FY24 Strategic University Research Partnership (SURP)

Rapid GPU Trajectory Optimization With New ALTRO Constrained Trajectory Optimizer

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Objectives: Our objective is to speed up the trajectory optimization process by 2-3 orders of magnitude through Co-I Manchester's new ALTRO optimization technology that can efficiently leverage the thousands of processor cores available on modern graphics processing units (GPUs). We achieve this goal by developing parallelized versions of three key solver components: (1) Implementing high-order integration methods with automatic differentiation on a GPU. Evaluation of spacecraft dynamics, Jacobians, and Hessian-vector products can be parallelized across timesteps in a trajectory. A 1000x speedup of these functions, which typically account for 70% of solve-time, is possible. (2) Implement parallel backtracking line-search on a GPU, a core part of nonlinear optimization solvers that is currently performed serially. By evaluating hundreds to thousands of step-lengths simultaneously, we can make more progress at each iteration while reducing search-time, resulting in a 2-3x speedup. (3) Develop a custom sparse linear-system solver on a GPU. This component is the core of any Newton-based solver algorithm and typically accounts for 30% of solution time in space trajectory applications. It is the most difficult to parallelize and requires fundamentally new matrix factorization algorithms. An efficient GPU implementation should achieve a 10x-100x speed up.

Background: The trajectory is a key, early element for mission design because every subsystem depends on it; telecom, thermal, propulsion, science coverage all require the orbit for their design. Perhaps the most important technology to speed up this process is the optimization of the trajectory as in our proposal. The trajectory optimization technology is also a key for automation such as needed in machine learning and autonomous navigation. For AI methods and automation of mission design, our proposed trajectory optimization work is an essential technology.

Approach and Results: For FY24, our focus is on contingency-aware station station keeping of chaotic libration orbits around the Moon and Enceladus. If propulsion fails in halo orbits, the S/C will likely crash. Halo orbits can be biased to escape into safe temporary orbits for recovery. We designed a convex model-predictive controller solving this problem.

For solar sail missions, we present a controller for long-term station keeping of halo orbits. Our controller determines the optimal sail orientation to minimize deviation from the nominal halo orbit. Traditional methods often linearize the solar-sail propulsion model around angles that define the sail orientation, but this can lead to inaccuracies as the model deviates from the linearization point [1]. Instead, we encode the set of possible thrust vectors as the boundary of a convex set, which we then relax to arrive at a global convex optimization problem. We demonstrate the performance of our algorithm through simulations in the Earth-Moon circular-restricted three-body problem (CR3BP), validating the effectiveness of this propulsion-free method for long-term station keeping. Figure 5 shows the angle profile of the sail with respect to the sun vector for revolution 1 out of a 100-revolution mission.

For impulsive station-keeping in unstable halo orbits, we add constraints to ensure safety in case of propulsion failure. Station keeping for halo-orbits typically use differential correctors. This aims to achieve specific objectives such as ensuring the velocity x-component is zero when crossing the Sun-Earth line in the rotating frame [2]. However, shooting methods are highly dependent on initial guesses and careful problem formulation is crucial to prevent ill conditioning [3], making it unsuitable for implementation in flight software. Instead, we formulate a convex trajectory-optimization problem to generate impulsive spacecraft maneuvers to loosely track a halo orbit using a receding-horizon approach. In the event propulsion is lost at any point in the mission, our solution provides a safe orbit departure strategy. We validate our algorithm in simulations of the 3-body Earth-Moon and Saturn-Enceladus systems, demonstrating both low total ΔV and a safe contingency plan throughout the mission. Figures 1 and 3 show the impulsive control strategy for both the Earth-Moon and Saturn Enceladus system, and Figure 2 shows the contingency plan for orbit departure through the right invariant manifold to avoid collision with the body. Figure 4 depicts the fuel consumption per year for conducting station keeping in both systems.

Significance/Benefits to JPL and NASA: During the EMBER proposal work in the last few years, we lacked high accuracy nonlinear station keeping tools to analyze and design the maneuvers to maintain halo orbits around the Enceladus L2. Moreover, due to the short period of Enceladus halo orbits (12 hours), 4 to 6 station keeping maneuvers are necessary to maintin these highly unstable orbits each day. This required AutoNav to maintain the halo orbits. But in the event the Spacecraft enters Fault Protection Mode and propulsion becomes unavailable, this would most likely lead to a crash. We were able to build a new convex model predictive station keeping control for a biased halo orbit. In the event propulsion is unavailable, the biased orbit enabled the spacecraft to escape into safe orbit around Saturn to await recovery from Earth. This solved one of the critical problems for the EMBER mission concept. This result demonstrated biased orbit is a workable solution to this problem. This result using the Circular Restricted 3 Body Problem is preliminary. More accurate JPL ephemeris and gravity models are needed for the control planned for Year 3 of our SURP Project.

New Technology: NTR 53064 – Contingency-Aware Station-Keeping Control of Halo Orbits (Pending)

This NTR is for station keeping of halo orbits, biased to escape into safe orbits around the larger body in case propulsion is not available.

References:

[1] Bookless, J. and McInnes, C., 2008. Control of Lagrange point orbits using solar sail propulsion. *Acta Astronautica*, *62*(2-3), pp.159-176.

[2] D. W. Dunham and C. E. Roberts, "Stationkeeping techniques for libration-point satellites," JAS, vol. 49, pp. 127–144, 2001.

[3] D. Folta et al., "Astrodynamics convention and modeling reference for lunar, cislunar, and libration point orbits," Tech. Rep., 2022

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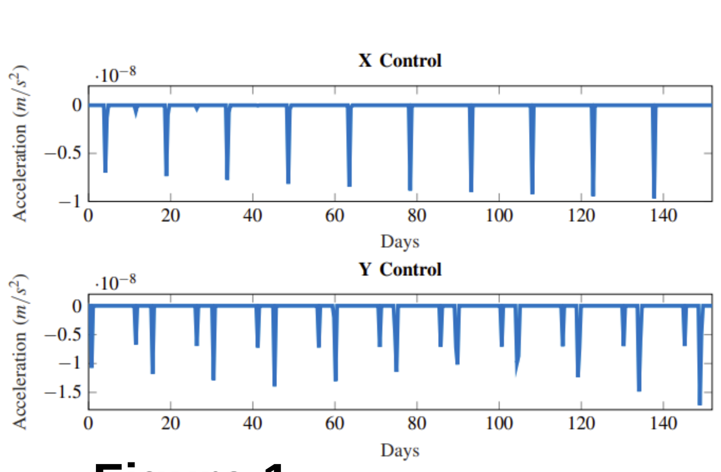

Figure 1.

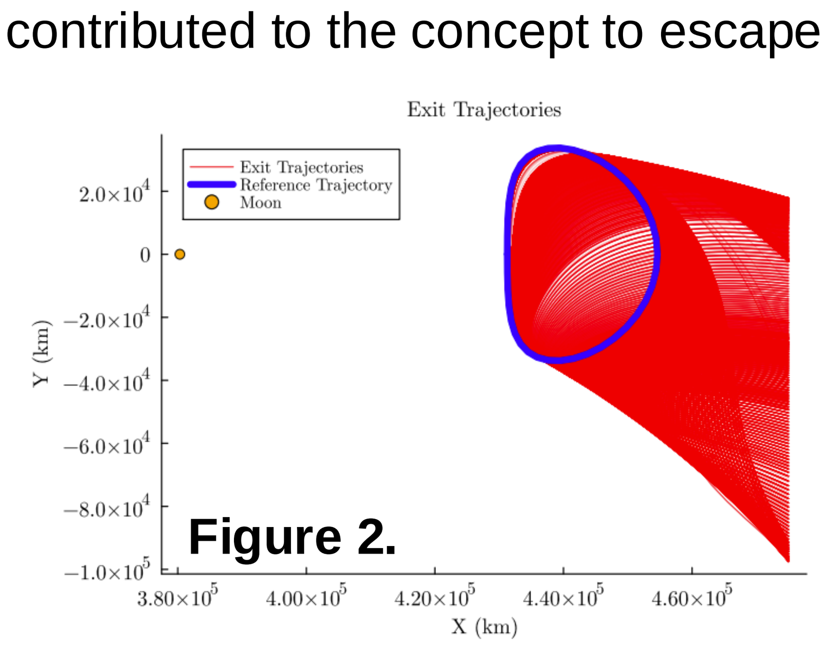

Figure 2.

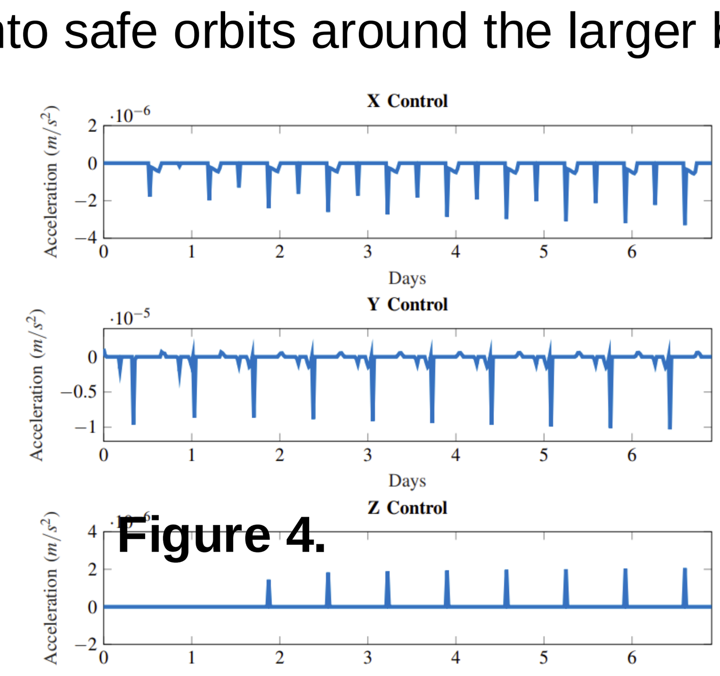

Figure 4.

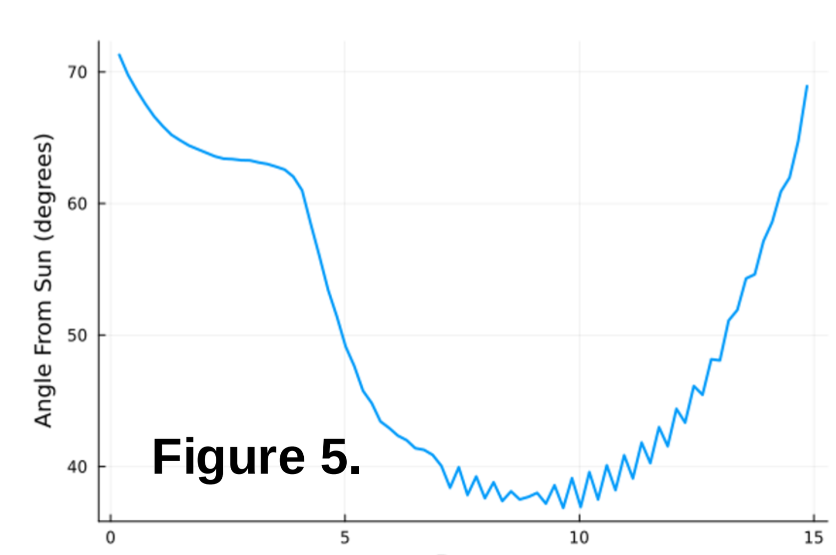

Figure 5.

System	State Constraint	Fuel Consumption $[\frac{m}{s}/yr]$
Earth-Moon	Euclidean Ball	0.712
Earth-Moon	Ellipsoid	0.668
Saturn-Enceladus	Euclidean Ball	30.16
Saturn-Enceladus	Ellipsoid	28.755

Figure 3.

Figure 1. Impulsive control of Rev 10-20 of Earth-Moon L2 halo orbit.
Figure 2. Unstable manifold for biased Enceladus halo orbit escape to Saturn orbit.
Figure 3. Impulsive control of Rev 10-20 of Saturn-EnceladusL2 halo orbit.
Figure 4. Fuel per year for 100 Rev L2 halo orbits of Moon and Enceladus..
Figure 5. Solar sail normal vector angle to sun for Rev 1 of 100 Revs.

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Publications:

Fausto Vega, M. Lo, Z. Manchester, "Convex Station-Keeping Control of Halo Orbits using a Solar Sail," submitted to 2025 IEEE Aerospace Conference, Big Sky, MT, 2025.
Fausto Vega, M. Lo, Zachary Manchester, "Contingency-Aware Station-Keeping Control of Halo Orbits," submitted to 2025 IEEE Aerospace Conference, Big Sky, MT, 2025.

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