The In-Space Propulsion Technology Project Low-Thrust Trajectory Tool Suite

I. Introduction

In the summer of 2002, NASA began the task of renovating its low thrust trajectory analysis capability to provide a set of tools that can provide consistent results and be widely available for both proposers and reviewers. Because there is no single tool appropriate for all missions, a team of experts within NASA, academia, and industry was established to develop the Low-Thrust Trajectory Tool Suite as an update to the legacy Chebytop and VARITOP derived tools. In March of 2006, the ISPT project released its first version of the LTTT suite including the optimization tools MALTO, Copernicus, OTIS, and Mystic. The tools have since received many updates and are used throughout NASA.

II. The Tools

The following is a brief description of the legacy and new LTTT suite optimization tools. CHEBYTOP, VARITOP, and SEPTOP were not part of the LTTT development effort, but have been used extensively in the past for mission design and trades. The LTTT development effort has yielding higher fidelity tools that are extensively documented with an increased ease of use. The tools have all been thoroughly compared to one another for a large set of missions, but have yet to be formally validated by flight data. The LTTT suite produces consistent results when used for their appropriate mission types.

A. CHEBYTOP

CHEBYTOP is a pseudo-acronym for the Chebyshev Trajectory Optimization Program. The tool was originally written by Forrester Johnson et al. at The Boeing Company in 1969, and was later updated by Boeing, the Jet Propulsion Laboratory (JPL) and analysts at the Glenn Research Center (GRC). CHEBYTOP uses Chebychev polynomials to represent state variables. These polynomials are then differentiated and integrated in closed form to solve a variable thrust trajectory. This solution can then be used to approximate the performance of the constant thrust trajectory. CHEBYTOP is not capable of analyzing multi-leg missions, i.e. round trip flights, intermediate flybys, multi-body trajectories, etc. CHEBYTOP is also limited to interplanetary missions with only the Sun's gravity field. CHEBYTOP is considered a low-fidelity program by today's standards, but has been highly valued for its capability to rapidly assess large trade spaces. CHEBYTOP is the only tool available without any user restrictions. CHEBYTOP can be downloaded directly at http://www.inspacepropulsion.com/LTTT/.

B. VARITOP, SEPTOP, and NEWSEP

VARITOP is the Variational calculus Trajectory Optimization Program developed by Carl Sauer at JPL. SEPTOP and NEWSEP are updates to the original VARITOP. VARITOP is the most general of the tools, handling nuclear electric propulsion (NEP) as well as solar electric propulsion (SEP) and solar sail trajectories. The three tools are all based on the same mathematical formulation sharing many common subroutines. The calculus of variations is used in the formulation of state and co-state equations integrated numerically to solve a two-point boundary value program. Optimization uses transversality conditions associated with the variational calculus, primer vector theory, and Pontryagin's maximum principle.

SEPTOP is the Solar Electric Propulsion Trajectory Optimization Program that can simulate thruster throttling and staging. SEPTOP can use thrust and propellant flow rate polynomials to represent specific thruster options. SEPTOP can also use polynomials to represent solar array performance as the spacecraft changes its distance from the sun.

NEWSEP is another variation of SEPTOP that can accept discreet values of a thruster's throttle table rather than estimating the infinite throttle point performance using a polynomial. NEWSEP was used to provide trajectory support for the Deep Space 1 mission. The VARITOP and derived legacy tools are considered medium fidelity. These tools are available for NASA and academic use only and are available directly through JPL. Software requests can be made through the website: https://download.jpl.nasa.gov/.

C. MALTO

The Mission Analysis Low-Thrust Optimization (MALTO) tool was specifically developed as a more "user friendly" low-thrust optimization tool with relatively easy convergence especially for missions with multiple gravity assists. MALTO uses many impulsive burns to simulate a continuous burn trajectory about a single gravitational source. The mission setup, parametric trades, and post processing can be performed with a MATLAB based graphical user interface (GUI). The thruster and power system modeling is comparable to the VARITOP programs. Optimization in MALTO is calculated using and requires the SNOPT code developed independently by Dr. Philip Gill at the University of California San Diego. MALTO is considered a medium fidelity tool and is available to NASA contractors and civil service and academia directly through the JPL website: https://download.jpl.nasa.gov/. Commercial licenses can be obtained through the Caltech Office of Technology Transfer: http://www.ott.caltech.edu/; submit requests through Karina Edmonds.

D. Copernicus

Copernicus was originally developed by the University of Texas at Austin under the technical direction from the Johnson Space Center. Copernicus is a generalized trajectory design and optimization program that allows the user to model simple to complex missions using many objective functions, optimization variables and constraint options. With Copernicus, one can model simple impulsive maneuvers about a point mass to multiple spacecraft with multiple finite and impulse maneuvers in complex gravitational fields. The tool uses a graphical output for real time feedback during the optimization process. Copernicus is an n-body tool and is considered high fidelity. Copernicus has been transferred to an in-house development effort specifically for the Constellation program. The updates to Copernicus are expected to be available to NASA and NASA contractors only, and requests can be submitted through the ISPT project website: http://www.inspacepropulsion.com/LTTT/.

E. OTIS

The Optimal Trajectories by Implicit Simulation (OTIS) program was developed by GRC and Boeing. Earlier versions of OTIS have primarily been launch vehicle trajectory and analysis programs, but have since been updated for robust and accurate interplanetary mission analyses, including low-thrust trajectories. The tool is named for its original implicit integration method, but also includes capabilities for explicit integration and analytic propagation. Vehicle models can be very sophisticated and can be simulated through six degrees of freedom. OTIS uses SLSQP and SNOPT to solve the nonlinear programming problem associated with the solution of the implicit integration method. OTIS is a high fidelity optimization and simulation program. OTIS is available to anybody in government, academia, and industry by contacting http://technology.grc.nasa.gov/ , but is subject to export control regulations.

F. Mystic

Mystic was developed by Dr. Greg Whiffen and others at the JPL. The tool uses a Static/Dynamic optimal control (SDC) method to perform nonlinear optimization. Mystic is an n-body tool and can analyze interplanetary missions as well as planet-centered missions in complex gravity fields. One of Mystic's strengths is its ability to automatically find and use gravity assists. Mystic also allows the user to plan for spacecraft operation and navigation activities. The mission input and post processing can be performed using a MATLAB based GUI. Mystic is currently used on the Dawn mission, and considered a high fidelity optimization and simulation program. Requests for Mystic should be made directly through the JPL website: https://download.jpl.nasa.gov/.

III. Summary

The ISPT project released its low-thrust trajectory tool suite in March of 2006. The LTTT suite tools range in capabilities, but represent the state-of-the art in NASA low-thrust trajectory optimization tools. The tools have all received considerable updates following the initial release, and they are available through their respective development centers or the ISPT project website.