Implementation of a Low-Thrust Trajectory Optimization Algorithm for Preliminary Design

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Condensed Abstract

A tool developed for the preliminary design of low-thrust trajectories is described. The trajectory is discretized into segments and a nonlinear programming method is used for optimization. The tool is easy to use, has robust convergence, and can handle many intermediate encounters. In addition, the tool has a wide variety of features, including several options for objective function and different low-thrust propulsion models (e.g., solar electric propulsion, nuclear electric propulsion, and solar sail). High-thrust, impulsive trajectories can also be optimized.

Extended Abstract

In this paper we describe a tool developed primarily for preliminary design of low-thrust interplanetary trajectories, including those with multiple gravity assists. The name of the tool is MALTO (Mission Analysis Low-Thrust Optimization).

Trajectory Structure

The trajectory is divided into legs that begin and end at *control nodes*. (See Figure 1.) Typically, the control nodes are associated with planets or small bodies, but they can be free points in space. On each leg is a single *match point*, and the trajectory is propagated forward in time from the leg's earlier control node to the match point and backward from the leg's later control node to the match point.

Continuous thrusting is modeled as a series of impulses. The legs are subdivided into *segments* with an impulsive ΔV in the middle of each segment. When modeling low-thrust propulsion systems, the magnitude of the impulse is limited by the amount of ΔV that could be accumulated over the duration of the segment.

The propagation between impulses and nodes is according to a two-body model with the Sun as the primary body. Flybys of planets are modeled as instantaneous changes in the direction of the $\mathbf{V}_\infty$ (relative velocity vector).

Optimization

This structure results in a constrained, nonlinear optimization problem which we solve using the nonlinear programming software SNOPT. The potential set of independent variables includes the state (position, velocity, and mass) of the spacecraft at each control node and the corresponding epoch. If a control node is associated with a solar system body, the position of the spacecraft is the same as the body and therefore is not independent. The initial mass following a launch is determined using launch vehicle performance data as a function of the magnitude of the $\mathbf{V}_\infty$. There are three variables representing the impulsive ΔV on each segment. Depending on the optimization objective function and engine model, the solar array reference power and engine specific impulse can be independent variables. We normally maximize final spacecraft mass or net mass (final spacecraft mass – propulsion system mass), but other objective functions are available.

The primary constraint on the optimization is that the position, velocity, and mass of the spacecraft must be continuous at the match points. The magnitude of the thrust may be constrained, and other constraints can be placed on the trajectory such as total flight time and total propellant mass. In addition, upper and lower bounds can be placed on any of the independent variables.

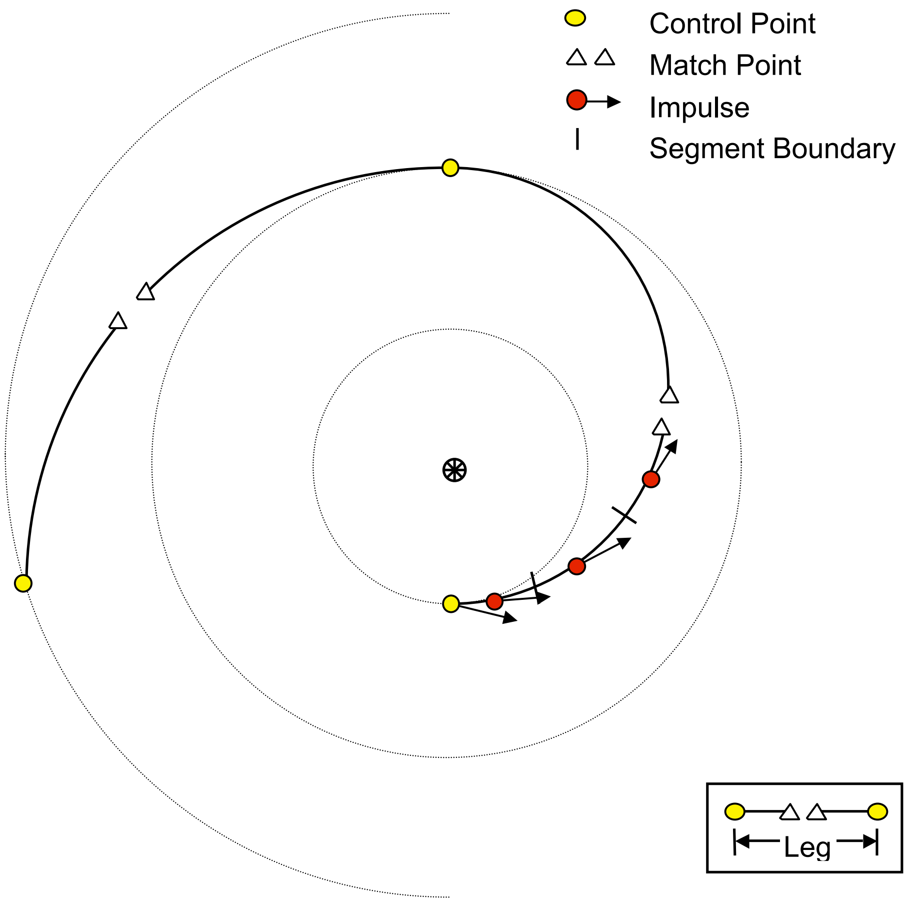

Figure 1 Trajectory Structure

Graphical User Interface

The MALTO graphical-user interface (GUI) is run through Matlab and allows users to graphically set up new input files, modify existing input files, and plot solutions. The main panel is shown in Figure 2, and Figures 3 and 4 are examples of the type of graphical output that is available.

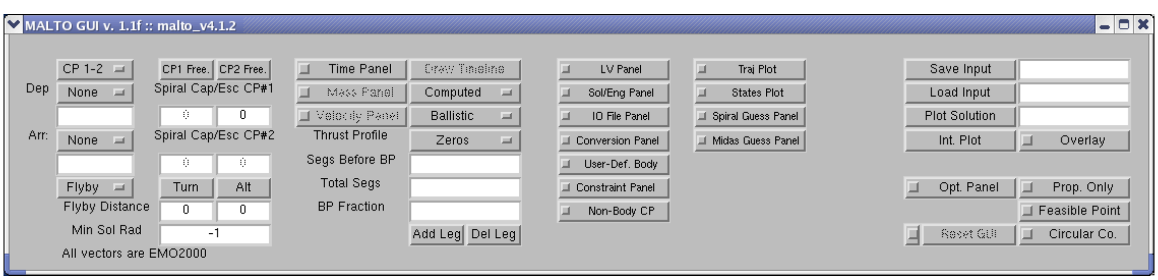

Figure 2 Main MALTO GUI panel

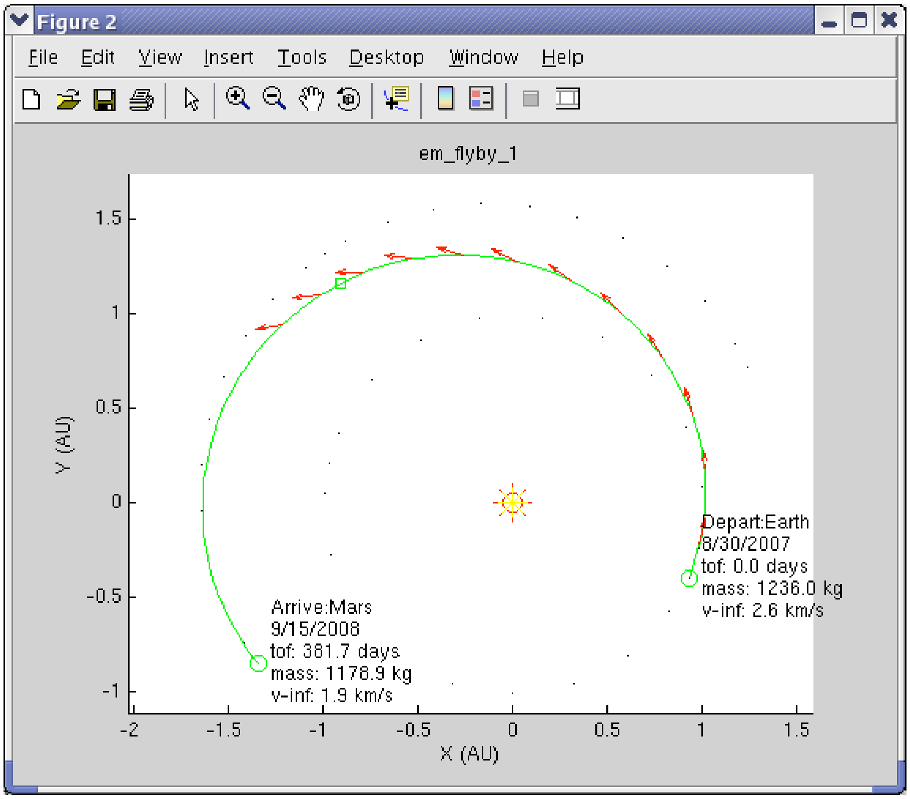

Figure 3 Example Trajectory Plot from MALTO GUI

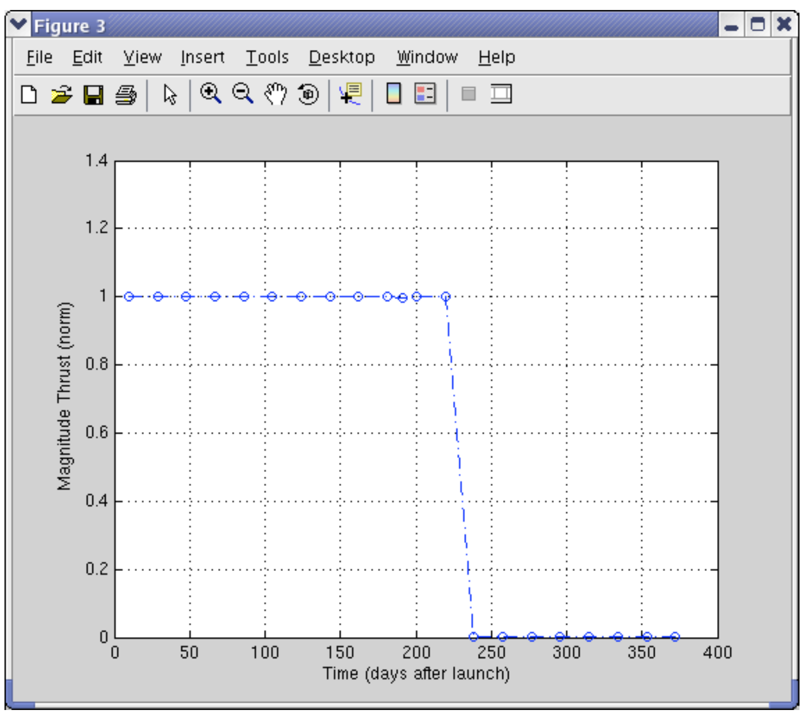

Figure 4 Example Output Data Plot from MALTO GUI

References

Sims, Jon A., and Flanagan, Steve N., "Preliminary Design of Low-Thrust Interplanetary Missions," Paper AAS 99-338, AAS/AIAA Astrodynamics Specialist Conference, Girdwood, Alaska, August 16-18, 1999.

Williams, Steven N., and Coverstone-Carroll, Victoria, "Benefits of Solar Electric Propulsion for the Next Generation of Planetary Exploration Missions," *Journal of the Astronautical Sciences*, Vol. 45, No. 2, April-June 1997, pp. 143-159.

Sauer, Carl G., Jr., and Yen, Chen-Wan L., "Planetary Mission Capability of Small Low Power Solar Electric Propulsion Systems," IAA-L-0706, IAA International Conference on Low-Cost Planetary Missions, Laurel, MD, April 12-15, 1994.

Rayman, Marc D., and Lehman, David H. "NASA's First New Millennium Deep-Space Technology Validation Flight," IAA-L-0502, Second IAA International Conference on Low-Cost Planetary Missions, Laurel, MD, April 16-19, 1996.

Sauer, Carl G., Jr., "Solar Electric Performance for Medlite and Delta Class Planetary Missions," Paper AAS 97-726, AAS/AIAA Astrodynamics Specialist Conference, Sun Valley, Idaho, August 4-7, 1997.

Betts, John T., "Optimal Interplanetary Orbit Transfers by Direct Transcription," *Journal of the Astronautical Sciences*, Vol. 42, No. 3, July-September 1994, pp. 247-268.

Coverstone-Carroll, Victoria, and Williams, Steven N., "Optimal Low Thrust Trajectories Using Differential Inclusion Concepts," *Journal of the Astronautical Sciences*, Vol. 42, No. 4, October-December 1994, pp. 379-393.

Kluever, Craig A., "Optimal Low-thrust Interplanetary Trajectories by Direct Method Techniques," *Journal of the Astronautical Sciences*, Vol. 45, No. 3, July-September 1997, pp. 247-262.

Tang, Sean, and Conway, Bruce A., "Optimization of Low-Thrust Interplanetary Trajectories Using Collocation and Nonlinear Programming," Journal of Guidance, Control, and Dynamics, Vol. 18, N0. 3, May-June 1995, pp. 599-604.

Gill, Philip E., Murray, Walter, and Saunders, Michael A., "User's Guide for SNOPT Version 7: A FORTRAN Package for Large-Scale Nonlinear Programming," December 4, 2004.

Polk, J. E., Anderson, J. R., Brophy, J. R., Rawlin, V. K., Patterson, M. J., and Sovey, J.S., "The Effect of Engine Wear on Performance in the NSTAR 8000 Hour Ion Engine

Endurance Test," Paper AIAA 97-3387, 33rd AIAA/ASME/SAE/ASEE Joint Propulsion Conference and Exhibit, Seattle, WA, July 6-9, 1997.