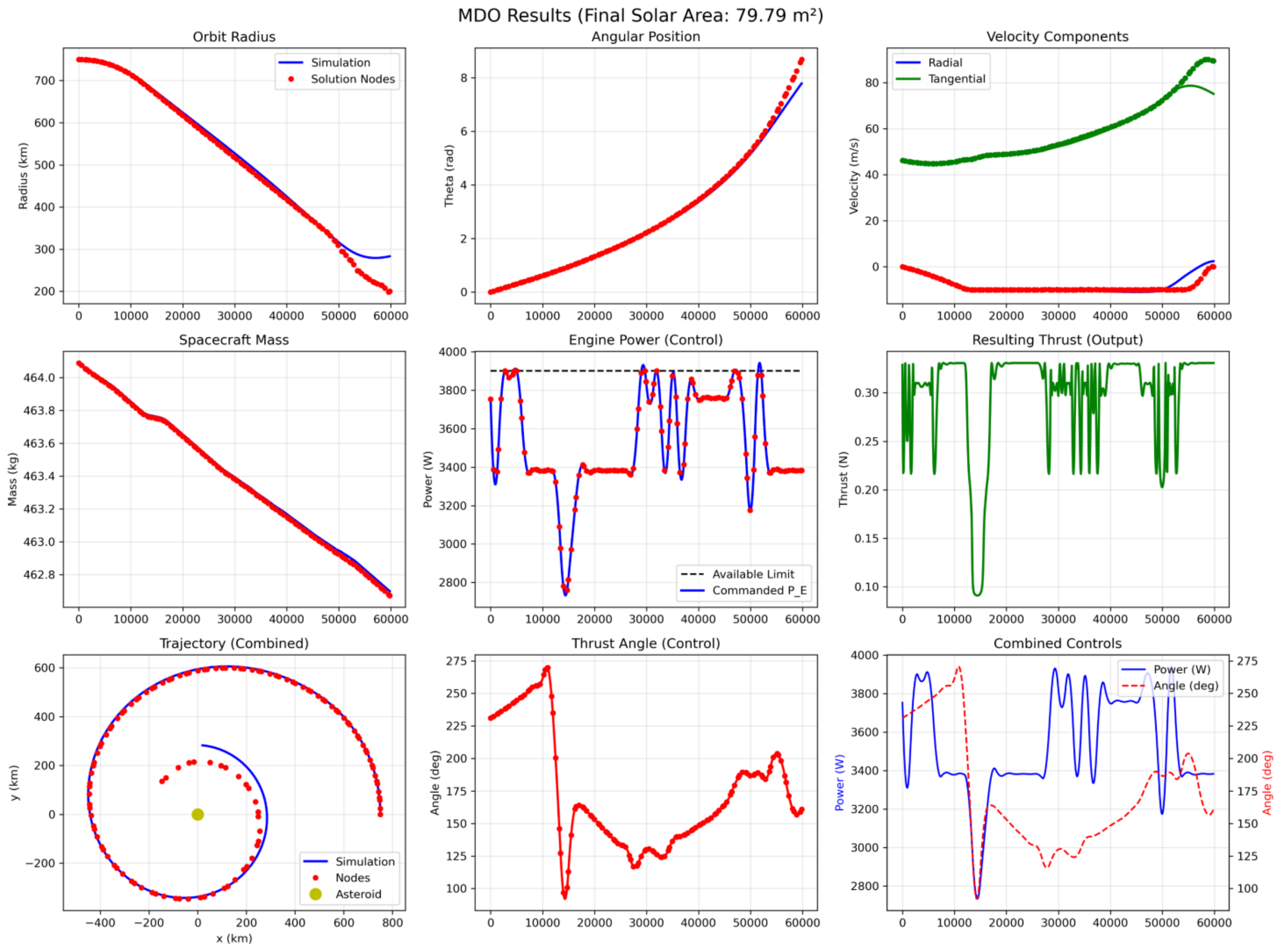
Optimizaed Trajectory –Only Model

- Final time: ≈74837.72 s
- Final radius: = 200 km
- Final mass: ≈417.34 kg
- Final tangential velocity: 89.829 m/s
- Final Angular Position: 14.563 rad
- Number of revolutions: ≈ 2.318



Optimizaed Coupled Model

- Final time: = 59815.55 s
- Final radius: = 200 km
- Final mass: ≈462.67 kg
- Final tangential velocity: 89.458 m/s
- Final Angular Position: 8.479 rad
- Number of revolutions: ≈ 1.33



Model Comparison

Variables	Initial Guess (FFS)	Optimized Result (Trajectory only)	Optimized Result (Coupled)
Final Time	81000 s	74837.72 s	59815.55 s
Initial Wet Mass	418 kg	418 kg	464.08kg
Final Mass	417.54 kg	417.34 kg	462.67 kg
Propellant Consumed	0.46 kg	0.66 kg	1.41 kg
Number Of Rev.	2.5	2.31	1.33
Area of Solar Pannel	50.00 m^2	50.00 m^2	79.79 m^2

Reduction in TOF by 20.07% but an increment in Propellant consumption by 113.6%.

Summary

- Fully coupled low-thrust MDO framework implemented.
- Feasible spiral descent achieved under power limitations.
- Smooth thrust and realistic mass evolution obtained.

Next Steps

- Alternative Objective Functions:
  - Minimizing fuel consumption.
- High-Performance Computing (HPC):
  - Enables increased segments, tighter tolerances and higher iterations for higher-confidence results.
- System Fidelity:
  - Incorporate additional subsystems (e.g., thermal control, attitude determination) into the MDO framework.

References

[1] K. Saloglu and E. Taher, *Co-Optimization of Spacecraft and Low-Thrust Trajectory with Direct Methods.*

[2] D. A. Smith, *An Integrated Approach to Modeling Solar Electric Propulsion Vehicles During Long-Duration, Near-Earth Orbit Transfers.*

[3] S. Marcuccio, A. Ruggiero, and P. Pergola, *Integrated Trajectory and Energy Management Simulator for Electric Propulsion Spacecraft.*

[4] G. W. Harris and P. He, *Low-Thrust Spacecraft Trajectory Optimization with Gravity-Assist Maneuver Using Dymos.*

Thank You!