Trajectory Design and Optimization Tool for Deep Space Exploring

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Abstract. The trajectory design and optimization based on astrodynamics plays an important role in the mission design of deep space exploring. A convenient tool for trajectory design and optimization of deep space exploring has been developed, which consists of three major functional modules. The first module can help design and optimize the trajectory using gravity-assist maneuvers, the second module is used to design and optimize the trajectory using low-thrust propulsion, and the third module helps design the low-thrust gravity-assist mixed trajectory. Moreover, friendly user interfaces are implemented for the problem inputs, and the results are shown by both the data reports and some customizable figures.

1. Introduction
Deep space exploring helps humankind explore and understand the space far from Earth and beyond, and the trajectory design and optimization based on astrodynamics plays an important role in both the mission design and control. To save propellant cost, a spacecraft for deep space exploring usually uses gravity-assist (GA) maneuvers or the low-thrust (LT) propulsion with a high specific impulse. Many studies on the trajectory optimization using GA or LT maneuvers have been published, but a convenient design and optimization software tool is still not available in China. A convenient software tool is very important in the design process of practical missions because the trajectory could be calculated many times due to the variations of requirements or parameters.

A convenient tool for trajectory design and optimization of deep space exploring has been developed, as shown in figure 1. It provides three major functional modules. The first module can help design and optimize the trajectory using GA maneuvers, the second module is used to design and optimize the trajectory using LT maneuvers, and the third module helps design the trajectory using both the GA and LT maneuvers. Moreover, some friendly user interfaces (UIs) are designed for the problem inputs, and the results are shown by both data reports and customizable figures.

2. Software Module for Gravity-Assist Trajectory
The technique of GA maneuvers is also called “swing-by” or “fly-by”, in which the velocity of a spacecraft could be changed with small or no propellant consumption when it passes by the neighborhood of a planet. It paved the way to missions such as Voyager and Pioneer by Minovitch [1, 2], and was also used in the missions Galileo [3], Cassini-Huygens [4], Messenger [5], etc. Details of GA models, including the model using deep space maneuvers (DSM) and the model using maneuvers at the planet periapsis, could be found in References [6,7].
The design process of a GA trajectory consists of six major steps: configure the initial state, specify the fly-by sequences of planets, configure the aiming terminal state, specify the dynamics model and optimization algorithm parameters, start the optimization calculation, and finally check and analyze the results. In each step, we have tried to provide some flexibilities and convenience for users.

For the initial state configuration part, the user can input the mission name, the earliest and latest depart time, the initial mass, the maximum thrust, the specific impulse, and the total mission duration. For improving the compatibility of the software, the center body can be chosen from the sun and some planets as required, and the GA model can be chosen from two models. Moreover, the initial position and velocity can be specified in three ways, including the way given by the position and velocity, the way given by a planet’s state, and the way with only given position. For the latter two ways, the initial velocity components are used as extra design variables.

For the fly-by sequences configuration part, the planets are chosen and inserted into the fly-by sequence one by one, and one planet in the sequence can also be removed. For each fly-by branch, the search intervals for the time of transfer, the nearest radius of GA, and the DSM time should be specified by the user, as shown in figure 2.

For the aiming terminal state configuration part, three types of the terminal state are considered, including rendezvous, impact and ballistic injection. Moreover, the aiming terminal state could be
interpolated from ephemerides if the terminal target is a planet, otherwise it could be calculated by the propagation from the given reference state if the terminal target is an asteroid.

For the dynamics model and optimization algorithm configuration part, the gravities of the planets or the sun except the center body of mission itself can be considered by selecting and inserting them into the third gravity perturbation list and then the GA process could be a high-precision one. The integration parameters and the optimization parameters are also configured in this page, as shown in figure 3.

The optimization calculation can be started by clicking a button on the bottom of this page, the results report can be checked in the report page as shown in figure 4, and the results figure can be observed and customized in the figure page as shown in figure 5.

![Figure 3. Configuration UI for dynamics model and optimization algorithm](image3.png)

![Figure 4. Part of screenshot for high-precision gravity-assist results report.](image4.png)

3. Software Module for Low-Thrust Trajectory
The technique of LT propulsion is employed due to its high specific impulse, and was used by Deep Space 1 [7], Dawn [8], SMART-1 [9], etc. The optimization methods of LT trajectories can be divided into three major types, including the direct method, the indirect method [10,11,12], and the mixed method. The solving method used in this software is the indirect method with the multi-phase patching and smoothing technique proposed in reference [13].

The design process of a LT trajectory consists of six major steps: configure the initial state, specify the aiming terminal state, configure the dynamics model parameters, configure the algorithm
parameters, start the optimization calculation, and finally check and analyze the results. In each step, we have tried to provide some flexibilities and convenience to users.

The configuration operations of the initial state and the aiming terminal state are similar to those of the GA trajectories. In the dynamics model configuration page, besides the gravities of other planets, three engine models can be chosen there, including the constant low-thrust model, the solar electric propulsion model, and the solar electric propulsion model interpolating engineering data table.

![Configuration page of low-thrust algorithm parameters](image)

Figure 6. Configuration page of low-thrust algorithm parameters

In the algorithm parameter configuration page, parameters of the optimization algorithm, integration algorithm, initial guess and homotopic path are needed to specify there, as shown in figure 6. The optimization calculation can be started by clicking a button on the bottom of this page, the results report can be checked in the report page, and the results figure can be observed and customized in the figure page as shown in figure 7 and figure 8.

4. Software Module for Low-Thrust Gravity-Assist Mixed Trajectory

The design process of a LT-GA mixed trajectory consists of seven major steps, and most of them are similar to those for the design of LT trajectory, except the configuration of GA process. For each GA branch, besides the search intervals for the time of transfer and the nearest radius of GA planet, the initial guess of design variables of the corresponding LT trajectory should be specified by the user, as shown in figure 9. To be compatible with the LT trajectory visiting multiple asteroids, the planet in the
GA sequence could be specified as an asteroid, and then the GA maneuver there doesn’t work. After the calculation, the results can be observed as shown in figure 10.

Figure 9. Configuration page of low-thrust gravity-assist mixed maneuvers

Figure 10. Results figure of low-thrust gravity-assist mixed maneuvers

The solving of a LT-GA mixed trajectory is difficult, and published studies mainly used the graphical method to get a good initial guess [14]. In this software, the indirect method combined with the multi-phase smoothing technique is used.

5. Conclusions

For providing convenience to the design process of a deep space mission, a trajectory design and optimization tool is developed. It can help design and optimize three types of trajectories based on the dynamics model considering the gravities of multiple planets, including the gravity-assist trajectory, the low-thrust trajectory and the low-thrust gravity-assist mixed trajectory. Some special designs are implemented to be compatible with more problem requirements and to provide convenience to the problem inputs and the results analysis. This software tool has been applied to the design of some
practical deep space missions, and will be improved from both the aspect of models and algorithms and the aspect of usage, according to the feedback of users.

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