

## 論文の内容の要旨

論文題目 B-plane Assisted Trajectory Design with Parameterized Swing-by  
Trajectories  
(規格化したスイングバイ軌道とB-planeを利用した軌道設計)

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This dissertation proposes a methodology for designing swing-by trajectories, suitable for both trajectory design and operation by making use of a conventional B-plane. The swing-by technique, a maneuver that changes the trajectory of a spacecraft through the gravitational forces exerted by celestial bodies, plays significantly important roles in deep space exploration missions. This method has been used in countless missions dating back to the early stages of space exploration and extending into current exploration missions. The main topic of this dissertation is the exploration of a design framework intended to facilitate the design of swing-by trajectories.

The process of designing swing-by trajectories within the context of deep space exploration revolves around the challenge of selecting trajectories that achieve predetermined objectives, such as transfer to a target body. Consequently, it is highly desirable to conduct the design process in a manner that encompasses a comprehensive analysis of post swing-by trajectory options. To accomplish this purpose, graphical methodologies have been extensively proposed as a means to visually understand the entirety of feasible candidate trajectories. In this dissertation, we propose a novel design

approach that incorporates operational considerations in conjunction with trajectory design perspectives. The underlying aim is to enhance the adaptability of nominal trajectory designs, thereby contributing to an improved responsiveness in the design of off-nominal trajectories for operational scenarios.

The aforementioned motivation has arisen in recent years, primarily driven by NASA's Artemis program. The Artemis program has garnered considerable attention for its advancements in transfer trajectories directed towards the Moon and beyond. Trajectories categorized as low-energy transfers towards the vicinity of the Moon, such as the weak stability boundary and ballistic lunar transfer, have been studied. Using the Moon swing-by in these trajectory classes contributes to a reduction in fuel consumption. In this investigation, we delve into the design of trajectories incorporating the Moon swing-by as a constraint for the initial condition. By imposing this constraint, our objective is to design trajectories similar to ride-shared small spacecraft flew with Artemis 1 toward the Moon swing-by.

To tackle the above swing-by design problem, especially in the Earth-Moon system, we propose a methodology that projects swing-by parameters onto a conventional B-plane, facilitating the efficient analysis and design of post swing-by trajectories. More specifically, we derive mappings of parameters before and after a swing-by with the B-plane as a reference frame, and propose a method for projecting various solutions onto the B-plane. Through this proposed approach, we not only foster a comprehensive understanding of all potential candidate solutions at each swing-by, but also improve adaptability and responsiveness to wide range of swing-by conditions. To show the applicability and practicality of this work, we apply the proposed method to transfer and operational problems in the Earth-Moon system.

The main contribution of this discussion is derived analytical mapping in Chapter 4. This mapping about swing-by parameters projects all candidate outgoing trajectories onto the B-plane. This projection enables us to design trajectories under a global perspective, i.e., doing trade-off analysis among all candidate trajectories based on given performance indices, such as  $\Delta v$  and time of flight. This characteristic can not only assist the trajectory design process but also enhance the robustness of missions and

the flexibility of maneuver design, for example, checking all candidate solutions on the B-plane during the operation. The main advantage of this method lies in its adaptability to post swing-by trajectories, i.e., any outgoing trajectories can be plotted on the B-plane as long as they are parameterized by the pump and crank angles. This is because  $v_{\infty}^{\pm}$ , relative velocity between spacecraft and swing-by body at the swing-by (+ and – indicate parameter before and after the swing-by, respectively), are separated by the proposed mapping as explained in Chapter 1. This fact implies that any external analysis including analytical development and numerical effort using pump and crank angles, such as transfer problem we presented in Chapter 5, can be applicable in this framework. Furthermore, this also suggests that the proposed method can be used recursively by connecting B-plane at each swing-by as far as using the same interface, which is pump and crank angles. The validity and applicability of the proposed method for both single swing-by case and recursive case are demonstrated through the transfer problems to Lyapunov orbit and halo orbit in the Earth-Moon system under Bicircular Restricted Four-body problem, leveraged by the Moon swing-by in Chapter 5.

We also present the applicability of this method in practical mission under full-ephemeris model during the launch attempt of NASA's Artemis 1, where we confirm that projected information about Moon-to-Moon transfers developed in Circular Restricted Three-body problem serves as initial guess even in full-ephemeris model. Although the actual operation of EQUULEUS did not activate this proposed method, off-nominal or backup trajectories might be designed quickly through this method.

Summary of main contributions:

- In the  $v_{\infty}$  globe type,  $v_{\infty}^+$  and  $v_{\infty}^-$  are separated, allowing for independent analyses of  $v_{\infty}^+$ , which characterizes the orbital properties after the swing-by. The analysis can be conducted using any level of fidelity as long as it can be described by the parameters pump angle  $\alpha$  and crank angle  $\kappa$ . In other words, it is possible to use analytical or numerical analysis.
- To facilitate the analysis of the trajectories after a swing-by, the mapping is derived where  $\alpha^+$  and  $\kappa^+$  can be expressed as functions of position and velocity. This mapping enables an explicit sensitivity analysis of  $\alpha^+$  and  $\kappa^+$ . This sensitivity analysis provides valuable insights into the behavior of the swing-by trajectories and assists trajectory design.

- Through the aforementioned mapping, it is now possible to transform the coordinates of  $\alpha^+$  and  $\kappa^+$  onto the B-plane used in actual operations. This allows for sensitivity analysis of the trajectory after a swing-by, enabling the consideration of multiple options and design of trajectories under uncertainty.
- The proposed swing-by framework is tested in the transfer problems in cis-lunar space with Lunar swing-bys.