Cislunar Spacecraft Trajectory Design for Low- and Hybrid-Thrust Propulsion Technologies

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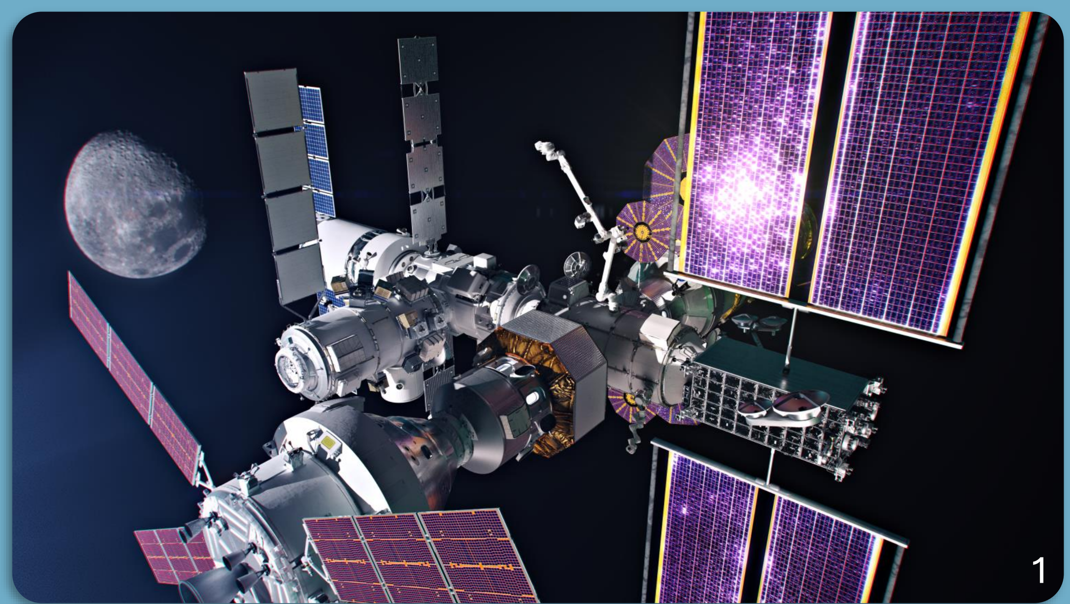
Cislunar space:

The next frontier

Cislunar space is attracting a lot of attention in the next decade. The Lunar Gateway (picture below) is the most visible, but up to 38 private and public US, Japanese, Chinese, and European missions are planned. It is to become a contested and congested space in the next few years; understanding how we move around it is critical.



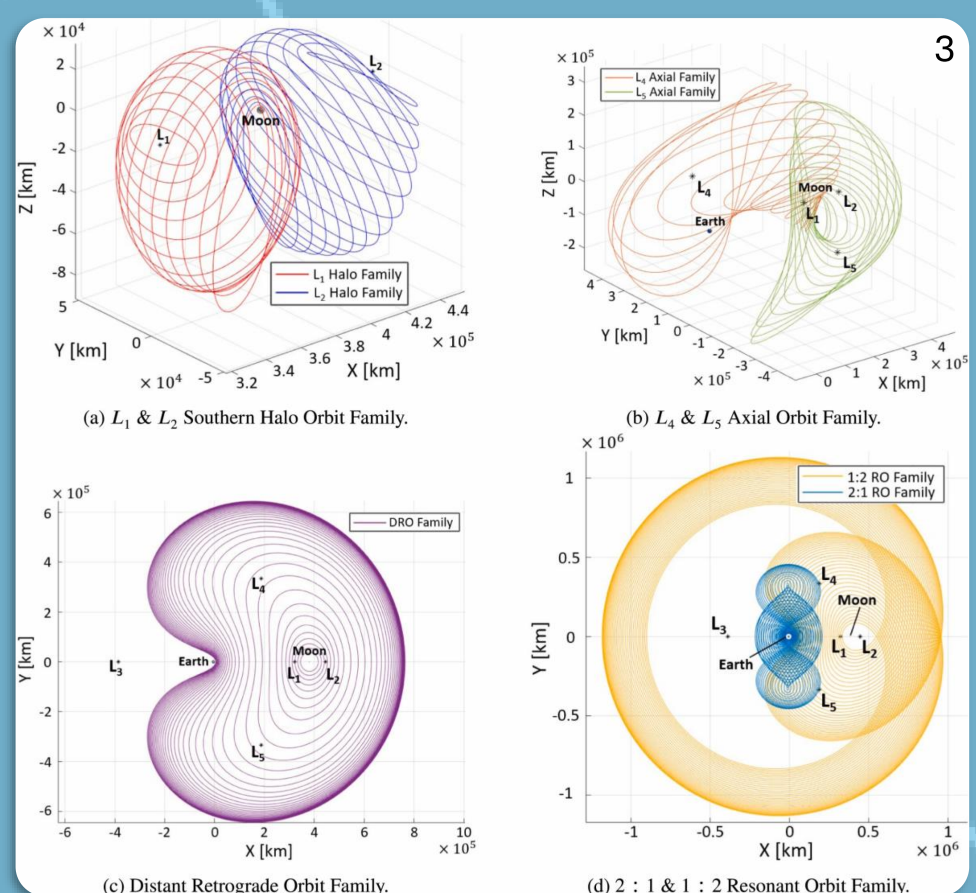
3-Body Dynamics:

A headache for navigators

- Extremely unstable and chaotic system; unique problem for navigators.
- Circular Restricted 3 Body Problem simplification[2]:

$$\ddot{x} = 2\dot{y} + x - (1-\mu)\frac{x+\mu}{r_1^3} - \mu\frac{x-1+\mu}{r_2^3}$$
$$\ddot{y} = -2\dot{x} + y - (1-\mu)\frac{y}{r_1^3} - \mu\frac{y}{r_2^3}$$
$$\ddot{z} = -(1-\mu)\frac{z}{r_1^3} - \mu\frac{z}{r_2^3}$$

- Families of orbits only possible in 3 (or more) body systems:



Trajectory design:

How do we get where we want to go?

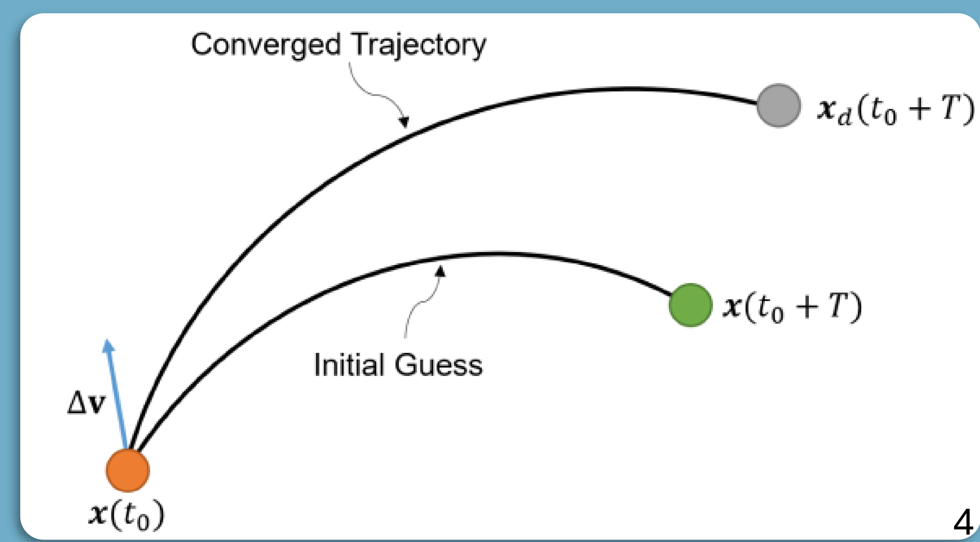
State Transition Matrix

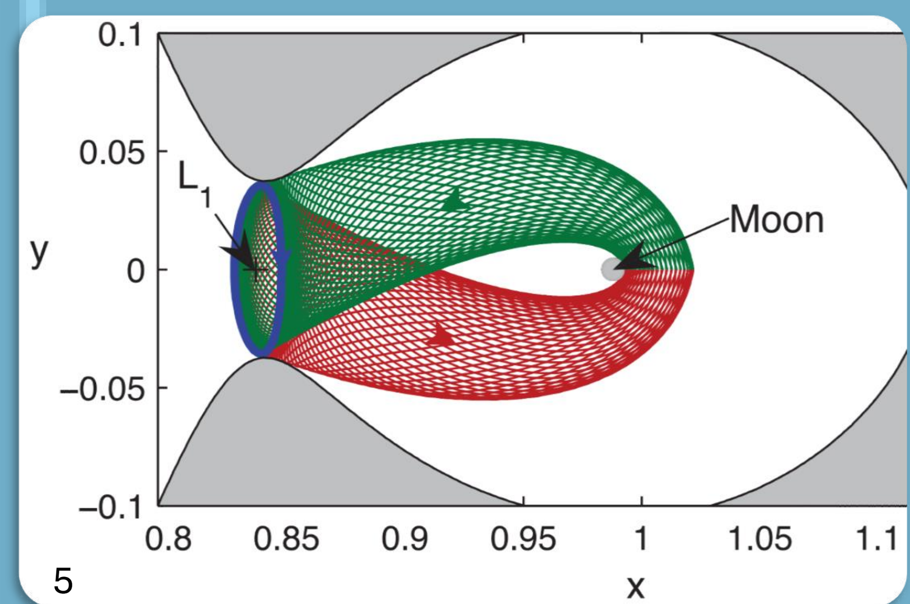
Maps how trajectories change with changing initial conditions[4]:

$$\boldsymbol{\Phi}(t, t_0) = \frac{\partial \boldsymbol{x}(t)}{\partial \boldsymbol{x}(t_0)}$$
$$\boldsymbol{x}_{t_k} = \boldsymbol{\Phi}(t_k, t_j)\boldsymbol{\Phi}(t_j, t_l) \dots \boldsymbol{\Phi}(t_n, t_i)\boldsymbol{x}_{t_i}$$
$$\delta\boldsymbol{x}_f = \boldsymbol{\Phi}(t_f, t_0)\Delta\boldsymbol{x}_0$$

Shooting Methods

We use the STM in a root-finding algorithm to reduce $\delta\boldsymbol{x}_f$ to as close to 0 as possible. Single- and multiple-shooting methods[2].





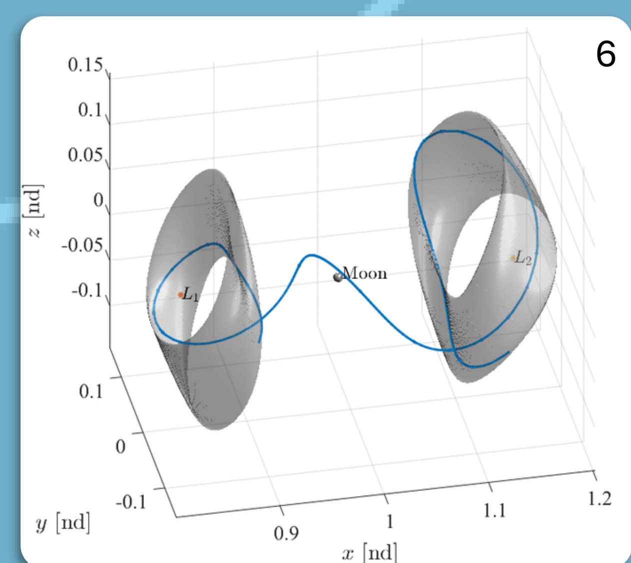
Invariant Manifolds

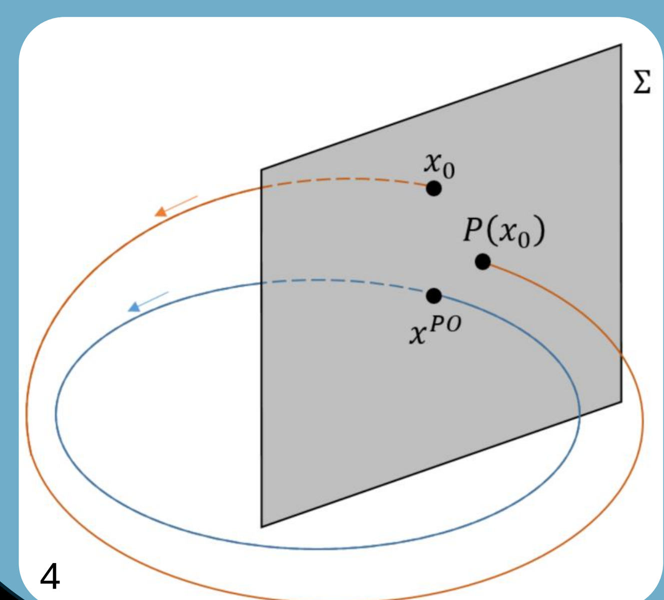
A state perturbed in the unstable eigen-direction of the STM departs orbit asymptotically, and vice-versa for stable direction. No orbit/transfer insertion manoeuvres necessary[2].

Hetero- & Homoclinic transfers

Heteroclinic: when a trajectory on an unstable manifold is on the stable manifold of another orbit.

Homoclinic: when the other orbit is the one we started on[2].





Poincaré Mapping

Examine where and when the trajectory intersects with a section of surface.

- Stability
- Periodicity
- Flow evolution

Analyse many trajectories at once: powerful trade-off tool[4].

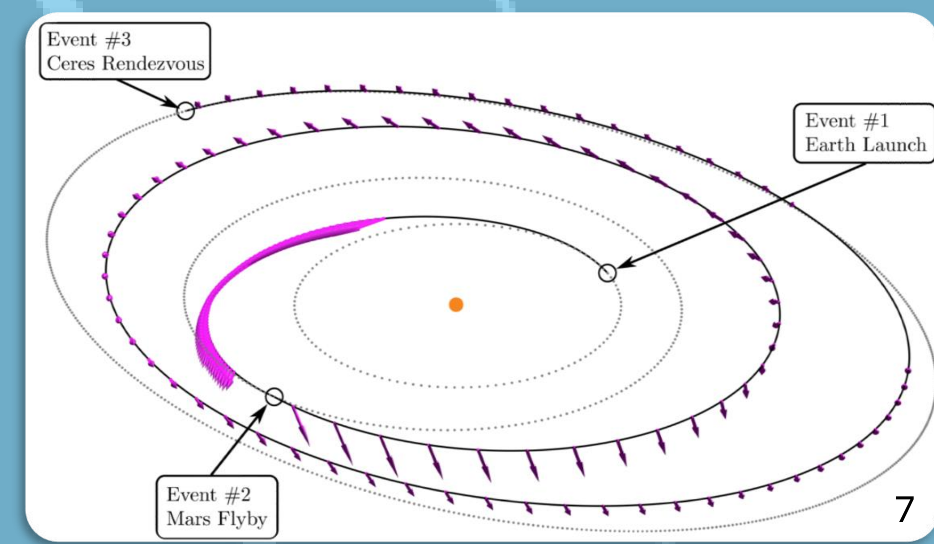
Potential Research Focus:

Where to next?

Two main areas: adaptation of these trajectory design ideas into low- and hybrid-thrust propulsion; and applying real-world operational constraints.

Propulsion Regimes

Can we understand the low-thrust trajectory design space structure? Can we transition impulsive solutions into a low-thrust regime?



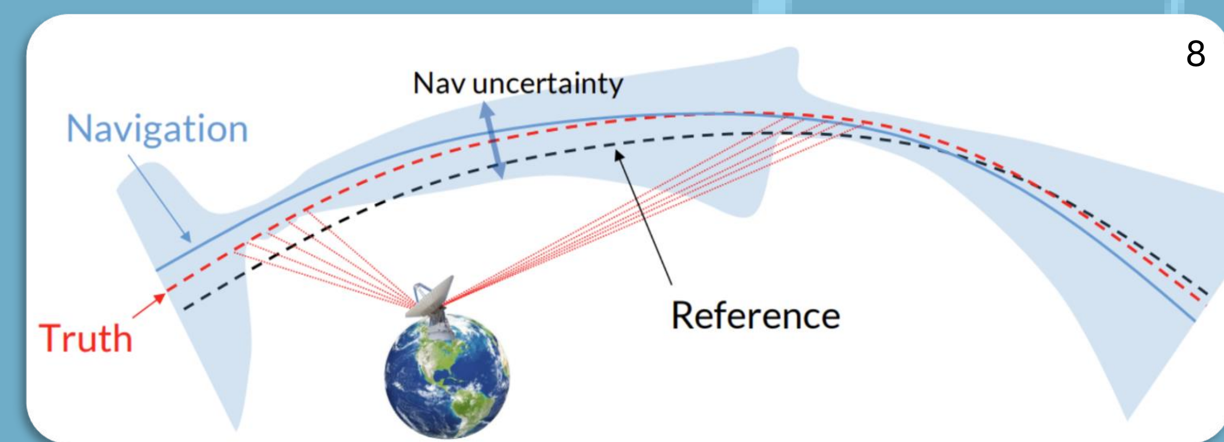
How does the design space change when utilizing both low- *and* impulsive-thrust to design trajectories?

Operational Constraints

How can these technologies impact remedial action in low-control events (e.g. missed thrust events, thrust execution errors, etc.)?

How does our OD uncertainty change these actions?

Can we minimize risk introduced by the dynamics?



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