An Automatic Medium to High Fidelity Low-Thrust Global Trajectory Toolchain; EMTG-GMAT

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Solving the global optimization, low-thrust, multiple-flyby interplanetary trajectory problem with high-fidelity dynamical models requires an unreasonable amount of computational resources. A better approach, and one that is demonstrated in this paper, is a multi-step process whereby the solution of the aforementioned problem is solved at a lower-fidelity and this solution is used as an initial guess for a higher-fidelity solver. The framework presented in this work uses two tools developed by NASA Goddard Space Flight Center: the Evolutionary Mission Trajectory Generator (EMTG) and the General Mission Analysis Tool (GMAT). EMTG is a medium to medium-high fidelity low-thrust interplanetary global optimization solver, which now has the capability to automatically generate GMAT script files for seeding a high-fidelity solution using GMAT's local optimization capabilities. A discussion of the dynamical models as well as thruster and power modeling for both EMTG and GMAT are given in this paper. Current capabilities are demonstrated with examples that highlight the toolchains ability to efficiently solve the difficult low-thrust global optimization problem with little human intervention.

I. Introduction

The application of a work-flow which builds on lower-fidelity solutions to create a high-fidelity solution is not new, but the existence of a work-flow that requires little human intervention for the low-thrust paradigm has not yet existed. The Jet Propulsion Laboratory (JPL) currently uses two approaches to generate high-fidelity solutions from lower-fidelity initial guesses. The approaches proceed by first conducting a wide search of the design space by using either the Satellite Tour Design Program (STOUR) [1], a ballistic trajectory model with gravity assist maneuvers, or the Satellite Tour Design Program - Low Thrust, Gravity Assist (STOUR-LTGA), which uses shape-based approximations for the low-thrust trajectory arcs. Solutions from STOUR or STOUR-LTGA are then used to seed the medium fidelity low-thrust tools Mission Analysis Low-Thrust Optimization (MALTO) [2] or Gravity Assisted Low-Thrust Local Optimization Program (GALLOP) [3], which both use the direct Sims-Flanagan transcription. Finally solutions from MALTO or GALLOP provide initial guesses to either Mystic [4], which uses the static/dynamic control (SDC) method, or Copernicus [5], which uses an indirect method. To the knowledge of the authors, there is no automated transition between the medium and high-fidelity stages of the work-flow.

As opposed to the JPL toolchain, the EMTG-GMAT toolchain begins the global optimization search at a medium-fidelity using EMTG's stochastic search that combines the Sims-Flanagan transcription with a special variant of monotonic basin-hopping (MBH) and the nonlinear programming solver, Sparse Nonlinear

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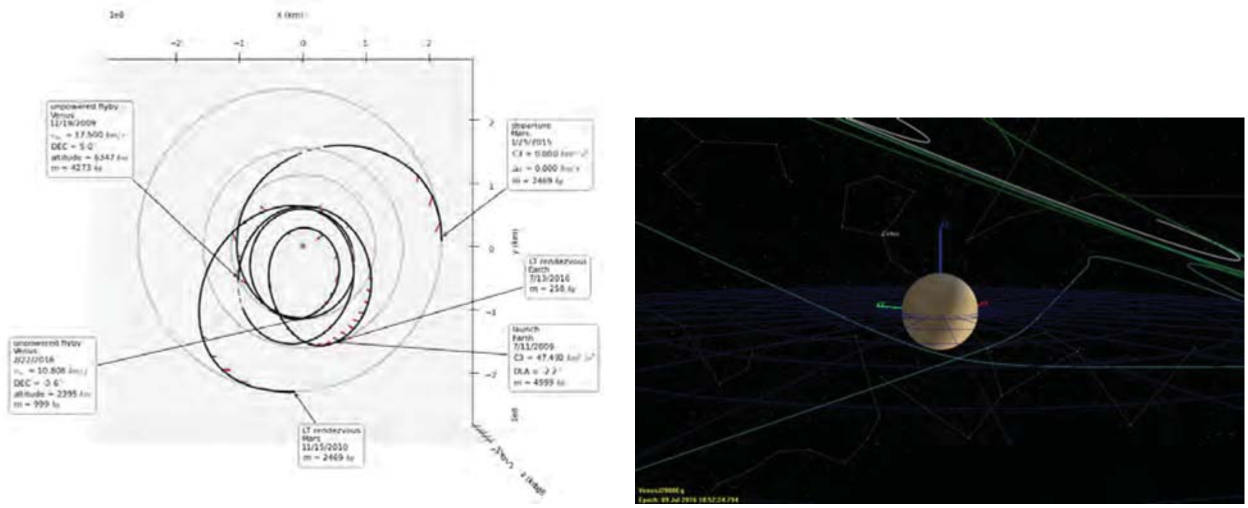
OPTimizer (SNOPT) [6] . This medium-fidelity mode includes real (public domain) launch-vehicle, thruster, and power system models [7–9] and the capability to automatically select the optimal flyby sequence using an integer genetic algorithm (GA) [7–10]. Solutions with desirable characteristics can then be re-optimized using the medium-high fidelity mode in EMTG, which uses the Sims-Flanagan transcription solution to seed a numerically integrated low-thrust solution. Lastly, from either the medium or medium-high fidelity EMTG solutions, a GMAT script is automatically generated. GMAT is a space mission design software system that includes high-fidelity space system models, local optimization and targeting capabilities, as well as user features like the fully-featured interactive Graphical User Interface (GUI) with customizable plots, reports and data products [11]. The EMTG-GMAT toolchain allows a nearly single-click automated optimization for a flight quality low-thrust trajectory from no initial guess. An example of an EMTG medium-fidelity solution to an Earth-Venus-Mars-Venus-Earth mission is shown below with a close-up view of the Venus flybys during the GMAT high-fidelity solve.



(a) EMTG medium-fidelity solution (b) Venus flybys in a Venus J2000Eq Frame in GMAT

Figure 1. Earth-Venus-Mars-Venus-Earth low-thrust multiple flyby mission using EMTG-GMAT toolchain

References

[1] Longuski, J. and Williams, S., "Automated design of gravity-assist trajectories to Mars and the outer planets," *Celestial Mechanics and Dynamical Astronomy*, Vol. 52, No. 3, 1991, pp. 207–220.

[2] Sims, J., Finlayson, P., Rinderle, E., Vavrina, M., and Kowalkowski, T., "Implementation of a low-thrust trajectory optimization algorithm for preliminary design," *AIAA/AAS Astrodynamics Specialist Conference*, August 2006.

[3] McConaghy, T. T., *GALLOP Version 4.5 User's Guide*, School of Aeronautics and Astronautics, Purdue University, 2005.

[4] Whiffen, G. J., "Mystic: Implementation of the Static Dynamic Optimal Control Algorithm for High-Fidelity, Low-Thrust Trajectory Design," *AIAA/AAS 2006-6741 Astrodynamics Specialist Conference and Exhibit*, Keystone, Colorado, August 21-24 2006.

[5] Ocampo, C., *Elements of a Software System for Spacecraft Trajectory Optimization*, Cambridge University Press, 2010, pp. 79–111.

[6] Gill, P. E., Murray, W., and Saunders, M. A., "SNOPT: An SQP Algorithm for Large-Scale Constrained Optimization," *SIAM Rev.*, Vol. 47, No. 1, 2005, pp. 99–131.

[7] Englander, J. A., Conway, B. A., and Williams, T., "Automated Interplanetary Mission Planning," *AAS/AIAA Astrodynamics Specialist Conference, Minneapolis, MN*, August 2012.

[8] Englander, J. A., *Automated Trajectory Planning for Multiple-Flyby Interplanetary Missions*, Ph.D. thesis, University of Illinois at Urbana-Champaign, April 2013.

[9] Ellison, D. H., Englander, J. A., and Conway, B. A., "Robust Global Optimzation of Low-Thrust, Multiple-Flyby Trajectories," *AAS/AIAA Astrodynamics Specialist Conference, Hilton Head, SC*, August 2013.

[10] Englander, J., Conway, B., and Williams, T., "Automated Mission Planning via Evolutionary Algorithms," *Journal of Guidance, Control, and Dynamics*, Vol. 35, No. 6, 2012, pp. 1878–1887.

[11] Hughes, S. P., Qureshi, R. H., Cooley, D. S., Parker, J. J. K., and Grubb, T. G., "Verification and Validation of the General Mission Analysis Tool (GMAT)," *AIAA/AAS Astrodynamics Specialist Conference, San Diego, CA*, August 4 - 7 2014.