Preliminary Study on the Orbit Planning of Near-Earth Asteroid Multi-Rendezvous Sample Return Mission
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Abstract
In this paper proposed is the exploration sequence construction method for the near-earth asteroid multi-rendezvous sample return mission. The constructed sequence is the Keplerian orbits connected with impulsive velocity changes including planetary gravity assists. Dynamical feasibility of the constructed sequence can be assessed quantitatively by the total required $\Delta v$, so that the method is available in the mission feasibility study. The constructed sequence is sufficiently definitive to restrict the framework and the range of the more detailed problem, such as the orbit design for the low thrust electric propulsion. Example of the constructed sequence is also presented.

1. Introduction
The asteroid explorer HAYABUSA launched in 2003 completes its earth swingby in May, 2004, and now continues its flight towards the asteroid ITOKAWA. Under this situation, the study of the next asteroid exploration mission is started supposing a launch in the first half of the 2010s.

Typically, the sequence of the asteroid exploration is constructed under strong restrictions. The exploration sequence, which includes the asteroids to be explored, the opportunity of the exploration, and the way of the exploration (flyby or rendezvous), cannot be determined freely in actual. The reason is that the feasible sequences are strongly limited from the orbital dynamics aspects. Once the dynamical feasibility of the exploration sequence is verified, it gives the fundamental preconditions to the spacecraft system design, such as the size of the spacecraft, the operation environment, or the launch opportunity. Therefore, the most important work in the beginning of the asteroid exploration mission investigation is the construction of the exploration sequence considering the dynamical feasibility and the scientific significance of the target asteroid.

Proposed in this paper is the construction method of the exploration sequence of the asteroid multi-rendezvous sample return missions.

2. Construction of Exploration Sequence
Generally, the asteroid exploration mission is a high energy mission which requires several km/s of $\Delta v$ after the escape from the earth's gravity field. In order to achieve this high $\Delta v$ within the scope of ordinary spacecraft design concept, the usage of high ISP propulsion, such as electric propulsion, is a practical approach. Following the former asteroid explorer HAYABUSA, the electric propulsion is also planned to be used in the next asteroid explorer.

Generally, the orbit design problem for the low thrust continuous propulsion is formulized as an optimal control problem. The solution of the problem gives the profile of the control variables (magnitude and direction of the thrust), which minimizes the performance index (fuel consumption) while satisfying the given boundary conditions. However, this kind of detailed analysis is applicable after the definition of the problem framework. Therefore, prior to the start of the detailed analysis, the framework of the problem, that is the exploration sequence in this case, must be constructed. Discussed in this paper is the investigation in this step.

Needless to say, in the construction of the exploration sequence, the scientific significance of the target asteroid must be considered as well. However, since the proportion of the dynamically feasible sequence is considerably
low, it is impractical to construct the exploration sequence for a given scientific requirements. More realistic approach is to construct the dynamically feasible sequences firstly, and then, select the favorable sequences from those candidates based on the scientific significance. The number of the candidates is expected to be sufficient, since the number of asteroids is large. This paper focuses on the first step, that is, the construction of the dynamically feasible exploration sequence.

The construction method with such a purpose should be equipped with the following characteristics. Firstly, the method should be able to assess the dynamical feasibility of the sequence quantitatively. Secondly, the constructed sequence should be sufficiently definitive to restrict the framework and the scope of the more detailed problem. Thirdly, the computational complexity should be suppressed since the sequence must be found from large search area.

Considering these characteristics, proposed in this paper is the construction method of the sequence of Keplerian orbits connected with impulsive velocity changes including planetary gravity assists.

The dynamical feasibility of the sequence can be assessed quantitatively by the total required $\Delta v$ excluding the velocity change due to the planetary gravity assists. Though the total $\Delta v$ must be compensated for the case of low thrust propulsion considering the maneuver efficiency, to compare the dynamical feasibility of the sequences, the estimation by the impulsive maneuver is sufficient. Moreover, the output sequence defines the asteroids to be explored, the opportunities of the explorations, the number of planetary gravity assists, and their opportunities. It is sufficiently definitive to restrict the framework and the scope of the more detailed problem, and at the same time, gives good initial estimate for them. Finally, since the sequence is composed of Keplerian orbits, various analytical methods for the two-body problem are applicable. This results in the savings of the computational complexity compared to the more detailed orbit design for the low thrust electric propulsion.

The details of the method is shown in the following sections.

3. Description of Construction Method

3.1 Overview of Construction Method

Fig. 1 illustrates the exploration sequence of an asteroid multi-rendezvous sample return mission. The sequence flows from the left to the right. Firstly, the spacecraft depart from the earth and transfer to the first target asteroid (Asteroid 1), stay for a while at Asteroid 1 for the observation and get the sample of the asteroid. Then, the spacecraft depart from Asteroid 1, come back to the earth and return the sample by separated reentry capsule. At the same time, the spacecraft uses the earth swing-by and transfer to the second target asteroid (Asteroid 2), stay for a while at Asteroid 2 for the observation and get the sample of the asteroid. Then, the spacecraft depart from Asteroid 2, come back to the earth and return the sample by separated reentry capsule. The point such as the earth departure, the asteroid arrival, or the earth swing-by is called Node, and the path that connects two Nodes are called Link. Moreover, a series of Nodes and Links is called Chain.

![Fig. 1. Asteroid Exploration Sequence](image)

A Chain is constructed by connecting Nodes and Links. The connection is classified into two types, Rigid Connection and Flexible Connection. For example, Node 1 in Fig.1 expresses the earth swing-by which connects two links, the return orbit from Asteroid 1 and the transfer orbit to Asteroid 2. In order to connect these two Links, two conditions must be satisfied. Firstly, the arrival time of the return orbit, $t_{Ea}$, and the departure time of the transfer orbit, $t_{Ed}$, must be the same. Note that, the sphere of influence of the earth is neglected here, and the velocity of the spacecraft is assumed to change instantaneously at the earth swing-by. Secondly, the magnitude of the spacecraft’s relative velocity with respect to the earth at the arrival, $\Delta v_{Ea}$, and the magnitude of the spacecraft’s relative velocity with respect to the earth, $\Delta v_{Ed}$, must be the same. Thus, if the boundary conditions before and after the connection are restricted strongly, it is called Rigid Connection. On the other hand, in case of Node 2 of Fig.1 which expresses the earth departure, only the upper limit of $\Delta v_{Ed}$ is constrained, and there are no strong restrictions which specify the value of $t_{Ed}$ or $\Delta v_{Ed}$. Similarly, in case of Link 3 of Fig.1 which expresses the stay at Asteroid 2, only the upper limit of $\Delta v_{Ad}$ and $\Delta v_{Ad}$, and the range of the duration of the asteroid stay are con-
strained, and there are no strong restrictions. Here, $\Delta v_{Ed}$ and $\Delta v_{Ad}$ stand for the magnitude of the spacecraft’s relative velocity with respect to the asteroid at the arrival and the departure respectively. Thus, if the boundary conditions before and after the connection are not restricted strongly, it is called Flexible Connection.

When connecting Nodes and Links, the connection by a Flexible Connection is easy. The Nodes and Links around the connection are prepared, and if the conditions of the Flexible Connection are satisfied, they are connected. No special pre-procedure is required to make the connection easier. The part of a Chain which has Flexible Connections in both ends is called Block. A Chain is built by connecting Blocks by Flexible Connections. The Blocks in the sequence of Fig. 1 is shown in Fig. 2. The construction method of a Block is explained later.

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Fig. 2 Blocks in the Sequence of Fig. 1

The part consists of a Link and two Nodes in both ends of the Link is called Piece. A Piece expresses the transfer sequence, which consists of the departure form a celestial body, the arrival at a celestial body, and a Keplerian orbit which connects them. Construction of a Piece is easy. For example, if two Nodes of the departure and arrival are specified, finite number of Keplerian orbits between two Nodes can be obtained by solving Lambert’s problem. When constructing a Piece in this paper, either the time of departure or arrival is specified, and the remaining degree of freedom is used in order to satisfy a specified condition. For the condition, minimization of $\Delta v$, or the specification of the magnitude of the relative velocity with respect to the celestial body at either end of the orbit, is used according to the situation.

A Block is built from Pieces. The simplest type of Block consists of only one Piece. Block 1 and Block 3 of Fig. 2 are the examples. Both ends of the Pieces are the Flexible Connection. A Block consists of two or more Pieces those connected by Rigid Connections, Block 2 of Fig. 2, is built by the following method. As mentioned before, the boundary conditions before and after the connection are restricted strongly in Rigid Connection. Therefore, the simple method used in the connection by Flexible Connection cannot be applied here. Almost no combinations of Pieces are found which satisfy the strong restrictions at the Rigid Connection without the special pre-procedures applied to the Pieces. In order to connect two or more Pieces by Rigid Connection, it is necessary to construct the Pieces beforehand in the form that can be easily connected by Rigid Connection. In other words, the Pieces need to be constructed in the form that the combination of the Pieces which satisfy the restrictions at the Rigid Connection are easily found. For example, at the Rigid Connection of Block 2 in Fig. 2, which expresses the earth swing-by, $t_{Ed}$ and $t_{Ed}$, $\Delta v_{Ed}$ and $\Delta v_{Ed}$, must be the same respectively. In this case, the Pieces before and after the swing-by are constructed so that $t_{Ed}$ and $t_{Ed}$ have common discrete values (for example, 0:00 UTC in every 7 days), at the same time, $\Delta v_{Ed}$ and $\Delta v_{Ed}$ have common discrete values (for example, 0.5km/s, 1.0km/s, ...). If the Pieces are prepared in this form, the combination of the Pieces which satisfy the restrictions at the Rigid Connection can be found easily. Thus, a Block consists of two or more Pieces connected by Rigid Connection is constructed.

The construction method of the exploration sequence is summarized as follows.

a) Construction of Piece
Construct the Pieces of the types which compose the exploration sequence. At this step, the Pieces which are going to be connected by the Rigid Connections must be constructed beforehand in the form that can be easily connected by Rigid Connection.

b) Construction of Block
Construct Block by connecting the Pieces by Rigid Connections. If both ends of the Piece are Flexible Connection, the Piece is taken as Block as it is.

c) Construction of Chain
Construct Chain by connecting the Blocks by Flexible Connections.

Hereafter, each step of the method is explained in detail using the example of constructing the exploration sequence of "Earth ↑ Asteroid 1 - Earth (swing-by) - Asteroid 2 - Earth". The target asteroids are selected from the list of the near earth asteroids whose perihelion distance is smaller than 1.523AU. There are 4078 asteroids on the list.
3.2 Construction of Piece

There are 4 types of Pieces which compose the exploration sequence mentioned above. They are,

1. Earth □ Asteroid 1
2. Asteroid 1 - Earth
3. Earth □ Asteroid 2
4. Asteroid 2 - Earth

The construction methods of each type of Piece are described below.

(1) Earth – Asteroid 1
Firstly, Asteroid 1 and the earth departure window are filtered by the required \( \Delta v \) in order to reduce the search area. For each combination of Asteroid 1 (all asteroids in the list are considered) and \( t_{Ed} \) (0:00 UTC in every 7 days for 10 years from January 1, 2013), the minimum value of the performance index \( J_1 \),

\[ J_1 = \frac{1}{2} \Delta v_{Ed} + \Delta v_{As} \]

is searched for the various value of the transfer time. And only when the minimum value of \( J_1 \) is smaller than 5km/s, the combination of Asteroid 1 and \( t_{Ed} \) are saved as the candidates of the Piece. Fundamentally, \( J_1 \) expresses the total required \( \Delta v \) for the transfer from the earth to Asteroid 1. Therefore, \( \Delta v_{Ed} \) is halved assuming the usage of EDVEGA. EDVEGA is the orbit control technique which is used in HAYABUSA as well. By launching the spacecraft about one year before \( t_{Ed} \), the combination of the electric propulsion and the earth swing-by enables to obtain \( \Delta v_{Ed} \) twice of the \( \Delta v \) acquired before swing-by by the electric propulsion. In other words, by using EDVEGA, only half of \( \Delta v_{Ed} \) need to be acquired by the electric propulsion. The factor 0.5 in \( J_1 \) reflects this effect. The sequence of EDVEGA is automatically determined from \( t_{Ed} \) and \( \Delta v_{Ed} \). Therefore, it is not included in the construction process of the exploration sequence, and it is only reflected in \( J_1 \). The upper limit of \( J_1 \), 5km/s, is set from the upper limit of \( \Delta v_{Ed} \), 5km/s, and the upper limit of \( \Delta v_{As} \), 2.5km/s.

Next, the Pieces are constructed for the combinations filtered above. For each combination of Asteroid 1 and \( t_{Ed} \) filtered above, the Keplerian orbits with \( \Delta v_{Ed} \) of 0.5km/s, 1.0km/s, ..., 5.0km/s are computed as the Link, and the Piece is constructed. The reason why \( \Delta v_{Ed} \) is specified to these values, even though the earth departure is a Flexible Connection, is to guarantee \( \Delta v_{Ed} \) to be less than 5km/s. 5km/s is the upper limit of the relative velocity with respect to the earth that the direction of the relative velocity can be deflected 90 degrees at the earth swing-by of EDVEGA. Although most of the filtered combinations of Asteroid 1 and \( t_{Ed} \) are supposed to satisfy this condition, some of them may violate this condition depending on the balance between \( \Delta v_{Ed} \) and \( \Delta v_{As} \). This is the reason why the value of \( \Delta v_{Ed} \) is checked at the Piece construction.

(2) Asteroid 1 - Earth
Firstly, Asteroid 1 and the earth arrival window are filtered by the required \( \Delta v \) in order to reduce the search area. For each combination of Asteroid 1 (all asteroids used in the Piece □ Asteroid 1 (considered) and \( t_{Ea} \) (0:00 UTC in every 7 days for 10 years from January 1, 2013), the minimum value of the performance index \( J_2 \),

\[ J_2 = \Delta v_{Ea} \]

is searched for the various value of the transfer time. And only when the minimum value of \( J_2 \) is smaller than 2.5km/s, the combination of Asteroid 1 and \( t_{Ea} \) are saved as the candidates of the Piece. Since no maneuver is executed at the earth arrival in this Piece, \( \Delta v_{Ea} \) is not included in \( J_2 \). Next, the Pieces are constructed for the combinations filtered above. For each combination of Asteroid 1 and \( t_{Ea} \) filtered above, the Keplerian orbits with \( \Delta v_{Ea} \) of 0.5km/s, 1.0km/s, ..., 5.0km/s are computed as the Link. And only when \( \Delta v_{Ea} \) is smaller than 2.5km/s, the Piece is constructed. This Piece is going to be connected by Rigid Link with the Piece □ Asteroid 2 □ Therefore, in order to connect easily, \( t_{Ea} \) and \( \Delta v_{Ea} \) have discrete values common with \( t_{Ed} \) and \( \Delta v_{Ed} \) of the Piece □ Asteroid 2 □ respectively.

There are two reasons why \( \Delta v_{Ea} \) is limited to be less than 5.0km/s. Firstly, 5km/s is the upper limit of the relative velocity with respect to the earth that the direction of the relative velocity can be deflected 90 degrees at the earth swing-by. Secondly, 5km/s is the upper limit of \( \Delta v_{Ea} \) which is acceptable from the thermal aspects of the reentry capsule used for the sample return of Asteroid 1.

(3) Earth – Asteroid 2
Firstly, Asteroid 2 and the earth departure window are filtered by the required \( \Delta v \) in order to reduce the search area. For each combination of Asteroid 2 (all asteroids in the list are considered) and \( t_{Ed} \) (0:00 UTC in every 7 days for 15 years from January 1, 2013), the minimum value of the performance index \( J_3 \),

\[ J_3 = \Delta v_{Ed} \]

is searched for the various value of the transfer time. And only when the minimum value of \( J_3 \) is smaller than 2.5km/s, the combination of Asteroid 2 and \( t_{Ed} \) are saved as the candidates of the Piece. Since no maneuver is executed at the earth departure in this Piece, \( \Delta v_{Ed} \) is not included in \( J_3 \). Next, the Pieces are constructed for the combinations filtered above. For each combination of Asteroid 2 and \( t_{Ed} \),...
filtered above, the Keplerian orbits with $\Delta v_{Ed}$ of 0.5km/s, 1.0km/s, ..., 5.0km/s are computed as the Link. And only when $\Delta v_{Ed}$ is smaller than 2.5km/s, the Piece is constructed. This Piece is going to be connected by Rigid Link with the Piece $\text{Asteroid 1 - Earth}$. Therefore, in order to connect easily, $t_{Ea}$ and $\Delta v_{Ed}$ have discrete values common with $t_{Ea}$ and $\Delta v_{Ed}$ of the Piece $\text{Asteroid 1 - Earth}$ respectively.

The reason why $\Delta v_{Ed}$ is limited to be less than 5.0km/s is that 5km/s is the upper limit of the relative velocity with respect to the earth that the direction of the relative velocity can be deflected 90 degrees at the earth swing-by.

(4) Asteroid 2 - Earth

Firstly, Asteroid 2 and the earth arrival window are filtered by the required $\Delta v$ in order to reduce the search area. For each combination of Asteroid 2 (all asteroids used in the Piece $\text{Earth - Asteroid 2}$ are considered) and $t_{Ea}$ (0:00 UTC in every 7 days for 15 years from January 1, 2013), the minimum value of the performance index $J_e$,

$$J_e = \Delta v_{Ed}$$

is searched for the various value of the transfer time. And only when the minimum value of $J_e$ is smaller than 2.5km/s, the combination of Asteroid 2 and $t_{Ea}$ are saved as the candidates of the Piece. Since no maneuver is executed at the earth arrival in this Piece, $\Delta v_{Ed}$ is not included in $J_e$.

Next, the Pieces are constructed for the combinations filtered above. For each combination of Asteroid 2 and $t_{Ea}$ filtered above, the Keplerian orbits with $\Delta v_{Ed}$ of 0.5km/s, 1.0km/s, ..., 5.0km/s are computed as the Link. And only when $\Delta v_{Ed}$ is smaller than 2.5km/s, the Piece is constructed. The reason why $\Delta v_{Ed}$ is specified to these values, even though the earth arrival is a Flexible Connection, is to guarantee $\Delta v_{Ed}$ to be less than 5km/s. 5km/s is the upper limit of $\Delta v_{Ed}$ which is acceptable from the thermal aspects of the reentry capsule used for the sample return of Asteroid 2.

3.3 Construction of Block

Using the Pieces constructed by the method mentioned above, Blocks are constructed.

Firstly, in case both ends of the Piece are the Flexible Connection, this is the case of the Pieces “Earth – Asteroid 1” and “Asteroid 2 – Earth”, the Piece is taken as Block as it is.

Next, the Pieces connected by Rigid Connection are connected to construct Blocks. This is the case of the Pieces “Asteroid 1 – Earth” and “Earth – Asteroid 2”. If a combination of the Pieces satisfies the restrictions at the earth swing-by, they are connected, and the Block is constructed. The restrictions are that $t_{Ea}$ and $t_{Ed}$, $\Delta v_{Ed}$ and $\Delta v_{Ed}$ to be the same respectively, and that the perigee radius at the earth swing-by calculated from $\Delta v_{Ed}$ and $\Delta v_{Ed}$ (using their magnitude and the deflection angle between them) to be larger than the earth radius. Since the Pieces “Asteroid 1 – Earth” and “Earth – Asteroid 2” are constructed so that $t_{Ea}$ and $t_{Ed}$, $\Delta v_{Ed}$ and $\Delta v_{Ed}$ have common discrete values respectively, it is easy to find the combination of the Pieces which satisfy the restrictions at the earth swing-by.

Consequently, 3 types of Blocks which compose the exploration sequence is constructed. They are,

(1) Earth $\sqcap$ Asteroid 1
(2) Asteroid 1 $\sqcap$ Earth $\sqcap$ Asteroid 2
(3) Asteroid 2 - Earth

3.4 Construction of Chain

Using the Blocks constructed by the method mentioned above, Chains are constructed.

Firstly, the Blocks “Earth $\sqcap$ Asteroid 1 $\sqcap$ and $\sqcap$ Asteroid 1 $\sqcap$ Earth $\sqcap$ Asteroid 2 $\sqcap$ are connected to construct the new type of larger Blocks “Earth $\sqcap$ Asteroid 1 $\sqcap$ Earth (swing-by) - Asteroid 2 $\sqcap$“. If a combination of the Blocks satisfies the conditions at the Asteroid 1 stay, they are connected. The conditions are that Asteroid 1 of the two Blocks to be the same, and that the duration of Asteroid 1 stay (that is the duration from $t_{Ea}$ to $t_{Ad}$) to be within the range of 90 days to 360 days.

Next, the Blocks “Earth $\sqcap$ Asteroid 1 $\sqcap$ Earth (swing-by) - Asteroid 2 $\sqcap$ and $\sqcap$ Asteroid 2 $\sqcap$ Earth $\sqcap$ are connected to construct the Chains “Earth - Asteroid 1 - Earth (swing-by) - Asteroid 2 - Earth”. If a combination of the Blocks satisfies the conditions at the Asteroid 2 stay, they are connected. The conditions are that Asteroid 2 of the two Blocks to be the same, and that the duration of Asteroid 2 stay (that is the duration from $t_{Ea}$ to $t_{Ad}$) to be within the range of 90 days to 360 days.

4. Example of Asteroid Exploration Sequence

Example of the asteroid exploration sequence constructed by the method mentioned above is shown in this section.

The mission concept is, to depart from the earth within 10 years from January 1, 2013, and rendezvous with two near-earth asteroids in the list (4078 asteroids whose peri-helion distance smaller than 1.523AU) and return the sample of the asteroids to the earth. By the method mentioned in the previous section, 16800 exploration sequences are constructed in all.

Shown in Table 1 is the exploration sequence with the
minimum total required $\Delta v$. The orbit profile of the sequence projected on the ecliptic plane is shown in Fig. 3. The profile is divided into two parts, the former and the latter part of the sequence. They are connected at the earth swing-by at November 29, 2022.

Table 1. Sequence of 2003 YS70/1999 SF10 Exploration

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<th>$\Delta v$</th>
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<td></td>
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5. Summary

The method of constructing the exploration sequence of the near-earth asteroid multi-rendezvous sample return mission is proposed. The constructed sequence is the Keplerian orbits connected with impulsive velocity changes including planetary gravity assists. Dynamical feasibility of the constructed sequence can be assessed quantitatively by the total required $\Delta v$. Moreover, the constructed sequence is sufficiently definitive to restrict the framework and the range of the more detailed problem, such as the orbit design for the low thrust electric propulsion. The method is applied to the mission study of the next asteroid exploration mission. Constructed in the study are not only the sequence shown in this paper, but also the sequence with mars swing-by, or the direct transfer between the asteroids.

Reference