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ORIGINAL ARTICLE

Capturing near-Earth asteroids into bounded Earth orbits using gravity assist

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Abstract In this paper, capturing Near-Earth asteroids (NEAs) into bounded orbits around the Earth is investigated. Several different potential schemes related with gravity assists are proposed. A global optimization method, the particle Swarm Optimization (PSO), is employed to obtain the minimal velocity increments for each scheme. With the optimized results, the minimum required velocity increments as well as the mission time are obtained. Results of numerical simulations also indicate that using MGAs is an efficient approach in the capturing mission. The conclusion complies with the analytical result in this paper that a NEA whose velocity relative to the Earth less than 1.8 km/s can be captured by Earth by just one MGA. For other situations, the combination of MGAs and EGAs is better in sense of the required velocity-increments.

Keywords Asteroid · Gravity assist · Capture · Orbit

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1 Introduction

There are many useful resources on the NEAs (Lewis 1997; Sonter 1997) so that many terrestrial resources shortages can be supplemented by mining NEAs. So far, many asteroid-related missions have been carried out (Zeng et al. 2014; Kawaguchi et al. 2008). Japanese Hayabusa mission is the first sample return mission in history. This mission returned a sample from asteroid Itokawa in 2003 (Kawaguchi et al. 2008). As for the asteroid capturing mission, NASA initiated Asteroid Redirect Mission (ARM) (Brophy et al. 2012; Strange et al. 2013). Two different ways to capture an asteroid were proposed in their study. The first one is to capture a whole asteroid and the second one is to bring a bulk of an asteroid to an orbit around the Moon. Recently, NASA decided to use the second scheme and they will pick up a ~ 7 m diameter rock off the surface of a > 100 m asteroid in 2020s.

As for the research works, Baoyin et al. (2010) firstly proposed the idea to capture an asteroid. In their work, a method that imposing an impulse at a NEA when it passes close to Earth so that the zero velocity curves will close in the framework of Earth-Sun circular restricted three-body problem. The best target is 2009BD for which the velocity increment is 410 m/s in their research. Another method proposed by Hasnain et al. (2012) uses the patched conics to transfer a target NEA into the Earth Sphere of Influence (SOI), and then captures it into a bounded geocentric orbit by an impulse maneuver. They listed 23 NEAs that can be captured within 10 years. Their lowest velocity increment for capturing 2007CB27 is 700 m/s. Also, they suggested that the capturing velocity increment would be decreased by using the Moon flyby at a proper time. Yárnoz et al. (2013) explored an alternate method for capturing NEAs. They defined easily retrievable objects that can be transported from unperturbed heliocentric orbits into the vicinity of the Earth at affordable costs using the invariant manifolds. They listed 12 different objects which can be retrieved with less than 500 m/s of velocity increment. Urrutxua et al. (2015) studied how to extend the time of the capture phase of the temporarily captured asteroids with the low thrust in a high-fidelity dynamic model. The simulations indicate that the capture duration could have been prolonged for five years with relatively low velocity increment of 32 m/s for the 2006RH120, during its latest temporary captured period.

The Gravity-assist method is an efficient way to reduce velocity increment costs and increase payloads in asteroid-related missions. Qiao et al. (2006) studied the accessibility of NEAs via Earth Gravity Assists (EGAs). In their work, the EGA is used to reduce the launch energy and the total velocity increment for a rendezvous mission with NEAs. Chen et al. (2014) investigated the accessibility of the main-belt asteroids using gravity assists. It is found that Mars is the most useful gravity-assist body for the main-belt asteroid missions. Yang et al. (2015) studied the low thrust transfer between a NEA and a main-belt asteroid using multiple-gravity assists. As for asteroid capture missions, Gong and Li (2015a) proposed to use MGAs (MGAs) for capturing NEAs in Earth-Moon three-body restricted problem. Gong and Li (2015b) also extended their previous work (Gong and Li 2015a) to a planar restricted four-body problem. Beyond MGAs, EGAs can also be considered as a gravity-assist way and used in asteroid capture missions. Considering both MGAs and EGAs, there can be four different ways: (1) both are not used; (2) only MGAs are used; (3) only EGAs are used; (4) both are used.

In previous works, these four different ways haven't been analyzed and compared. This paper contains a numerical study on how MGAs and EGAs reduce the velocity increments required in the capturing procedure. Simulations indicate that a reasonably selected gravity-assist body would decrease the capturing velocity increment greatly. In this work, global optimizations are carried out to minimize the velocity increment required in the inbound process that captures NEAs into bounded orbits around the Earth using Particle Swarm Optimization (PSO) method for the four schemes mentioned above. This paper has two main purposes. The first one is to list the NEAs candidates for capturing as well as their minimal required velocity increments for each scheme. The second purpose of this paper is to compare the efficiency of the four different schemes. It should be noted that the outbound fuel consumption has a negligible impact on the fuel consumption of the whole mission. However, the inbound fuel consumption is always much larger than the outbound fuel consumption because of the larger mass of the spacecraft's system after capturing an asteroid. A brief discussion will be given in Sect. 3. Hence, this work only focuses on the inbound trajectories. In this case, it is easier

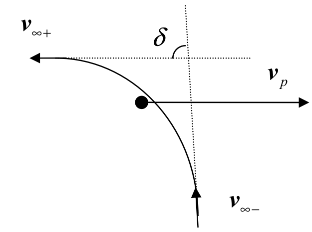

Fig. 1 Illustration of the impulsive gravity-assist model

to analyze the effects of various ways of gravity assists on the velocity increments.

This paper is organized in the following way. In Sect. 2, the impulse gravity-assist model is introduced and the ability of MGAs is analysis in an analytical way. The global PSO optimization methods with different gravity-assist schemes are described in Sect. 3. The efficiency of the four schemes about the gravity assist is discussed in Sect. 4. Concluding remarks are given in Sect. 5.

2 Dynamics

2.1 Impulse model of gravity assist

In a planetary mission, the flight time of spacecraft inside the influence region of gravity-assist body is very short relative to whole mission time. Hence, an assumption is always made that the position of the spacecraft keeps and the velocity has an instantaneous change during the gravity assist. Such a simplified gravity-assist model is often used in the preliminary space mission design and analysis, because of its simplicity and computational efficiency (Jiang et al. 2012; Chen et al. 2014; Yang et al. 2015).

The impulse gravity-assist model is illustrated in Fig. 1 and the following equations are satisfied in this model.

$$v_- = v_p + v_{\infty-} \tag{1}$$

$$v_+ = v_p + v_{\infty+} \tag{2}$$

where v^- and v^+ denote the velocity vector of asteroid before and after the gravity assist, v_P is velocity vector of the gravity-assist planet, $v_{\infty-}$ and $v_{\infty+}$ are inbound or outbound hyperbolic excess velocity of asteroid with respect to the gravity-assist body, respectively, and δ is the turn angle. The turn angle δ is obtained as (Sergeyevsky et al. 1983)

$$\delta = 2\arcsin\left(\frac{1}{1 + r_p v_\infty^2/\mu_p}\right) \tag{3}$$

where μ_P is gravitational constant of the gravity-assist body and r_p is the gravity-assist radius.

To describe the geometry of three-dimensional gravity assists, a local coordinate system o-ijk is defined as follows:

$$i = \frac{v_{\infty-}}{v_{\infty-}}, \qquad k = \frac{v_p \times v_{\infty-}}{\|v_p \times v_{\infty-}\|}, \qquad j = k \times i \tag{4}$$

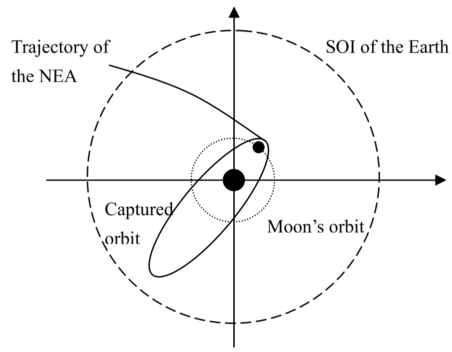

Fig. 2 Illustration of the endgame with one MGA

Then, the outbound velocity can be obtained as (Chen et al. 2014; Yang et al. 2015)

$$v_{\infty+} = v_\infty(\cos\delta i + \sin\delta\sin\varphi j + \sin\delta\cos\varphi k) \tag{5}$$

where φ is the direction angle.

The velocity increment induced by gravity assist is

$$\begin{aligned}\Delta v_{GA} &= v_{\infty+} - v_{\infty-} \\ &= v_\infty\big[(\cos\delta - 1)i + \sin\delta\sin\varphi j + \sin\delta\cos\varphi k\big]\end{aligned} \tag{6}$$

2.2 Analysis of MGAs

MGAs play a very important role in capturing asteroids. In the work of Gong and Li (2015a), it was found that the required velocity increment can be very low with the help of MGAs. Meanwhile, MGAs are also used for endgame braking in the mission design for NASA Asteroid Redirect Robotic Mission concept (Strange et al. 2013). In order to look insight to the ability of MGAs for capturing asteroids, the following analysis is carried out. This analysis will also help understanding numerical optimized results with or without MGAs in Sect. 4.

The endgame with one MGA in the capture mission is illustrated in Fig. 2. At the start of the endgame, the NEA is assumed to be located at the sphere of influence (SOI) of the Earth. The NEA then moves towards the Moon for the gravity assist. In Fig. 2, the case that the NEA captured into an Earth orbit after the gravity assist is shown.

To understand the ability of the MGA, the relationship of the minimum energy of a NEA relative to the Earth after the MGA with the velocity on the SOI should be established. This purpose can be achieved with the next two steps.

Firstly, the minimum energy after MGA is connected with the inbound velocity before the MGA. The planar MGA is considered and its geometry is illustrated in Fig. 3. v_{in} is the velocity of the NEA before the MGA, v_m is the velocity of the Moon, $v_{\infty-}$ is the inbound velocity relative to Moon, $v_{\infty+}$ is the outbound velocity relative to Moon, and v_{out} is the velocity of the NEA after the MGA. To obtain the minimum energy after the MGA, the magnitude of the v_{out} should be minimized. With the help of Fig. 3, the following

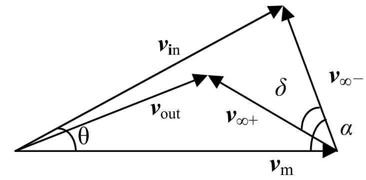

Fig. 3 Geometry of the planar MGA

relationship can be found:

$$v_{out} = \begin{cases} v_m - v_{\infty-} \quad (\alpha \le \delta_{\max}) \\ \sqrt{v_m^2 + v_{\infty-}^2 - 2v_m v_{\infty-}\cos(\alpha - \delta_{\max})} \\ \quad (\alpha > \delta_{\max}) \end{cases} \tag{7}$$

where $\delta_{\max}$ is the maximum deflection angle of NEA at minimum MGA radius $r_{\min}$, α is the angle between Moon velocity and inbound velocity of NEA. Recall Eq. (3), the $\delta_{\max}$ can be obtained by

$$\delta_{\max} = 2\arcsin\left(\frac{1}{1 + \frac{r_{\min}v_\infty^2}{\mu_m}}\right) \tag{8}$$

The α can be easily calculated with the following relationship:

$$\alpha = \arccos\big(\big(v_{\infty-}^2 + v_m^2 - v_{in}^2\big)/(2v_m v_{\infty-})\big) \tag{9}$$

Besides, the magnitude of the $v_{\infty-}$ in Eq. (7) can be obtained with the magnitude of the v_{in} and v_m by

$$v_{\infty-} = \sqrt{v_m^2 + v_{in}^2 - 2v_m v_{in}\cos\theta} \tag{10}$$

where θ is the angle between Moon velocity and NEA inbound velocity with respect to the Earth. With the calculated magnitude of the v_{out}, the energy of NEA after the MGA is obtained as

$$E = \frac{v_{out}^2}{2} - \frac{2\mu_E}{r_m} \tag{11}$$

where r_m is the radius of the Moon's orbit.

Secondly, the magnitude of the velocity of NEA at the Earth's SOI V can be related to the magnitude of the v_{in} according to the Keplerian energy conservation, as

$$v_{\text{in}} = \sqrt{(V)^2 + 2\mu_E/r_m} \tag{12}$$

So far, the minimum energy after the MGA can be analytically related to the velocity on the SOI with Eqs. (7)–(12).

According the analysis above, the energy of NEA after the MGA varies with its velocity V at the SOI of the Earth and the angle between Moon velocity and NEA inbound velocity. The variation is illustrated in Fig. 4 and the capture condition analysis is given in Fig. 5. Because of the symmetry in location of Moon and NEA at the SOI of the Earth, only the case that θ varies from 0 to $\pi/2$ is considered here.

It can be found from the figures above that a NEA whose velocity is less than 1.8 km/s at the SOI of the Earth can be captured by Earth at a proper θ. In addition, the highest efficiency of the MGA is achieved (i.e. the peak) when θ takes

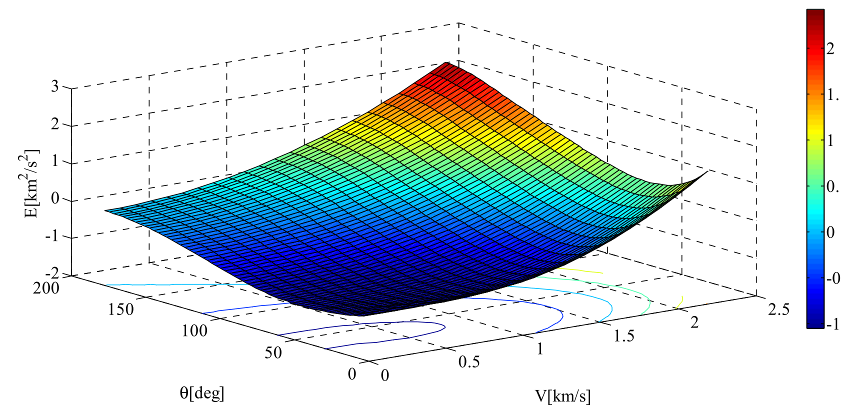

Fig. 4 Energy after the MGA

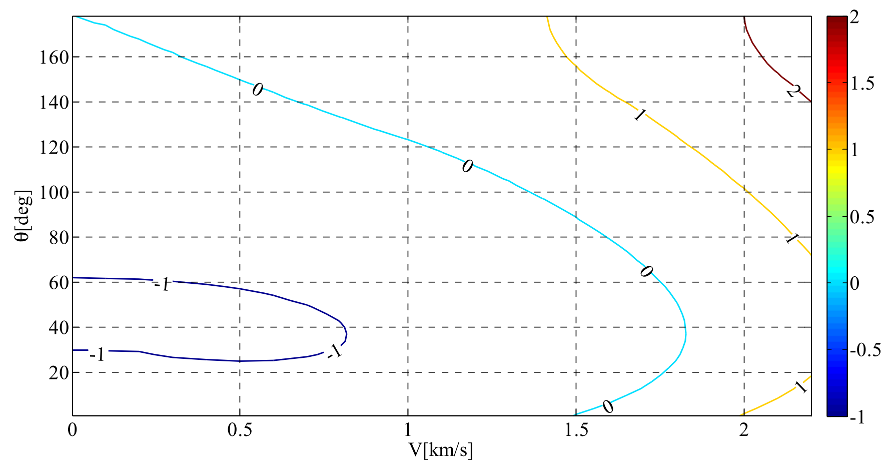

Fig. 5 Capture condition analysis ($E < 0$) after the MGA

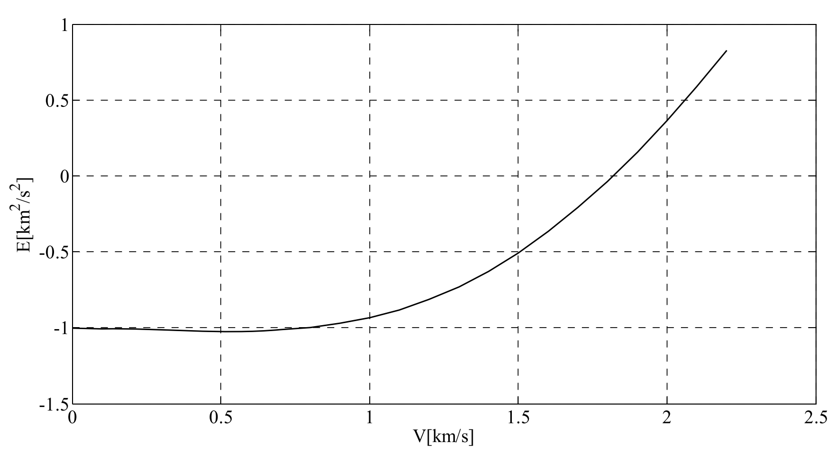

Fig. 6 Energy after the gravity assist with respect to V when $\theta = \pi/4$

about 40 degree. The NEA's energy change with velocity at the SOI of the Earth and θ can be more clearly illustrated in Fig. 6 and Fig. 7, respectively.

3 Global minimum delta-V orbits searching method

PSO is an evolutionary computation technique developed by Eberhart and Kennedy (1995). PSO is often used in global optimization of space missions, because of its global optimization ability (Pontani and Conway 2010; Chen et al. 2014; Yang et al. 2015). PSO will be used to optimize the velocity increment of the inbound process of capturing mission in this paper. The capturing process has two steps: the first is the spacecraft transfer from the Earth parking orbit to the target asteroid and the second is to lasso the target asteroid and pull it from its original orbit to the vicinity of the Earth. The mass of the target capturing asteroid plays a deci-

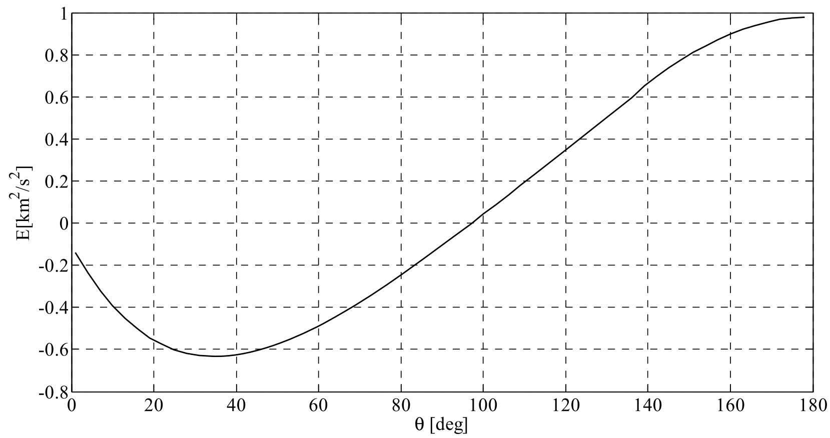

Fig. 7 Energy after the gravity assist with respect to θ when $V = 1$ km/s

Table 1 Fuel consumption results using direct approach

Object number	Object	C3 (km^2/s^2)	Outbound velocity increment (m/s)	Inbound velocity increment (m/s)	Inbound fuel consumption (%)
1	2000SG344	2.08	57.61	941.08	98.52
2	2006RH120	2.09	565.73	1267.05	86.39
3	2008UA202	6.14	162.61	1510.85	95.91
4	2012TF79	0.83	743.29	1874.1	82.58
5	2014WX202	2.57	554.93	1967.91	86.8
6	2014QN266	8.01	124.97	2162.77	96.85
7	2008EA9	2.53	1091.92	2283.05	75.66
8	2008JL24	4.61	279.8	2376.41	93.11
9	2011BL45	2.23	637.97	2389.04	84.89
10	2012LA	3.06	766.4	2805.41	82.25
11	2009YR	10.68	427.6	2806.53	89.66
12	2012EP10	2.79	713.19	2852.56	83.38
13	2013GH66	6.34	642.59	2927	84.81
14	2012WR10	7.5	657.8	3287.48	84.55
15	2000LG6	2.09	1426.42	3623.41	69.52
16	2013WA44	9.63	1992.69	4063.36	59.99
17	2014UV210	0.46	2087.89	4103.41	58.64
18	2015DU	3.77	2108.09	4287.35	58.34
19	2014YD	2.68	495.78	5304.2	88.11
20	2014KD45	9.84	3468.41	5528.7	41.24

sive role in the fuel consumption of the whole capturing mission so that the fuel consumption of the second step decides the whole fuel consumption in the mission. Take picking a bulk of roughly 5 m in diameter corresponding to masses 100 tons from the candidate asteroids as an example. The computational results of escape energy C3, outbound velocity increment, inbound velocity increment, fuel consumption percentage using the PSO optimized direct approach are listed in Table 1. The fuel consumption is calculated by the following equation

$$\Delta m = m_0\left(1 - e^{\frac{-\Delta v}{Isp \cdot g_0}}\right) \tag{13}$$

where m_0 is the initial mass of the spacecraft, the specific impulse Isp is assumed to be 400 s and g_0 is the standard sea level acceleration of gravity.

It can be seen from Table 1 that in 14 cases the percentage of the inbound fuel consumption is more than 80 % and only in 4 cases the percentage is less than 60 %. Therefore, only the optimization of the inbound velocity increment is considered in this paper and it is assumed that the spacecraft and the target asteroid are connected at the initial time of the optimization.

According to the gravity-assist body, four different schemes will be investigated in this section: direct capture,

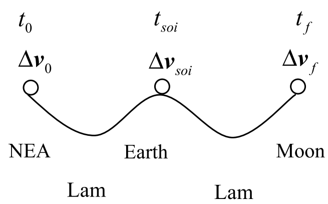

Fig. 8 Illustration of the patched conic method using one MGA

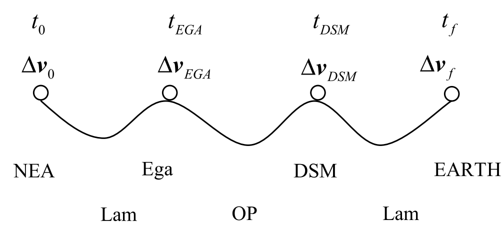

Fig. 9 Illustration of the patched conic method using one EGA

capture using only MGA, capture using only EGA and capture using both Earth and MGA.

Case 1: direct capture

In this case, the time when the NEA starts to deviate its original orbit, t_0, and the time arriving at the Earth, t_f, are chosen as optimization variables. The sum of the velocity increments in the capturing mission is chosen as the object function:

$$J = \|\Delta v_0\| + \|\Delta v_f\| \tag{14}$$

where Δv_0 is the impulse executed at t_0 and Δv_f is the impulse executed at t_f. With the given time of the impulses, the transfer leg can be solved by the Lambert method. Then, Δv_0 and Δv_f are obtained by the following equations

$$\Delta v_0 = v_{scd} - v_a \tag{15}$$

$$\Delta v_f = v_{sca} - v_E \tag{16}$$

where v_a is velocity of NEA at t_0, v_E is velocity of the Earth at t_f, v_{scd} and v_{sca} are velocity of the NEA after and before the impulse, respectively.

To solve the optimal problem, x_i $(i = 1, 2) \in [0, 1]$ are chosen as input variables of the PSO method, so that the initial and final time can be written as

$$\begin{aligned} t_0 &= t_{ad\,\min} + dt_{ad}x_1 \\ t_f &= t_0 + dt_{\max}x_2 \end{aligned} \tag{17}$$

where $t_{ad\,\min}$ is the earliest NEA deviating time, dt_{ad} is the window width of the NEA deviating time and $dt_{\max}$ is the maximum allowed mission time. Then, the object function is obtained by the patched conic method.

Case 2: using one MGA

The patched conic method using one MGA is illustrated in Fig. 8. In the figure above, Lam means the transfer leg is solved by the Lambert method. The definitions of optimization variables are as follow: t_0 is the time of the joint spacecraft-NEA system departing their original orbit, t_{soi} is time of the joint system arriving at the SOI of the Earth, t_f is the time of the MGA, α and β are location angles on the SOI of the Earth, δ_{MGA} and φ_{MGA} are the direction angle and turn angle of the MGA, respectively. Three impulses are executed in the capturing mission, Δv_0 is the impulse at t_0, Δv_{soi} is impulse at t_{soi}, Δv_f is the impulse after the MGA. Lam means that the transfer leg is solved by Lambert method.

The sum of these three impulses is chosen as the object function

$$J = \|\Delta v_0\| + \|\Delta v_{soi}\| + \|\Delta v_f\| \tag{18}$$

where Δv_0 is obtained by Eq. (15) and Δv_{soi} is velocity increment at the Earth's SOI to guidance the spacecraft-NEA system to the Moon. If the energy of the joint system relative to the Earth is greater than zero after MGA, the magnitude of Δv_f is obtained by following equation

$$\Delta v_f = |v_{scm} - \sqrt{2\mu_E/r_m}| \tag{19}$$

where v_{scm} is the magnitude of velocity of the joint system at the Moon arrival, r_m is the magnitude of the Moon position vector at gravity assist, μ_E is the gravitational constant of the Earth.

To solve the optimal problem, x_i $(i = 1, \ldots, 7) \in [0, 1]$ are chosen as input variables, then the object function obtained by the patched conic method is determined by the these input variables:

$$\begin{aligned} t_0 &= t_{ad\,\min} + dt_{ad}x_1 \\ t_{soi} &= t_0 + dt_{\max}x_2 \\ t_f &= t_{soi} + (dt_{\max} - dt_{\max}x_2)x_3 \\ \alpha &= 2\pi x_4 \\ \beta &= -0.5\pi + \pi x_5 \\ \varphi_{MGA} &= 2\pi x_6 \\ \delta_{MGA} &= \delta_{\max}x_7 \end{aligned} \tag{20}$$

where the definitions of $t_{ad\,\min}$, dt_{ad} and $dt_{\max}$ are the same as Case 1.

Case 3: using one EGA

The patched conic method using one EGA is illustrated in Fig. 9. In this case, the definitions of optimization variables are as follow: t_0 is the time of the joint spacecraft-NEA system departing their original orbit, t_{EGA} is the time of the joint system arrive at the EGA, t_{DSM} is the time of the deep space maneuver (DSM), t_f is the time of the joint system arrive at the Earth, δ_{EGA} and φ_{EGA} are the direction angle and turn angle at the EGA, respectively. OP means the orbit propagation.

The overall velocity-increment of the capturing mission is chosen as the object function

$$J = \|\Delta v_0\| + \|\Delta v_{DSM}\| + \|\Delta v_f\| \tag{21}$$

where Δv_0 is the impulse at the NEA departure, Δv_f is the impulse at the Earth arrival, and Δv_{DSM} is the impulse of the deep space maneuver. Δv_0 and Δv_f are decided by

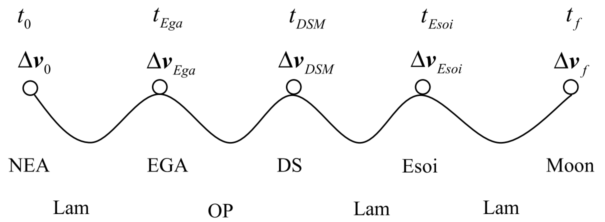

Fig. 10 Illustration of the patched conic method using one EGA and one MGA

Eqs. (15) and (16). Δv_{DSM} is the difference of the velocity of the OP leg and the velocity of the Lam leg at this point.

To solve the optimal problem, x_i $(i = 1, \ldots, 6) \in [0, 1]$ are chosen as input variables of PSO method, then the object function obtained by the patched conic method is determined by the these input variables:

$$\begin{aligned}
t_0 &= t_{ad\min} + dt_{ad} x_1 \\
t_{Ega} &= t_0 + dt_{\max} x_2 \\
t_{DSM} &= t_{Ega} + (dt_{\max} - dt_{\max} x_2) x_3 \\
t_f &= t_{DSM} + (dt_{\max} - dt_{\max} x_2 - (dt_{\max} - dt_{\max} x_2) x_3) x_4 \\
\varphi_{EGA} &= 2\pi x_5 \\
\delta_{EGA} &= \delta_{\max} x_6
\end{aligned} \tag{22}$$

where the definitions of $t_{ad\min}$, dt_{ad} and $dt_{\max}$ are the same as previous cases.

Case 4: using one EGA and one MGA

The patched conic method using one Earth and one MGA is illustrated in Fig. 10. The definitions of the optimization variables are as follows, t_0 is the time of the joint spacecraft-NEA system departing their original orbit, t_{EGA} is the time of joint system arrive at the EGA, t_{DSM} is the time of the deep space maneuver, t_{Esoi} is the time of the impulse at the Earth's SOI, t_f is the time of the joint system at the Moon, α and β are location angles on the SOI of the Earth, φ_{MGA} and δ_{MGA} are the direction angle and turn angle of the MGA, respectively. There are all five impulses provided by the thruster. Δv_0 is the impulse at t_0, Δv_{EGA} is the impulse at the EGA, Δv_{DSM} is the impulse of the deep space maneuver, Δv_{Esoi} is the impulse at the Earth's SOI, Δv_f is the impulse after the MGA.

The velocity of the asteroid after the EGA is obtained as follows

$$v_{after} = v_{before} + \Delta v_{EGA} \tag{23}$$

where the Δv_{EGA} is determined by the two gravity-assist angles δ_{EGA} and φ_{EGA} as shown in Fig. 1. The velocity-increment of the capturing mission is chosen as the object function

$$J = \|\Delta v_0\| + \|\Delta v_{DSM}\| + \|\Delta v_{Esoi}\| + \|\Delta v_f\| \tag{24}$$

To solve the optimal problem, x_i $(i = 1, \ldots, 11) \in [0, 1]$ are chosen as the input variables of the PSO method, then the object function obtained by the patched conic method is determined by the these input variables:

$$\begin{aligned}
t_0 &= t_{ad\min} + dt_{ad} x_1 \\
t_{Ega} &= t_0 + dt_{\max} x_2 \\
t_{DSM} &= t_{Ega} + (dt_{\max} - (t_{Ega} - t_0)) x_3 \\
t_{Esoi} &= t_{DSM} + (dt_{\max} - (t_{DSM} - t_0)) x_4 \\
t_f &= t_{Esoi} + (dt_{max} - (t_{Esoi} - t_0)) x_5 \\
\alpha &= 2\pi x_6 \\
\beta &= -0.5\pi + \pi x_7 \\
\varphi_{EGA} &= 2\pi x_8 \\
\delta_{EGA} &= \delta_{\max} x_9 \\
\varphi_{MGA} &= 2\pi x_{10} \\
\delta_{MGA} &= \delta_{\max} x_{11}
\end{aligned} \tag{25}$$

4 Numerical simulation and discussion

4.1 Numerical simulation results

In the numerical simulation, the orbital elements of the asteroids are all from the Near-Earth Objects Dynamic Site.[1] For the computational efficiency, only the NEAs whose inclination less than 7 deg and eccentricity less than 0.2 are selected. Firstly, 20 best candidate NEAs that can be captured in the direct way are selected. Then, the optimum velocity increments for these 20 candidates in four different ways are calculated. Given the associated parameter, the optimal variables can be achieved by the PSO optimizer using the method presented in the previous section.

The constraint parameters are given as follows

$$\begin{aligned}
T_{ad\min} &= \text{1st Jan, 2025} \\
dt_{Ld} &= \text{5 years} \\
dt_{\max} &= \text{1000 days}
\end{aligned}$$

The optimal results of the 20 candidates NEAs in the different four cases are in Tables 2, 3 and 4.

An example of capturing the 2000SG344 using EGA is illustrated in Fig. 11.

4.2 Discussion

For the comparison, the total velocity increment and mission time of the different cases are illustrated in Figs. 12 and 13.

Within specified time constraints, it can be seen clearly from Fig. 12 that the minimum capturing velocity increment in Case 1 is 700 m/s for the candidate NEA 2006RH120, the maximum velocity increment is 2226.14 m/s for NEA 2013GH66, such a high velocity increment requirement is beyond the current thruster capability. Therefore, a mission

[1] http://newton.dm.unipi.it/neodys/ [retrieved on 25 March 2015].

Table 2 The optimal result of PSO method without gravity-assist

Object number	Object	Delta-V at NEA departure (m/s)	Delta-V at Earth arrival (m/s)	Total mission time (day)	Total delta-V (m/s)
1	2006RH120	157.74	542.35	197.87	700.08
2	2000SG344	232.36	583.73	204.15	816.09
3	2012TF79	631.52	413.55	165.32	1045.07
4	2008UA202	440.07	870.37	253.21	1310.44
5	2008EA9	270.95	1220.87	356.26	1491.82
6	2014QN266	556.95	1136.05	264.77	1693.00
7	2014WX202	42.59	1659.37	340.54	1701.96
8	2011BL45	1662.70	88.37	300.71	1751.07
9	2012WR10	329.55	1425.65	282.13	1755.20
10	2013WA44	777.73	1234.69	323.85	2012.42
11	2014UV210	1843.20	171.30	233.74	2014.50
12	2012LA	374.61	1661.92	280.99	2036.54
13	2009YR	543.87	1502.40	203.48	2046.27
14	2012EP10	970.31	1085.91	246.00	2056.22
15	2014KD45	812.88	1247.41	327.89	2060.29
16	2008JL24	762.84	1303.84	239.03	2066.68
17	2000LG6	372.44	1788.18	288.65	2160.62
18	2014YD	1498.49	676.16	303.47	2174.65
19	2015DU	1478.71	700.56	323.78	2179.27
20	2013GH66	1218.51	1007.63	244.14	2226.14

Table 3 The optimal result of PSO method using MGA

Object number	Object	Delta-V at NEA departure (m/s)	Delta-V at Earth SOI (m/s)	Delta-V after MGA (m/s)	Total mission time (day)	Total delta-V (m/s)
1	2006RH120	457.29	0.00	0.00	125.05	457.29
2	2000SG344	78.75	0.00	0.00	236.30	78.75
3	2012TF79	870.19	0.00	0.00	302.53	870.19
4	2008UA202	387.84	0.00	0.00	261.67	387.84
5	2008EA9	256.59	12.88	0.00	365.29	269.47
6	2014QN266	469.31	0.00	0.00	312.56	469.31
7	2014WX202	449.43	0.00	0.00	345.72	449.43
8	2011BL45	262.58	0.00	0.00	302.33	262.58
9	2012WR10	325.50	0.00	0.00	294.65	325.50
10	2013WA44	611.53	0.07	0.00	338.81	611.60
11	2014UV210	527.14	338.87	0.00	339.24	866.01
12	2012LA	610.64	503.62	0.00	240.08	1114.26
13	2009YR	483.94	285.62	0.00	251.83	769.56
14	2012EP10	328.10	397.01	0.00	318.00	725.12
15	2014KD45	807.00	388.26	0.00	342.15	1195.26
16	2008JL24	334.16	366.85	0.00	248.94	701.01
17	2000LG6	339.65	0.00	0.00	290.38	339.65
18	2014YD	1365.75	0.00	0.00	213.80	1365.75
19	2015DU	1107.52	0.00	0.00	330.03	1107.52
20	2013GH66	796.12	0.00	0.00	140.94	796.12

without a gravity assist is infeasible now. As for Case 2, MGA greatly decrease the capturing velocity increment. The minimum capturing velocity increment is 78.75 m/s for the NEA 2000SG344 and the maximum capturing velocity increment is 1365.75 m/s for the NEA 2014YD. As for Case 3, the minimum capturing velocity increment is 462.9 m/s for

Table 4 The optimal result of PSO method using EGA

Object number	Object	Delta-V at NEA (m/s)	Delta-V at deep space (m/s)	Delta-V at Earth arrival (m/s)	Total mission time (day)	Total delta-V (m/s)
1	2006RH120	158.66	207.90	96.34	851.80	462.90
2	2000SG344	229.42	156.68	122.56	680.71	508.66
3	2012TF79	476.77	147.86	133.32	582.56	757.95
4	2008UA202	434.15	226.47	200.27	709.85	860.89
5	2008EA9	240.87	341.84	282.49	819.56	865.20
6	2014QN266	544.46	291.67	275.49	721.52	1111.62
7	2014WX202	41.62	454.19	371.10	817.66	866.91
8	2011BL45	524.59	415.56	340.65	810.27	1280.81
9	2012WR10	340.05	376.40	322.83	737.25	1039.28
10	2013WA44	642.14	375.26	318.99	801.23	1336.39
11	2014UV210	1847.58	54.86	32.49	733.24	1934.93
12	2012LA	374.77	436.07	380.89	741.08	1191.72
13	2009YR	495.25	428.43	348.32	679.52	1272.00
14	2012EP10	958.03	281.65	260.01	692.47	1499.69
15	2014KD45	821.04	323.75	286.69	779.20	1431.48
16	2008JL24	192.25	544.00	558.34	700.03	1294.60
17	2000LG6	344.34	656.68	302.38	913.47	1303.39
18	2014YD	1477.87	177.05	158.78	751.82	1813.70
19	2015DU	1081.40	336.61	318.32	791.60	1736.34
20	2013GH66	117.42	569.16	486.58	738.58	1173.16

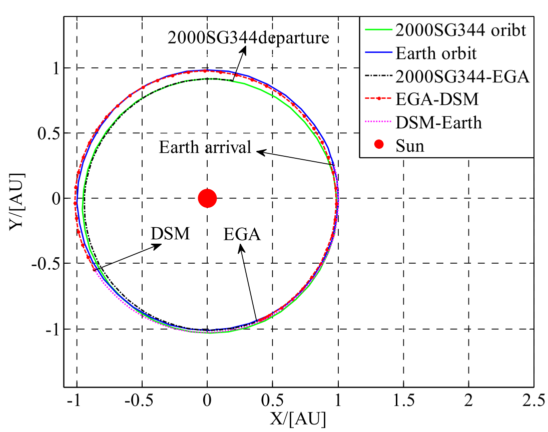

Fig. 11 Transfer trajectory of the 2000SG344 NEA in heliocentric coordinate system

the NEA 2006RH120 and the maximum capturing velocity increment is 1934.93 m/s for the NEA 2014UV210. As for Case 4, the minimum capturing velocity increment is 92.65 m/s for the NEA 2000SG344 and the maximum capturing velocity increment is 1630.48 m/s for the NEA 2014YD. In general, the methods using MGA and EGA are more efficient than the others. For example, the capturing velocity increment for the 2000LG6 NEA using MGA can save 1821 m/s compared with cases where gravity assists are not used.

Form the 5th column of Table 3 and 6th column of Table 5, a conclusion can be drew that the NEAs can be captured by the Earth after just one MGA. The conclusion is consistent with previous analysis. By comparing the 4th column of Table 3 and the 5th column of Table 5, it can be seen that the EGA decrease the velocity-increment at the SOI of the Earth greatly. However, such a method will increase the mission time. It can be seen from Fig. 13 that the cases using EGA have the mission time increased an average of 460 days.

It should be pointed out that all the results given above are based on the fact that only the inbound trajectories are considered. For a whole mission of capturing an asteroid, the fuel consumption of the outbound trajectories may play an important role and should be further analyzed. Besides, the whole or part of the escape energy is provided by the launcher so that the escape energy should not exceed the launcher's capability and the corresponding propellant budget should also be checked in actual missions.

5 Conclusion

In this paper, four different cases of capturing NEAs according to the gravity assists are studied. For each case, the way of using the PSO method to obtain the minimal velocity increments in the inbound process is proposed. Through the

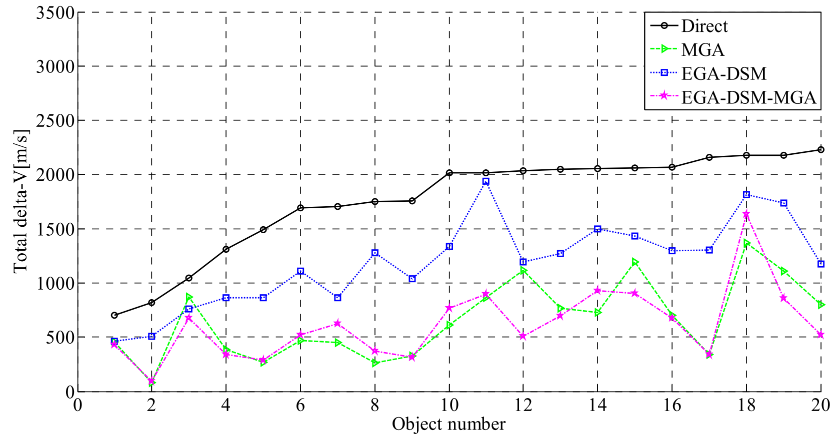

Fig. 12 Total delta-V for different cases

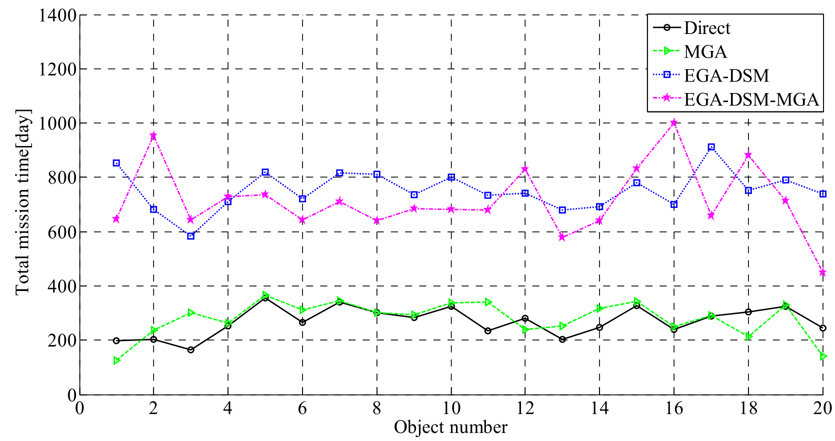

Fig. 13 Total mission time for different cases

Table 5 the optimal result of PSO method using EGA and MGA

Object number	Object	Delta-V at NEA (m/s)	Delta-V at deep space (m/s)	Delta-V at Earth SOI (m/s)	Delta-V after MGA (m/s)	Total mission time (day)	Total delta-V (m/s)
1	2006RH120	141.72	264.81	25.30	0.00	645.85	431.83
2	2000SG344	91.97	0.68	0.00	0.00	954.69	92.65
3	2012TF79	497.04	178.23	0.07	0.00	642.41	675.34
4	2008UA202	107.01	234.07	0.00	0.00	728.74	341.08
5	2008EA9	287.22	0.14	0.00	0.00	736.30	287.37
6	2014QN266	519.09	0.37	0.00	0.00	644.28	519.46
7	2014WX202	624.06	1.77	0.00	0.00	710.08	625.83
8	2011BL45	286.74	82.37	1.35	0.00	640.90	371.56
9	2012WR10	310.78	1.24	0.00	0.00	683.93	312.01
10	2013WA44	757.49	6.95	0.00	0.00	682.48	764.43
11	2014UV210	559.07	0.34	338.28	0.00	680.14	897.69
12	2012LA	427.95	80.46	0.01	0.00	830.20	508.41
13	2009YR	647.53	50.38	0.00	0.00	578.46	697.91
14	2012EP10	925.64	0.39	0.00	0.00	639.40	926.03
15	2014KD45	879.76	22.76	0.00	0.00	831.23	902.52
16	2008JL24	539.26	137.67	0.13	0.00	1001.27	677.06
17	2000LG6	334.99	1.69	0.00	0.00	658.13	336.68
18	2014YD	1450.43	180.05	0.00	0.00	881.86	1630.48
19	2015DU	844.98	10.33	0.16	0.00	714.09	855.47
20	2013GH66	159.58	0.41	361.25	0.00	448.48	521.24

optimization, the minimal velocity-increment requirements for capturing the NEAs between 2025 and 2030 are presented for the selected targets. These results can offer references for preliminary mission designs in the future. The conclusions on the optimization of capturing NEAs to the bounded Earth orbit are summarized as follows

1. The results of PSO optimization method with MGA and the EGA indicate that both types of gravity assists are similar in reducing velocity increments. However, the latter takes more time than the former. The NEA candidate list can be enlarged by using MGAs or EGAs.
2. The minimum delta-V for capture NEA is 78.75 m/s with MGA and the target is 2000SG344.
3. According to the analysis of MGAs, the NEAs whose velocity at the SOI of Earth less than 1.8 km/s can be captured by Earth after just one MGA. If its velocity exceeds 1.8 km/s, EGAs can be used to decrease this value to be less than 1.8 km/s. Then, it can be captured by using MGA again. The simulation results comply with the analysis in Sect. 2.

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References

Baoyin, H.X., Chen, Y., Li, J.F.: Capturing near Earth objects. Res. Astron. Astrophys. **10**(6), 587 (2010)

Brophy, J., Culick, F., Friedman, L., Allen, C., Baughman, D., Bellerose, J., Yeomans, D.: Asteroid retrieval feasibility study. Keck Institute for Space Studies, Califonia Institute of Technology, Jet Propulsion Laboratory (2012)

Chen, Y., Baoyin, H., Li, J.: Accessibility of main-belt asteroids via gravity assists. J. Guid. Control Dyn. **37**(2), 623–632 (2014)

Eberhart, R.C., Kennedy, J.: A new optimizer using particle swarm theory. In: Proceedings of the Sixth International Symposium on Micro Machine and Human Science, vol. 1, pp. 39–43 (1995)

Gong, S., Li, J.: Asteroid capture using lunar flyby. Adv. Space Res. (2015a)

Gong, S., Li, J.: Planetary capture and escape in the planar four-body problem. Astrophys. Space Sci. **357**(2), 1–10 (2015b)

Hasnain, Z., Lamb, C.A., Ross, S.D.: Capturing near-Earth asteroids around Earth. Acta Astronaut. **81**(2), 523–531 (2012)

Jiang, F., Baoyin, H., Li, J.: Practical techniques for low-thrust trajectory optimization with homotopic approach. J. Guid. Control Dyn. **35**(1), 245–258 (2012)

Kawaguchi, J.I., Fujiwara, A., Uesugi, T.: Hayabusa—its technology and science accomplishment summary and Hayabusa-2. Acta Astronaut. **62**(10), 639–647 (2008)

Lewis, J.S.: Resources of the asteroids. J. Br. Interplanet. Soc. **50**(2), 51–58 (1997)

Pontani, M., Conway, B.A.: Particle swarm optimization applied to space trajectories. J. Guid. Control Dyn. **33**(5), 1429–1441 (2010)

Qiao, D., Cui, H., Cui, P.: Evaluating accessibility of near-Earth asteroids via EGAs. J. Guid. Control Dyn. **29**(2), 502–505 (2006)

Sergeyevsky, A.B., Snyder, G.C., Cunniff, R.A.: Interplanetary Mission Design Handbook, vol. I, Part 2. JPL Publication 82-43, Pasadena (1983)

Sonter, M.J.: The technical and economic feasibility of mining the near-Earth asteroids. Acta Astronaut. **41**(4), 637–647 (1997)

Strange, N., Landau, T.M., Lantoine, G., Lam, T., McGuire, M., Burke, L., Dankanich, J.: Overview of mission design for NASA asteroid redirect robotic mission concept. In: 33rd International Electric Propulsion Conference, The George Washington University, Washington, DC (2013)

Urrutxua, H., Scheeres, D.J., Bombardelli, C., Gonzalo, J.L., Peláez, J.: Temporarily captured asteroids as a pathway to affordable asteroid retrieval missions. J. Guid. Control Dyn. (2015)

Zeng, X., Gong, S., Li, J.: Fast solar sail rendezvous mission to near Earth asteroids. Acta Astronaut. **105**(1), 40–56 (2014)

Yárnoz, D.G., Sanchez, J.P., McInnes, C.R.: Easily retrievable objects among the NEO population. Celest. Mech. Dyn. Astron. **116**(4), 367–388 (2013)

Yang, H., Li, J., Baoyin, H.: Low-cost transfer between asteroids with distant orbits using multiple gravity assists. Adv. Space Res. (2015)