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Efficient Computation of Optimal Low Thrust Perturbed Orbit Transfers

Principal Investigator: Robyn Woollands (392D)
Co-I: John Junkins (Texas A&M University)
Team: Vishala Arya, Sandeep Singh, Joe Peterson, Ehsan Taheri (Texas A&M University)
Program: Topic
Assigned Presentation #

Jet Propulsion Laboratory
California Institute of Technology

Team

Dr. Robyn Woollands (PI)
Mission Design Engineer
Jet Propulsion Lab

Dr. John Junkins (Co-I)
Distinguished Professor
Aerospa Engineering
Texa M University

Dr. Ehsan Taheri
Assistant Professor
Aerospace Engineering
Auburn University
Previously at **Texas A&M University**

Vishala Arya
PhD Student
Aerospace Engineering
Texas A&M University

Joe Peterson
PhD Student
Aerospace Engineering
Texas A&M University

Sandeep Singh
PhD Student
Aerospace Engineering
Texas A&M University

Introduction & Problem Description

Context: Why this problem and why now?

Low thrust is becoming an increasingly more attractive option for space missions because of the lower fuel requirements and lower launch mass for these missions. With increased interest in missions to and around the Moon, Mars, Venus (and of course Earth), inclusion of high-fidelity gravity models is essential for accurate orbit propagation.

Comparison with state-of-the-art

- Generally, a direct low-thrust optimization approach is preferred over an indirect approach due to relative improved convergence. The indirect optimal control formulation ensures the solution is locally optimal, however it is typically very sensitive to the initial costate guess. In our work, we employ a continuation method, hyperbolic tangent smoothing, to approximate non-smooth components in the dynamics during the early iterations, thereby increasing the domain over which the indirect method will converge.

- We include a high-fidelity gravity model into the equations of motion and use the Picard-Chebyshev integrator for propagating these equations. The two-point boundary value problem (TPBVP) is solved using the method of particular solutions. Combining these two techniques is beyond the state-of-the-practice and allows for improved computational efficiency when a high-fidelity gravity model is required.

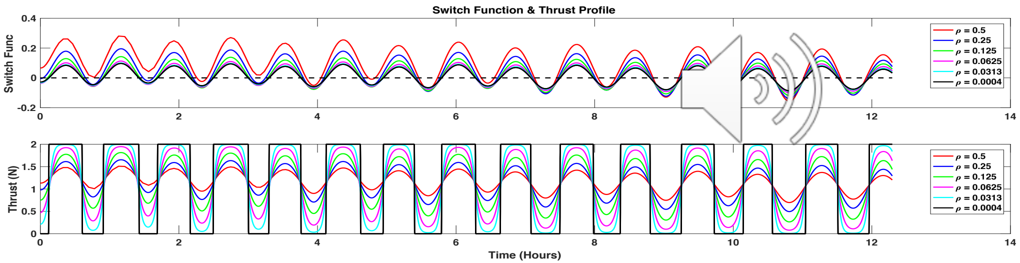
Relevance to NASA and JPL (Impact on current or future programs)

This work could be used for trajectory design and operation of future low thrust missions, both interplanetary, and those in the vicinity of bodies with known high-fidelity gravity models (Earth, Moon, Mars, Venus and some asteroids).

Methodology

Indirect Optimal Control Formulation: We present new methods for computing *fuel-optimal* and *time-optimal* low thrust orbit transfers for interplanetary missions as well as for missions in close proximity to a body (planets/moons/asteroids) that require a high-fidelity spherical harmonic gravity model for accurate orbit propagation.

Continuation & Smoothing: Our algorithms are formulated via the indirect optimal control, which leads to a two-point-boundary-value-problem (TPBVP) and a switch function. ***Hyperbolic tangent smoothing*** is used to approximate non-smooth components in the dynamics, thereby increasing the domain of convergence of the resulting TPBVPs.



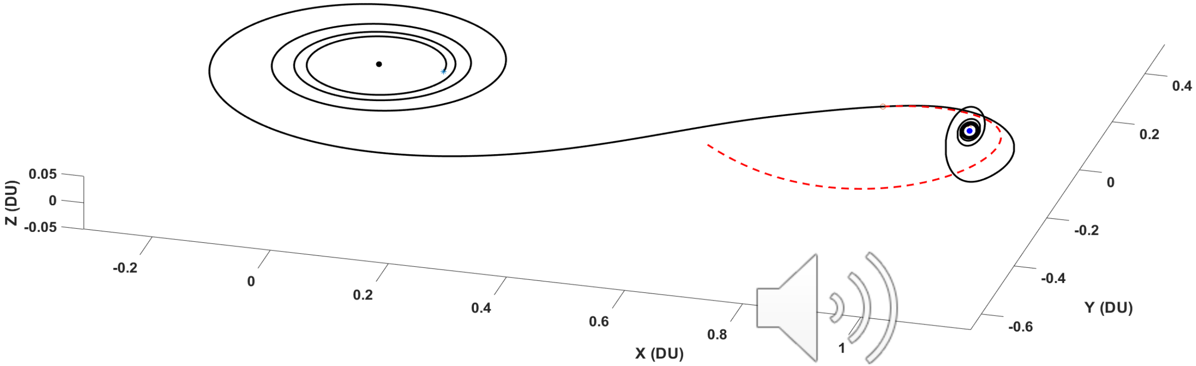
LEFT: Continuation of parameter ρ the switch function and thrust profile.

Switch Surfaces: A family of neighboring extremals and an associated switch surface can be computed for various thrust magnitudes. The switch surface can be used by mission designers for sizing spacecraft engines and evaluating mission design alternatives.

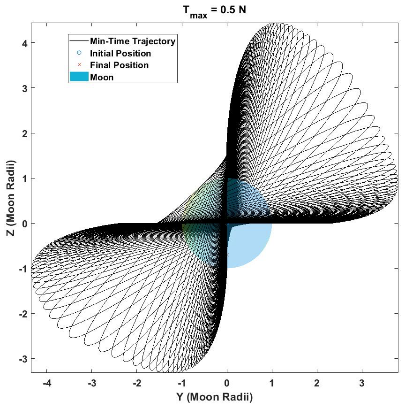
Picard-Chebyshev methods: The optimal control TPBVPs, requiring a high-fidelity gravity model, are solved using the ***method of particular solutions*** shooting method and the ***Picard-Chebyshev*** path iteration numerical integrator. We take advantage of the fixed-point nature of convergent path approximations associated with Picard-Chebyshev iteration and implement a ***variable fidelity gravity model*** for propagating the trajectory. This high-fidelity algorithm is coded in C with python wrappers, and is parallelized using OpenMP.

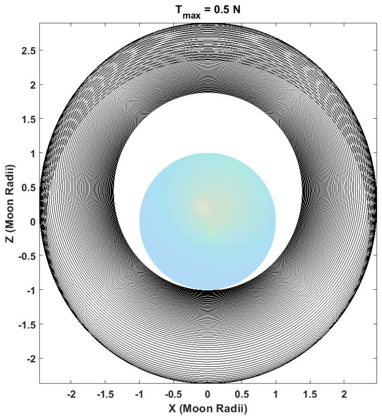
Results: GEO to Lunar Quasi-Frozen Orbit

More details are given in references [1], [2], [3].



Low-thrust time-optimal orbit transfer from GEO to Polar LLO.



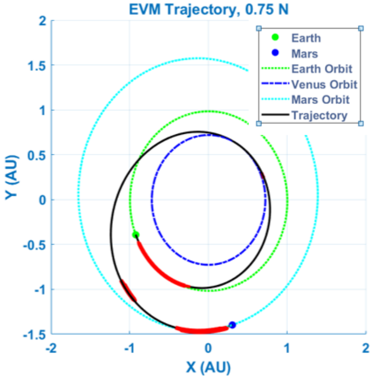


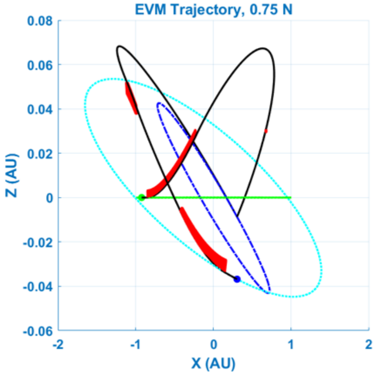
Trajectory Sequence	Total Transfer Time (days)	Number of Revs.		
		Leg 1	Leg 2	Leg 3
GEO – QFO via Equatorial LLO:	43.7	4	6	152
GEO – QFO via (i = 45°) LLO:	40.6	4	6	124
GEO – QFO via Polar LLO:	27.9	4	6	80

Far left: Equatorial circular LLO to QFO.
Left: Polar circular LLO to QFO.

Results: Hybrid Direct/Indirect Planetary Flyby

More details are given in reference [4].

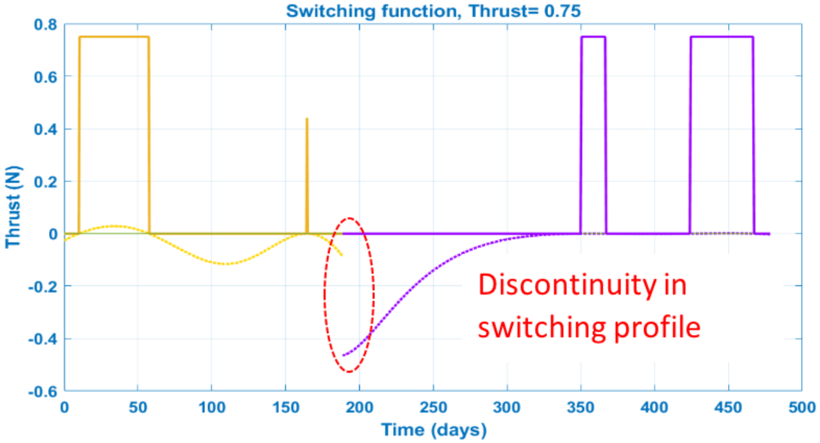




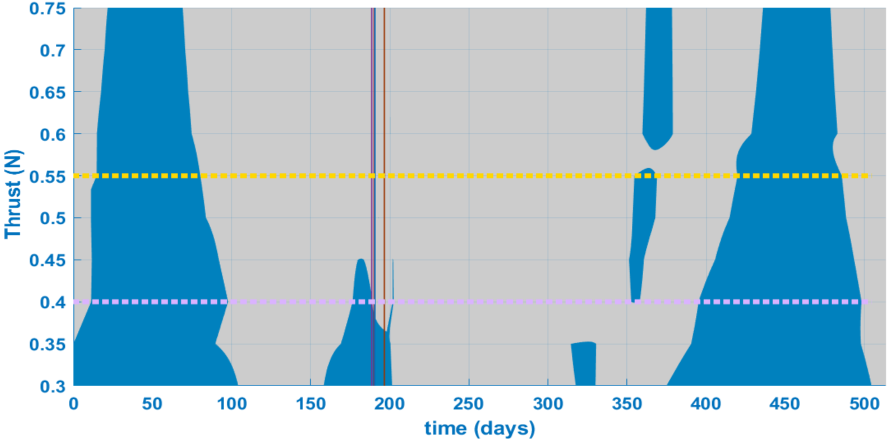
LEFT: Low-thrust fuel-optimal orbit transfer from Earth to Mars, with a flyby of Venus. Four thrust arcs and five coast arcs are present.

BOTTOM LEFT: Switch function and thrust profile for the optimal trajectory.

BOTTOM RIGHT: Switching surface contour plot made via continuation of thrust magnitude.

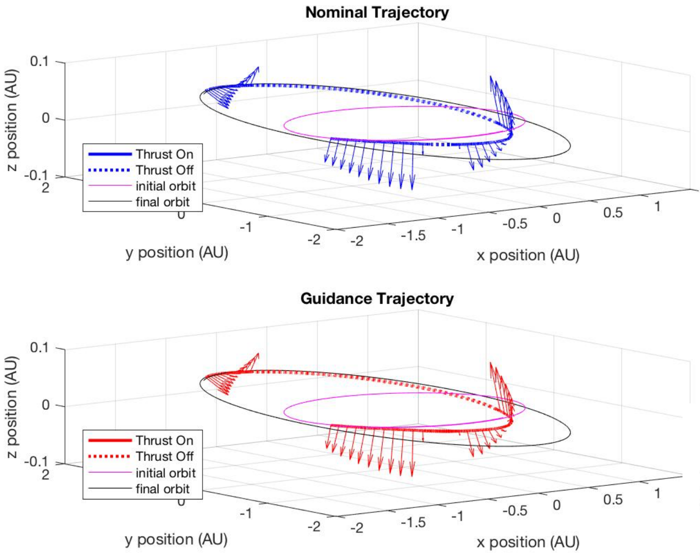


Discontinuity in switching profile



Results: Autonomous Guidance Algorithm

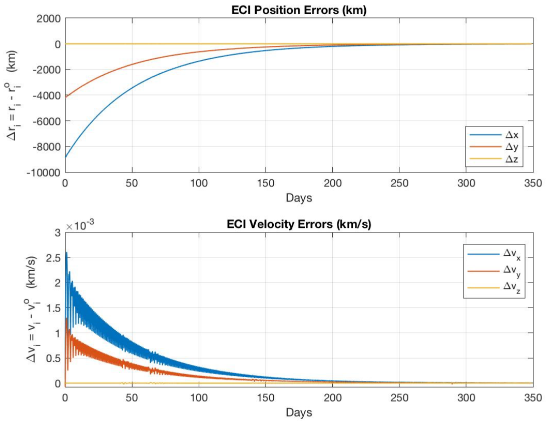
More details are given in references [5], [6].

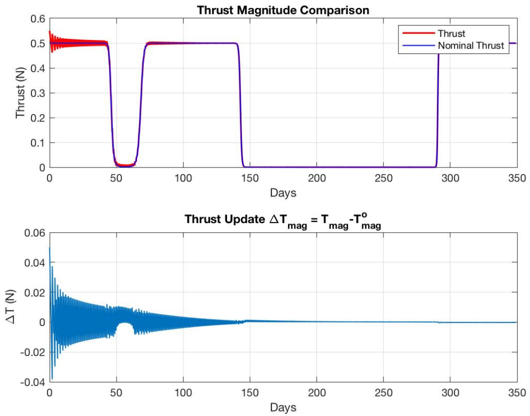


LEFT: Guidance and nominal trajectory comparison for an orbit transfer from Earth to Mars.

BOTTOM LEFT: Position and velocity errors for the transfer.

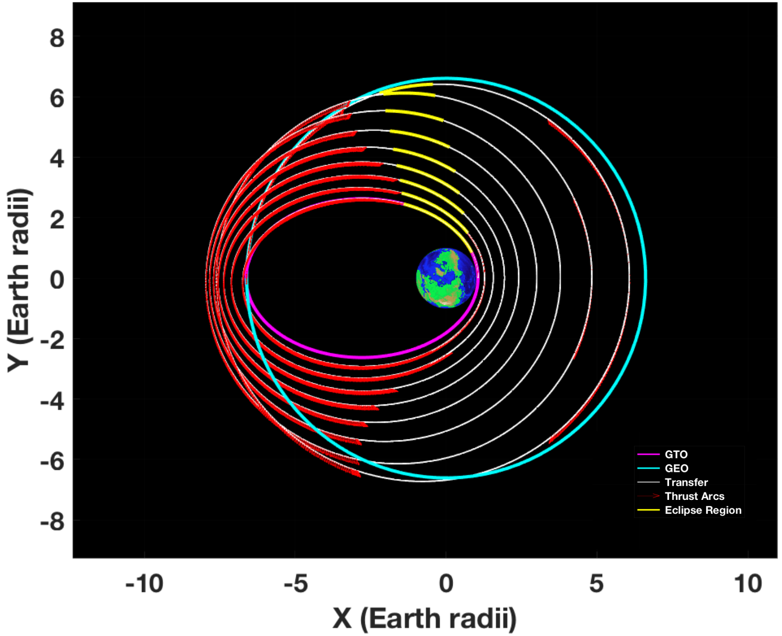
BOTTOM RIGHT: Nominal trajectory and guidance trajectory thrust profile comparison.



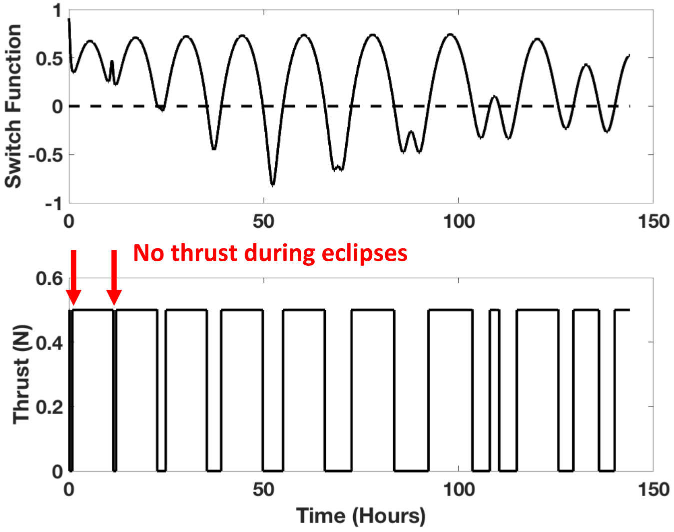


Results: High-fidelity Gravity Model

More details are given in references [7], [8], [9].



Low thrust, minimum fuel, orbit transfer from GTO to GEO.



No thrust during eclipses

Switch function and thrust profile

Conclusion

- Developed a new method for solving *time-optimal* and *fuel-optimal* orbit transfers using an indirect optimization approach
- Innovations
    - Hyperbolic tangent smoothing
    - Switch surfaces
    - High-fidelity gravity models
    - Picard-Chebyshev integration (variable fidelity gravity model, radially adaptive gravity)
    - Method of particular solutions (solving TPBVP)
    - Parallelization
- Presented several example problems

Next Steps

The software can be used as a stand-alone tool or it could be infused into the Mission Design & Navigation Section Software to support design and operations of future missions.

Publications and References

1. “Mission Design for Close-Range Lunar Mapping by Quasi-Frozen Orbits”, S. Singh, E. Taheri, R. Woollands, J. Junkins, 70th International Astronautical Congress, Washington, DC, Oct 2019.
2. “Feasibility of Quasi-Frozen, Near-Polar and Extremely Low-Altitude Lunar Orbits”, S. Singh, R. Woollands, E. Taheri, J. Junkins, Acta Astronautica, Vol 166, pages 450-468, Jan 2020.
3. “Feasibility Study of Quasi-Frozen, Near-Polar and Extremely Low-Altitude Lunar Orbits”, S. Singh, R. Woollands, E. Taheri, J. Junkins, 29th AAS/AIAA Space Flight Mechanics Conference, Maui, HI, Jan 2019.
4. “Gravity Assist Fuel-Optimal Low Thrust Trajectory Design using Hybrid Optimization Techniques”, V. Arya, E. Taheri, R. Woollands, J. Junkins, 70th International Astronautical Congress, Washington, DC, Oct 2019.
5. “Lyapunov Guidance in Orbit Element Space for Low-Thrust Cislunar Trajectories”, J. Peterson, S. Singh, J. Junkins, E. Taheri, 43rd Annual AAS Guidance, Navigation and Control Conference, Breckenridge, CO, Feb 2020.
6. “Autonomous and Adaptive Guidance for Low-Thrust Interplanetary Trajectories”, J. Peterson, J. Junkins, 70th International Astronautical Congress, Washington, DC, Oct 2019.
7. “Optimal Low-Thrust Gravity Perturbed Orbit Transfers with Shadow Constraints”, R. Woollands, E. Taheri, Astrodynamics Specialist Conference, Portland, ME, Aug 2019.
8. “Efficient Computation of Optimal Low Thrust Perturbed Orbit Transfers”, R. Woollands, E. Taheri, J. Junkins, Journal of Astronautical Sciences, May 2019.
9. “Efficient Computation of Optimal Low Thrust Perturbed Orbit Transfers”, R. Woollands, E. Taheri, J. Junkins, 29th AAS/AIAA Space Flight Mechanics Conference, Maui, HI, Jan 2019.
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