THE LUNAR ICECUBE MISSION CHALLENGE:
ATTAINING SCIENCE ORBIT PARAMETERS FROM A
CONSTRAINED APPROACH TRAJECTORY

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Motivation

• Combination of Technology and Cost
  ◦ Miniaturization of spacecraft technologies
  ◦ Independent launch vehicle accessibility

• Selection of CubeSats as Secondary Deployment by the Exploration Mission-1 (EM-1) Space Launch System
  ◦ Translunar trajectory with a lunar flyby
  ◦ Deployed after Orion is place onto lunar trajectory

• Challenges
  ◦ Fixed departure asymptote with translunar energy with a predefined launch window
  ◦ Limited propulsion capabilities, a low thrust system
  ◦ Constrained approach energy and direction; Sun-Earth to Earth Moon
  ◦ Attain science orbit Keplerian elements, i ~ 90, e ~ 0.57, ω ~ 0, RAAN optimal for lifetime

• Solution
  ◦ Leverage dynamical system techniques to design trajectories that evolve to meet science orbit requirements
Lunar Ice Cube Mission Overview

• Lunar IceCube, is a 6U, 14kg CubeSat, selected for participation in the Next Space Technologies for Exploration Partnerships (NEXTSTEP)
• Primary objective is to prospect for water in solid, liquid and vapor forms, while also detecting other lunar volatiles
• Design includes radiation-hardened subsystems, a JPL IRIS-2 transceiver, a high power solar panel/actuator system and a robust payload processor
• Science requirement is ~90 deg inclination, 100 x 5000 km orbit with perilune at equatorial crossing
• Propulsion provided by a Busek Ion Thruster 3-cm (BIT-3) system using 1.5 kg iodine propellant with a baseline thrust < 1.15 mN and Isp ~ 2500 sec
Dynamical Models and Techniques

• Explore the lunar capture design space for low-thrust enabled transfers that link the arrival trajectory with the lunar science orbit
• Employ dynamical models of varying levels of fidelity: from CR3BP to an operational modeling environment
  ◦ CR3BP provides autonomous approximation to Sun-Earth and Earth-Moon system dynamics
  ◦ Place bounds on motion in the Earth-Moon system
  ◦ Pass to ephemeris modeling to incorporate Sun, Earth, Moon and low thrust accelerations
  ◦ Final design using operational models
• CR3BP analysis performed using the Adaptive Trajectory Design (ATD) and related Matlab algorithms
• Designs are then transitioned to a full ephemeris model such as those found in GSFC’s General Mission Analysis Tool (GMAT) and AGI’s STK Astrogator Module
A Sample Transfer

- Transfer trajectory from a constrained outbound asymptote with a trailing edge lunar gravity assist
- Transfer leverages a combination of natural (blue) and low-thrust-enabled (red) arcs to produce motion that is captured around the Moon
- But without dynamical information for design inputs, the achieved science orbit inclination is not readily achievable
Sensitivity of Arrival and Lunar Capture

- Sensitivity of this design explored using a measure of the energy: lunar C3
- Thrusting arc timeline altered by 2 days from nominal
- Due to the chaotic nature of the multi-body Cislunar gravitational environment, small differences result in two distinctly different paths, reference trajectory (red) and perturbed trajectory (blue)
- Challenge includes obtaining motion that is quickly captured to the lunar vicinity and eventually evolves to an elliptical orbit with the desired orbital elements

![Graph showing C3 vs Lunar Arrival Date](image)

**Lunar C3**

- C3 = 0 line
- Escape via Earth-moon Gateway
- Capture in to Stable Orbit

**Earth-Moon rotating frame**

- Begin Low thrust Maneuver, +/- 2 day
- Capture Orbit (red)
- Perturbed Orbit (blue)
Science Orbit

- Trajectories that approach / depart the science orbit computed via forward & backward integration
- Analyze with various RAAN (which determine the orbital lifetime)
- Thrust profiles for arcs can be limited heuristically by the total required thrust time
- Assumed thrust direction anti-velocity and magnitude 0.90 mN
- Affects Keplerian elements and rates and affects the ‘entry’ into the multi-body region
- Determine what design matches with predefined arrival conditions
Gateway analysis in the Earth-Moon CR3BP enables exploration of trajectory behavior as s/c approaches the lunar orbit.

Consider the process for generating a science orbit approach path: feasible science orbit is integrated backwards in time with the low-thrust.

For a given Jacobi constant, the L₁ and L₂ gateways are closed and motion cannot escape.

Velocity of the spacecraft increases over time, Jacobi constant decreases.

Examine orbit for Jacobi constant equivalent outside the L₂ gateway to guide construction of the trajectory generation process.

In particular, each initial condition located at a given true anomaly along a feasible science orbit is integrated backwards in time in a point mass ephemeris model with the thruster activated in the anti-velocity direction until a Jacobi constant equivalent to that of L₂ is achieved.

\[(a) \quad C > C(L₁), C(L₂) \quad (b) \quad C(L₁) > C > C(L₂) \quad (c) \quad C(L₁), C(L₂) > C\]
Manifolds of Feasible Approaches

- For feasible science approach paths, each of the apses at which the low-thrust engine is activated must lie close to the unstable manifold of an $L_2$ libration point orbit.
- States that lie within these manifolds pass through the $L_2$ gateway prior to evolving towards the lunar vicinity.
- Implement a Surface of Section (SoS) mapping at E-M $L_2$, with $y$ and $z$ seeded on hyperplane.
- For each combination of position variables, $(x,y,z)$, several velocities are defined to possess a negative $x$-component, with the relative values of the $y$- and $z$-components then varied.
- Integrated forwards until their first periapsis.
- Sample set of periapses in purple corresponding to trajectories that pass through the $L_2$ gateway, i.e., the unstable manifolds of $L_2$ periodic and quasi-periodic orbits, at a Jacobi constant of $C = 3.138$. 
Visualization of Science Orbit Approach Paths

- $L_2$ gateway map depicts crossings of trajectories that arrive at the lunar science orbit in forward time with the assistance of a low-thrust engine.
- Colored by Jacobi constant in the Earth-Moon CR3BP and the time of flight to the hyperplane.
- At each periapsis or apoapsis with a Jacobi constant below that of $L_2$, the spacecraft state is propagated until it reaches the defined surface of section.
- RAAN in the range $[0, 360]$ in increments of 20 degrees.
- Crossing of each feasible science orbit approach arc with the surface of section is represented by its $y$- and $z$-coordinates in an Earth-Moon rotating frame.
- Velocity that is directed in the negative $x$ direction and the negative $y$ direction.
Example of an L\textsubscript{2} Gateway Map
Capturing Motion

- L\textsubscript{2} gateway map captures motion that evolves towards the desired lunar orbit with a high inclination and periapsis over the equator
- Analysis reveals two types of trajectories that approach the desired polar science orbit:
  - A low Jacobi constant and longer time of flight to the L\textsubscript{2} gateway
  - A higher Jacobi constant and a shorter time of flight to the L\textsubscript{2} gateway
  - An example appears in an Earth-Moon rotating frame with blue arcs indicating natural motion and red curves locating low-thrust-enabled segments.
Comparison to Existing Point Solutions

- Visualization of the natural flow through the Earth-Moon L₂ gateway and subsequent low-thrust-enabled capture via dynamical systems techniques useful in analysis of existing point solutions
- These point solutions, constructed in an operational high-fidelity model include transfers that reach a polar orbit and those that do not
- Arrival and capture trajectory in an Earth-Moon rotating frame and shows the inbound surface of section crossings
- Captured to a 93 deg inclined polar orbit with \( \omega = 0 \) deg
- Directional low thrust maneuver alters the acceleration profile may be required to attain the precise orbital element requirements
Comparison to Existing Point Solutions

- Generated science orbit approach paths are compared to existing point designs via their $L_2$ gateway map crossings.
- $L_2$ gateway map captures motion that evolves towards the desired lunar orbit with a high inclination and periapsis over the equator.
- Map crossings for a selected set of epoch values, colored by their Jacobi constant.
- Map crossing marked by a light blue filled square represents the existing 93 deg inclined point solution – and is similar to Jacobi constant of nearby map crossings.
- Blue vectors are added to map crossings that possess a value of the Jacobi constant.
- Nearby the sample point solution, in position and Jacobi constant, the velocity vectors are pointed in a similar direction.
- Map crossing associated with the sample solution falls in a region of the map where crossings occur and possesses a similar energy and velocity direction.
Maps support the analysis of problematic lunar approach arcs, i.e. those that do not reach a polar lunar orbit, the 45 deg inclined case

- Map crossings for a selected set of epoch values, colored by their Jacobi constant
- Map crossing marked by a cyan filled circle represents the existing 45 deg inclined case
- Blue vectors attached to each map crossing indicate the y- and z-component of velocity
- The scarcity of map crossings at a similar energy level in the vicinity of this point solution may indicate increased difficulty or sensitivity in attaining a polar orbit
  - Feasible transfers occur for a lower energy or higher Jacobi constant
  - Shift the crossing of the L₂ gateway hyperplane closer to the x-axis of the Earth-Moon rotating frame near the cyan map crossings
  - Adjustments to the energy and velocity produce a point solution with a similar crossing of the L₂ hyperplane in position coordinates, but with a lower velocity, Jacobi constant is above ~3.05

Comparison to Existing Point Solutions

Map crossing for sample point solution
Concluding Remarks

- Address challenges involved in designing multi-body transfers into stable lunar orbits limited by a low thrust system.
- Process that leverages dynamical system theory to identify transfers from a Moon-centered multibody trajectory to a stable, polar lunar orbit.
- Use CR3BP, high fidelity models, and surface of section (hyperplane) to identify useful position states and Jacobi Constant values.
- Moon-centered manifolds employed to identify states and energies.
- Low-thrust acceleration enables transfers from a stable lunar orbit to the hyperplane using backward integration.
- Verified with operational software using forward integration and differential correction targeting.
- Via dynamics systems several lunar arrival conditions that link to high energy deployment trajectories are identified and are successfully employed in a Lunar IceCube mission design process.
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Thank You