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LOW-ENERGY CAPTURE OF ASTEROIDS FOR THE LOGISTIC SUPPORT OF FUTURE MARS MISSIONS

Minghu Tan,[*] Colin McInnes,[†] and Matteo Ceriotti [‡]

Low energy strategies for capturing asteroids and inserting them into orbits in the vicinity of the Sun-Mars L_1/L_2 libration points may be of significant benefit for future Mars missions. Such strategies could deliver resources to Lagrange point staging posts to support future crewed missions. Three asteroid capture strategies are investigated to achieve efficient delivery of asteroid resources. In the first strategy, the target asteroid is assumed to be deflected from its heliocentric orbit using some initial maneuver. Then, with a second maneuver, the candidate asteroid is inserted onto the stable manifold associated with the Sun-Mars L_1/L_2 periodic orbits. In principle it will then be asymptotically captured onto the final target periodic orbit without any propellant consumption. Therefore, the entire transfer trajectory for capturing the candidate asteroid can be designed by patching together the Sun-centered two-body problem and the stable manifold in the Sun-Mars circular restricted three-body problem. Moreover, a Mars flyby is also considered to capture asteroids onto the final periodic orbits around the Sun-Mars libration points. According to the periapsis distance threshold for aerobaking, two asteroid capture strategies using the Mars flyby are considered: a Mars flyby with aerobraking and without aerobraking to enhance the transfer trajectory from the candidate asteroid orbit to the stable manifolds associated with the Sun-Mars L_1/L_2 periodic orbits. Furthermore, all transfers are optimized with a global optimization method, using the total transfer cost as the objective function. Results show that the Mars flyby can enable some asteroids to be captured with a lower cost than the asteroid capture strategy without a Mars flyby in terms of energy requirements.

INTRODUCTION

Recently, Mars has generated significant interest for future human space exploration missions and possible long-term colonization [1, 2]. Moreover, families of accessible asteroids have been identified as candidate sources of in-situ resources such as water and metals to support future space exploration ventures [3]. Therefore, capturing asteroids and inserting them in the vicinity of Sun-Mars L_1/L_2 libration points may be of significant benefit for future Mars missions. In particular, water-rich asteroids captured at low energy cost could provide in-situ propellant resources,

[*] PhD candidate, School of Engineering, University of Glasgow, G12 8QQ.
[†] James Watt Chair, Professor, School of Engineering, University of Glasgow, G12 8QQ.
[‡] Lecturer, School of Engineering, University of Glasgow, Member AIAA, G12 8QQ.

with the L_1/L_2 points used as a staging post for arriving/departing vehicles, similar to Lagrange point staging posts considered in the Sun-Earth system [4]. The family of asteroids which can be captured into orbits the Sun-Mars L_1/L_2 libration points at low cost represent an alternative source of resources to Phobos and Deimos, both of which are in orbits deep within Mars' gravity well.

At present, most work on asteroid capture focuses on capturing asteroids into orbits in the vicinity of the Earth [5-11]. In these studies, the Sun-Earth L_1 and L_2 libration points orbits are considered to be preferred parking orbits for captured asteroids, with the Sun-Earth L_1 or L_2 points being natural gateways to other systems such as Mars [12]. The invariant manifolds have been considered in some detail as an efficient means of designing low-energy transfer trajectories for capturing asteroids. One of the simplest ways to design transfer trajectories for capture is to patch together a target periodic orbit's stable manifold and a Lambert arc [13]. Once the captured asteroid is injected onto the stable manifold, it would be captured onto the final periodic orbit along the stale mnaifold, in principle without further maneuvers. Based on this strategy, low cost capture of near-Earth asteroids (NEAs) onto periodic orbits around the L_1 and L_2 libration points in the Sun–Earth CRTBP system has been investigated and those NEAs that can be captured with a total cost less than 500 m/s defined as the easily retrievable objects (EROs) [13]. More EROs have recently been found [7] and low thrust technology has been employed to design transfer trajectory for the ERO missions in order to further increase the retrieved mass [14, 15]. Moreover, invariant manifold theory has also been used to study asteroid capture strategies onto the Earth-Moon L_2 point periodic orbits, since the Earth-Moon L_2 point is also viewed as a candidate gateway for future space missions [16, 17]. Mingotti, Sanchez [18] proposed to capture asteroids onto the target Earth–Moon L_2 point periodic orbits in the model of the patched circular restricted three-body problem to. In this strategy, after the asteroid is captured onto a periodic orbit around the Sun-Earth L_1/L_2 point, it would then move from the unstable manifold in the Sun-Earth system to the stable manifold in the Earth-Moon system. Nevertheless, a significant flight time would be required for the asteroid to be captured into the vicinity of the Sun-Earth L_1 or L_2 points along the stable manifold[11]. For this reason, a relatively fast asteroid capture strategy was proposed. In this capture strategy, a first maneuver is required to deflect the candidate asteroid from its orbit and then the asteroid will be inserted onto the an Earth-Moon L_2 periodic orbit's stable manifold directly with a second maneuver [6].

Gravity assist is also a basic and useful tool in interplanetary mission design and so can provide additional opportunities for asteroid missions. For example, the required transfer energy to NEAs can be reduced by using Earth gravity assists [19]. Moreover, it has been proved that Mars is the most useful celestial body for gravity assist in the transfer to main-belt asteroids and thus Mars gravity assists can be used to design transfer trajectories to these asteroids with low energy [20, 21]. Meanwhile, multiple-gravity assists were widely used to design interplanetary transfers for the asteroid/comet exploration missions [22, 23]. Moreover, in the asteroid capture missions, lunar flybys have been considered to temporarily capture an NEA in the vicinity of the Earth, with 4 asteroids found that can be captured with a total cost below 300 m/s [24]. Furthermore, when a spacecraft swings-by a planet such as the Earth or Mars, if the perigee height is low enough, the planetary atmosphere can provide an aerobraking maneuver. Therefore, Baoyin, Chen [25] considered that aerobraking could significantly reduce the total cost of capturing asteroids. Then, Sanchez and McInnes [26] estimated the mass of the asteroids which can be retrieved and returned to the vicinity of the Earth using aerobraking. More recently, an Earth flyby with aerobraking and an Earth flyby with a high attitude were proposed for the design of low energy transfer trajectories to capture asteroids onto the Lyapunov orbits around the Sun-Earth L_1 and L_2 points [5]. Accordingly, a general analysis of aerobraking was undertaken and aerobraking was proposed to directly capture asteroids at the Earth [27]. Moreover, Mars aerobraking has been considered extensively for Mars missions, especially Mars landers [28-32]. Similar to asteroid capture using Earth aerobraking, the Martial atmosphere could provide an aerobrkiang maneuver for the asteroid capture, in order to achieve low energy capture of asteroids onto periodic orbits around the Sun-Mars L_1/L_2 points.

In this paper, we propose to use the methods discussed above to capture asteroids onto periodic orbits around the Sun-Mars libration points L_1 and L_2 for the logistic support of future crewed Mars missions at Lagrange point staging posts. It is assumed that a spacecraft is first launched to rendezvous with a candidate asteroid. With an initial propulsive impulse, the candidate asteroid is deflected from its heliocentric orbit and then the subsequent transfer is modelled as a Sun-centered two body problem. Then, with a second propulsive impulse, the candidate asteroid can be inserted onto a stable manifold associated with the Sun-Mars L_1/L_2 libration point orbits. The magnitude of the two maneuvers can be determined by calculating a bi-impulse Lambert arc between the asteroid's initial orbit and the stable manifold. Moreover, the transfer will be optimized with a global optimization method [33], using the total cost in term of velocity increment as the objective function. The methodology can then be used to search for candidate asteroids which can be captured at the Sun-Mars L_1/L_2 libration points with low energy costs. Furthermore, Mars flybys are investigated to reduce the total cost of the transfer trajectories for capturing a candidate asteroid onto the final Sun-Mars L_1/L_2 periodic orbits. Similarly, a global optimization of the asteroid capture strategy using a Mars flyby is again undertaken, using the total cost in term of velocity increment as the objective function. Simulation results show that the asteroid capture strategy using a Mars flyby may have the potential to save the total cost in terms of the velocity increment than a direct asteroid capture strategy without the flyby.

DYANMICAL MODEL

In this Section, a model of the Sun-Mars circular restricted three-body problem (CRTBP) is defined to describe the motion of the captured asteroid in the Sun-Mars system. Based on this model, the Sun-Mars libration point periodic orbits and their associated invariant manifolds are then calculated.

Sun-Mars circular restricted three-body problem

It is assumed that the Sun and Mars move in circular orbits around their barycenter. A rotating frame of reference centered at their barycenter is considered with the *x*-axis connecting the two primary masses, the *z*-axis normal to the plane and the *y*-axis completing the triad. The frame rotates with the same angular velocity as the two primary masses around their barycenter. The motion of a body in the mutual gravitational field of the Sun and Mars can therefore be described by the circular restricted three-body problem (CRTBP) as follows [34].

$$\ddot{x} - 2\dot{y} = \frac{\partial \Omega}{\partial x}, \ddot{y} + 2\dot{x} = \frac{\partial \Omega}{\partial y}, \ddot{z} = \frac{\partial \Omega}{\partial z} \tag{1}$$

where

$$\Omega(x, y, z, \mu) = \frac{1}{2}[(x^2 + y^2) + \mu(1-\mu)] + \frac{1-\mu}{r_1} + \frac{\mu}{r_2}$$

$$r_1 = \sqrt{(x+\mu)^2 + y^2 + z^2}\ , r_2 = \sqrt{(x-1+\mu)^2 + y^2 + z^2}$$

and μ is the non-dimensional mass parameter for the Sun-Mars CRTBP, assumed to be 3.2271675×10^{-7} [35].

From Eq. (1), one can obtain

$$\dot{x}\ddot{x} + \dot{y}\ddot{y} + \dot{z}\ddot{z} = \frac{\partial \Omega}{\partial x}\dot{x} + \frac{\partial \Omega}{\partial y}\dot{y} + \frac{\partial \Omega}{\partial z}\dot{z} \tag{2}$$

Thus, there exists a constant of the energy integral of Eq. (2), termed Jacobi constant *C*, as follows

$$C = 2\Omega(x, y, z, \mu) - (\dot{x}^2 + \dot{y}^2 + \dot{z}^2) \tag{3}$$

Moreover, when $\dot{x}^2 + \dot{y}^2 + \dot{z}^2 = 0$ and $\ddot{x}^2 + \ddot{y}^2 + \ddot{z}^2 = 0$, one can obtain the five libration points. Among these five libration points, L_1, L_2 and L_3 are in a line along the *x*-axis and thus are termed the collinear libration points. L_4 and L_5 are termed triangular points since each of them and the two primary masses form an equilateral triangle. In this paper, the collinear libration point L_1 and L_2 are regarded as target points for captured asteroids.

Periodic orbits around the Sun-Mars libration points

The Sun-Mars CRTBP defined above can now be used to find target the Sun-Mars L_1 and L_2 periodic orbits. In general, there are two types of periodic obits around the collinear libration points: halo orbits and Lyapunov orbits. Such periodic orbits around the Sun-Mars L_1 and L_2 points can be estimated by means of Richardson's third order approximation [37] and then the accurate initial state of the periodic orbit can be computed by utilizing the differential correction method [36],. Then, this process can be repeated by numerical continuation to generate a series of periodic orbits with increasing or decreasing Jacobi constant *C*, as shown in Figure 1.

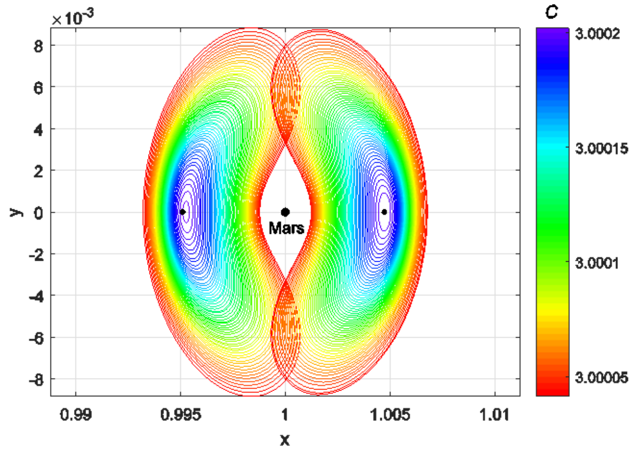
Invariant manifolds

Both halo orbits and Lyapunov orbits are unstable [38]. This means that an object on such a periodic orbit will leave the periodic orbit due to a small perturbation in forward propagation. Invariant manifolds are therefore defined as the set of trajectories that asymptotically depart or approach a periodic orbit. Moreover, invariant manifolds can be classified as stable manifolds and unstable manifolds, corresponding to the stable or unstable eigenvectors of the monodromy matrix evaluated on the periodic orbit. In this paper, stable manifolds are utilized to capture asteroids around the Sun-Mars L_1 and L_2 points. The set of stable manifolds W^S contains all the trajectories of an object that asymptotically wind onto the final periodic orbit. Their initial states $\boldsymbol{X}_S$ can be determined with a given deviation along the direction of the stable eigenvector as follows

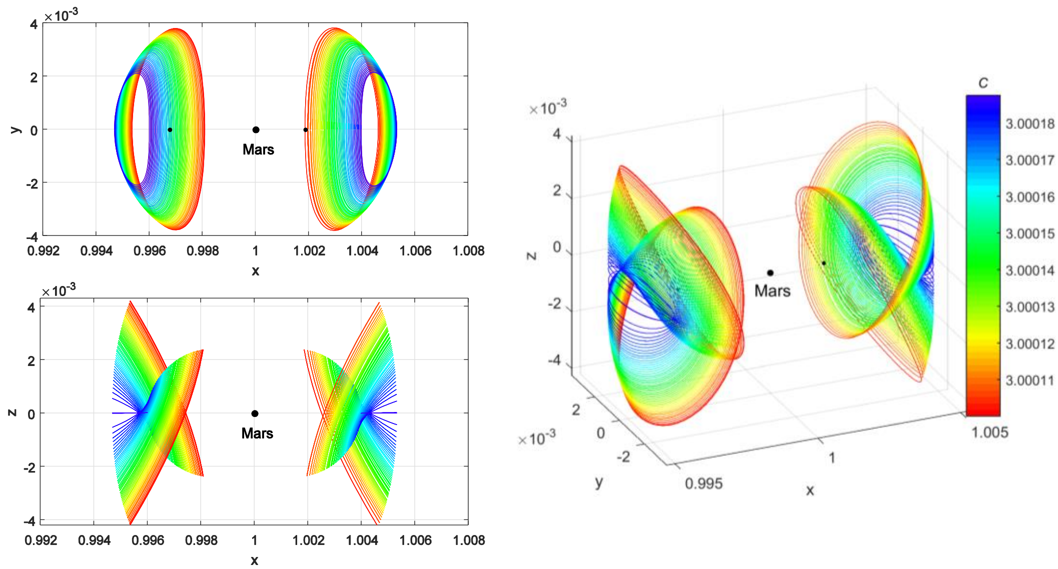
$$\boldsymbol{X}_S = \boldsymbol{X}_0 \pm \varepsilon \boldsymbol{V}_S \tag{4}$$

where $\boldsymbol{X}_0$ is the state of a point on the target periodic orbit and $\boldsymbol{V}_S$ is the stable eigenvector and the parameter ε represents the magnitude of the deviation, along the direction of the stable eigenvector. From Eq. (4), it can be seen that each periodic orbit has two branches of stable manifolds, corresponding to the ± sign. Accordingly, these two branches of stable manifolds are labelled as W^{S+} and W^{S-}. An example of stable manifolds associated with Lyapunov orbits around the Sun-Mars L_1 and L_2 points is shown in Figure 2. It should be noted that the subscript "1" and

“2” represents the L_1 point and L_2 point, respectively. In the following Sections, the branches of the stable manifolds W_1^{S+} and W_2^{S-} will be patched together with a Lambert arc in the asteroid capture strategy using stable manifolds directly. Moreover, the branches of stable manifolds W_1^{S-} and W_2^{S+} will be utilized in the asteroid capture strategies using an Mars flyby with a high attitude (i.e. no aerobraking) and a Mars flyby with aerobraking.



(a)



(b)

Figure 1. (a) Lyapunov orbits with Jacobi constant [3.00004611, 3.00020207] and (b) halo orbits with Jacobi constant [3.00004900, 3.00018750] around L_1 and L_2 points in the Sun-Mars system.

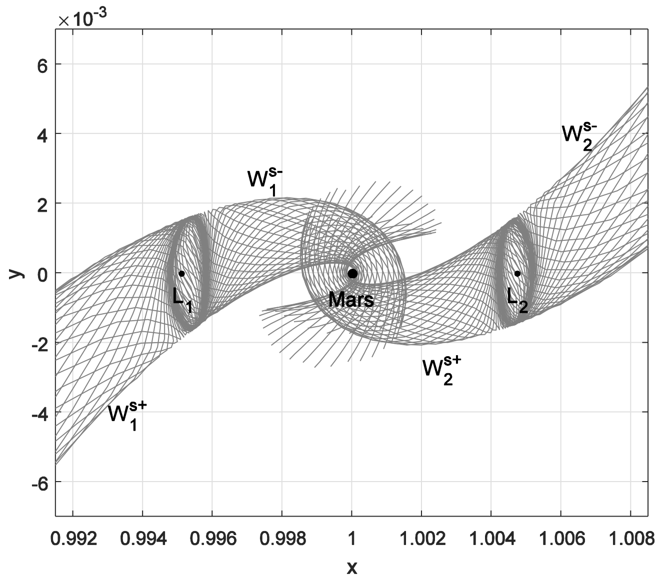


Figure 2 Stable manifolds associated with a Lyapunov orbit around the Sun-Mars L_1 point and a Lyapunov orbit around the Sun-Mars L_2 point.

CANDIDATE ASTEROIDS

The JPL Small Bodies Database* is now used to filter candidate asteroids for capture. The database provides the current catalogue of asteroids, including those whose orbit is close to that of Mars. Assuming that each asteroid is a homogeneous spherical object with diameter D and density ρ_a, the diameter D of the asteroid can be estimated using [39]

$$D = 1329\text{km} \times 10^{-H/5} p_v^{-1/2} \tag{5}$$

where p_v is the albedo of the asteroid and H is its absolute magnitude. Here we assume that the asteroids have properties such that p_v = 0.154 and ρ_a = 2600 kg/m^3 [39].

According to the analysis of prior work on low energy capture of asteroids to the vicinity of the Earth [11, 13], it is necessary to discard those asteroids whose semi-major axis is far from that of Mars, as well as asteroids in highly inclined orbits. Therefore, those asteroids whose orbit is close to that of Mars's are considered as the candidate asteroids. Using the filter noted above, 6 candidate asteroids should be these asteroids with semi-major $a \in$ [1.4, 1.6] and inclination $i \in$ [0., 2 deg], and their parameters are shown in Table 1, while their orbits are shown in Figure 3.

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* https://ssd.jpl.nasa.gov/?sb_elem

Table 1. Parameters of candidate asteroids

Asteroid	Semi-major, AU	Eccentricity	Inclination, deg	Diameter, m
2010OH117	1.5755	0.0787	0.4581	890.8
2013PH10	1.4191	0.1772	1.2164	74.1
2013UT11	1.5236	0.1422	0.2501	154.8
2014HM187	1.5261	0.1897	0.6071	177.7
2014UJ118	1.5832	0.0577	1.7477	371.3
2015CG62	1.4959	0.1884	1.8329	162.1

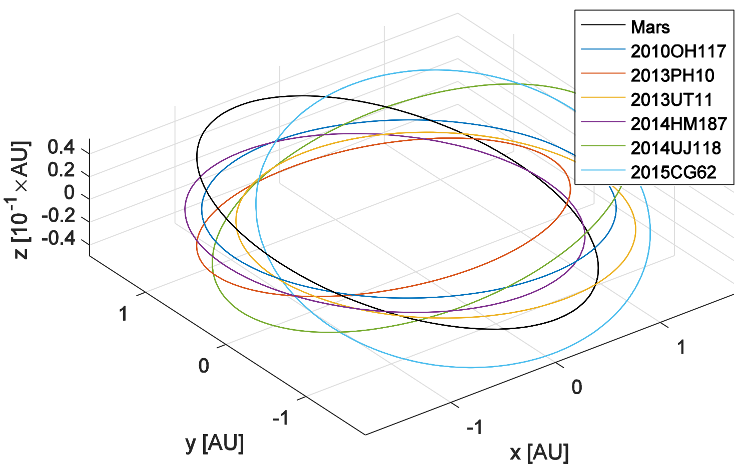

Figure 3 Orbits of Mars and candidate asteroids in Table 1.

DIRECT ASTEROID CAPTURE USING STABLE MANIFOLDS

The utilization of the stable manifolds has been widely applied to the design of transfer trajectories for capturing asteroids onto a target a libration point periodic orbit. This can be achieved by patching together the associated stable manifold and a Lambert arc that connects the asteroid's initial orbit and the stable manifold [11, 13]. In this capture strategy a spacecraft is first launched to rendezvous with a candidate asteroid. Then, with a first maneuver, the candidate asteroid is deflected from its heliocentric orbit and the subsequent transfer is modelled as a Sun-centered two body problem. Then, with a second maneuver, the candidate asteroid is inserted onto a stable manifold of a Sun-Mars L_1 or L_2 periodic orbit and will be captured onto the final target orbit along the stable manifold without any additional maneuvers. The magnitude of the two maneuvers can be calculated by solving a Lambert arc that connects the asteroid's initial orbit and the stable manifold. Therefore, the entire transfer trajectory for capturing the candidate asteroid can be designed by patching together the asteroid's trajectory in the Sun-centered two-body problem and the stable manifold in the Sun-Mars circular restricted three-body problem. A schematic of this asteroid capture strategy is shown in Figure 4.

In this direct capture strategy, 6 variables will define the transfer to capture:

- T_0: epoch when the candidate asteroid is deflected from its initial orbit with a first maneuver, assumed to be in the range [2019, 2050] (58484 MJD -70171 MJD);
- T_{fly1}: flight time between the first propulsive impulse and the second propulsive impulse;
- T_{fly2}: flight time along the stable manifold;
- C: Jacobi constant of the final target Sun-Earth L_1/L_2 periodic orbit;
- t_p: time determining the state on the final periodic orbit from where the stable manifold is propagated backwards.

Then, the entire transfer with these 6 variables will be optimized with a global optimization method: NSGA-II [33], using $\Delta v = \Delta v_1 + \Delta v_2$ as the objective function. The optimized results for capturing candidate asteroids around the Sun-Mars L_1/L_2 points are listed in Table 2. It should be noted that in the Table 1, 1L, 1H 2L, 2H, are short for the planar Lyapunov orbit around L_1, the Halo orbit around L_1, the planar Lyapunov orbit around L_2 and the Halo orbit around L_2, respectively. As will be seen next, the capture costs can be reduced by the used of aerobraking at Mars prior to injection onto the final periodic orbit's stable manifold of the target Lagrange point.

Comparing the results of capturing asteroids in the Sun-Mars system and the results of capturing asteroids in the Sun-Earth system [11, 13], it can be seen that the asteroid capture strategy in the Sun-Earth system can easily achieve low energy transfers for asteroid capture. This is because the candidate asteroids for the Sun-Earth system have a close orbit to the Earth's. Although the asteroids whose orbits are close to the Mars' are selected as candidate asteroids, As for the candidate asteroids for Sun-Mars system in Table 1, their orbits are relatively farther from the Mars' compared with the candidate asteroids in the Sun-Earth system. Accordingly, more energy would be required to move the asteroids from its initial orbits to the vicinity of the Sun-Mars libraiton points.

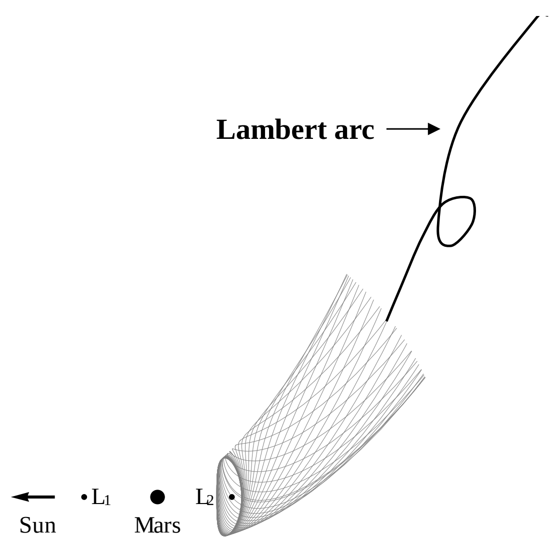

Figure 4 The direct asteroid capture strategy by patching together the stable manifold and Lambert arc.

Table 2 Results of capturing asteroids onto the Sun-Mars L_1/L_2 periodic orbits using stable invariant manifolds directly

Asteroid	Total cost [m/s]	Capture date [MJD]	Flight time [day]	Jacobi constant	Target
2010OH117	725.06	59484.8	2917.2	2.99993616	2L
2010OH117	766.57	61720.9	2163.8	3.00008615	1H
2013PH10	2234.28	65451.8	1916	3.00002001	2L
2013PH10	2256.29	59889.2	3672.6	3.00012998	2H
2014HM187	806.52	61762.3	2892.7	2.99997068	1L
2014HM187	2165.22	58686.6	1964.9	3.00008484	1H
2014UJ118	877.01	58767.6	3428.9	2.99993465	2L
2014UJ118	839.80	59140.6	2170.5	3.00012532	2H
2015CG62	2214.98	69059	2651.9	2.99995948	2L
2015CG62	2240.63	69457.2	3037.5	3.00014911	1H
2016TK95	1911.42	62622.4	2899.9	3.00002517	2L
2016TK95	1867.03	60830.2	2039.2	3.00007447	1H

ASTEROID CAPTURE USING MARS FLYBY

In this section, a Mars flyby is used to design an alternative transfer strategy for capturing asteroids around the Sun-Mars L_1 and L_2 points. According to the periapsis height during the flyby, the strategies of capturing asteroids using a Mars flyby can be considered with and without an aerobraking.

Aerobraking model

If the candidate asteroid swings by Mars at low altitude, the Martian atmosphere may provide an aerobraking maneuver. This aerobraking maneuver can then be used to insert the captured asteroid onto the stable manifold of the Sun-Mars L_1 or L_2 periodic orbits.

During the flyby, the captured asteroid can be assumed to be in a hyperbolic orbit with respect to the Mars. Therefore, the captured asteroid would only remain in the Martin atmosphere for a short duration and then the aerobraking maneuver $\Delta \boldsymbol{v}_a$ can be estimated by [40, 41]

$$\Delta \boldsymbol{v}_a = (1 - e^{B\rho\sqrt{2\pi r_p H_s (e+1)/e}})\boldsymbol{v}_p \tag{6}$$

where $\boldsymbol{v}_p$ is the relative velocity of the asteroid at periapsis with respect to Mars; e is the eccentricity of the flyby orbit; r_p is the periapsis distance of the flyby relative to the center of the Mars; H_s is the atmosphere scale height. Then, the asteroid ballistic coefficient B can be calculated using

$$B = 0.75 C_d \frac{1}{D\rho_a} \tag{7}$$

where the drag coefficient C_d of a sphere is assumed here to be 0.47 [41]; D is the diameter of the asteroid and ρ_a = 2600 kg/m^3 [39].

One challenge in designing aerobraking maneuvers is the uncertainty of the Martian atmosphere model, and therefore a range of models have been developed [42-45]. In this paper, we use a simple exponential atmospheric model for preliminary analysis which can be defined by

$$\rho = \rho_0 e^{-\frac{h}{H_s}} \tag{8}$$

where the density of the Martian atmosphere at the surface is ρ_0 = 0.01474 kg/m^3 and the scale height is H_s = 8.8057 km [45]. The density of the Martian atmosphere as a function of height is shown in Figure 5.

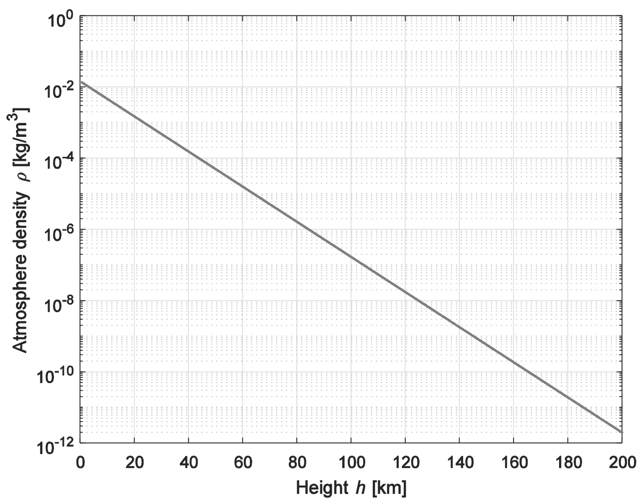

Figure 5 Density of Martian atmosphere as a function of height *h*.

It should be noted that the aerobraking model in Eq. (6) is defined in the Mars-centered inertial frame. Therefore, this model should be transformed into the Sun-Mars rotating frame when designing the transfer trajectory for capturing an asteroid into a target orbit at the Sun-Mars L_1/L_2 libration points. The transformation can be defined as [5]

$$\boldsymbol{X}_{\boldsymbol{p}-} = \mathrm{M}_1^{-1}\mathrm{M}_2(\boldsymbol{X}_{\boldsymbol{p}+} - \boldsymbol{X}_{Mars}) + \boldsymbol{X}_{Mars} \tag{9}$$

where $\boldsymbol{X}_{p-}$ and $\boldsymbol{X}_{p+}$ are the periapsis states before and after aerobraking in the Sun-Mars rotating frame, respectively; $\boldsymbol{X}_{Mars} = [1-\mu, 0, 0, 0, 0, 0]^T$ is the state of Mars in the Sun-Mars rotating frame; M_1 and M_2 are transformation matrices which can be found in Reference [5].

According to the aerobraking model in Eq. (6), the aerobraking maneuver for the candidate asteroids in Table 1 can be estimated with a given relative velocity $\boldsymbol{v}_p$. Thus, Figure 6 illustrates two examples of aerobraking maneuvers provided by the Martian atmosphere with different periapsis heights *h*. As shown in Figure 6, it can be found that once the height *h* at periapsis above Mars' surface is large than 60 km, the aerobraking maneuver provided by the Martian atmosphere can be neglected. Therefore, $h_{threshold}$ = 60 km is defined here as the height threshold of aerobaking. That is, $r_{threshold} = r_{Mars}$ + 60 km = 3456 km is the distance threshold of aerobaking to the center of the Mars, where r_{Mars} = 3396 km is the radius of Mars.

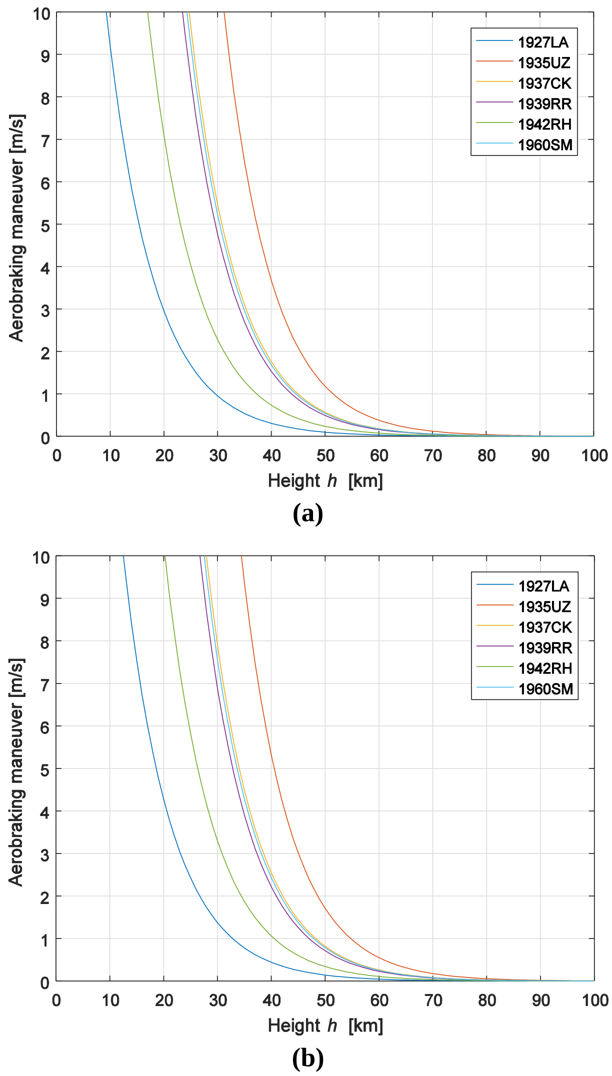

Figure 6 Aerobraking maneuver generated from the Martian atmosphere grazing with different periapsis heights *h*, (a) v_p = 15 km/s and (b) v_p = 22 km/s.

Asteroid capture with a Mars flyby without aerobraking

To reduce the total cost of capturing asteroids onto Lyapunov orbits in the Sun-Earth system, the Mars flyby was utilized to capture asteroids with low energy. Results show that the Earth flyby can enable some asteroids to be captured with a relatively lower cost [5]. Therefore, the flyby method will be extended to capture asteroids in the Sun-Mars system. In this capture strategy, the candidate asteroid is moved from its orbit with an initial maneuver $\Delta\boldsymbol{v}_1$, and then the subsequent transfer trajectory is designed in the Sun-Mars CRTBP. With a second maneuver $\Delta\boldsymbol{v}_2$, the asteroid moves in a close distance to the Mars and then it arrives at periapsis with height h > 60 km, shown in Figure 7. Finally, a third maneuver $\Delta\boldsymbol{v}_3$ which is parallel to the asteroid's velocity vector is applied to the asteroid at the periapsis and then the asteroid inserts onto the stable manifold associated with a the Sun-Mars L_1 or L_2 periodic orbit and will then be asymptotically captured.

Therefore, for each candidate asteroid, 6 variables will again define the asteroid capture using a Mars flyby without aerobraking:

- T_0 : epoch when candidate asteroid leaves its initial orbit with the first maneuver;
- T_{fly1}: flight time between the first propulsive impulse and the second propulsive impulsive;
- T_{fly2}: flight time between the second propulsive impulse and the third propulsive impulse;
- C: Jacobi constant of the final target periodic orbit;
- t_p time determining the state on the periodic orbit from where the stable manifold is propagated backwards;
- Δv_3: third maneuver that is parallel to the velocity vector of the asteroid at the periapsis.

The transfer in this capture strategy can again be designed by solve the differential shooting problem, using the Lambert arc as an approximation [5]. Thus, the first two maneuvers $\Delta\boldsymbol{v}_1$ and $\Delta\boldsymbol{v}_2$ can be determined. Then transfers for capturing asteroids can be optimized by minimizing the total cost $\Delta v = \Delta v_1 + \Delta v_2 + \Delta v_3$ which is determined by these 6 parameters (T_0, T_{fly1}, T_{fly2}, C, t_p, Δv_3) using NSGA-II [33]. The optimal results of asteroid capture using the Mars flyby without aerobraking are shown in Table 3.

Comparing the results in the Table 2 and Table 3, it can be seen that the asteroid capture strategy using a Mars flyby has the potential to be cheaper than the direct asteroid capture strategy using the stable manifold, especially for 2010OH117 and 2014UJ118. Moreover, since the asteroid capture using the Mars flyby does need not much time for the captured asteroid to move along the stable manifold in the Sun-Mars system, this capture strategy also has the potential to achieve relative faster transfers, e.g. 2010OH117, 2014UJ118 and 2016TK95. Furthermore, the minimum total cost for the asteroid capture strategy using a Mars flyby without aerobraking is under 400 m/s, corresponding the transfer for capturing 2014UJ118 into a halo orbit around the Sun-Mars L_1 point.

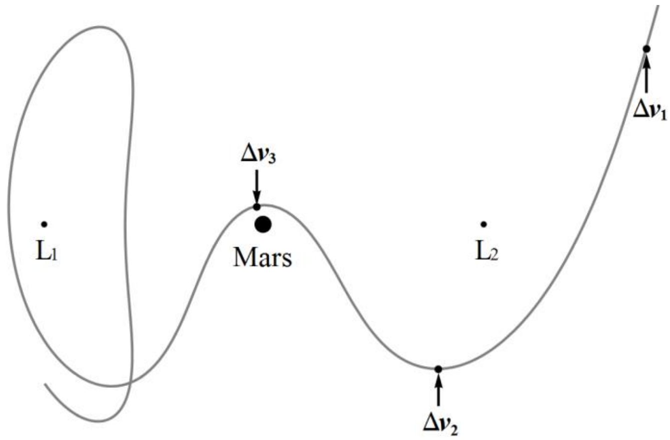

Figure 7 Schematic of asteroid capture using a Mars flyby without aerobraking

Table 3 Results of capturing asteroids onto the Sun-Mars L_1/L_2 periodic orbits using a Mars flyby without aerobraking

Asteroid	Total cost [m/s]	Capture date [MJD]	Flight time [day]	Jacobi constant	Target
2010OH117	520.740	58563.3	3111.20	2.99994895	2L
2010OH117	482.820	59125	1611	3.00017890	1H
2013PH10	1472.23	62038.3	1861.30	3.00015627	2L
2013PH10	1544.83	62028.8	2601.80	3.00017725	2H
2014HM187	1728.45	59217.2	1758.50	2.99997595	1L
2014HM187	1526.36	69668	1883.90	3.00017717	2H
2014UJ118	839.170	58721.8	2458.70	3.00000416	1L
2014UJ118	310.88	59210.6	1413.4	3.00017028	1H
2015CG62	1617.19	64427.8	1847.10	3.00015651	2L
2015CG62	1340.10	64412.9	1877.30	3.00017664	2H
2016TK95	1454.07	60426.7	2756.20	2.99998114	1L
2016TK95	1231.90	58849.7	1493.20	3.00018147	1H

Asteroid capture using aerobarking

In Reference [5], an Earth flyby with aerobraking was utilized to design low energy capture of asteroids into the Lyapunov orbits around the Sun-Earth L_1 and L_2 points. Accordingly, the Earth aerobraking was proposed to directly capture asteroids into bound orbits around the Earth [27]. In this paper, the aerobraking method will be used to design the low energy capture of asteroids onto periodic orbits around the Sun-Mars libration points. Different from the asteroid capture strategy using the Earth aerobraking, Martian atmosphere is much thinner than the Earth's and thus the Martian atmosphere may be not able to provide a required aerobraking maneuver to insert the candidate asteroid onto the target periodic orbit's stable manifold. Therefore, it is assumed an additional impulse $\Delta\boldsymbol{v}_3$ will be imposed on the asteroid immediately after aerobraking to insert the asteroid onto the stable manifold. Similar to the asteroid capture strategy using the Mars flyby with a high attitude (without aerobraking, h > 60 km), the candidate leaves its orbit and then approaches the vicinity of Mars with two maneuvers $\Delta\boldsymbol{v}_1$ and $\Delta\boldsymbol{v}_2$. The key difference is that the perigee height of the Mars flyby is lower than 60 km and thus an aerobraking maneuver is imposed on the asteroid, followed by the third impulse $\Delta\boldsymbol{v}_3$. Accordingly, with an aerobraking maneuver that is imposed on the candidate asteroid, the asteroid inserts onto the stable manifold and then will be asymptotically captured onto the final target orbit around Sun-Mars L_1 or L_2 point, shown in Figure 8.

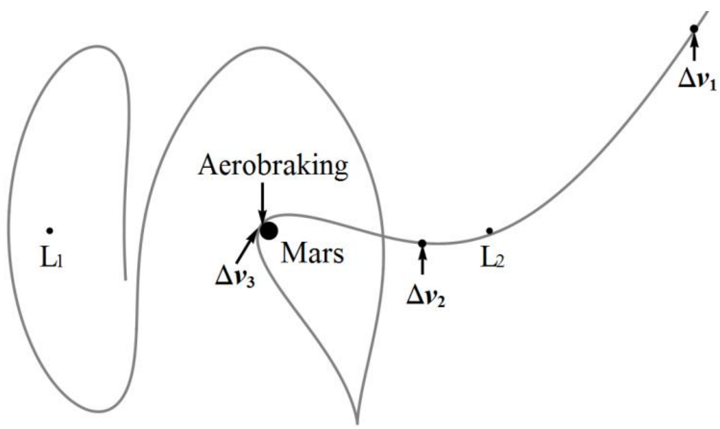

Figure 8 Schematic diagram of asteroid capture using Mars aerobraking

Therefore, for each candidate asteroid, there are now 6 parameters to determine the entire transfer for this asteroid capture strategy as follows:

- T_0 : epoch when candidate asteroid leaves its initial orbit with the first propulsive impulse;
- T_{fly1}: flight time between the first propulsive impulse and the second propulsive impulse;
- T_{fly2}: flight time between the second propulsive impulse and the third propulsive impulse;
- C: Jacobi constant of the final target periodic orbit;

- t_p: time determining the state on the periodic orbit from where the stable manifold is propagated backwards.
- Δv_3: third propulsive impulse that is parallel to the velocity vector of the asteroid at the periapsis after aerobraking.

Table 4 Results of capturing asteroids onto the Sun-Mars L_1/L_2 periodic orbits using a Mars flyby with aerobraking

Asteroid	Total cost [m/s]	Capture date [MJD]	Flight time [day]	Jacobi constant	Target
2010OH117	534.65	59185	1788.8	3.00002601	1L
2010OH117	376.73	59156	1599.6	3.0001762	1H
2013PH10	1899.08	65524.1	2391.2	3.00002539	1L
2013PH10	1669.3	65022.6	3380.5	3.00017333	1H
2014HM187	1629.8	58983.7	2345.1	3.00002129	1L
2014HM187	1676.91	66281.1	1166.1	3.00017688	2H
2014UJ118	788.10	69692.3	3561.9	3.00002532	1L
2014UJ118	227.34	58484.2	2153	3.00016966	1H
2015CG62	1616.41	59436.5	3336.1	3.00003868	1L
2015CG62	1470.03	58744.8	3084.9	3.00017494	1H
2016TK95	1603.65	59054.7	2921.5	3.0000250	1L
2016TK95	1137.65	59069	1984	3.00017746	1H

It should be noted that the two maneuvers $\Delta \boldsymbol{v}_1$ and $\Delta \boldsymbol{v}_2$ can again be determined by using the differential correction method in the Sun-Mars CRTBP [5]. Then transfers for capturing asteroids can be again optimized by minimizing the total cost $\Delta v = \Delta v_1 + \Delta v_2 + \Delta v_3$ which is determined by these 6 parameters (T_0, T_{fly1}, T_{fly2}, C, t_p, Δv_3) using NSGA-II [33]. The optimal results of asteroid capture using Mars aerobraking are shown in Table 4.

Form Table 4, it can be seen that the cheapest capture has a cost of 227 m/s, corresponding to a capture of 2014UJ118 onto a halo orbit around the Sun-Mars L_1 point. Comparing the results in the Table 2 and Table 4, it can be seen that Mars aerobraking has a potential to reduce energy requirements and so this capture strategy can achieve a relatively cheaper transfer for asteroid capture than the direct asteroid capture using stable manifold, especially 2010OH117 and 2014HM187. Moreover, the asteroid capture strategy using aerobraking also has the potential to save flight times, as with the asteroid capture strategy using a Mars flyby with a high attitude (without aerobraking). In addition, comparing the results of Table 3 and Table 4, it can found that Mars atmosphere can provide an aerobraking maneuver which can enable the asteroid to be captured with a relatively lower cost than the asteroid capture strategy using Mars flyby without aerobraking, e.g. 2014UJ118 and 2016TK95.

CONCLUSION

Since asteroids can provide useful resources for spacecraft propellant, life support and metals, capturing asteroids onto the Sun-Mars L_1 or L_2 periodic orbits may be of significant benefit to future Mars missions by supplying staging posts for crewed missions. Therefore, three asteroid capture strategies have been studied in this paper. The candidate asteroid is first assumed to be deflected from its orbit with a propulsive impulse. In the first strategy, a second maneuver would be required to insert the asteroid onto the stable manifold associated with Sun-Mars L_1 or L_2 periodic orbits, and thus the entire transfer can be designed by patching together the stable manifold and a Lambert arc. In the asteroid capture using a Mars flyby, after the first maneuver, the asteroid would then approach the vicinity of the Mars. During the flyby of the Mars, an aerobraking maneuver may be generated by grazing the Martian atmosphere. Meanwhile, a propulsive maneuver is required at the periapsis of the flyby. After the flyby of Mars, the candidate asteroid inserts onto the stable manifold and will be captured onto the final target orbit around the Sun-Mars L_1 or L_2 point along the stable manifold.

Comparing the results of three methods, it can be seen that asteroid capture using a Mars flyby with a high attitude and the asteroid capture with aerobraking both have the potential to save the total cost in terms of the velocity increment cost than the direct capture strategy using stable manifold. Moreover, since significant time is no longer required to move along the stable manifold of the Sun–Mars L_1/L_2 periodic orbits, asteroid capture strategies using a Mars flyby also have the potential to achieve quicker transfers. Finally, it has been found that the cheapest capture has a cost of 227 m/s, corresponding to a capture of 2014UJ118 onto a halo orbit around the Sun-Mars L_1 point in the asteroid capture strategy using Mars aerobraking.

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