Targeting for Trans-Earth Injection Maneuvers

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The Orion spacecraft guidance, navigation, and control (GNC), as part of the Exploration Architecture System, must meet a number of constraints. These are defined by the Crew Exploration Vehicle (CEV) Subsystem Requirements Specification document (CEV-T-031210). The requirements articulate a need for on-board computation of "translational maneuver targets" (GNC.0561) as well as for specific additional constraints on the mission relating to the timeline of various maneuver sequences. Translational maneuver targets include lunar orbit insertion, trans-Earth injection (TEI), plus any required trajectory correction maneuvers (TCMs). This on-board capability is generally assumed to be supplemental to any ground computation in nominal mission operations, and is primarily considered a viable alternative in loss-of-communications contingencies.

Of these maneuvers, the ability to accurately and consistently establish a flyable three-burn TEI target sequence is especially critical. The TEI is the sole means by which a crew can successfully return from a moon orbit to a narrowly banded Earth entry interface (EI) state that relies entirely on the TEI sequence plus any small TCMs to complete the transit. This ability is made even more critical by the desire for global access on the lunar surface. Currently, the designed propellant load is based on fully optimized TEI solutions for the worst-case geometries associated with the accepted range of epochs and landing sites. Thus, in addition to being feasible, the targets must not include burn sequences that exceed the anticipated propellant load. This is currently listed as a risk for the Operations Management Team GNC design.

It is well known that analytic solutions for transfers in the three-body problem are unknown. Thus, if a fully targeted solution is desired, a patched conic method must first be used to establish a so-called feasible initial guess. At this point, an iterative scheme that minimizes the discrepancy in the states is necessary. To address both of these needs (i.e., a reasonable initial guess and a robust iterative algorithm to converge on a flyable solution), we developed an adaptive targeting algorithm. This algorithm has flexible application to either ground-based targeting and/or on-board computation as it is designed to converge on fully optimized solutions quickly and efficiently.

The TEI three-burn maneuver sequence is uniquely tailored to minimize the ΔV cost for the full range of mission scenarios. While both single- and three-burn solutions can be obtained, the total cost of a three-burn sequence is almost always less expensive. This is especially true when the geometry requires a large plane change from the initial moon orbit to the Earth-moon transfer arc. Regardless of the date or orbit, the three-burn sequence has the same basic structure: (1) The first burn significantly raises the apolune of the 100-km circular orbit. This is generally the largest maneuver of the three conducted in the plane of the initial moon orbit. (2) The second burn occurs at or near to the apolune of this new large elliptical orbit and places the spacecraft in the departure plane. The cost to change the direction of the velocity vector is cheapest when the velocity magnitude is at a minimum. This is generally the least expensive maneuver. (3) The third and final burn occurs when the spacecraft sweeps back towards the moon near perilune. This final burn places the spacecraft on a very specific trajectory designed to hit a particular EI condition that can, depending on the landing site, have very tight constraints. Parameters involved in the selection of a viable EI state include altitude, flight path angle, azimuth, longitude, and latitude targets.

Figure 1 delineates the architecture for the three-burn sequence. In this particular example, the plane change (or relative declination to the Earth-moon plane) is large, near the maximum possible value.

Flexibility to accurately set up targets for the full range of epochs and orbits autonomously is an important attribute of the algorithm. To that end, we employed a vector-based approach that purposely avoids the use of complex trigonometric expressions due to their intrinsic singularities. As such, we derived vector equations to compute an associated v_∞ vector for an Earth return trajectory analytically. We determined this vector by the desired flight time and calculated from the resultant transfer arc between the current moon state and the associated antipode state at the Earth.

Targeting a v_∞ vector differs from successfully reaching a specific EI state. Over a multiple-day transfer, the impact of Earth and sun gravitational perturbations

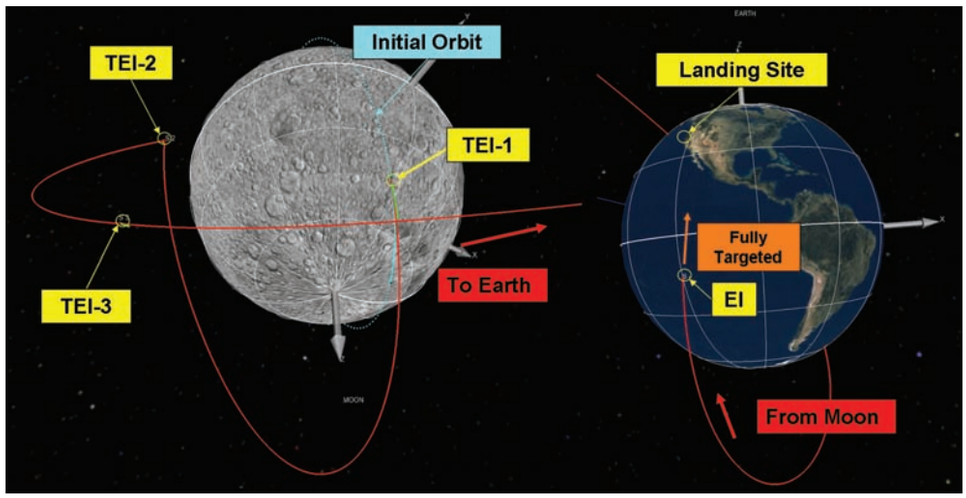

Fig. 1. *Burn TEI transfer design.*

can invoke large changes in the final state at the Earth, leading the spacecraft far from the desired EI targets. To correct these discrepancies, instead of propagating forward to EI, the optimization parameters associated with the target Earth state are propagated backwards in time. Setting a single point to match position and velocity for a continuous trajectory in the moon sphere of influence reduces the convergence difficulties associated with the large swings in EI parameters that correspond to small changes near the moon.

The desire for a flexible autonomous algorithm is naturally coupled with the need to minimize excessive iteration. Once the analytic guess is determined, it is vital that the targeter quickly converge to a feasible, flyable solution. Optimization-based algorithms take advantage of the assumption that the solution lies within the vicinity of the initial guess by designing search directions for variable optimization parameters that point towards the minimum feasible solution as efficiently as possible. We selected a sequential quadratic program due to its robust capability to solve nonlinear problems where the initial guess is in the vicinity of the solution.

Different modes of iteration are available depending on the requirements for expediency of obtaining a solution. The primary mode is full optimization, where the constraints and total fuel consumption objective function are simultaneously minimized. A feasible mode is available that does not attempt to minimize the solution but finds solutions within a few iterations and converges robustly. Another mode allows the targeter to conduct pre-optimization in a conics-only approach that minimizes the velocity increments tightly for the initial v_∞ vector. This can than be the initial guess for either the feasible or the optimal mode. Finally, a feasible constrained mode is available that simply adds a maximum ΔV magnitude constraint.

Our final goal is to have a stand-alone algorithm that always converges and does so efficiently. Testing is under way to assess the robustness of the algorithm and determine how to further expand its capability. We are currently investigating finite-burn modes that invoke steering laws similar to the anticipated closed-loop guidance that will fly out the targeted solutions.

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