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Research paper

A multiple-vehicle strategy for near-Earth asteroid capture

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ABSTRACT

The use of asteroid resources could benefit future space missions. Instead of lifting the necessary materials off the Earth, they can be then sourced directly in space. Asteroid capture missions aim to bring asteroids closer to Earth, where they can be permanently accessed. This paper introduces a new strategy for asteroid capture missions, where two spacecraft are used for capturing near-Earth asteroids. These spacecraft act together as a 'pitcher' spacecraft and 'catcher' spacecraft, where the pitcher spacecraft hops from asteroid to asteroid and deflects them towards an orbit in the vicinity of Earth, while the catcher spacecraft is stationed at the Earth and captures the incoming asteroids. This novel two-spacecraft strategy is compared to a conventional one-spacecraft strategy using three analyses; a preliminary analysis using coplanar and circular orbits to define the problem, a statistical analysis using fictional near-Earth asteroids to obtain a large set of data, and an analysis where real near-Earth asteroids are used as mission targets. A mass model is developed to compute the retrieved asteroid mass per unit of initial wet spacecraft mass for missions aiming to retrieve multiple asteroids. Results show that the two-spacecraft strategy is capable of returning more asteroid mass and often at a shorter mission duration.

1. Introduction

With an increasing interest in the exploration and potentially colonisation of space, the obstacles on the way to achieving this have become more apparent. To build an infrastructure in space, a considerable amount of materials is required. Instead of having to lift these off the Earth, which is currently the only option, attention has been directed to sourcing the materials directly from space. In-space resource utilisation has been a subject of interest in multiple studies, and asteroids are often cited as a promising source of useful materials. They contain valuable materials such as water, other volatiles, and metals, which could be used for life support, propellant or in-space manufacturing [1]. By sourcing these materials directly from space, the cost of deep space or crewed missions could in principle be greatly reduced [2]. Moreover, some asteroids contain materials that could be useful on Earth, such as platinum group metals, but also selenium and gallium. These materials could be vital for renewable energy technologies [3].

Asteroid capture missions aim to bring useful asteroids closer to Earth, such that they can be permanently accessed by future space missions. Near-Earth asteroids (NEAs) are of particular interest because these are easily reached from Earth and would therefore be ideal candidates for capture. Near-Earth objects (NEOs), of which the majority are NEAs [4], are defined as having a perihelion distance less than 1.3 AU and an aphelion distance more than 0.983 AU [5]. Making the asteroids better accessible from Earth would also facilitate missions with a scientific interest, as asteroids are known to hold crucial information about the formation of the Solar System [6]. Mission concepts where captured asteroids are used as a protection mechanism for asteroid impact hazards have also been studied [7,8].

Numerous studies have investigated strategies for asteroid capture missions. Baoyin et al. [9] studied the capture of near-Earth objects when they closely approach the Earth. Two asteroids were found that could be captured with a maximum ΔV of 1 km/s. Urrutxua et al. [10] explored how naturally occurring temporarily captured asteroids could be nudged in order to extend their period in orbit around the Earth, and found that a ΔV of only 32 m/s would have been required to extend the capture of asteroid 2006 RH120 by five years. Bao et al. [11] studied asteroid capture using gravity assists around the Earth and Moon, which reduced the total ΔV requirement of the mission. Hasnain et al. [1] examined the capture of asteroids with low inclination and eccentricity in the Earth's sphere of influence. Fourteen suitable asteroids were found for a maximum mission duration of 10 years. Llado et al. [12] computed for 39 selected NEAs the required ΔV for a low-thrust transfer targeted at the Sun–Earth Lagrangian point, which happened to be lower than 4 km/s for 70% of the cases. Landau et al. [13] showed that the deflection of an asteroid of 10^6 kg with low-thrust propulsion is possible using existing technology. He et al. [14] optimised the low-thrust trajectories in the Sun–Earth–Moon system.

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Nomenclature

ΔV	Change in velocity
μ	Gravitational parameter
Ω	Longitude of the ascending node
ω	Argument of pericenter
ρ	Ratio of orbital radii
a	Semi-major axis
e	Eccentricity
f_{dry}	Dry mass fraction
i	Inclination
I_{sp}	Specific impulse
k	Mass fraction for the two-spacecraft strategy
M	Mean anomaly
M_0	Initial wet mass
M_a/M_0	Ratio of retrieved mass per asteroid to initial wet mass
M_a	Mass retrieved from one asteroid
m_n	Ratio of total retrieved asteroid mass to initial wet mass
n	Number of asteroids
r	Orbital radius
r_E	Radius of Earth's orbit
r_{ast}	Radius of asteroid orbit
$t_{mission}$	Mission duration
t_{start}	Start date of optimisation
t_{step}	Time step
$t_{wait,max}$	Maximum wait time
t_{wait}	Wait time before transfer
TOF	Time of flight
V_e	Exhaust velocity

Subscripts

$1sc$	One-spacecraft strategy
$2sc$	Two-spacecraft strategy
$ast1$	Asteroid 1
$ast2$	Asteroid 2
$ast3$	Asteroid 3
ast	Asteroid
C	Catcher spacecraft
c	Circular
E	Earth
it	Initial transfer
max	Maximum
min	Minimum
P	Pitcher spacecraft

Sanchez and McInnes [15] argue that the same spacecraft that can capture an asteroid, can also be used for deflecting potential hazardous asteroids. Liu et al. [16] studied a mission scenario where a binary asteroid pair experiences a close encounter with a planetary body, which then captures the smaller asteroid of the pair. Xie et al. [17] made an inventory of feasible capture missions for a large number of near-Earth asteroids, and indicated which of the targets were most suitable for the mining of water, PGMs or siliceous minerals. Multiple studies considered flyby manoeuvres as a means of lowering the required energy for capture [11,13,18,19]. Garcia Yarnoz et al. [6] made an inventory of near-Earth objects that can be retrieved using a ΔV of less than 500 m/s by making use of invariant manifolds, the so-called easily retrievable objects (EROs). These have been subject to further trajectory analyses and the list of EROs has been extended in the meantime [20–22].

While a considerable number of near-Earth asteroids have been identified and catalogued, it is believed that a large number have not been discovered yet [4,6]. Being relatively small in size compared to other celestial bodies, they are difficult to spot from Earth. However, several models have been developed in order to estimate the total amount of NEAs [23].

No asteroid capture missions have been realised thus far, however NASA recently launched its DART mission, which is the first space mission aiming to change an asteroid's orbit [24]. After the DART mission is completed, ESA's Hera mission will follow up to further investigate the impact of the spacecraft [25].

This paper introduces a new approach to capture asteroids. Instead of using a single spacecraft that transfers to the asteroid and then brings the asteroid, or material from the asteroid, back to Earth's vicinity, two spacecraft act together as a 'pitcher' and a 'catcher'. The pitcher hops from asteroid to asteroid to deflect them towards an orbit in the vicinity of Earth, where the catcher is stationed to capture them upon arrival. In this way, the spacecraft does not need to make round trips to retrieve the asteroids, but instead the pitcher spacecraft transfers directly to the next asteroid.

The aim of this paper is to investigate the benefit of an asteroid capture mission using the two-spacecraft strategy in comparison to the one-spacecraft strategy. The following assumptions are being used. All the asteroid capture missions target NEAs. Also, impulsive manoeuvres are assumed and Kepler orbits in the two-body heliocentric problem are used. A capture mission can retrieve one or more asteroids or material from asteroids. It is assumed that an equal amount of mass is retrieved from each asteroid that is visited during a mission. The type of material that is returned from the asteroids is not considered.

Three analyses are made with regard to the comparison of these strategies. A preliminary analysis considering Hohmann transfers is used to see whether the new strategy has any advantage in terms of ΔV or retrieved mass (Section 2). Then, a statistical analysis using simulated NEAs is performed to further investigate the strategies using a more detailed mission scenario (Section 3). Lastly, the mission scenario is made more realistic using real NEAs and incorporating the mission duration (Section 4). The conclusions are discussed in Section 5.

2. Preliminary analysis

In this section, a preliminary analysis is made to compare the two-spacecraft and one-spacecraft strategy. Two mission performance parameters are considered: the total velocity change ΔV and the normalised retrieved mass m_n, where a low ΔV and a large retrieved mass are desired.

First, the assumptions made for the preliminary analysis and the mission schematics are discussed. Then, the ΔV and mass retrieved analyses are presented and their implications are described.

2.1. Mission schematics

As a preliminary investigation of the two-spacecraft strategy, the asteroid's and Earth's orbits are assumed to be circular and coplanar. The phasing of the asteroids and Earth is neglected at this stage. The orbital transfers have been modelled using Hohmann transfers.

The schematic trajectories for the one-spacecraft and two-spacecraft strategies are shown in Fig. 1, where r_{ast} is the radius of the asteroid orbit and r_E is the radius of Earth's orbit. A capture mission sets out to capture n asteroids. For the preliminary analysis, all asteroids are assumed to be in the same orbit with radius r_{ast}.

For the one-spacecraft strategy, the spacecraft starts at the Earth, then transfers to the asteroid orbit where it will rendezvous with the asteroid. It then deflects part of or the entire asteroid onto a

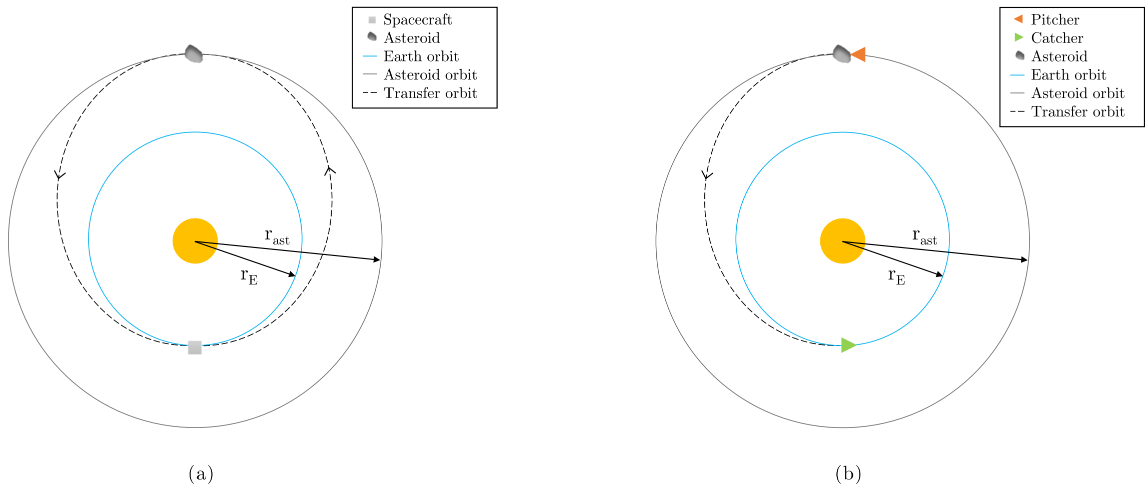

Fig. 1. Schematic trajectories of the one-spacecraft strategy (a) and two-spacecraft strategy (b).

transfer orbit towards the Earth. At the rendezvous with the Earth, the spacecraft applies an impulse such that it matches Earth's heliocentric orbit. The capture of the asteroid in an orbit around the Earth is not considered.

For the two-spacecraft strategy, the pitcher spacecraft first needs to transfer from the Earth to the asteroid (not shown in Fig. 1). This is referred to as the initial transfer for the two-spacecraft strategy. After this, the pitcher spacecraft deflects a part of or the entire asteroid on a trajectory towards the Earth. The pitcher spacecraft itself remains in the asteroid's orbit. Then, the catcher spacecraft, which is stationed at the Earth, captures the asteroid in Earth's heliocentric orbit.

Since the angular positions of the Earth and asteroids are not considered, capturing multiple asteroids means that the above mentioned manoeuvres will be simply performed multiple times (except for the initial transfer of the two-spacecraft strategy). The mission duration is not taken into consideration at this stage.

2.2. ΔV Analysis

In this section, the required ΔV for both the one-spacecraft and two-spacecraft strategies is analysed. In this analysis, the ΔVs required for the capture of one asteroid are considered for a mission where n asteroids are captured in total. This means that the effect of the initial transfer of the pitcher is not taken into account for the two-spacecraft strategy. Since this transfer only occurs once, it will be included at the end of the analysis.

2.2.1. Mission scenario 1

The first mission scenario is based on the schematics shown in Fig. 1. In this scenario, all asteroids are on the same orbit. The specific ΔV manoeuvres for the capture of one asteroid for each strategy are depicted in Fig. 2. For the one-spacecraft strategy, the ΔVs required for the outbound and inbound legs are equal but in opposite direction ($2\Delta V_1 + 2\Delta V_2$).

For the two-spacecraft strategy, the pitcher deflects the asteroid using ΔV_2, after which it has to stay in the same orbit, such that an equal but opposite ΔV is required. The same is true for the catcher: it first needs to accelerate to catch up with the asteroid, and then decelerate through the same ΔV in the opposite direction to bring the asteroid to the Earth's orbit.

Note that since the departure and target orbits are the same in both strategies, and Hohmann transfers are assumed, these ΔVs will be equal. So, for each asteroid capture, the total required ΔV is the same for both the two-spacecraft and one-spacecraft strategy. By also considering the initial transfer necessary for the two-spacecraft strategy, it can be concluded that, in terms of ΔV, the one-spacecraft strategy is advantageous over the two-spacecraft strategy for this mission scenario.

2.2.2. Mission scenario 2

In this scenario, asteroids are on circular, coplanar orbits with different radii, hence the pitcher transfers to an asteroid that is positioned in a different orbit after having deflected the asteroid that it is currently positioned at. This second mission scenario is investigated for all possible positions of the next asteroid orbit.

For example, the next asteroid could be positioned in a lower orbit. This mission geometry is shown in Fig. 3, where r_{ast1} and r_{ast2} are the radii of the first and second asteroid orbit, respectively.

In this case, the pitcher will require two ΔVs for the transfer to the next asteroid (ΔV_3 and ΔV_4), instead of the initial ΔV_2 required to remain in the same orbit. For the total required ΔV of the two-spacecraft strategy to be less than that of the one-spacecraft strategy, the following inequality needs to hold:

$$\Delta V_3 + \Delta V_4 < \Delta V_2 \tag{1}$$

Considering Hohmann transfers and by inspecting Fig. 3, the ΔVs in Eq. (1) can be obtained as follows:

$$\Delta V_2 = \sqrt{\frac{\mu}{r_{ast1}}} - \sqrt{\frac{\mu}{r_{ast1}}}\sqrt{\frac{2r_E}{r_E + r_{ast1}}} \tag{2}$$

$$\Delta V_3 = \sqrt{\frac{\mu}{r_{ast1}}}\sqrt{\frac{2r_{ast2}}{r_{ast2} + r_{ast1}}} - \sqrt{\frac{\mu}{r_{ast1}}}\sqrt{\frac{2r_E}{r_E + r_{ast1}}} \tag{3}$$

$$\Delta V_4 = \sqrt{\frac{\mu}{r_{ast2}}}\sqrt{\frac{2r_{ast1}}{r_{ast2} + r_{ast1}}} - \sqrt{\frac{\mu}{r_{ast2}}} \tag{4}$$

Then, substituting Eqs. (2) to (4) in Eq. (1), the following inequality is obtained:

$$V_{c,a}\left[\sqrt{\frac{2\rho}{1+\rho}} - \sqrt{\frac{2\rho_E}{1+\rho_E}}\right] + V_{c,a}\sqrt{\frac{1}{\rho}}\left[\sqrt{\frac{2}{1+\rho}} - 1\right] < V_{c,a}\left[1 - \sqrt{\frac{2\rho_E}{1+\rho_E}}\right] \tag{5}$$

with

$$V_{c,a} = \sqrt{\frac{\mu}{r_{ast1}}} \tag{6}$$

$$\rho = \frac{r_{ast2}}{r_{ast1}} \tag{7}$$

$$\rho_E = \frac{r_E}{r_{ast1}} \tag{8}$$

Simplifying Eq. (5) results in:

$$\sqrt{2(\rho+1)} - \sqrt{\rho} < 1 \tag{9}$$

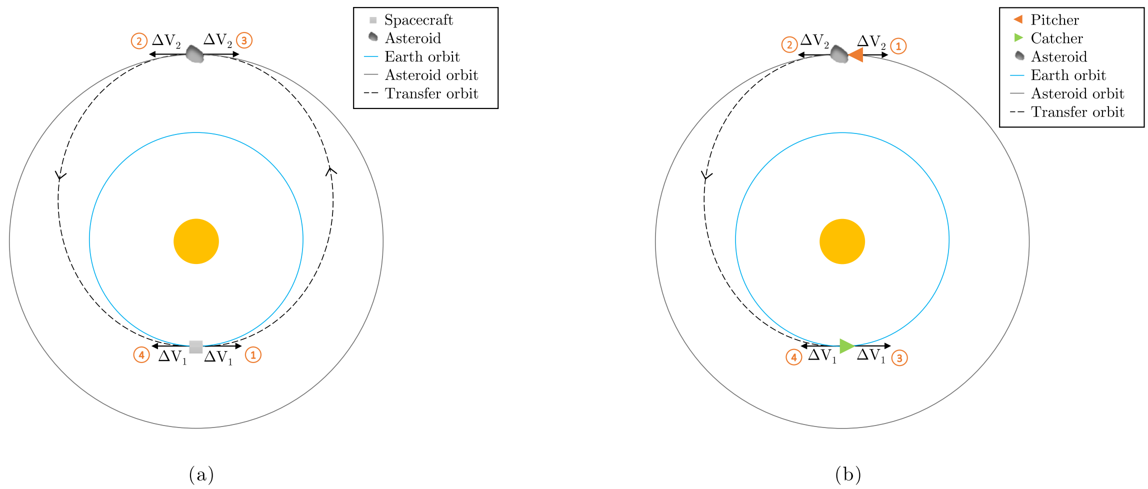

Fig. 2. Required ΔVs of the one-spacecraft strategy (a) and two-spacecraft strategy (b) for the capture of one asteroid. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

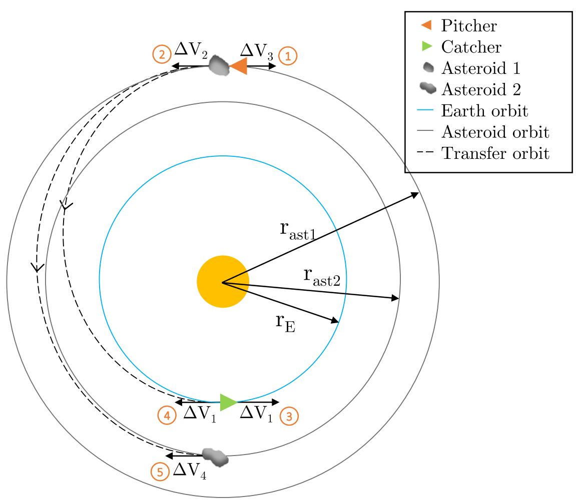

Fig. 3. Required ΔVs for the two-spacecraft strategy if the pitcher transfers to a lower asteroid orbit.

It was assumed that asteroid 2 is in a lower orbit than asteroid 1, thus $r_E < r_{ast2} < r_{ast1}$. This means that $\rho < 1$, thus Eq. (9) is not satisfied. Thus, the two-spacecraft strategy also does not have an advantage over the one-spacecraft strategy regarding the required ΔV in this case.

Five other mission geometries can be distinguished, depending on the relative positions of the orbits of the Earth, asteroid 1 and asteroid 2. These are shown in Table 1, with the mission geometry discussed above in the first row. In this paper, the semi-major axes of the asteroids are assumed to be between 0.8 AU and 1.3 AU. Therefore, $0.62 < \rho < 1.63$ and $0.77 < \rho_E < 1.25$. In addition to these numerical boundaries, ρ and ρ_E are also bounded by the mission geometry as shown in third column of Table 1.

The inequality is only satisfied for the mission geometry where $r_{ast1} < r_{ast2} < r_E$, thus when the pitcher spacecraft starts in an orbit lower than Earth's orbit, and transfers to a higher asteroid orbit, but one that is still lower than the Earth's orbit. However, the initial transfer of the pitcher for the two-spacecraft strategy has not been taken into account for the above analysis. If, for example, the first asteroid is positioned in an orbit at 0.8 AU, the initial ΔV to transfer to this orbit would be 3.5 km/s. If the second asteroid would be positioned at 0.99 AU, such that the advantage in ΔV is maximised, this would result in an advantage of 89.5 m/s with respect to the one-spacecraft strategy, which is lower than the required ΔV for the initial transfer. If the pitcher did not transfer directly, but would gradually transfer to orbits that are 0.01 AU apart, the total advantage from 0.8 AU to 0.99 AU would be just 4.7 m/s.

2.2.3. Discussion

Two mission scenarios were investigated with respect to the required ΔV. This resulted in either an equivalent or higher value for the two-spacecraft strategy. Thus, it can be concluded that with regard to required ΔV, the two-spacecraft strategy has no advantage with respect to the one-spacecraft strategy.

2.3. Retrieved mass analysis

The analysis showed that the two-spacecraft strategy does not impact the required ΔV in a beneficial manner. However, the aim of an asteroid capture mission is to retrieve useful mass to the vicinity of the Earth. Thus, an additional analysis is made to compare the retrieved mass for each of the strategies. Contrary to the ΔV analysis, the initial transfer of the pitcher from the Earth to the asteroid is taken into account for this analysis. First, a mass model is derived for computing the retrieved mass. Then, the results are shown and the two strategies are compared.

2.3.1. Mass model

In this section, a mass model has been made to compute the retrieved asteroid mass. It is assumed that all asteroids are in the same orbit and that each time the same amount of asteroid mass is returned. Also, all spacecraft are assumed to have the same exhaust velocity. The model is then derived by using the rocket equation consecutively for each manoeuvre, where the final mass after a manoeuvre is the initial mass for the next manoeuvre. This procedure is described separately for the one-spacecraft and two-spacecraft strategy.

One-spacecraft strategy In Fig. 2(a), the four manoeuvres to capture one asteroid with the one-spacecraft strategy are shown, indicated with the circular, orange labels. First, the spacecraft transfers to the asteroid (manoeuvre 1 and 2), then the asteroid is deflected and captured in Earth's orbit. The mass of the spacecraft after each manoeuvre can be computed using Tsiolkovksy's rocket equation. This is shown in Eq. (10), where $M_{1sc,i}$ is the mass of the single spacecraft after manoeuvre i, M_0 is the initial mass of the spacecraft, M_a is the mass that is retrieved each time from the asteroid, ΔV is the change in velocity caused by the manoeuvre, and V_e is the exhaust velocity. For the first two manoeuvres, only the mass of the spacecraft is relevant. At manoeuvre 3 and 4, the mass of the retrieved material M_a also needs

Table 1
The six mission geometries and their inequalities and boundaries such that the two-spacecraft strategy requires less ΔV than the one-spacecraft strategy, and whether these are satisfied.

Mission geometry	Inequality	Boundaries	Satisfied?
$r_E < r_{ast2} < r_{ast1}$	$\sqrt{2(\rho+1)} - \sqrt{\rho} < 1$	$\rho < 1$	No
$r_{ast1} < r_{ast2} < r_E$	$\sqrt{2(\rho+1)} - \sqrt{\rho} > 1$	$\rho > 1$	Yes
$r_E < r_{ast1} < r_{ast2}$	$\sqrt{\rho} - \sqrt{2}(\rho-1)\sqrt{\frac{1}{\rho+1}} > 1$	$\rho > 1$	No
$r_{ast2} < r_{ast1} < r_E$	$\sqrt{\rho} - \sqrt{2}(\rho-1)\sqrt{\frac{1}{\rho+1}} < 1$	$\rho < 1$	No
$r_{ast2} < r_E < r_{ast1}$	$2\sqrt{2}\sqrt{\frac{\rho_E}{\rho_E+1}} < 1 + \sqrt{\frac{1}{\rho}} - (1-\rho)\sqrt{\frac{1}{\rho}}\sqrt{\frac{2}{\rho+1}}$	$\rho < \rho_E < 1$	No
$r_{ast1} < r_E < r_{ast2}$	$2\sqrt{2}\sqrt{\frac{\rho_E}{\rho_E+1}} > 1 + \sqrt{\frac{1}{\rho}} - (1-\rho)\sqrt{\frac{1}{\rho}}\sqrt{\frac{2}{1+\rho}}$	$1 < \rho_E < \rho$	No

to be taken into account, since the propulsion system will have to apply an impulse to both the spacecraft and the asteroid. Therefore, it can be seen that:

$$M_{1sc,1} = \frac{M_0}{e^{\Delta V_1/V_e}} = M_0 e^{-\Delta V_1/V_e} \tag{10a}$$

$$M_{1sc,2} = \frac{M_{1sc,1}}{e^{\Delta V_2/V_e}} = M_0 e^{-(\Delta V_1+\Delta V_2)/V_e} \tag{10b}$$

$$M_{1sc,3} = \frac{M_{1sc,2}+M_a}{e^{\Delta V_2/V_e}} - M_a = M_0 e^{-(\Delta V_1+2\Delta V_2)/V_e} + M_a e^{-\Delta V_2/V_e} - M_a \tag{10c}$$

$$M_{1sc,4} = \frac{M_{1sc,3}+M_a}{e^{\Delta V_1/V_e}} - M_a = M_0 e^{-(2\Delta V_1+2\Delta V_2)/V_e} + M_a e^{-(\Delta V_1+\Delta V_2)/V_e} - M_a \tag{10d}$$

After manoeuvre 4, the spacecraft has returned to the Earth. If only one asteroid is returned, then the final mass of the spacecraft would be $M_{1sc,4}$. However, if the single spacecraft is used to retrieve n asteroids, then the four manoeuvres shown in Eq. (10) have to be repeated n times. The mass after the next manoeuvre would then be:

$$M_{1sc,5} = \frac{M_{1sc,4}}{e^{\Delta V_1/V_e}} = M_0 e^{-(3\Delta V_1+2\Delta V_2)/V_e} + M_a e^{-(2\Delta V_1+\Delta V_2)/V_e} - M_a e^{-\Delta V_1/V_e} \tag{11}$$

Since the same four manoeuvres are continually repeated, a pattern can be noted in the mass at the end of a capture mission. This can be represented in the following expression for the final mass $M_{1sc,final}$, after all n asteroids have been retrieved:

$$M_{1sc,final} = M_0 e^{-2n(\Delta V_1+\Delta V_2)/V_e} + M_a \sum_{i=0}^{2n-1} (-1)^{i-1} e^{-i(\Delta V_1+\Delta V_2)/V_e} \tag{12}$$

In order to calculate the maximum asteroid mass that can be returned, it is assumed that all propellant is consumed at the end of the manoeuvre sequence so that:

$$M_{1sc,final} = f_{dry} M_0 \tag{13}$$

where f_{dry} is the dry mass fraction of the spacecraft. Also, it has been assumed that the same asteroid mass M_a is returned on each trip. Then, Eq. (12) can be solved for the returned mass per asteroid visit per unit of initial wet spacecraft mass for the one-spacecraft strategy:

$$\left(\frac{M_a}{M_0}\right)_{1sc} = \frac{f_{dry} - e^{-2n(\Delta V_1+\Delta V_2)/V_e}}{\sum_{i=0}^{2n-1}(-1)^{i-1} e^{-i(\Delta V_1+\Delta V_2)/V_e}} \tag{14}$$

Eq. (14) gives the ratio M_a/M_0 for each of the n asteroids that are captured for a given r_{ast}, n, V_e and f_{dry}. Thus, the total retrieved mass at the end of a mission per unit of initial wet mass is given by:

$$m_{n,1sc} = n\left(\frac{M_a}{M_0}\right)_{1sc} \tag{15}$$

Two-spacecraft strategy The same procedure as for the one-spacecraft strategy can be used for the two-spacecraft strategy, with a separate derivation for the catcher and pitcher.

The manoeuvres for the capture of an asteroid for the two-spacecraft strategy are shown in Fig. 2(b). However, since the pitcher is at Earth at the start of the mission, it first needs to transfer to the asteroid. This initial transfer is not shown in Fig. 2(b). There are two impulses required for this manoeuvre, ΔV_1 and ΔV_2. After the initial transfer, the pitcher deflects the asteroid towards the Earth (manoeuvre 1 in Fig. 2(b)), thus the mass of the asteroid M_a needs to be taken into account. Since for this preliminary analysis it is assumed that all the asteroids are in the same orbit, the pitcher will then need to perform a manoeuvre to remain in the same orbit (manoeuvre 2 in Fig. 2(b)). The mass of the spacecraft during these manoeuvres can be written as shown in Eq. (16), where $M_{0,P}$ is the initial wet mass of the pitcher, $M_{2sc,it1}$ and $M_{2sc,it2}$ are the masses of the pitcher after the two impulses for the initial transfer have been performed, and $M_{2sc,i}$ is the mass after manoeuvre i.

$$M_{2sc,it1} = \frac{M_{0,P}}{e^{\Delta V_1/V_e}} = M_0 e^{-\Delta V_1/V_e} \tag{16a}$$

$$M_{2sc,it2} = \frac{M_{2sc,it1}}{e^{\Delta V_2/V_e}} = M_0 e^{-(\Delta V_1+\Delta V_2)/V_e} \tag{16b}$$

$$M_{2sc,1} = \frac{M_{2sc,it1}+M_a}{e^{\Delta V_2/V_e}} - M_a = M_0 e^{-(\Delta V_1+2\Delta V_2)/V_e} + M_a e^{-\Delta V_2/V_e} - M_a \tag{16c}$$

$$M_{2sc,2} = \frac{M_{2sc,1}}{e^{\Delta V_2/V_e}} = M_0 e^{-(\Delta V_1+3\Delta V_2)/V_e} + M_a e^{-2\Delta V_2/V_e} - M_a e^{-\Delta V_2/V_e} \tag{16d}$$

After manoeuvre 2, the pitcher deflects the next asteroid towards the Earth. Thus, the initial transfer is performed once while manoeuvres 1 and 2 are repeated n times for the retrieval of n asteroids. Again, it is assumed that all the propellant is consumed at the end of the mission, such that:

$$\frac{M_a}{M_{0,P}} = \frac{f_{dry} - e^{-(\Delta V_1+(2n+1)\Delta V_2)/V_e}}{\sum_{i=1}^{2n}(-1)^i e^{-i\Delta V_2/V_e}} \tag{17}$$

The catcher is stationed at the Earth and inserts the asteroids into Earth's heliocentric orbit when they arrive. It first accelerates to the velocity of the incoming asteroid (manoeuvre 3 in Fig. 2(b)), after which it applies the same impulse but in opposite direction to decelerate the asteroid into the target orbit (manoeuvre 4 in Fig. 2(b)). It is assumed that these two manoeuvres are applied instantaneously. The mass equations for these two manoeuvres are the following, where $M_{0,C}$ is the initial wet mass of the catcher:

$$M_{2sc,3} = \frac{M_{0,C}}{e^{\Delta V_1/V_e}} \tag{18a}$$

$$M_{2sc,4} = \frac{M_{2sc,3}+M_a}{e^{\Delta V_1/V_e}} - M_a = M_0 e^{-2\Delta V_1/V_e} + M_a e^{-\Delta V_1/V_e} - M_a \tag{18b}$$

The catcher does not require an initial transfer, so for the capture of n asteroids, manoeuvres 3 and 4 have to be repeated n times. If all the propellant mass is consumed at the end, then:

$$\frac{M_a}{M_{0,C}} = \frac{f_{dry} - e^{-2n\Delta V_1/V_e}}{\sum_{i=0}^{2n-1}(-1)^{i-1}e^{i\Delta V_1/V_e}} \tag{19}$$

An additional conclusion can be drawn by considering Eqs. (14), (17) and (19). In all three fractions, the denominator is always negative. For feasible missions, M_a/M_0 should be positive, implying that the numerator should be negative as well. By inspecting the numerator, it can be seen that it contains the total ΔV required by the respective spacecraft (i.e. $2n(\Delta V_1 + \Delta V_2)$ for the single spacecraft and $2n\Delta V_1$ and $2n\Delta V_2$ for the catcher and pitcher, respectively). Therefore, the following inequality must hold:

$$f_{dry} - e^{-\Delta V_{max}/V_e} < 0 \tag{20}$$

This can be rewritten as:

$$\Delta V_{max} < V_e \ln\left(\frac{1}{f_{dry}}\right) \tag{21}$$

Thus, depending on V_e and f_{dry}, a maximum ΔV budget can be given to each spacecraft. Note that this maximum is for each spacecraft individually, which means that the two-spacecraft strategy has twice the amount of ΔV available across both spacecraft compared to the one-spacecraft strategy. The ΔV_{max} represents the case where no asteroid mass is moved. Thus, the actual ΔV budget will be lower, depending on how much mass is captured. It does mean that having a higher ΔV_{max} allows the capture mission to retrieve more mass.

To make a fair comparison between the two strategies, the combined initial masses of the pitcher and catcher are equal to the initial mass of the single spacecraft. The distribution of the mass is denoted by the fraction k, such that,

$$M_{0,C} = kM_0 \tag{22a}$$

$$M_{0,P} = (1-k)M_0 \tag{22b}$$

and thus,

$$\left(\frac{M_a}{M_0}\right)_{2sc} = k\frac{M_a}{M_{0,C}} = (1-k)\frac{M_a}{M_{0,P}} \tag{23}$$

The mass fraction can be then obtained with:

$$k = \frac{\frac{M_a}{M_{0,P}}}{\frac{M_a}{M_{0,C}} + \frac{M_a}{M_{0,P}}} \tag{24}$$

The mass fraction indicates what portion the catcher needs from the total initial mass M_0. Thus if $k > 0.5$, the catcher will be more massive than the pitcher. On the other hand, if $k < 0.5$, then the pitcher will need the majority of the initial mass. This is directly dependent on the required ΔV of each of the spacecraft.

Similarly to the one-spacecraft strategy, the total retrieved asteroid mass for n asteroids per unit of initial wet mass for the two-spacecraft strategy is given by:

$$m_{n,2sc} = n\left(\frac{M_a}{M_0}\right)_{2sc} \tag{25}$$

or separately for the pitcher and catcher:

$$m_{n,P} = n\frac{M_a}{M_{0,P}} \tag{26}$$

$$m_{n,C} = n\frac{M_a}{M_{0,C}} \tag{27}$$

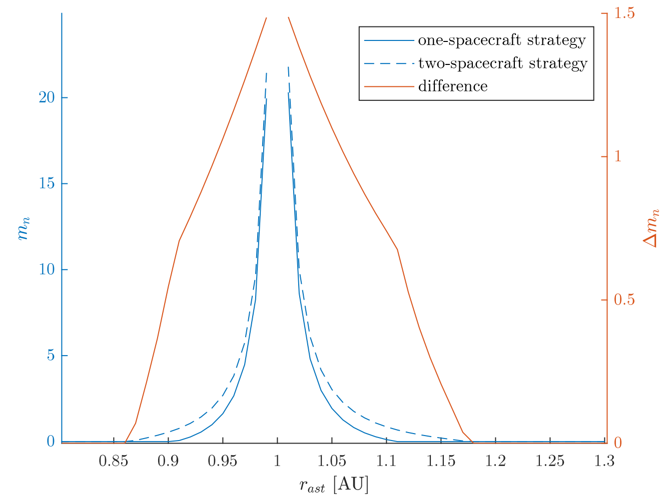

Fig. 4. m_n versus r_{ast} for both the one-spacecraft and two-spacecraft strategy, and their difference Δm_n.

2.3.2. Results

To compare the total retrieved mass per unit of initial wet mass m_n for the one-spacecraft and two-spacecraft strategy, it is assumed that I_{sp} = 400 s. Furthermore, the dry mass of the spacecraft is assumed to be 10% of its initial mass [26], i.e. f_{dry} = 0.1. Then, the asteroid orbit radius as depicted in Fig. 1 has been varied from 0.8 to 1.3 AU, while the number of asteroids n has been set to 3. The results for both strategies are shown in Fig. 4. Note that if a mission exceeds the maximum ΔV_{total}, the resulting m_n becomes negative, i.e. the mission is infeasible. In this case, m_n is set to zero, since the mission will not be able to return any asteroid mass. In the same figure, the difference in m_n between the two strategies is shown, which is defined as:

$$\Delta m_n = m_{n,2sc} - m_{n,1sc} \tag{28}$$

It is clear that the two-spacecraft strategy is able to return more mass than the one-spacecraft strategy. This advantage increases when the asteroid orbit lies closer to Earth's orbit, with up to $1.5M_0$ more returned mass. Also, the two-spacecraft strategy yields feasible missions for a larger range in r_{ast} than the one-spacecraft strategy. This is also visible in the figure as a break point for Δm_n. At this point, the one-spacecraft strategy becomes infeasible and is therefore equal to zero, changing the slope of the plot indicating Δm_n.

Thus although there is no real ΔV advantage, the two-spacecraft strategy is able to return more asteroid mass. This can be explained by the fact that the initial wet mass that is required for the single spacecraft is divided between the pitcher and the catcher in the two-spacecraft strategy. This causes a staging effect, where less propellant is required for accelerating the spacecraft, which means that more propellant is left to retrieve asteroid mass.

Fig. 5 shows the separate m_n for the pitcher and catcher spacecraft (as defined by Eqs. (26) and (27)), together with the mass fraction k. It can be noted that close to r_{ast} = 1 AU, k is approximately 0.5, which means that the mass is distributed evenly between the two spacecraft. This is because the required ΔVs for the spacecraft are close to one another. As r_{ast} increases or decreases, m_n of the pitcher becomes smaller than that of the catcher. According to Eq. (24), the mass fraction k decreases as well, which means that the pitcher spacecraft will require a larger fraction of the initial wet mass M_0.

In addition to varying r_{ast}, the influence of the number of retrieved asteroids can be investigated. Fig. 6 shows m_n as a function of number of asteroids, while r_{ast} has been fixed at 1.06 AU for all retrieved asteroids. Again, an advantage in retrieved mass for the two-spacecraft strategy can be seen. Also, a higher number of asteroids can be retrieved

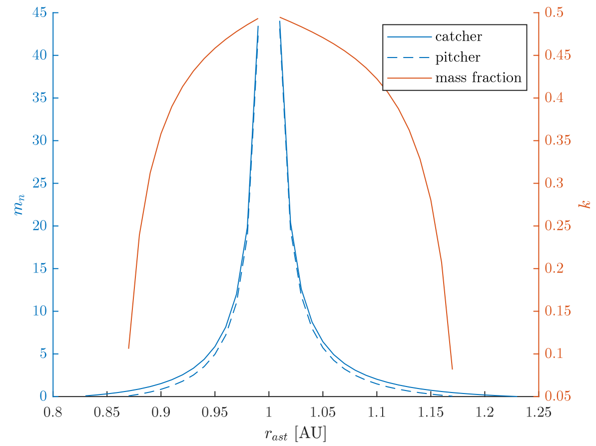

Fig. 5. Separate m_n for the pitcher and catcher and the mass fraction k.

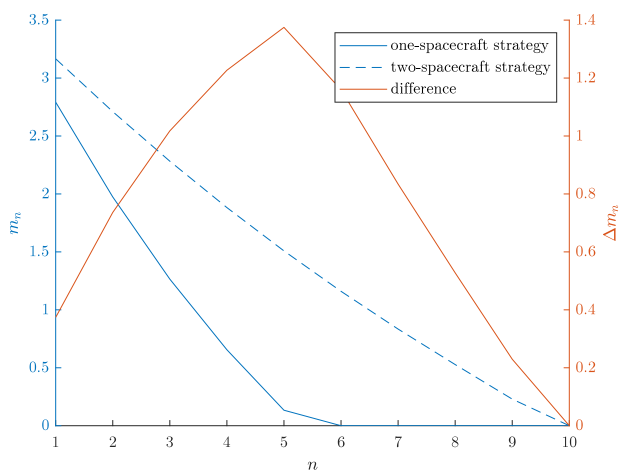

Fig. 6. m_n versus n for both the one-spacecraft and two-spacecraft strategy, and their difference Δm_n.

by the two-spacecraft strategy before the mission becomes infeasible. While the mission using a single spacecraft becomes infeasible for more than 5 asteroids, the two-spacecraft strategy becomes infeasible at $n = 10$. This figure also shows the difference in m_n between the strategies, which increases up to $1.4M_0$ as the number of asteroids increases, after which it starts decreasing.

2.3.3. Discussion

The preliminary analysis shows a higher retrieved mass for the two-spacecraft strategy, making this strategy more advantageous.

The assumption that an equal amount of mass is retrieved from each asteroid aids the analytical derivation of the mass model, although it is not likely that this will be true for actual capture missions since asteroids can vary in size. However, it could be argued that only a part of the asteroid is returned, for example if mining equipment is already present on the asteroid such that the mined material only needs to be retrieved.

In the next section, a less simplified version of the mission scenario is explored.

3. Statistical analysis using fictitious NEAs

In the previous section, the mission scenario was simplified by assuming coplanar and circular orbits, and by ignoring orbit phasing. In reality, the asteroid orbits can have various orbital elements, and the phasing of the celestial bodies puts a constraint on retrieved asteroid mass and mission duration. Therefore, in this section, the orbital elements of the asteroids will be randomly generated within specified ranges in order to generate statistical data on the relative performance of the one-spacecraft and two-spacecraft strategies. Furthermore, orbit phasing is considered, therefore Lambert arcs instead of Hohmann arcs will be used. The orbital elements of the asteroids are assumed to stay fixed over the course of a mission, while for the Earth's orbit its ephemeris is used. The Lambert's problem solver used for the computation of the arcs is based on the algorithm provided by Battin [27], with the addition of multi-revolution solutions using the method provided by Shen and Tsiotras [28]. A maximum of two full revolutions is considered. Since mission duration is an important element in the analysis, allowing for more than two revolutions might have a significant impact on the transfer time. Adding more revolutions would also increase the computational time for the optimisation, since more options will have to be investigated. Thus, to limit both the total mission duration and the computational time of the simulations, the maximum has been set to two revolutions.

3.1. Mission scenario

For the one-spacecraft strategy, the mission scenario is similar that of the preliminary analysis. The spacecraft starts at the Earth, transfers to an asteroid, returns material to the Earth, after which it sets out to the next asteroid.

For the two-spacecraft strategy, the pitcher spacecraft transfers from asteroid to asteroid, rather than staying in the same asteroid orbit. Therefore, an extra transfer arc needs to be taken into consideration. After an asteroid has been deflected towards the Earth by the pitcher, the spacecraft transfers to the next asteroid. Before doing so, the pitcher is allowed to remain in the transfer orbit of the asteroid for a certain period of time. This increases the flexibility of the mission, as the pitcher can now wait for the best opportunity to transfer to the next target. After the final asteroid is deflected, the pitcher travels together with the asteroid to Earth and is then inserted in Earth's heliocentric orbit. The asteroid itself is captured by the catcher.

3.2. Mass model

To compute the returned mass, a similar model as explained in Section 2 is used (see Eqs. (14), (17) and (19)). In this case, the ΔVs differ for each transfer, resulting in the following equations:

$$\left(\frac{M_a}{M_0}\right)_{1sc} = \frac{f_{dry} - e^{-\Delta V_{total,1sc}/V_e}}{\sum_{i=1}^{2n-1}\left((-1)^{i-1} e^{-\sum_{j=2i+1}^{4n} \Delta V_j/V_e}\right) - 1} \tag{29}$$

$$\frac{M_a}{M_{0,P}} = \frac{f_{dry} - e^{-\Delta V_{total,P}/V_e}}{\sum_{i=1}^{n}\left(e^{-\sum_{j=3i}^{3n+1} \Delta V_j/V_e} - e^{-\sum_{j=3i+1}^{3n+1} \Delta V_j/V_e}\right)} \tag{30}$$

$$\frac{M_a}{M_{0,C}} = \frac{f_{dry} - e^{-\Delta V_{total,C}/V_e}}{\sum_{i=2}^{2n}\left((-1)^{i} e^{-\sum_{j=i}^{2n} \Delta V_j/V_e}\right) - 1} \tag{31}$$

To obtain the mass retrieved per unit of initial total mass for the two-spacecraft strategy and its associated mass fraction, Eqs. (23) and (24) are used. Finally, the total fraction of retrieved mass m_n is computed with Eqs. (15) and (25).

3.3. Mission optimisation

A capture mission is set out to capture n asteroids, of which the orbital elements are randomly generated and remain fixed for the duration of the mission. Both the one-spacecraft strategy and two-spacecraft strategy visit the same asteroids in the same order. The objective is to maximise the retrieved asteroid mass. The retrieved asteroid mass can only be computed after the ΔVs for all transfers of

Table 2
Fixed parameters for the sequential optimisation.

Parameter	Value
t_{start}	01-01-2035
t_{step}	50 days
$t_{wait,max}$	1 synodic period in days
TOF_{min}	100 days
TOF_{max}	2.5 years
I_{sp}	400 s
f_{dry}	0.1

the entire mission have been determined. In this case, the transfers are optimised separately and therefore the objective for each transfer is set to minimising the required ΔV for that specific transfer. This is achieved by searching for the wait time and time of flight of each arc which results in the lowest ΔV for that particular transfer. The solution vector therefore consist of $2n$ wait times and $2n$ times of flights. After each transfer arc has been optimised, the obtained ΔVs are then used to compute the retrieved asteroid mass.

The optimisation is performed using a grid search. The transfers are optimised sequentially, thus multiple grid searches are performed for the optimisation of a single mission. The algorithm for the optimisation of a capture mission requires the following fixed parameters:

- t_{start}: the start time at which the first grid search starts searching for the optimal ΔV for the first transfer
- t_{step}: the time step of the grid search
- $t_{wait,max}$: the maximum time that a spacecraft can wait in an orbit before performing the subsequent manoeuvre
- TOF_{min}: the minimum time of flight for a transfer
- TOF_{max}: the maximum time of flight for a transfer
- I_{sp}: the specific impulse of the rocket engine
- f_{dry}: the fraction of the dry mass of the spacecraft

The optimisation algorithm searches for each of the transfer arcs to determine the start time and time of flight yielding the objective minimum ΔV. The time at which the spacecraft arrives at its destination, i.e. at the end of the transfer arc, is used as the earliest start time for the next transfer arc. This sequential optimisation has the disadvantage that the global optimum is not necessarily achieved; a sub-optimal solution for a specific transfer may result in a lower optimal ΔV for the next transfer, therefore decreasing the total amount of ΔV required for the entire mission. However, doing a grid search through the entire mission would be too computationally expensive. To minimise the effect of the sequential optimisation, the maximum wait time for each transfer is set to the synodic period between the target and departure orbit. Even though this still does not ensure that the global optimum is found, it is considered to be sufficient for the comparison of the two strategies. All the parameters for the optimisation are shown in Table 2.

Besides the above-mentioned parameters, there is a second set of parameters that affect the mission objective. These are the number of asteroids n and the ranges of the randomly generated orbital elements of the asteroids. Four batches of mission simulations are distinguished; this second set of parameters stays constant for all the mission simulations of a batch, but can be different for different batches. This is done to investigate the influence of the various parameters on the mission outcome. The parameters for each batch are shown in Table 3.

3.4. Results

In the following sections, the results for each of the four batches with mission simulations are presented.

Table 3
Ranges of the second set of parameters for each batch of mission simulations.

Variable	Batch 1	Batch 2	Batch 3	Batch 4
n	3	[1, 10]	3	3
a [AU]	[0.8, 1.3]	[1.01, 1.1]	[1.01, 1.1]	[1.01, 1.1]
e	[0, 0.05]	[0, 0.05]	[0, 0.2]	[0, 0.05]
i [deg]	[0, 1]	[0, 1]	[0, 1]	[0, 5]
Ω [deg]	[0, 360]	[0, 360]	[0, 360]	[0, 360]
ω [deg]	[0, 360]	[0, 360]	[0, 360]	[0, 360]
M [deg]	[0, 360]	[0, 360]	[0, 360]	[0, 360]

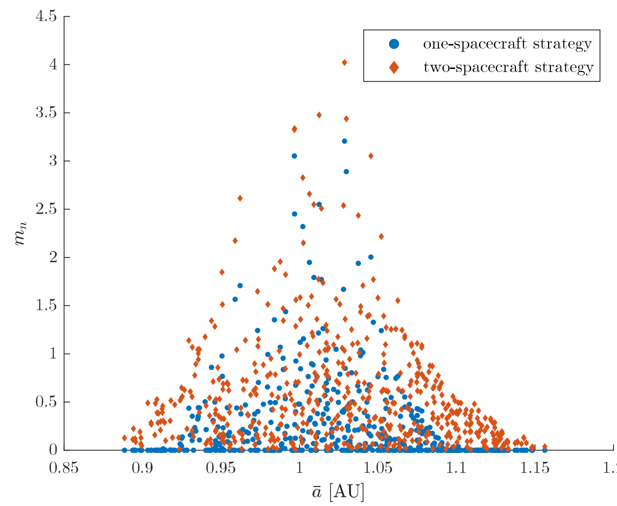

Fig. 7. m_n versus $\bar{a}$ for both the one-spacecraft and two-spacecraft strategy.

3.4.1. Mission simulations batch 1

For batch 1, the range of the semi-major axis is relatively large in order to investigate its effect on the returned asteroid mass (see the second column of Table 3).

A total of 2000 mission simulations have been optimised by the algorithm for both the one-spacecraft and two-spacecraft strategy, each mission visiting three asteroids. Of these, 1474 missions turned out to be infeasible for both the one-spacecraft and two-spacecraft strategy. Since no comparison could be made for these missions, they have been discarded. The remaining 526 missions have been plotted in Fig. 7. The retrieved asteroid mass fraction m_n is shown on the vertical axis, in order to compare the one-spacecraft and two-spacecraft strategy. To examine the influence of the semi-major axis on the mission outcome, the average of the semi-major axes $\bar{a}$ of the three asteroids is shown on the horizontal axis, which is defined as:

$$\bar{a} = (a_{ast1} + a_{ast2} + a_{ast3})/3 \tag{32}$$

From Fig. 7 it can be deduced that the further the average semi-major axis is from 1 AU, the smaller the mass returned. The maximum m_n is 4.02 for the two-spacecraft strategy and 3.21 for the one-spacecraft strategy. Also, the two-spacecraft strategy has a larger range of $\bar{a}$ with feasible missions, so that a larger set of asteroids could be considered for a capture mission.

Fig. 8 shows the difference in m_n between the two-spacecraft and one-spacecraft strategy for each mission against $\bar{a}$. At only one mission, less asteroid mass is returned by the two-spacecraft strategy than by the one-spacecraft strategy. The other missions all show an advantage for the two-spacecraft strategy, up to $1.05M_0$.

Fig. 9 shows the ΔV versus the average semi-major axis of the three asteroids for both strategies. For all missions, the ΔV for the two-spacecraft strategy is larger than for the one-spacecraft strategy. This corresponds to the results from the previous section. Also, the lowest ΔVs are present near $\bar{a}$ = 1 AU. Since all asteroids are deflected to

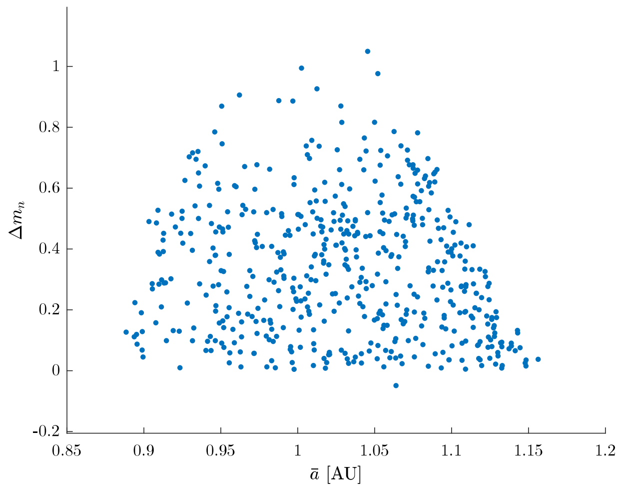

Fig. 8. Differences in m_n versus $\bar{a}$.

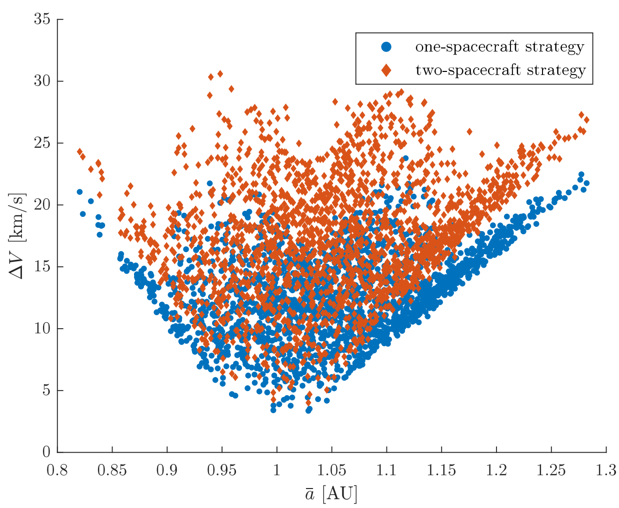

Fig. 9. Total required ΔV for each mission versus $\bar{a}$ for both the one-spacecraft and two-spacecraft strategy.

Earth's orbit, having an asteroid orbit close to Earth's orbit will require less ΔV for the transfer.

However, requiring a higher ΔV does not necessarily mean that less mass is returned. The relation between ΔV and m_n is shown in Fig. 10.

For the one-spacecraft strategy a clear correlation can be seen, where a higher ΔV results in a lower m_n. It is also worth noting that the maximum ΔV given by Eq. (21) for $I_{sp} = 400$ s and $f_{dry} = 0.1$ is $\Delta V_{total} = 9.035$ km/s. This is clearly visible in the figure. While the general trend is the same for the two-spacecraft strategy, more scatter is present. Therefore, the ΔVs required for the pitcher and catcher separately are also plotted. Similarly to the one-spacecraft strategy, each of the spacecraft can use up to 9.035 km/s individually. However, if one of the two spacecraft exceeds this limit, the mission is viewed as infeasible even if the other spacecraft is still within the limits. This is why the results for the spacecraft combined seems to be limited at a lower value than 18.07 km/s. The pitcher follows the trend of the one-spacecraft strategy. As this spacecraft needs to transfer from asteroid to asteroid in addition to deflecting asteroids, it is more likely that it will reach its maximum ΔV budget before the catcher does. Therefore, the catcher rarely gets to its ΔV budget limit, but rather has a larger scatter of possible values.

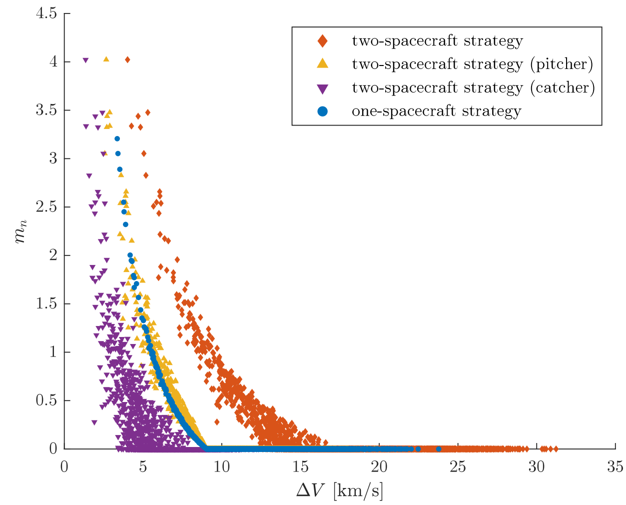

Fig. 10. m_n versus ΔV for the two-spacecraft strategy (for the pitcher, catcher and total) and the one-spacecraft strategy.

When comparing the two strategies, it can be concluded that the two-spacecraft strategy is able to return a larger amount of asteroid mass for the same ΔV.

3.4.2. Mission simulations batch 2

The second batch of mission simulations is used to compare the retrieved mass for a varying number of asteroids. To focus on the number of asteroids n as a variable, the range of the semi-major axis is decreased with respect to batch 1, while n ranges from 1 to 10. The ranges for all the variables of this batch can be found in the third column of Table 3.

The algorithm optimised 5000 mission simulations in total for both the one-spacecraft and two-spacecraft strategy, 500 for each n. Fig. 11 shows the average value of m_n, denoted by $\overline{m}_n$, over the 500 mission simulations for each n and strategy.

This figure shows that the two-spacecraft strategy can retrieve more asteroid mass than the one-spacecraft strategy on average, regardless of the number of asteroids visited. Also, feasible missions are found for up to nine asteroids for the two-spacecraft strategy, while for the one-spacecraft strategy the returned mass approaches zero for six asteroids or more. None of the strategies have any feasible mission for $n = 10$.

3.4.3. Mission simulations batches 3 and 4

Batch 3 and 4 of the mission simulations investigated the effect of the eccentricity and inclination on the mission outcome, respectively. This was done by increasing their ranges, as can be seen in the fourth and fifth column of Table 3. Similarly to batch 1, 2000 missions have been simulated in which for each mission three asteroids are visited. Of these, 1001 missions of batch 3 and 1601 missions of batch 4 are used for comparison based on their feasibility. The remaining missions can be seen in Figs. 12 and 13. Moreover, the results have been fitted with a sixth degree polynomial for ease of visual inspection. In both figures, the overall trend of the retrieved mass is downwards with increasing average eccentricity or inclination. This shows that having a larger eccentricity or inclination, which requires a higher ΔV for the transfers, indeed results in less retrieved mass. The observed maximum in the polynomial fit of Fig. 12 stems from the low number of missions with a low average eccentricity, therefore reducing the chance of finding a mission with a higher m_n (as is the case for higher $\bar{e}$, where a large range of m_n is seen). Also, just 5 missions yield more retrieved mass for the one-spacecraft strategy than for the two-spacecraft strategy in Fig. 12, while the two-spacecraft strategy is advantageous for all simulated missions in Fig. 13.

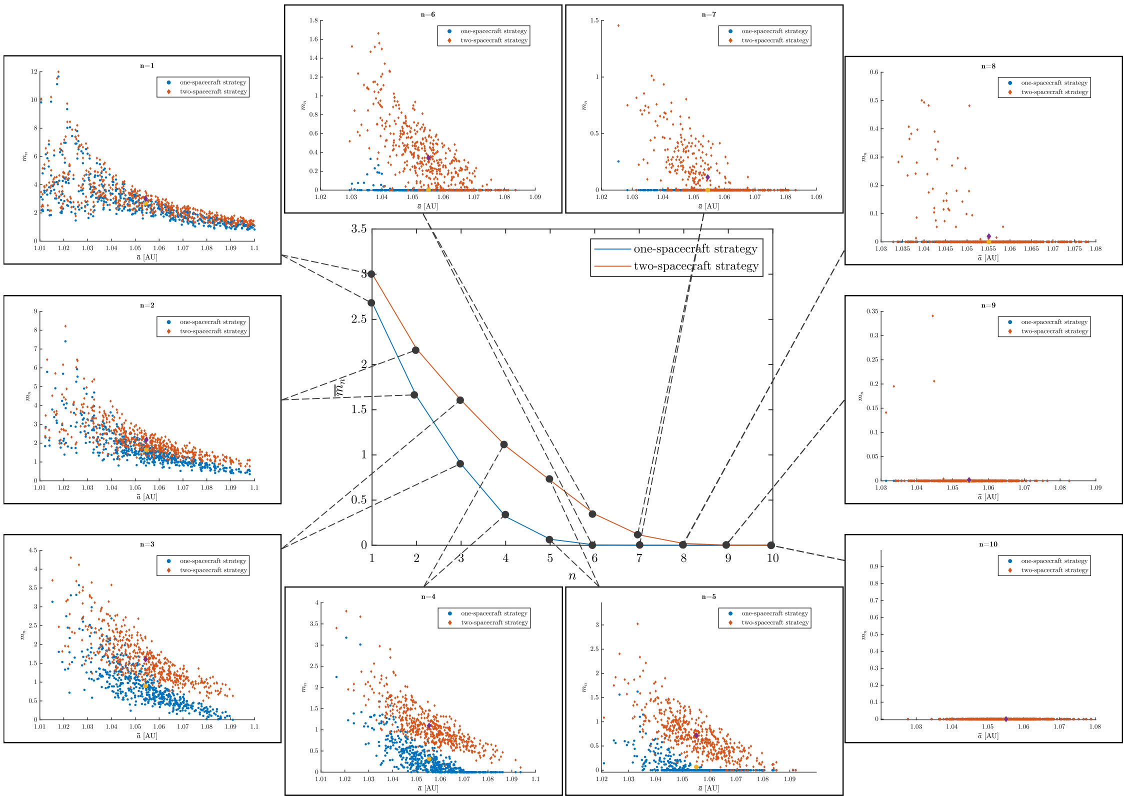

Fig. 11. $\overline{m}_n$ versus the number of asteroids captured.

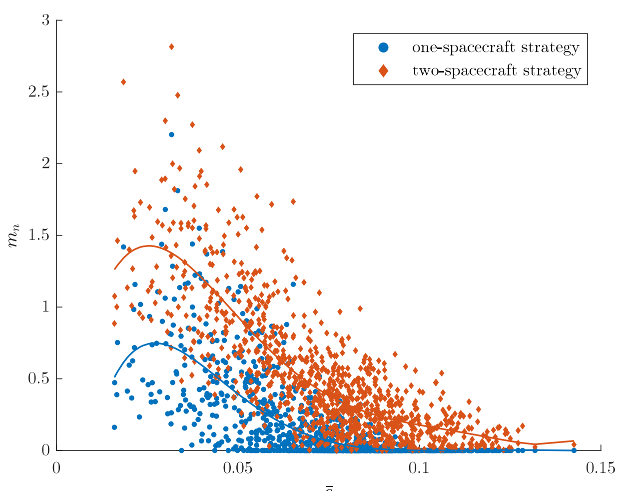

Fig. 12. m_n versus $\bar{e}$ for both the one-spacecraft and two-spacecraft strategy.

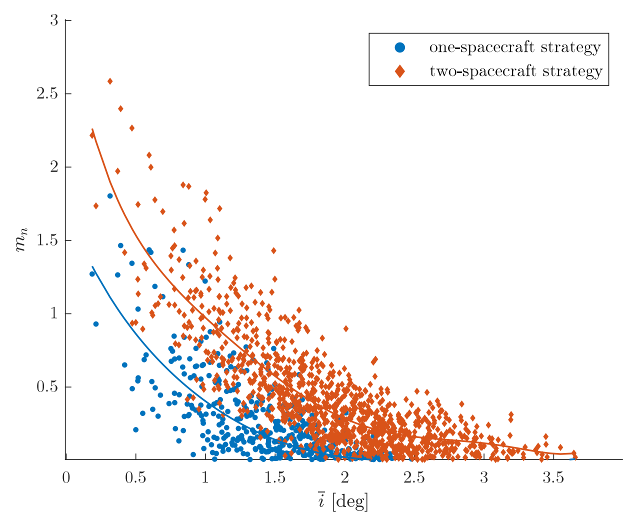

Fig. 13. m_n versus $\bar{i}$ for both the one-spacecraft and two-spacecraft strategy.

3.5. Comparison to the preliminary analysis

In this section, a comparison is made between the results of the preliminary analysis from Section 2 and the analysis in this section. The results on the retrieved mass for both analyses as a function of the semi-major axis of the asteroid orbit are shown together in Fig. 14. The differences in returned mass between the two strategies have been combined in Fig. 15.

From these figures, it can be concluded that the preliminary analysis using Hohmann transfers provides an upper limit of the returned asteroid mass, as all the data points from the statistical analysis fall within the area that is delimited by the Hohmann transfer results. The large amount of scatter in the statistical analysis is attributed to several reasons. First, the average semi-major axis of the statistical analysis is compared with r_{ast} of the preliminary analysis. That means that, while the average semi-major axis can lie close to 1 AU, which would mean a high m_n for r_{ast}, the semi-major axes of the individual asteroids can be far apart. This increases the required ΔV, and, consequently, this results in a lower m_n. Secondly, instead of having one asteroid orbit with zero eccentricity and zero inclination, the asteroids are located in different orbits with realistic orbital elements. Again, an increase in ΔV is expected. Furthermore, although the wait times are allowed to be one synodic period, the Lambert's problem solver is constrained by a maximum time of flight of 2.5 years and a maximum of two full revolutions. Since NEAs are considered, the spacecraft transfer between

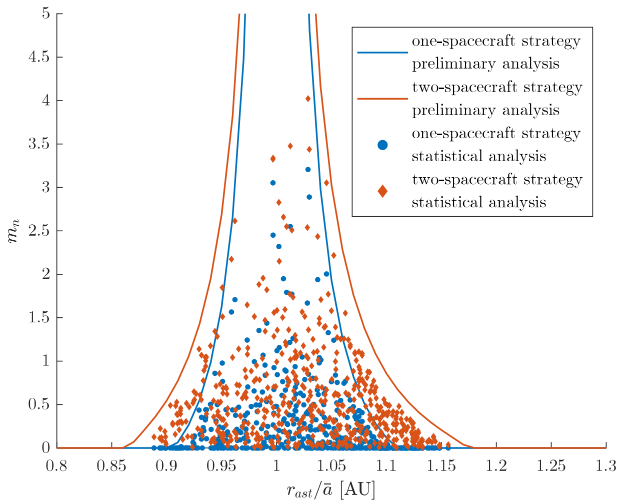

Fig. 14. Total retrieved mass ratio versus the asteroid radius or average semi-major axis from both the preliminary analysis and the statistical analysis.

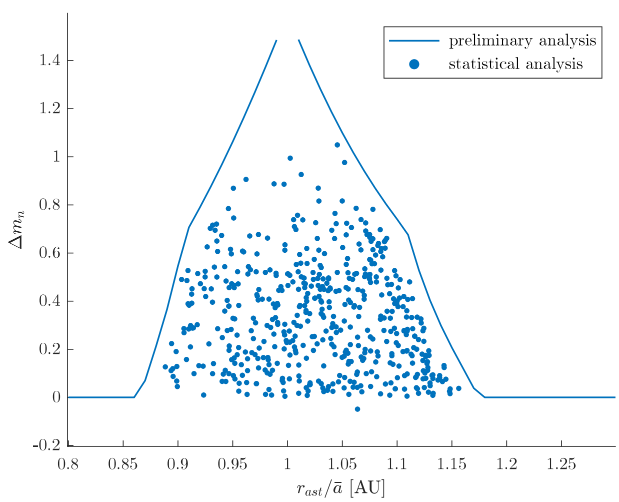

Fig. 15. Difference in total retrieved mass ratio versus the asteroid radius or average semi-major axis from both the preliminary analysis and the statistical analysis.

orbits close to each other. The longer the transfer time is allowed to be, the more phasing opportunities are found leading to lower ΔV. Increasing the maximum time of flight and maximum number of revolutions is therefore expected to benefit the mission outcome.

A comparison between the two strategies can also be made regarding the results with the varying number of asteroids n (Figs. 6 and 11). This comparison is shown in Fig. 16.

Again, the preliminary analysis provides an upper limit of the potentially retrieved asteroid mass. However, the results start to deviate as n increases, especially for the two-spacecraft strategy. For the preliminary analysis, the pitcher was not modelled to transfer from asteroid to asteroid, but rather stayed in the same asteroid orbit. Therefore, actually visiting multiple asteroids could lead to a higher ΔV, which accumulates as more asteroids are visited. However, it is still clear that the two-spacecraft strategy is able to return more asteroid mass, as well as targeting more asteroids.

3.6. Discussion

Similarly to the preliminary analysis, the analysis in this section shows that the two-spacecraft strategy has a higher return in asteroid mass than the one-spacecraft strategy in almost all of the simulated

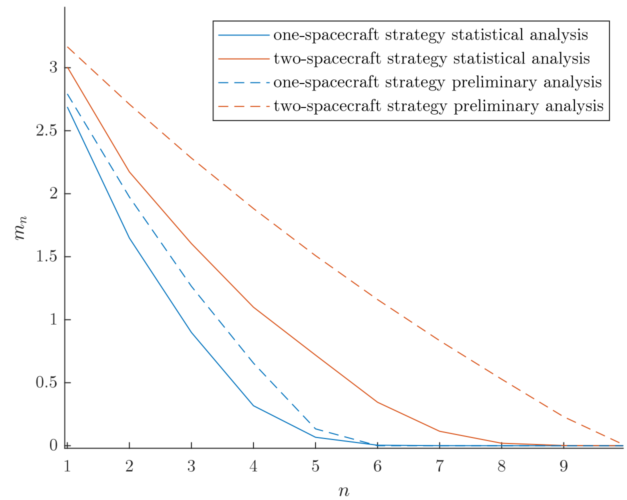

Fig. 16. m_n versus n for both the preliminary analysis and the statistical analysis.

missions. The results from the preliminary analysis provide an upper limit of this objective variable. Again, this advantage in retrieved mass for the two-spacecraft strategy is attributed to the staging effect that occurs from dividing the propellant mass between the two spacecraft.

Furthermore, it can be concluded that increasing the eccentricity or inclination of the asteroid orbits, or increasing the number of asteroids returned, or increasing the difference in semi-major axis between the asteroid orbits and the Earth orbit, all negatively impact the retrieved asteroid mass.

In the next section, the real ephemerides of NEAs is used for the mission optimisation.

4. Analysis using real NEAs

One of the potential benefits of the two-spacecraft strategy is the added flexibility in the orbit transfers of the pitcher, which could decrease the overall mission duration. In the previous sections, the mission duration has not been taken into account in assessing the mission performance. In this section, the optimisation is performed using a genetic algorithm. This allows optimisation for realistic mission durations, while also reducing the chances of arriving at an unfavourable local minimum.

Furthermore, NEAs are used from the JPL Small-Body Database,[1] rather than a randomly-generated set. A search has been performed for asteroids with orbit elements within the ranges of $0.9 < a < 1.1$ AU, $e < 0.05$ and $i < 2$ deg, resulting in eleven asteroids. The orbital elements of these asteroids are shown in Table 4.

4.1. Mission optimisation

Similar to the statistical analysis, a capture mission sets out to capture three asteroids ($n = 3$). The mission scenarios for both strategies are as presented in Section 3 and the same mass model is used. Each combination of three asteroids is optimised for retrieved asteroid mass for both the one-spacecraft and two-spacecraft strategy. However, unlike for the sequential optimisation, the order in which the asteroids are visited is not fixed. All permutations of each combination are optimised, and the best permutation is used for comparison. Since there are eleven asteroids in total, and each mission visits three asteroids, this results in 990 mission optimisations per strategy.

[1] https://ssd.jpl.nasa.gov/tools/sbdb_query.html accessed on 19 October 2021.

Table 4
The selected asteroids and their orbital elements at epoch 2021-07-01.

Asteroid	a [AU]	e	i [deg]	ω [deg]	Ω [deg]	M [deg]
2006 RH120	1.03	0.02	0.59	10.08	51.18	340.79
2010 VQ98	1.02	0.03	1.48	341.74	46.17	120.23
2011 UD21	0.98	0.03	1.06	209.90	22.35	157.37
2012 TF79	1.05	0.04	1.01	265.75	199.87	314.96
2016 RD34	1.05	0.03	1.96	11.06	349.59	164.57
2017 SV19	1.06	0.04	1.30	156.88	343.83	20.21
2017 TP4	1.08	0.04	1.56	137.81	281.23	76.11
2019 GF1	0.99	0.05	1.24	325.94	4.19	324.08
2020 CD3	1.03	0.01	0.63	50.02	82.21	129.53
2020 WY	1.02	0.03	1.70	179.03	107.25	343.86
2021 GM1	0.98	0.03	1.16	220.72	178.18	242.95

Table 5
Core parameters for the genetic optimisation.

Parameter	Value
Solution vector size	12
Population size	500
Relative function tolerance	10^{-6}
Crossover fraction	0.8
Elite count	25
Maximum generations	2400

Table 6
Fixed input parameters for the genetic algorithm.

Parameter	Value
t_{start}	01-01-2035
$t_{wait,max}$	2.5 years
TOF_{min}	100 days
TOF_{max}	2.5 years
I_{sp}	400 s
f_{dry}	0.1

The genetic algorithm in MATLAB is used for the optimisation of a mission. The core parameters of the genetic algorithm are shown in Table 5.

Each mission consisting of the same three asteroids in the same order is optimised five times, each time with a different random seed. The best objective value resulting from these five optimisations is chosen as the result for that specific permutation. Since the complete mission is now optimised at once instead of sequentially, the optimisation objective is switched from ΔV to M_a/M_0 (which will be used later for the computation of m_n). However, at the start of the optimisation, this will result mostly in negative M_a/M_0, i.e. infeasible missions. Therefore, to guide the algorithm in the right direction, the optimisation objective is set to ΔV as long as M_a/M_0 is negative. As soon as the mission has been optimised thus far that a positive retrieved mass is possible, the optimisation objective switches to M_a/M_0.

The fixed input parameters for the optimisation are shown in Table 6. Instead of taking the synodic period as the maximum wait time, this is limited to 2.5 years. This allows reasonable time to search for the next optimal transfer, while also putting a limitation on the mission duration. The remaining optimisation parameters are the same as for the sequential optimisation.

4.2. Results

The resulting retrieved mass fraction and mission duration are shown in Fig. 17 for all the feasible missions of both strategies. Each point corresponds to one mission of three asteroids using either the one-spacecraft or two-spacecraft strategy. For the computation of the mission duration, the wait time at the start of the mission has not been taken into account. It is clear that the two-spacecraft strategy dominates the right half of this figure, meaning that, probabilistically, it has the potential of returning an overall larger mass than the one-spacecraft strategy. What is also noticeable is that the missions with the shortest mission duration are also flown by the two-spacecraft strategy, with the most notable mission retrieving a mass of $0.78M_0$ within just 6.03 years. Although having a m_n smaller than 1 implies that less material is returned than is put into a mission, such a mission could still be profitable when the returned materials have a relatively high value, for example metals.

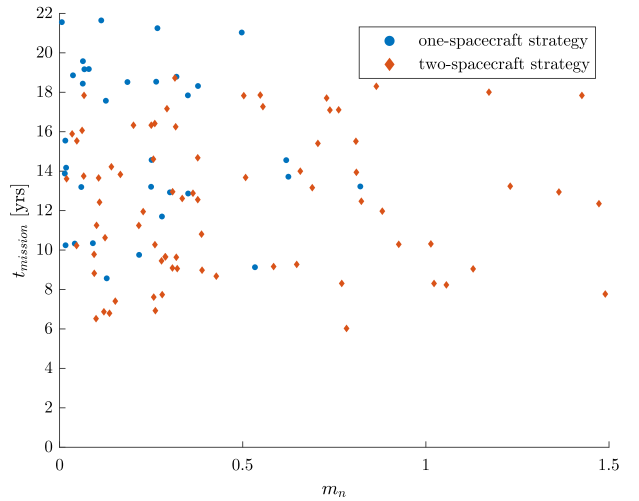

Fig. 17. Retrieved asteroid mass fraction and mission duration for the feasible missions resulting from the genetic algorithm optimisation.

The results shown in Fig. 17 are obtained by choosing the highest value of m_n from the five optimisations performed for each mission. To analyse the difference in optimisation results between the two strategies, the standard deviation of all feasible m_n resulting from the five optimisations for a mission has been computed. On average, the standard deviation of the solutions of the two-spacecraft strategy was approximately twice as large as that of the one-spacecraft strategy. This can be explained by the increase in complexity for the optimisation problem of the two-spacecraft strategy, which is caused by the fact that the transfer orbits for two separate spacecraft have to be optimised simultaneously while also being dependent on each other.

The specifics of two selected missions are detailed in Tables 7 and 8, with the respective trajectories depicted in Figs. 18 and 19, where the arc numbers in the tables correspond to those in the figures. The two-spacecraft strategy performed best in these two missions in terms of m_n. For both missions, the two-spacecraft strategy is able to return more mass in a shorter duration. For mission 1, the two-spacecraft mission is able to return $1.49M_0$ within 7.77 years. Compared to the one-spacecraft strategy, the difference in returned mass is $0.96M_0$, which arrives 1.36 years earlier than the mass from the one-spacecraft mission. This increase in returned mass also means that the two-spacecraft mission is able to bring back more material than is initially invested in it ($m_n > 1$); this is favourable when the returned materials will be used for propellant (e.g. water). Similarly, mission 2 is completed by the two-spacecraft strategy with a returned mass of $1.47M_0$ within 12.35 years. This is $0.85M_0$ more than the one-spacecraft strategy, while also arriving approximately one and a half year earlier. For this mission, it is noted that t_{wait} for the two-spacecraft strategy reaches the maximum of 2.5 years (913 days) twice. This could indicate that, if more time was allowed to wait in the respective orbits (Earth's orbit and the first transfer orbit to Earth), the mission could have brought back more mass. However, this would come at the expense of the total mission duration, which could increase significantly. It is also noted that both missions contain the asteroids 2011 UD12 and 2021 CD3. It seems that for the specific start date chosen for this optimisation, these are two of the most favourable asteroids for a capture mission in terms of relative positions and consequentially low-ΔV transfers.

Table 7
Details of example mission 1 obtained with the genetic algorithm optimisation.

Two-spacecraft strategy					One-spacecraft strategy			
m_n		1.49			m_n	0.53		
$t_{mission}$		7.77 years			$t_{mission}$	9.13 years		
Arc	Departure from	Arrival at	t_{wait} [days]	TOF [days]	Departure from	Arrival at	t_{wait} [days]	TOF [days]
1	Earth	2010 VQ98	695	665	Earth	2010 VQ98	695	665
2	2010 VQ98	Earth	385	603	2010 VQ98	Earth	404	670
3	2010 VQ98	2011 UD21	401	661	Earth	2011 UD21	82	301
4	2011 UD21	Earth	59	667	2011 UD21	Earth	37	282
5	2011 UD21	2020 CD3	87	297	Earth	2020 CD3	12	257
6	2020 CD3	Earth	0	204	2020 CD3	Earth	0	625

Table 8
Details of example mission 2 obtained with the genetic algorithm optimisation.

Two-spacecraft strategy					One-spacecraft strategy			
m_n		1.47			m_n	0.62		
$t_{mission}$		12.35 years			$t_{mission}$	13.72 years		
Arc	Departure from	Arrival at	t_{wait} [days]	TOF [days]	Departure from	Arrival at	t_{wait} [days]	TOF [days]
1	Earth	2011 UD21	913	863	Earth	2011 UD21	615	819
2	2011 UD21	Earth	336	817	2011 UD21	Earth	512	580
3	2011 UD21	2020 CD3	913	213	Earth	2020 CD3	631	254
4	2020 CD3	Earth	2	210	2020 CD3	Earth	0	626
5	2020 CD3	2006 RH120	815	649	Earth	2006 RH120	712	641
6	2006 RH120	Earth	562	157	2006 RH120	Earth	0	237

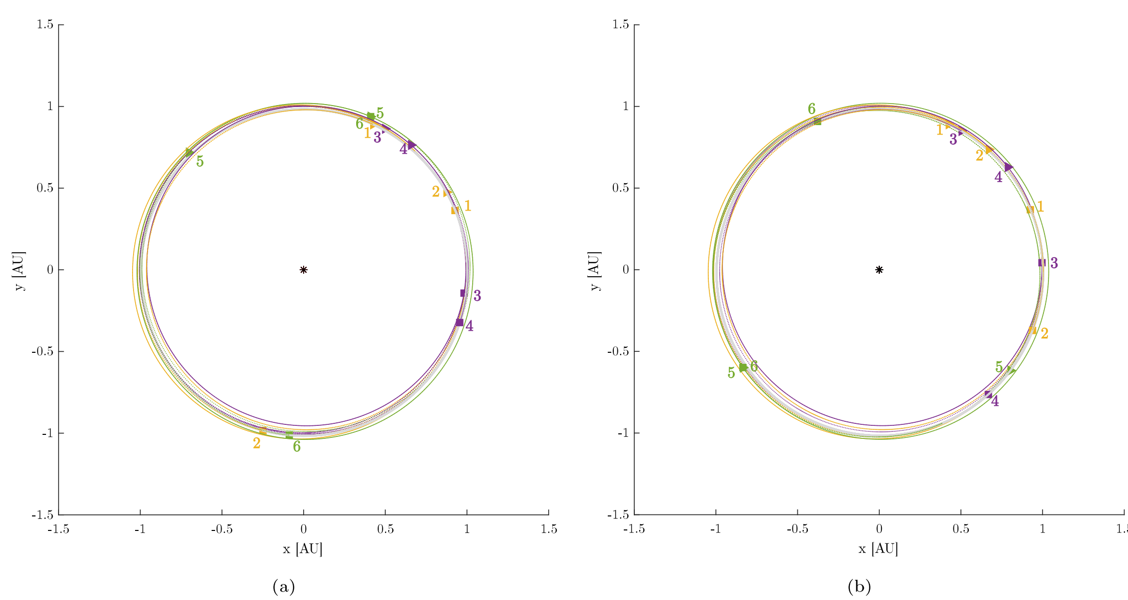

Fig. 18. Transfer trajectories for mission 1 for the two-spacecraft strategy (a) and one-spacecraft strategy (b).

However, changing the start date could also significantly change the starting positions, thus making other asteroids more favourable.

The SpaceX Starship has a maximum payload of 136 metric tonnes [29]. If this is taken as the initial wet mass of the spacecraft (M_0), then the retrieved asteroid mass for each strategy can be computed. For mission 1, the two-spacecraft strategy would be able to return 203 tonnes of asteroid material, whereas the one-space strategy returns 72 tonnes. This increases to 84 tonnes when mission 2 is considered, while the two-spacecraft strategy drops to 200 tonnes of returned mass. However, the difference between the two strategies is still significant, with the advantage for the two-spacecraft strategy.

4.3. Discussion

The two-spacecraft strategy increases the complexity of an asteroid capture mission, since two separate spacecraft need to be developed, launched and operated. This directly impacts the mission costs. However, the success of the mission is better defined by its Net Present Value, which weighs the costs against the revenue of the mission [30]. The advantages of the two-spacecraft strategy are a larger quantity of retrieved mass and a shorter mission duration. Both imply a potential increase in revenue. Also, while the operational costs per unit of time will be higher for a mission with two spacecraft, these are partly countered by the shorter mission duration required. Moreover, a redundancy is introduced by operating two spacecraft. If one of the two fails, then the other one can take over its tasks, essentially reducing to the one-spacecraft strategy.

5. Conclusion

Two strategies for capturing asteroids have been investigated in this paper, either with a single spacecraft or two spacecraft. It has

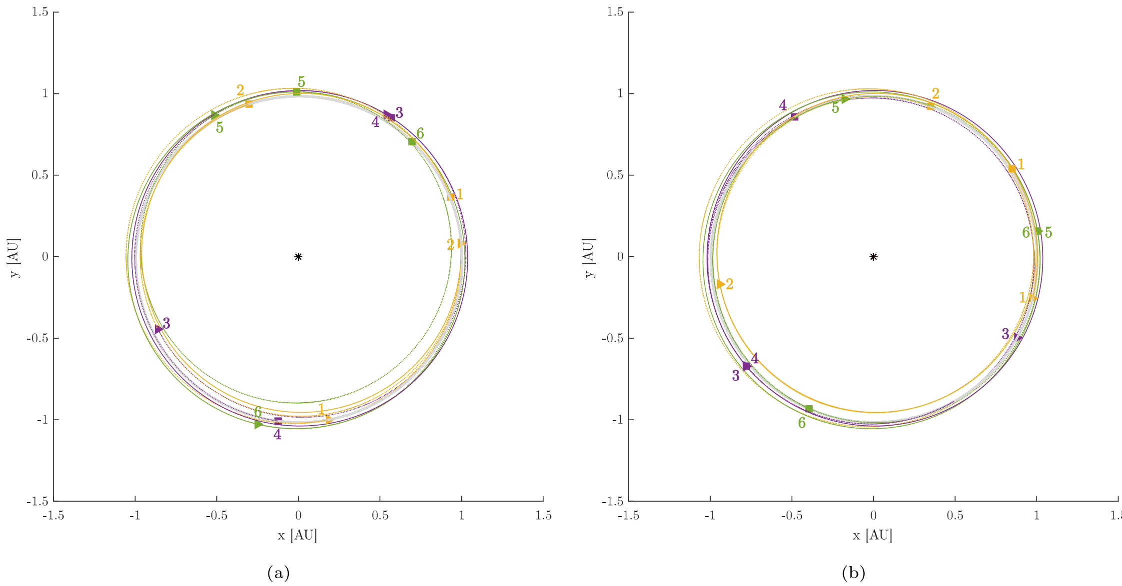

Fig. 19. Transfer trajectories for mission 2 for the two-spacecraft strategy (a) and one-spacecraft strategy (b).

been shown that the two-spacecraft strategy is able to return more asteroid mass for the majority of the simulated missions. Since the total launch mass is divided over two spacecraft, the individual spacecraft are lighter. Therefore, a staging effect is observed, where each of the manoeuvres requires less propellant.

The effect of varying various orbital elements of the asteroids has been investigated. As expected, the largest retrieved asteroid mass is obtained when the orbital elements of the asteroids are relatively close to Earth's orbit, and their eccentricity and inclination are small. Another factor influencing the retrieved mass is the number of asteroids retrieved, where the total retrieved mass decreases as the number of asteroids increases, again as expected. This is due to the fact that more transfers are needed, thus a larger portion of propellant is used for the transfers to and from the asteroid.

Two mission cases have been presented with three target asteroids, where the two-spacecraft strategy is able to return approximately 1.5 times its initial mass, while the one-spacecraft strategy is only capable of bringing less than its initial mass. Note that this does not necessarily means that the mission should be discarded. While it would be disadvantageous if the returned material is used for propellant, it could still be worthwhile when metals are sourced from the asteroids, as these have a higher value per unit of mass.

The two-spacecraft strategy also has the shortest mission duration for both the two mission cases, where a mission with three asteroids can be completed approximately 1.8 years faster on average than the one-spacecraft strategy. Although, the two-spacecraft strategy can bring the advantage of a shorter mission duration, this also depends on the chosen start date of the mission, as the initial position of the asteroids impact the optimisation of the transfers significantly.

Thus, the two-spacecraft has the potential to deliver a larger mass within a smaller amount of time, but it still remains dependent on the targeted asteroids and launch date, such that a case-by-case analysis is necessary.

A disadvantage of the two-spacecraft strategy would be the increased complexity of the operational effort by having two spacecraft that have to work together in order to complete the mission. Also, impulse errors are harder to correct since the asteroids are only deflected towards the Earth by the pitcher and thus it does not travel alongside them (except for the duration of the wait time in the transfer orbit). The catcher should therefore account for any corrections that the pitcher could not perform after separating with the asteroid. Thus, a trade-off should be made during the mission design phase to evaluate whether the increased mass return overcomes the additional operational challenges. On the other hand, the pitcher could in principle refuel after arriving at Earth with an empty tank, even making use of the resources it has brought from the asteroids. Then, it could set out for new targets, thereby creating a steady income of resources. Moreover, using multiple pitchers could increase the incoming rate of these asteroid resources, while also increasing the knowledge on the two-spacecraft operations, overall decreasing its complexity.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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