Preliminary design of a multi-spacecraft mission to investigate solar system

Deccia, CMA; Parker, JS; de Smet, S; Herman, JFC; Noomen, R

Publication date
2015

Document Version
Final published version

Published in
Proceedings of the AAS/AIAA astrodynamics specialist conference

Citation (APA)
Deccia, CMA., Parker, JS., de Smet, S., Herman, JFC., & Noomen, R. (2015). Preliminary design of a multi-spacecraft mission to investigate solar system. In M. Majji (Ed.), *Proceedings of the AAS/AIAA astrodynamics specialist conference* Article AAS 15-765 (Advances in the Astronautical Sciences Astrodynamics; Vol. 156). AAS.

AAS 15-765

PRELIMINARY DESIGN OF A MULTI-SPACECRAFT MISSION TO INVESTIGATE SOLAR SYSTEM EVOLUTION USING SOLAR ELECTRIC PROPULSION

Carlos M. A. Deccia[*] **Jeffrey S. Parker**[†] **Stijn De Smet**[‡]
Jonathan F. C. Herman[‡] **Ron Noomen**[§]

This paper discusses a mission design concept that uses high-power solar electric propulsion (SEP) to re-direct one asteroid into the path of another, generating a low-velocity impact as a means of studying solar system evolution. In order to validate existing models and gain further insight in the processes involved, a multi-spacecraft approach is proposed. This concept involves stationing a spacecraft at each asteroid, using them to achieve precise orbits of both asteroids, and one of the spacecraft with high-power SEP to deflect its asteroid into a low-velocity collision with the other. This study will show that it is possible to achieve asteroid collisions with a relative velocity below 10 km/s, allowing direct observations to study solar system dynamics.

PROBLEM STATEMENT

Planet formation and solar system evolution models are built and refined using theories that try to match simulations with the observable solar system. These models trace the processes that formed the planets starting from a protoplanetary disc, a process that involves significant collisions between progressively larger protoplanets.[1] Existing models trace the processes that formed planets starting from a protoplanetary disc. Despite the fidelity of these models, many aspects of planetary formation remain unclear and are of great scientific interest.[2] Few possibilities to test the hypotheses related to these theories exist, since observable collisions in the solar system are scarce and distant. It was evident that comet Shoemaker-Levy 9 was fully merged with Jupiter when it collided in 1994. In contrast, the Deep Impact missions impactor excavated millions of kilograms of mass when it struck Tempel 1 on July 4th, 2005 at a relative velocity of 10.3 km/s.[3,4] Both of these collisions involved relatively small objects striking larger objects, a regime where mutually catastrophic collisions do not occur. These sorts of collisions, between objects of very different sizes, have been observed in recent years.[5,6,7,8] As telescope technology improves it is possible that we will be able to observe more impacts, albeit very rarely and from very large distances. Of greater fundamental interest, are impacts where both bodies are potentially of similar size, resulting in mutually catastrophic collision. Such collisions have occurred in the planetary embryo stage and continue to occur in the asteroid belt, creating asteroid families.

---

[*] MSc Student, Delft University of Technology, Delft, The Netherlands.

[†] Assistant Professor, Colorado Center for Astrodynamics Research, University of Colorado, Boulder, CO 80309.

[‡] Graduate Research Assistant, Colorado Center for Astrodynamics Research, University of Colorado, Boulder, CO 80309.

[§] Assistant Professor, Delft University of Technology, Delft, The Netherlands.

CONCEPT DESCRIPTION

The concept design is based on a multi-spacecraft mission. Two spacecraft are directed to preselected asteroids: the spacecraft “Shepherd” will carry a high-power SEP system to the asteroid that is intended to be redirected; the spacecraft “Spotter” will be sent as an observer to the other asteroid. Each spacecraft arrives at its asteroid early enough to characterize the asteroid, and possibly deploy instruments on the surface. The *Shepherd* spacecraft will then commence redirecting its asteroid in the same fashion as the Asteroid Redirect Mission (ARM).[9] The two spacecraft will be carefully tracked in order to achieve the precise navigation needed to ensure that the two asteroids impact - a key goal of this research. Once the asteroids are confidently on an impact course, the *Shepherd* will move away to monitor the impact and resulting disruption and aggregation. The largest remaining post-collision object is expected to be on a trajectory far different than either of the asteroids prior to the collision. One or both of the spacecraft will be directed to chase and rendezvous with one or more relevant post-collision asteroids to continue monitoring the aggregation processes. A graphical representation of the mission concept can be seen in Figure 1.

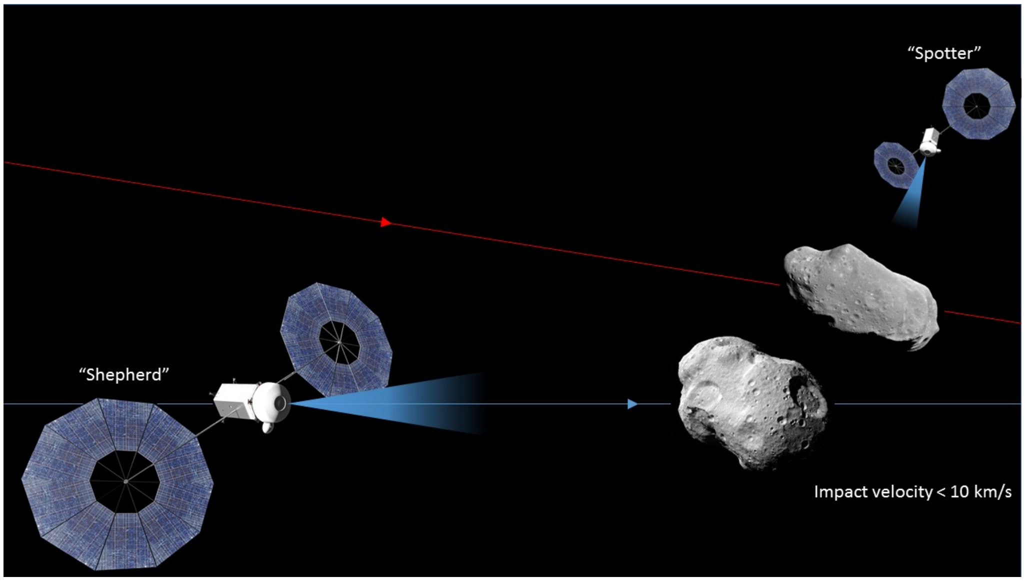

Figure 1. Mission concept. The relative inclination angle of 13 degrees between the two asteroids has been exaggerated for illustration purposes. *Shepherd* and *Spotter* artwork courtesy of Siceloff.[10] Asteroid pictures courtesy of NASA.[11]

METHOD

Using technologies that are being developed in the next decade small-body collision can be induced at energies that could lead to mutual catastrophic disruption and allow a first-hand study of the impact. ARM, including its high-power SEP system,[12] can be used to directly study planet-formation and other solar system evolutionary processes by redirecting an asteroid into the path of another asteroid at relative speeds below 10 km/s. A spacecraft will be placed in the vicinity of each asteroid to study it in depth prior to the collision. Both spacecraft will observe the collision from close proximity, studying the impact, disruption, and aggregation dynamics. The high-power SEP system enables at least one spacecraft to chase and rendezvous with the largest body after the impact to study long-term aggregation processes.

Low-thrust trajectory design

The choice of low-thrust tool is mainly based on the complexity and accuracy that is required. There is a variety of tools and methods that are available such as SEPTOP/VARITOP,[13] Sims-Flanagan/MALTO,[14] Mystic[15] and many more. Due to this being a first order analysis the choice of the tools was driven by speed of computations and the ability to quickly run through the search space had a higher priority rather than the accuracy of the results. Therefore a low-fidelity fast computing software is needed. Boulder Optimization of Low-Thrust Trajectories (BOLTT) tool[16, 17] uses a two point direct shooting method with discrete bounded control similar to the Sims-Flanagan method.[14] Therefore it makes it appropriate software for this proof-of-concept.

Trajectory representation

The Sims-Flanagan approach uses multiple impulsive maneuvers as a way to approximate the continuous thrust done by a low-thrust propulsion system. In order to do that the trajectory is sectioned in several smaller sections that are constrained by control points. These points can, but do not have to necessarily represent a physical occurrence, such as a gravity assist or others. They represent the constrains at the end of each leg of the trajectory. Each leg on its own is then sectioned into segments. The thrust is applied in the middle of each of these segments. From the starting control node the trajectory will be forward propagated and from the next control node it will be backwards propagated until they meet at a so called match point. Both the control nodes as well as the match points guarantee that discontinuity is constrained. The initial conditions that are fed at the control nodes are position, velocity and mass of the spacecraft. A graphical representation of this approach is shown in Figure 2.

In this study, the control nodes represent the spacecraft's encounters with the asteroid of interest. For the *Shepherd's* case the control nodes bounding the first leg represent the launch from Earth and the rendezvous with the first asteroid. The control nodes bounding the second leg represent the departure from the first asteroid and the impact of the first with the second asteroid. In case of the *Spotter* satellite only one leg has been used in order to represent the trajectory leaving from Earth to the rendezvous of the second asteroid.

Propagating these initial conditions through the various segments we use the magnitude and direction of the maneuver along with the specific impulse as control parameters. This propagation makes use of a $RK7(8)13M$ integrator[18] and a two body model. Both the forward as well as the backwards propagations should match in their parameters, those being position, velocity and mass, in order to ensure a reproducible trajectory.

Target selection

Using the Jet Propulsion Laboratory's HORIZONS database[19] 658,882 asteroids with ephemerides ranging from January 1st, 2025 to December 31st, 2035 have been analyzed. Since many of the asteroids do not have a quantifiable data for their mass, this research evaluates what asteroid mass is possible to be moved. Once more data on the asteroid mass is available this design process may be repeated.

Due to ARM's limitations[9] regarding the size of the asteroid that can be moved, which is 500 tons, an upper limit of 200 tons is set for the asteroid mass. This would leave a margin of error of a factor of 2.5. In order to keep the proposed mission timeline feasible for the near future and to ease accessibility to the target asteroid's, only near-Earth objects have been selected as part of this study.

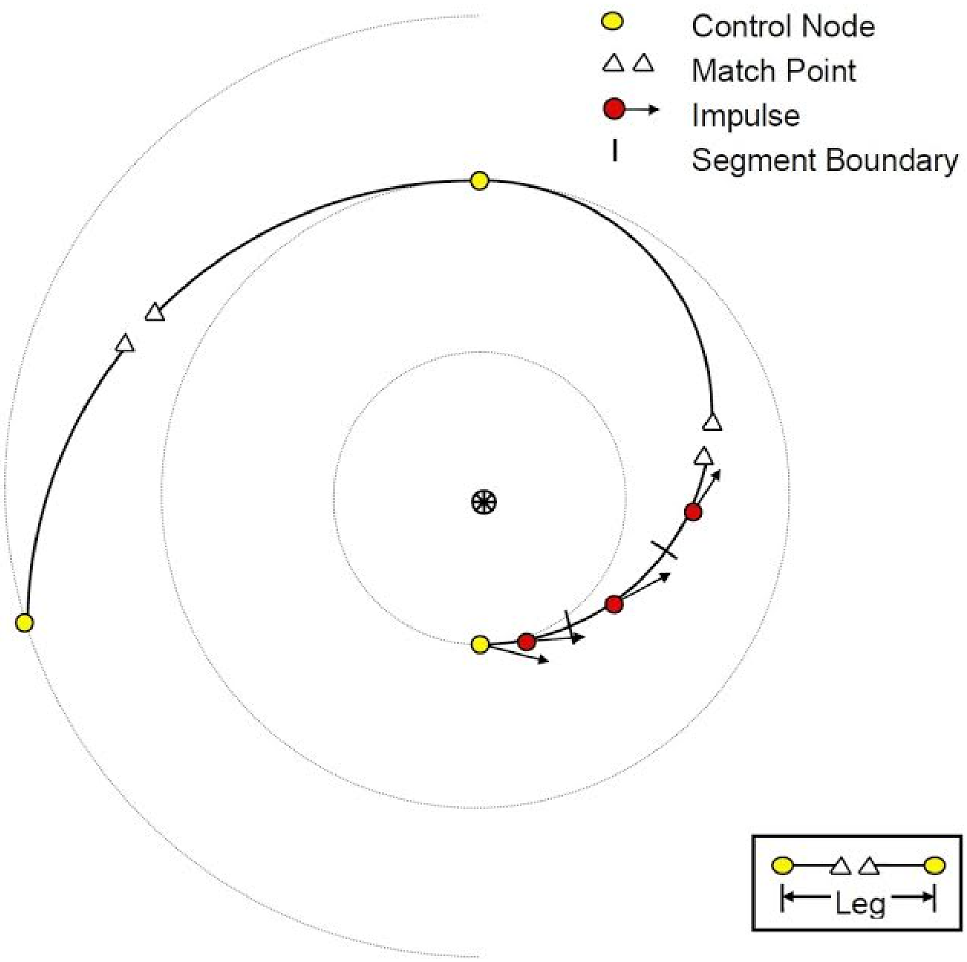

Figure 2. Structure of the Sims-Flanagan formulation on a generic trajectory[14]

This also makes these asteroid easier to be reached rather than objects further away. The asteroid selection has been restricted to asteroids that are either near-Earth or cross the semi-major axis of Earth in the selected time frame. These conditions are described in Equation 1, 2 and 3, where $a_{asteroid}$ and a_{Earth} are the semi-major axis of the asteroid and of Earth respectively and $r_{p,asteroid}$ and $r_{a,asteroid}$ the peri- and apocenter position of the asteroids. If a real mission should follow from this study, further distant objects should be considered instead of near-Earth objects. This would decrease the risk considerably of possible collisions of Earth and/or Earth orbiting satellites with post impact asteroids.

$$0.7AU \leq a_{asteroid} \leq 1.5AU \tag{1}$$

$$r_{p,asteroid} < a_{Earth} \tag{2}$$

$$r_{a,asteroid} > a_{Earth} \tag{3}$$

This filtering process limits the number from the previously mentioned 658,882 down to 3,561. After this process the asteroid's positions relative to each other have been analyzed, compared to each other and ranked according to minimum Euclidean distance.

Preliminary searches have identified several potential asteroid pairs that enable this mission concept.[19] The analyzed missions achieve a relative velocity of less than 10 km/s and occur between 2025 and 2035. Based on these considerations the closest pairing for the asteroids found was asteroid "2001 UN_{16}" and "2008 HF_2". The closest approach occurs on June 3rd, 2032 with a relative distance of 142,870 km between the asteroids and a geocentric distance of 1.712 AU.

RESULTS

Using the promising candidate pair "2001 UN_{16}" and "2008 HF_2" a proof-of-concept is based upon. When comparing the inclinations of "2001 UN_{16}" and "2008 HF_2" of 1.65 and 14.6 degrees it can be estimated that the propellant needed to reach "2008 HF_2" will be considerably higher than in the case of "2001 UN_{16}". Therefore it has been decided to deviate "2001 UN_{16}" instead of "2008 HF_2". The *Shepherd* would in this case redirect asteroid "2001 UN_{16}" onto a collision course with asteroid "2008 HF_2". This has been choosen in order to alleviate the design of the *Spotter* satellite.

The relative velocity greatly depends on the actual mass of "2001 UN_{16}". Using the identified close approach a trajectory for both the *Shepherd* and the *Spotter* have been designed. A graphical representation of the *Shepherd's* trajectory and thrust profile has been computed using BOLTT[16,20] and can be seen in Figures 3 and 4. In Figure 3 the unperturbed trajectory of "2001 UN_{16}" has been omitted due to its closeness to the perturbed trajectory. Figures 5 and 6 show the trajectory and thrust profile of the *Spotter* satellite. For both the *Shepherd* and the *Spotter* we assumed 40 kW of spacecraft power with a 60% jet efficiency and an I_{sp} of 3000 s. Additionally a forced coast of 30 days has been implemented for the *Shepherd* in order to allow a detachment before the impact of "2001 UN_{16}" with "2008 HF_2".

Shepherd Using the date of closest approach of the asteroids a matching trajectory with a minimum TOF has been designed. The data for this trajectory is summarized in Table 1. This trajectory has a total mission time of 980 days, 500 of which are needed to reach asteroid "2001 UN_{16}", 30 days of proximity operation and 450 days in order to reach the impact point. The designed trajectory can deviate "2001 UN_{16}" if it has a mass of up to 86739 kg to an impact course towards the trajectory of "2008 HF_2". The relative velocity between "2001 UN_{16}" and "2008 HF_2" is 7154 m/s. Table 2 gives an overview of the mission time line.

As can be seen from the profile in Figure 4 the selected trajectory uses close to no thrust in the second leg, but still allows for an asteroid mass of about 86 tons to be deflected.

Spotter The *Spotter* uses considerably more propellant than the *Shepherd* satellite since the trajectory of asteroid "2008 HF_2" is in an inclined orbit with an inclination of 14.6 degrees relative to the ecliptic. This can be seen in Table 3. This trajectory allows the *Spotter* spacecraft to arrive at asteroid "2008 HF_2" 30 days before its impact with "2001 UN_{16}" using a total time of flight of 1122 days. This is a longer duration as in the *Shepherd's* case, meaning that this satellite would need to be launched earlier and therefore two launchers would be necessary. The overall mission time line is shown in Table 4. For this case the closest position of the *Spotter* relative to the Sun is 0.3 AU.

Table 1. Relevant data of the *Shepherd's* trajectory

Description	Leg	Value
Initial mass	1	6747 kg
Propellant mass	1	1586 kg
Final mass	1	5161 kg
Asteroid mass	2	86739 kg
Initial mass	2	91900 kg
Propellant mass	2	11 kg
Final mass incl. asteroid	2	91889 kg
Final mass without asteroid	2	5150 kg
Dry mass[21]	-	3950 kg
Total Propellant mass	1 & 2	1597 kg
V_∞ at departure	1	5959 m/s
V_∞ at impact	2	7154 m/s

Table 2. Mission time line of the *Shepherd's* trajectory

Description	Date
Launch date	September 27 2029
Arrival at "2001 UN_{16}"	February 9 2031
End of proximity operations	March 11 2031
Asteroid impact with "2008 HF_2"	June 3 2032

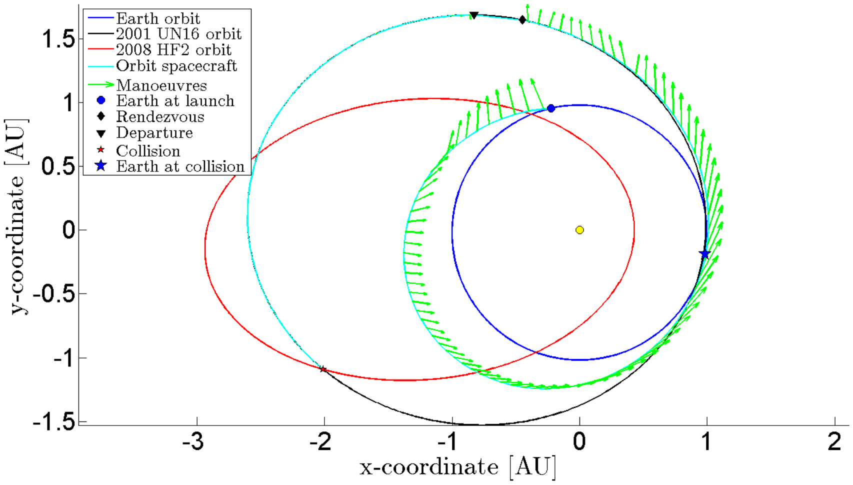

Figure 3. Shepherd trajectory design

Table 3. Relevant data of the *Spotter's*' trajectory

Description	Value
Initial mass	10719 kg
Final mass	5150 kg
Propellant mass	5569 kg
Dry mass	5150 kg
V_∞ at departure	6000 m/s

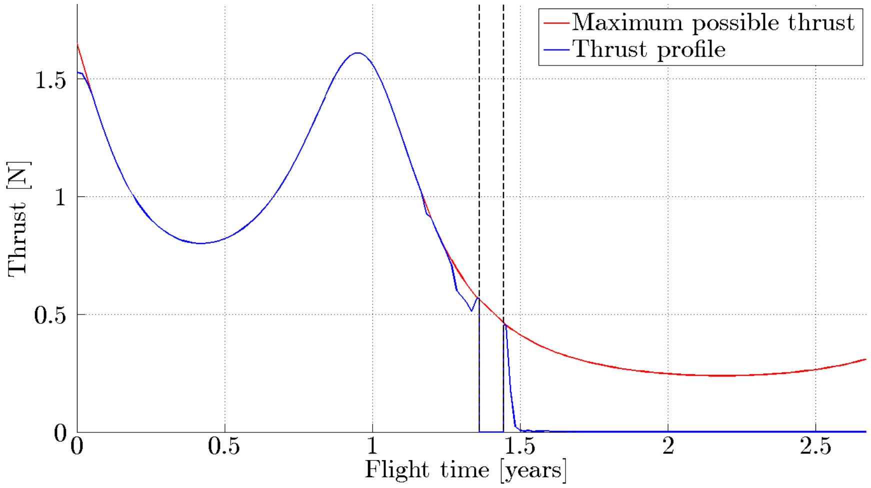

Figure 4. ***Shepherd's*** **thrust profile**

Table 4. Mission time line of the *Spotter's* trajectory

Description	Date
Launch date	April 8 2029
Arrival at "2008 HF$_2$"	May 4 2032
Asteroid impact with "2001 UN$_{16}$"	June 3 2032

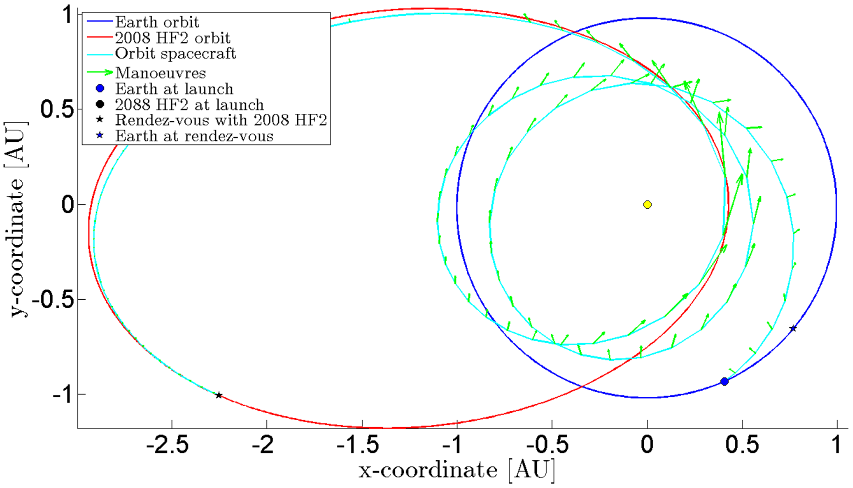

Figure 5. ***Spotter's*** **trajectory profile**

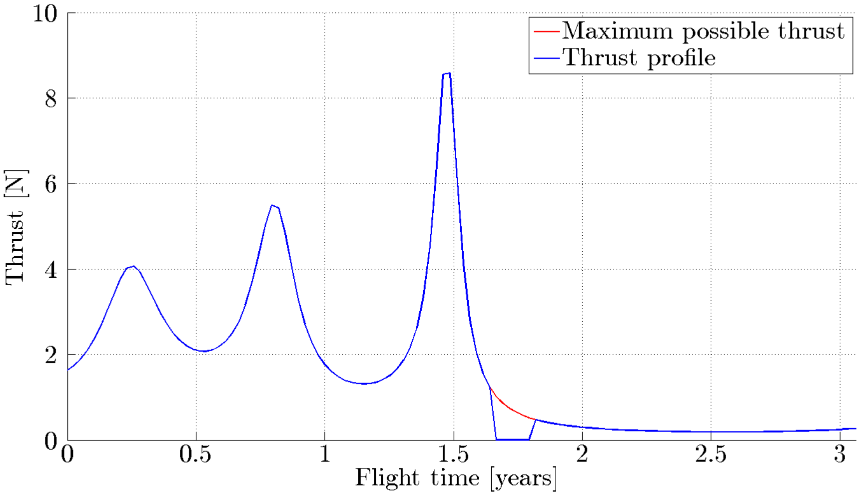

Figure 6. ***Spotter's*** **thrust profile**

CASE 2: IMPACTING 20 DAYS EARLIER

A variation of the first trajectory for both the *Shepherd* and the *Spotter* has been analyzed. In this case the impact between "2001 UN_{16}" and "2008 HF_2" does not occur on their relative closest distance to each other, but 20 days earlier. This additional time would be beneficial for the *Shepherd's* navigation and guidance towards the collision point.

Shepherd Table 5 summarizes the data of this trajectory. The total mission duration is of 1020 days, 521 of which are needed to reach asteroid "2001 UN_{16}", 30 days of proximity operation and 467 days in order to reach the impact point. The designed trajectory can deviate "2001 UN_{16}" if it has a mass of up to 9324 kg to an impact course towards the trajectory of "2008 HF_2". The relative velocity between "2001 UN_{16}" and "2008 HF_2" is 7645 m/s. Table 6 gives an overview of the mission time line.

Table 5. Relevant data of the ***Shepherd's*** **trajectory for case 2**

Description	Leg	Value
Initial mass	1	7258 kg
Propellant mass	1	1738 kg
Final mass	1	5520 kg
Asteroid mass	2	9324 kg
Initial mass	2	14844 kg
Propellant mass	2	370 kg
Final mass incl. asteroid	2	14474 kg
Final mass without asteroid	2	5150 kg
Dry mass[21]	-	3950 kg
Total Propellant mass	1 & 2	2108 kg
V_∞ at departure	1	3763 m/s
V_∞ at impact	2	7645 m/s

Table 6. Mission time line of the *Shepherd's* trajectory for case 2

Description	Date
Launch date	July 29 2029
Arrival at "2001 UN_{16}"	January 1 2031
End of proximity operations	February 2 2031
Asteroid impact with "2008 HF_2"	May 14 2032
Total time of flight	1020 days

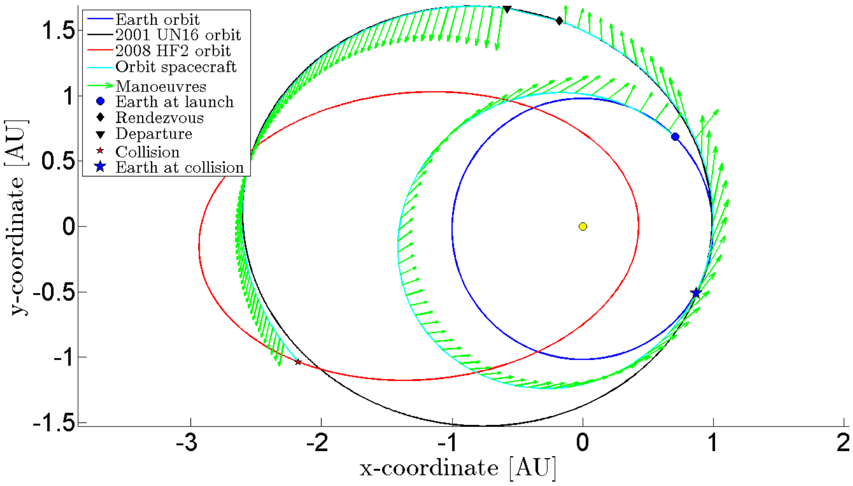

Figure 7. *Shepherd's* trajectory design

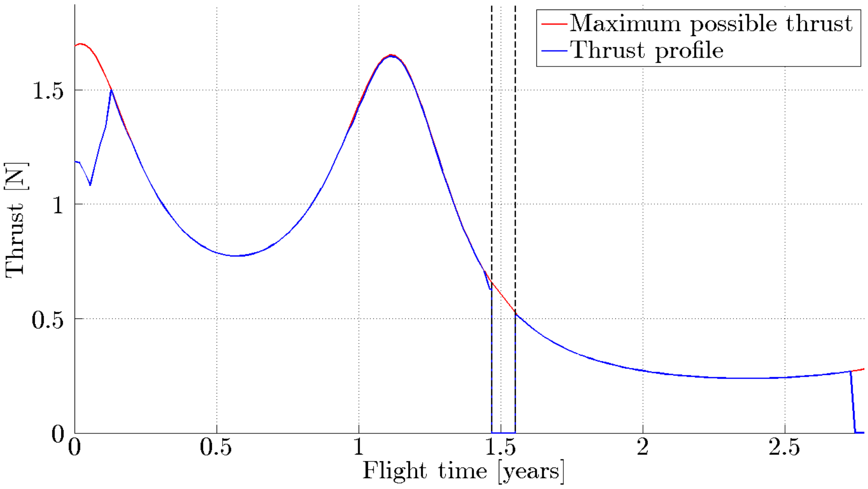

Figure 8. *Shepherd's* thrust profile

Spotter For this case the *Spotter* uses 3216 kg more propellant than in the previous case. This can be seen comparing Tables 3 and 7. The total time of flight for this case is of 1125, which is 3 days longer than in the previous case. Relevant data for this case is shown in Table 7, where the overall mission time line is shown in Table 8. Figures 9 and 10 show the trajectory and the thrust profile for the *Spotter*. Due to the suboptimality of the arrival date the *Spotter* requires additional energy and therefore approaches the Sun at 0.2 AU which is a a closer relative position than in the previous case.

Table 7. Relevant data of the *Spotter's* trajectory for case 2

Description	Value
Initial mass	13935 kg
Final mass	5150 kg
Propellant mass	8785 kg
Dry mass	5150 kg
V_∞ at departure	6000 m/s

Table 8. Mission time line of the *Spotter's* trajectory

Description	Date
Launch date	March 17 2029
Arrival at “2008 HF_2”	April 14 2032
Asteroid impact with “2001 UN_{16}”	May 14 2032

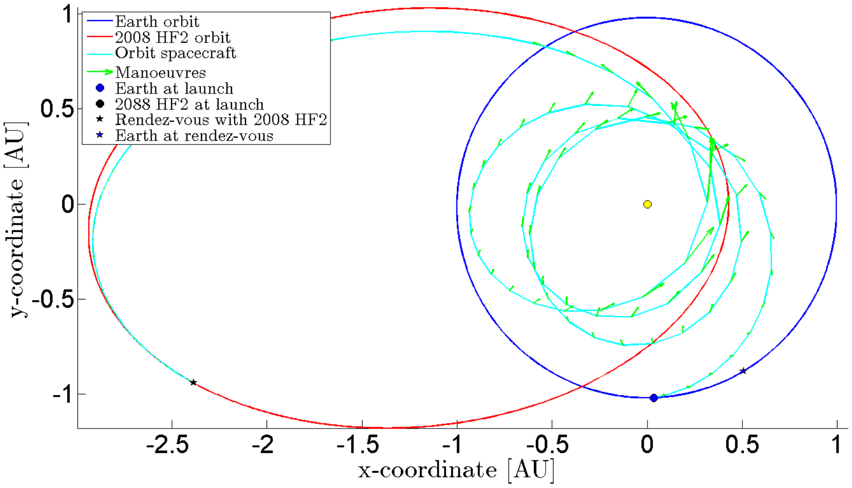

Figure 9. *Spotter's* trajectory profile

Considerations For this mission design the closest relative position to the Sun is 0.3 AU, for the first case, and 0.2 AU for the second analyzed case. Due to the close position relative to the Sun degradation due to solar radiation could be a limiting factor in designing the necessary hardware. Therefore special attention should be given to this when designing the thermal control design. Alternatively, the trajectory could be redesigned to keep a larger distance from the Sun.

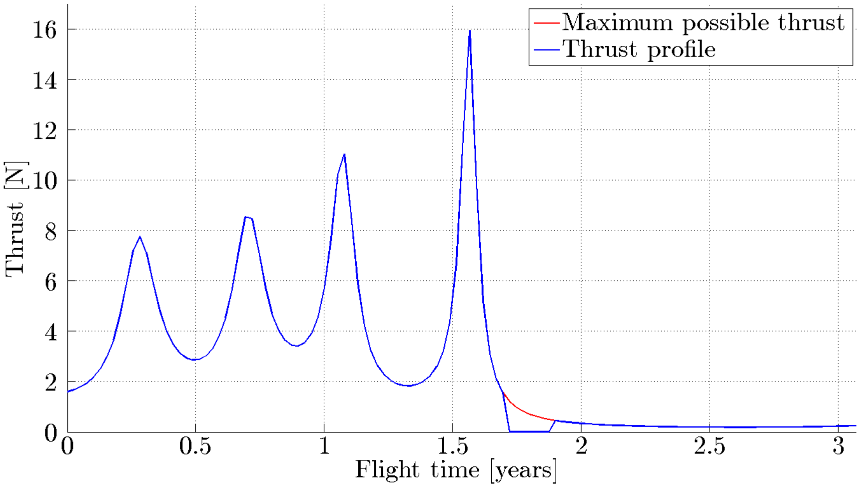

Figure 10. ***Spotter's*** **thrust profile**

Regarding the first analyzed case, it is remarkable that the second leg of the *Shepherd's* satellite uses only 11 kg of propellant. This is not surprising since both asteroids are almost on collision course.

The offset of impact from the first case analyzed, which occurs at the closest relative position of both asteroids, is of 20 days. This relatively small variation has a considerable increase of propellant mass of 511 kg and of the possible asteroid mass that can be deflected, which is a factor of 9 times smaller. This shows that a relative small variation has a significant impact on the mission design, making it very sensitive to changes in their setup.

SIGNIFICANCE TO ASTRODYNAMICS AND/OR SPACE-FLIGHT MECHANICS

The most significant scientific benefit of this concept is to directly observe a collision between two asteroids of similar mass, simulating one step in a planet-formation process.[22] Should this result in a catastrophic disruption of either asteroid or not, this mission concept probes the interior structure of two small bodies and their responses to a major collision.

This concept provides elaborate and direct observations of the very dynamics that transform solar systems from dust clouds into diverse families of planets orbiting a star. This knowledge is relevant both for the understanding of Earth itself, as well as for any planet, Moon, or small body in the solar system.

This paper offers an additional benefit; the utilization of these techniques in a potential asteroid deflection scenario to avoid an Earth impact. Utilizing one small body to deflect another, either through a direct kinetic impact or using it as a gravity tractor, may prove to be a highly effective method depending on which asteroid is at risk of impacting Earth. Every technique developed in this paper, from the initial search for promising small body pairs to the optimal low-thrust trajectory design will help to prepare for an eventual asteroid deflection scenario.

CONCLUSION

To conclude it can be said that in theory a mission such as described in this paper could be achieved with technology that should be available within the next decade. Additional extensive research needs to be done in the areas of threat detection such as near-Earth asteroids observation especially regarding their mass and composition.

This paper has shown that two vehicles may visit two different asteroids, using 7,166 kg of fuel, a 40 kW SEP system, and a total of 1122 days. Thirty days of proximity operations are on the short side, but may be sufficient to determine the shape, position, size, spin rate and other mission relevant data of "2001 UN_{16}". This is necessary for the terminal guidance navigation in order to guarantee a successful impact with "2008 HF_2". This one will on the other hand be observed by the *Spotter* which will determine its position, shape, spin rate, chemical composition, density and other mission relevant data. Using this information from the *Shepherd* and *Spotter* this will ensure a successful impact of the targeted asteroids.

The trajectory of the first case of this proof-of-concept has been designed with minimum time of flight in mind. A variation of it, namely case 2, gave an additional 20 days for the guidance and navigation during the last leg before impact, but this came with a 511 kg increase of propellant relative to *Shepherd's* trajectory of the first case.

ACKNOWLEDGMENT

A special thanks goes to Daniel J. Scheeres, that provided insightful experience and helped to guide the research direction of this paper, and to the Colorado Center of Astrodynamic Research (CCAR) for hosting and supporting this research.

REFERENCES

[1] S. Taylor, *Solar System Evolution: A New Perspective,2nd Edition*. Cambridge University Press, 2001.

[2] Committee on the Planetary Science Decadal Survey, *Vision and Voyages for Planetary Science in the Decade 2013-2022*. The National Academies Press, 2011.

[3] J. Amos, "Impactor ejects mighty water mass," April 4 2006. `http://news.bbc.co.uk/2/hi/science/nature/4871934.stm`.

[4] M. McKee, "Deep Impact collision ejected the stuff of life," September 7 2005. `http://www.newscientist.com/article.ns?id=dn7961`.

[5] D. Jewitt, H. Weaver, J. Agarwal, M. Mutchler, and M. Drahus, "A recent disruption of the main-belt asteroid P/2010 A2," *Nature*, Vol. 467, 2010, pp. 817–819.

[6] C. Snodgrass, C. Tubiana, J.-B. Vincent, H. Sierks, S. Hviid, R. Moissl, H. Boehnhardt, C. Barbieri, D. Koschny, P. Lamy, H. Rickman, R. Rodrigo, B. Carry, S. Lowry, R. J. M. Laird, P. R. Weissman, F. A., S. Marchi, and t. OSIRIS team, "A collision in 2009 as the origin of the debris trail of asteroid P/2010 A2," *Nature*, Vol. 467, 2010, pp. 814–816.

[7] J. Harrington, D. Weaver, and D. Jewitt, "NASAs Hubble captures first images of aftermath of possible asteroid collision," October 13, 2010. `http://www.nasa.gov/home/hqnews/2010/oct/HQ_10-253_HST_Astro_Collison.html`.

[8] D. Jewitt, "The Active Asteroids," *The Astronomical Journal*, Vol. 143, No. 66, 2012.

[9] J. Brophy, L. Friedman, and F. Culick, "Asteroid Retrieval Feasibility," *IEEE Aerospace Conf.*, 2012.

[10] S. Siceloff, "Study: Asteroids Provide Sustainable Resource," `http://www.nasa.gov/mission_pages/asteroids/news/asteroidmining.html#.Vb_wLflViko`.

[11] NASA, "Images of asteroids Ida & Dactyl," `http://neo.jpl.nasa.gov/images/ida.html`.

[12] N. Strange, D. Landau, T. McElrath, G. Lantoine, T. Lam, M. McGuire, L. Burke, M. Martini, and D. J., "Overview of Mission Design for NASA Asteroid Redirect Robotic Mission Concept," *33rd International Electric Propulsion Conference (IEPC2013)*, Washington, D.C., October 6-10, 2013.

[13] C. Sauer, "VARITOP/SEPTOP/SAIL User's Manual," tech. rep., Jet Propulsion Laboratory, 2003.

[14] J. Sims, P. Finlayson, E. Rinderle, and T. Vavrina, M.A.and Kowalkowski, "Implementation of a Low-Thrust Trajectory Optimization Algorithm for Preliminary Design," *Collection of Technical Papers - AIAA/AAS Astrodynamics Specialist Conference and Exhibit*, Keystone, Colorado, 21-24 August 2006.

[15] G. Whiffen, "Mystic: Implementation of the Static Dynamic Optimal Control Algorithm for High-Fidelity, Low-Thrust Trajectory Design," *Collection of Technical Papers - AIAA/AAS Astrodynamics Specialist Conference and Exhibit*, Keystone, Colorado, 21-24 August 2006.

[16] S. De Smet, J. Parker, J. Herman, and R. Noomen, “Preliminary Design of a Crewed Mars Flyby Mission using Solar Electric Propulsion,” *24th AAS/AIAA Space Flight Mechanics meeting - AAS 14-366*, Santa Fe, NM, January 26-30, 2014.

[17] S. De Smet, J. Parker, J. Herman, and R. Noomen, “Mission Design for a Crewed Earth-Venus-Mars-Flyby Mission using Solar Electric Propulsion,” *32nd annual AAS Guidance and Control Conference - AAS 15-091*, Breckenridge, CO, January 30 - February 4, 2015.

[18] P. Prince and J. Dormand, “High order embedded Runge-Kutta formulae,” *Journal of Computational and Applied Mathematics*, Vol. 7, No. 1, 1981, pp. 67 – 75, http://dx.doi.org/10.1016/0771-050X(81)90010-3.

[19] J. Giorgini, D. Yeomans, A. Chamberlin, P. Chodas, R. Jacobson, M. Keesey, J. Lieske, S. Ostro, E. Standish, and R. Wimberly, “JPL’s On-Line Solar System Data Service,” *Bulletin of the American Astronomical Society*, Vol. 32, No. 3, 2005, pp. 71–92.

[20] S. De Smet, “Preliminary Design of a Crewed Mars Flyby Solar Electric Propulsion Mission,” Master’s thesis, Delft University of Technology, December 2014. `http://repository.tudelft.nl/view/ir/uuid%3A289554a2-77bf-4692-9e47-39ff75015a19/`.

[21] “Asteroid Redirect Mission Reference Concept,” `http://www.nasa.gov/pdf/756122main_Asteroid%20Redirect%20Mission%20Reference%20Concept%20Description.pdf`.

[22] Z. Leinhardt and S. Stewart, “Full numerical simulations of catastrophic small body collisions,” *Icarus*, Vol. 199, 2009, pp. 542–559.