Trajectory Browser: An Online Tool for Interplanetary Trajectory Analysis and Visualization

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Abstract—**The Trajectory Browser is a web-based tool developed at the NASA Ames Research Center for finding preliminary trajectories to planetary bodies and for providing relevant launch date, time-of-flight and ΔV requirements. The site hosts a database of transfer trajectories from Earth to planets and small-bodies for various types of missions such as rendezvous, sample return or flybys. A search engine allows the user to find trajectories meeting desired constraints on the launch window, mission duration and ΔV capability, while a trajectory viewer tool allows the visualization of the heliocentric trajectory and the detailed mission itinerary. The anticipated user base of this tool consists primarily of scientists and engineers designing interplanetary missions in the context of pre-phase A studies, particularly for performing accessibility surveys to large populations of small-bodies. The educational potential of the website is also recognized for academia and the public with regards to trajectory design, a field that has generally been poorly understood by the public. The website is currently hosted on NASA-internal URL http://trajbrowser.arc.nasa.gov/ with plans for a public release in early 2013.**

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NOMENCLATURE

C3	Characteristic specific energy (km^2/s^2)
DSM	Deep Space Maneuver
ΔV	Change in velocity (km/s)
LEO	Low Earth Orbit
NEO	Near Earth Object
TCM	Trajectory Correction Maneuver

1. INTRODUCTION

During the conceptual design phase of a spacecraft mission, there is typically a need to determine the constraints a particular transfer trajectory will impose on the mission. For example, for a Mars-bound spacecraft, when are the available launch windows for the next ten years? How do the launch C3 requirements vary for each launch window? While it may be possible to determine trajectory requirements to a single well-known body such as Mars from published tables [1], it is usually not possible to do so for missions to small-bodies, a class of celestial bodies that are of increasing interest to space agencies for both robotic and human exploration. For example, if performing a design study for an asteroid sample-return mission, one would want to know what objects larger than 1 km can be reached during a given launch year and with given mission duration and ΔV (indicator of propellant requirements) constraints. If there are multiple asteroids that meet these constraints, a particular object could be selected based on the type of asteroid and science potential. However if there are no asteroids that meet these constraints, one would want to know what is the largest asteroid that can be visited under the same mission constraints. Alternatively, how much additional ΔV is required to reach the desired 1 km-sized asteroid? What are the backup opportunities if there is a launch slip?

Another class of mission design questions relate to trajectories for round-trip transfers to Near-Earth Objects (NEOs) for human missions in the next decade. For example, a mission designer sizing a robotic precursor spacecraft would want an up-to-date list of low-ΔV NEO candidates for a human mission, and then want to find out what are the ΔV and mission duration requirements to visit this object with a robotic precursor. When is the earliest opportunity to do so, and for how long can the precursor explore the asteroid before a human mission is staged?

This paper describes a tool to answer these typical questions and others posed during the conceptual design phase of a mission. A web-based interface allows any individual (who need not have a background in orbital mechanics) to find transfer trajectories from Earth to planets and small-bodies in the Solar System. By specifying constraints on typical mission parameters like launch year, mission duration and total ΔV, a user can rapidly and iteratively perform early design trades to determine mission feasibility and produce a preliminary assessment of the trajectory requirements.

This web-based tool is called the Trajectory Browser, and is hosted at the NASA Ames Research Center at the URL http://trajbrowser.arc.nasa.gov/ . This paper will first explain how transfer trajectories are computed and stored in a database, then describe the website interface and search engine for querying this database, and finally discuss the potential of the website for participatory exploration.

2. TRAJECTORY GENERATION

The Trajectory Browser is a search engine that allows a user to find impulsive trajectories to planetary destinations meeting specific constraints. The tool does not solve trajectories when queried, but instead pulls desired solutions from a pre-computed database of trajectories that is periodically maintained with some of the latest small-body discoveries. It is meant to be used as a first-cut survey to obtain preliminary accessibility results from a large population of small-bodies. Results can then be used as initial guesses for trajectory design software yielding high-fidelity impulsive or low-thrust solutions.

Ephemerides

The Trajectory Browser currently holds solutions for transfers from Earth to all planets and known NEOs. Ephemerides for the planets make use of DE-421 [2], while the JPL HORIZONS system [3] is used to obtain annual state vectors of NEOs from 2010 through 2050. To compute position and velocity information at a given epoch, a weighted extrapolation of two-body propagation is used from the bounding state vectors, providing sufficient ephemeris accuracy for most small-bodies in the context of a preliminary trajectory survey. However, this extrapolation suffers when a small-body makes a close planetary approach since a massive body will considerably perturb its orbit. Therefore, for a small number of near-Earth asteroids making close-approaches to the Earth or other massive bodies, a coarser sampling of state vectors is obtained around the close-approach event to provide improved accuracy for trajectories launching or returning near these close-approaches. Up-to-date lists of known NEOs, as well as their designation, name, absolute magnitude and orbit condition code are obtained from the JPL Small-Body Database [4].

Transfer Trajectories

The transfer orbits stored in the Trajectory Browser are computed with a Lambert solver, an approximate but computationally-efficient method ideal for broad surveys of small-bodies. An iterative patched conic algorithm solves for local trajectories within a body's sphere of influence (e.g. Earth departure hyperbola) ensuring a continuous conic trajectory throughout the mission's itinerary. Perturbations from third-bodies, solar radiation pressures, finite-duration burns and other sources are not considered and deemed to be outside the scope of a preliminary trajectory survey.

A high-fidelity orbit would also include small trajectory-correction maneuvers (TCM) to compensate for navigation errors, but these are not accounted for in the patched conic trajectory model and are assumed to be within the noise of its approximate model.

Table 1. Computed mission classes

Trajectory Type	Encounter Type	Example Mission
One-way	Flyby	Mariner 4
	Rendezvous	NEAR Shoemaker
Round-trip	Flyby	Stardust
	Rendezvous	Hayabusa

Four classes of missions are computed as displayed in Table 1. All trajectories are assumed to launch from Earth and visit a single destination. In addition to direct transfers from Earth to destination, gravity-assist trajectories are also computed that swing-by the Earth (2:1 resonance), Venus or Mars.

Database

A user performing a search in the Trajectory Browser is in effect filtering through a database of trajectories with specific constraints on destination, launch date, duration and ΔV. A user is therefore limited to searching a subset of pre-computed trajectories, since the trajectories entered into the database were themselves calculated with constraints in mind. This means that a user cannot set higher constraints than those used to generate the database. These constraints vary by mission type and destination and are summarized in Table 2. ΔVs are evaluated from a 200 km altitude low-Earth orbit (LEO).

Table 2. Global constraints

Earth launch window	Jan-01-2010 to Jan-01-2040
Maximum mission duration	10 years for round-trip rendezvous 5 years for others
Minimum stay time at destination (round-trip rendezvous)	5-100 days depending on mission duration
Maximum total ΔV	10 km/s for rendezvous 6 km/s for one-way flyby 7 km/s for round-trip flyby
Solver time-step	5-16 days depending on mission duration

To allow a user to trade total mission ΔV with duration, the locally optimal pareto frontier points of each transfer opportunity (sometimes referred to as 'pork chops') are stored in the Trajectory Browser database (Figure 1).

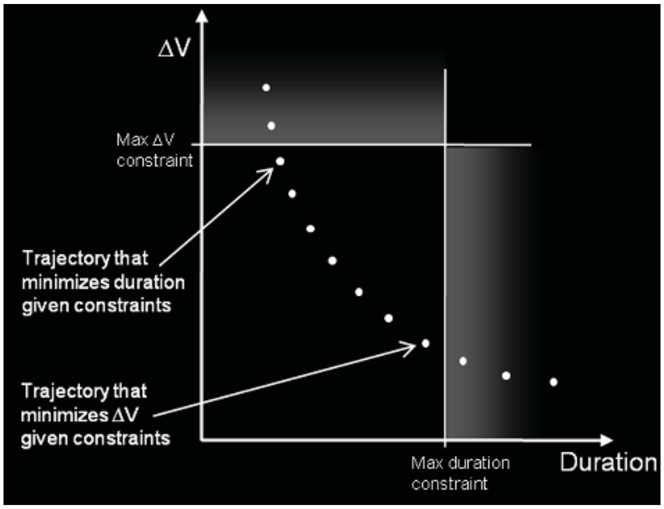


Figure 1. Pareto-optimal trajectories minimizing ΔV and mission duration given user-specified constraints.

Trajectories are routinely updated to incorporate the latest NEO discoveries and updated orbit solutions.

Limitations

It is important to note that the Trajectory Browser is a tool for performing preliminary surveys of mission feasibility to planetary bodies. Listed trajectories constitute a first order approximation and are insufficient for detailed design or operations. Due to ephemeris uncertainty, fidelity, time-space discretization and patched-conic methods, trajectories stored on the website only represent approximations of actual trajectories that would be found using high-precision numerical propagators and design methods. Furthermore, the Trajectory Browser does not hold all possible trajectory configurations, only the most-straightforward ones: it is always possible to craft complex gravity assist trajectories and with higher ΔV or duration constraints.

It is also important to understand limitations of the Trajectory Browser with respect to design trades. While it is possible to crudely trade total ΔV with mission duration, there are many more trades that are not available in the Trajectory Browser and outside the scope of its use as a preliminary trajectory survey. For example, using numerical techniques one can trade C3 vs. post-injection ΔV vs. rendezvous stay time vs. flyby speed, etc. A user cannot specify constraints on these other parameters since the trajectories in the database were only selected for a ΔV vs. mission duration trade, and so such a constraint will not give a fair representation of available trajectories.

3. WEBSITE INTERFACE

The Trajectory Browser features a web-based search form in which the user inputs desired trajectory constraints. After clicking 'Search' the website loads a list of trajectories meeting the user's constraints. The user can then handpick a trajectory of interest among the returned results and view its detailed itinerary and the heliocentric view of its trajectory.

Search

The search form has two sections (see Figure 2): one for choosing the destination and another for specifying the trajectory constraints.

A user can choose to search through all known NEOs and specify if they are only interested in asteroids and/or comets, and put constraints on its absolute magnitude (indicator of the size of a small-body) and orbit condition code (indicator of how well the object's orbit is known). Alternatively, or in addition to, the user can specify a custom list of objects to include in the search. These can either be objects in the database that are not NEOs, such as a planet, or a custom list of NEOs relevant to the user's mission which can be generated with the JPL Small-Body Search Engine [4]. Objects may be entered by SPK-ID, asteroid number or name/designation. For example, to search for trajectories to the asteroid Apophis, one may enter its SPK-ID '2099942', its asteroid number '99942' or simply its name 'Apophis'.

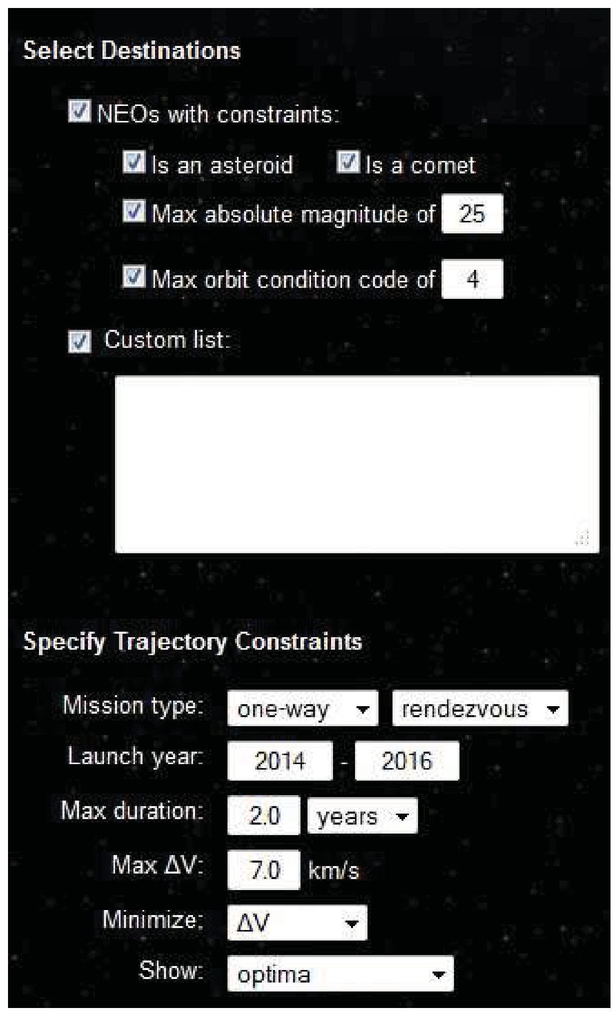


Figure 2. Search page

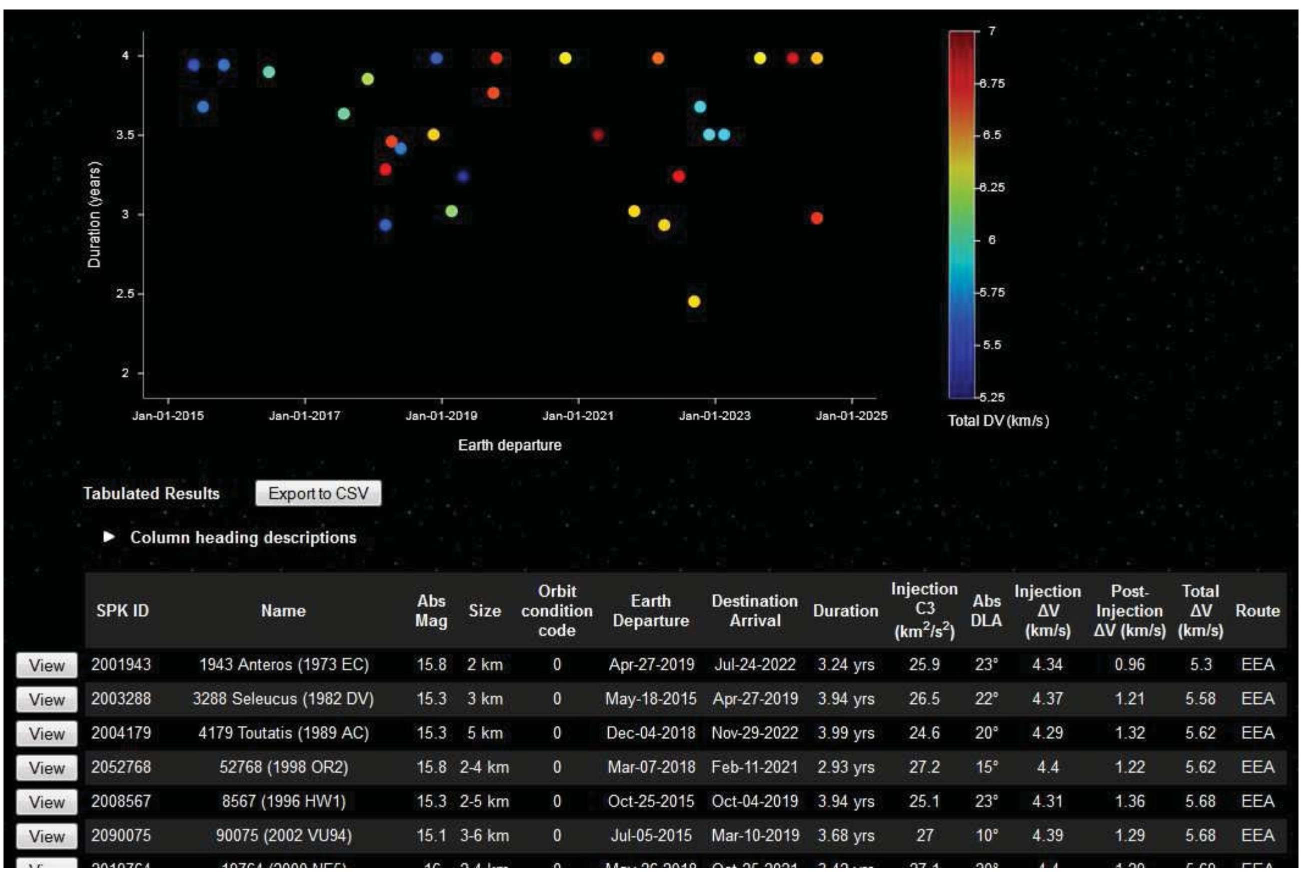
A user can then specify the nature of the mission, which can be either a one-way or round-trip rendezvous or flyby, as indicated in Table 1. Next, a range of acceptable launch years for the mission is chosen, followed by the maximum desirable mission duration. A bound is then placed on the maximum mission ΔV from a starting 200 km altitude circular LEO through the end of the mission. This ΔV includes the launch vehicle's injection burn past Earth escape velocity (minimum of 3.1 km/s) as well as any maneuvers required after injection such as asteroid rendezvous and departure burns. For some missions such as one-way flybys no other maneuvers may be required after injection.

The user then specifies the parameter to minimize if more than one trajectory per destination is found to meet their desired constraints, which can be either ΔV (typical for most missions) or total mission duration. Finally, the user can choose to display either the optimal trajectories (as defined by the user in the previous boxes) for each destination object under consideration, or display their local optima. The latter option allows the same destination object to appear multiple times in the search results if it can be accessed on more than one opportunity within the specified launch window, which is most useful when looking for a list of launch opportunities to the same object across a broad launch window.

Results

Figure 3 shows the screenshot of a typical search results page. Trajectories that were found to meet the user's constraints are displayed in both graphical and tabular formats. The graphical results show the scatter of trajectories as a function of launch date (x-axis) and mission duration (y-axis) and color-coded by total ΔV. This perspective is useful for visualizing the distribution of available opportunities within the available launch window and trajectory constraints.

Below this graph, the same results are presented in tabular format with one row per trajectory. The columns consist of relevant parameters of the destination (ID, name, absolute magnitude, orbit condition code) and the trajectory (Launch date, arrival date, stay time at destination, injection C3, ΔV, flyby speed, etc). The user has the option of sorting and showing/hiding columns to facilitate the hand-picking of one or several trajectories suitable for their mission design. If not satisfied with the results, the user can modify constraints from the search page that may be too restrictive, for example allowing a longer mission duration that would enable more interesting asteroids to visited, thus quickly iterating the design process. When satisfied with the results, the user can then either export the results to a comma-separated value (CSV) file or can bookmark the URL of the results page containing the user's search criteria. The latter



	SPK ID	Name	Abs Mag	Size	Orbit condition code	Earth Departure	Destination Arrival	Duration	Injection C3 (km^2/s^2)	Abs DLA	Injection ΔV (km/s)	Post-Injection ΔV (km/s)	Total ΔV (km/s)	Route
View	2001943	1943 Anteros (1973 EC)	15.8	2 km	0	Apr-27-2019	Jul-24-2022	3.24 yrs	25.9	23°	4.34	0.96	5.3	EEA
View	2003288	3288 Seleucus (1982 DV)	15.3	3 km	0	May-18-2015	Apr-27-2019	3.94 yrs	26.5	22°	4.37	1.21	5.58	EEA
View	2004179	4179 Toutatis (1989 AC)	15.3	5 km	0	Dec-04-2018	Nov-29-2022	3.99 yrs	24.6	20°	4.29	1.32	5.62	EEA
View	2052768	52768 (1998 OR2)	15.8	2-4 km	0	Mar-07-2018	Feb-11-2021	2.93 yrs	27.2	15°	4.4	1.22	5.62	EEA
View	2008567	8567 (1996 HW1)	15.3	2-5 km	0	Oct-25-2015	Oct-04-2019	3.94 yrs	25.1	23°	4.31	1.36	5.68	EEA
View	2090075	90075 (2002 VU94)	15.1	3-6 km	0	Jul-05-2015	Mar-10-2019	3.68 yrs	27	10°	4.39	1.29	5.68	EEA

Figure 3. Results page

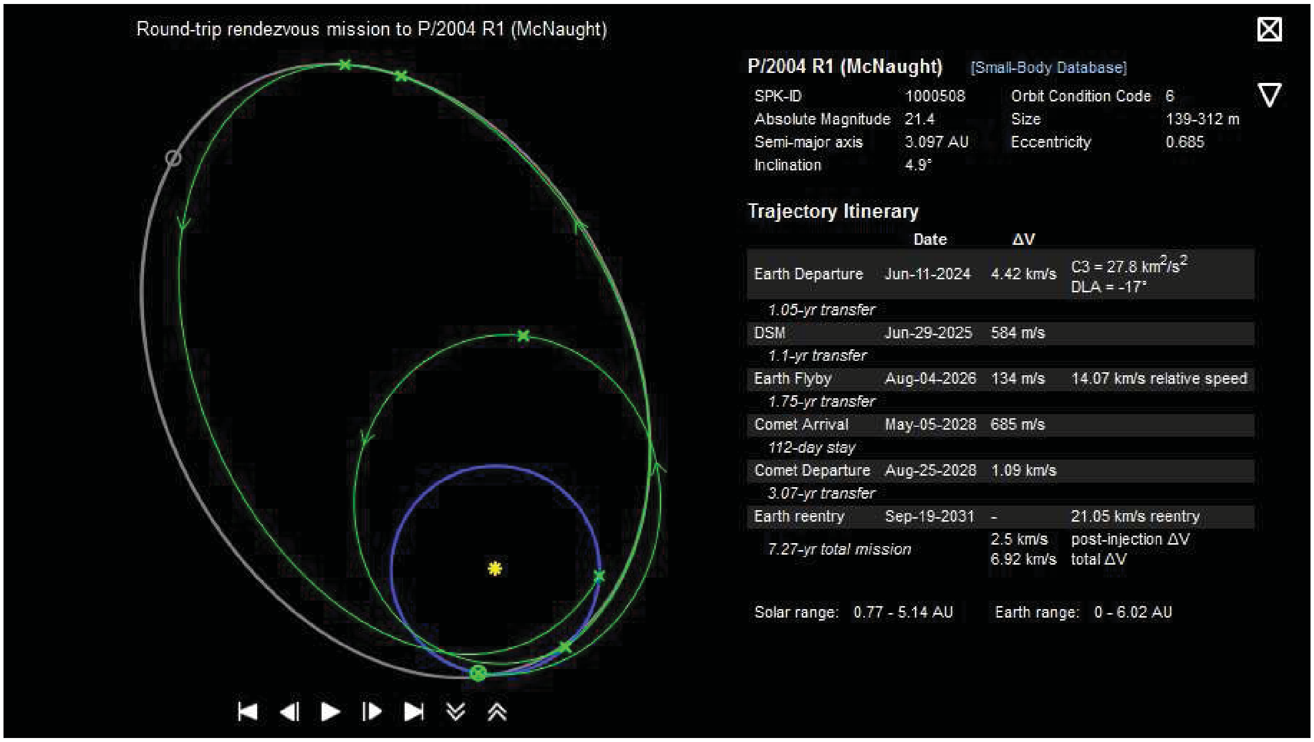


Figure 4. Trajectory viewer diagram

method is useful if a user wishes to repeatedly perform the same search to check for new small-body discoveries that match their mission parameters.

Viewer

While browsing the graphical or tabulated results, a user may click on a trajectory of interest to view its detailed itinerary and trajectory diagram in a popup window as illustrated in Figure 4. The detailed itinerary allows the user to see the date and ΔV requirement of every event along the trajectory, such as launch date and C3, rendezvous ΔV, departure date, flyby distance, etc, and the elapsed time between these events. The popup also displays the destination’s osculating orbital parameters and estimated size. Also available are the minimum and maximum distances the spacecraft would be at from the Earth and the Sun throughout its trajectory, which is useful for scaling spacecraft communication and power budgets respectively. A heliocentric view of the trajectory aides the user in visualizing the transfers and events of a trajectory.

4. Participatory Exploration

The primary intended user base for the Trajectory Browser consists of scientists and engineers performing pre-phase A studies for interplanetary missions. These users may come from NASA, government contractors, the private sector, the science community or international groups. The rapid-search nature of the tool allows them to find mission opportunities for their particular application.

It is also recognized that a public-facing Trajectory Browser website would also serve as a great resource and educational tool for academia and interested members of the public. NASA defines participatory exploration, an open government initiative, as [5]:

> “Participatory exploration is the active involvement of individuals as contributors to and collaborators in NASA's research, science, and exploration activities. Participatory Exploration embodies far more than simply exposing people to or educating them about NASA's discoveries and exploration activities. It encourages individuals to contribute their creativity and capabilities to NASA's mission of discovery and invites them to share in the excitement of building our future”

Trajectory design is a field that is maybe not very well understood by the general public due to its unintuitive nature. A side benefit of the Trajectory Browser website is the democratization of trajectory design: any person can now search for trajectories and better understand what types of orbital transfers are possible by varying the constraints on the search page and comparing the results. For example, one can understand the tradeoff between mission ΔV and duration for a round-trip Mars mission be varying the appropriate constraints, and “discover” that extra ΔV is more likely to reduce the transit time to and from Mars and allow a significantly longer time to be spent on Mars even though total mission duration maybe slightly shorter.

To capitalize on the potential on the website for education, an online user guide is provided that explains in detail the methodologies used to compute the trajectories stored on the website. More importantly, it also describes the limitations of the tool and what it can and cannot be used for, which also serves as a reference to experienced scientists and engineers using the tool for conceptual mission design.

A webpage with example Trajectory Browser queries is provided as a starting point for exploring the diversity of trajectories and destinations available on the website. Several generic queries are listed such as 'Rendezvous opportunities with Mars for the next 10 years' or ' NEOs accessible on a 1-year mission in the 2020's'. Once a user clicks on a particular query, he/she may then adjust specific constraints as desired to obtain a suitable trajectory.

One can envision, for example, undergraduate course homework to find trajectory opportunities for robotic precursor missions to asteroids that may one day be visited on a human mission. The student would first have to obtain a list of NEO candidates that meet the round-trip human mission constraint, and then find one-way robotic trajectories before the human mission is set to occur to these same objects.

To aid with the visualization and understanding of the dynamics of trajectories in the Solar System, the trajectory viewer tool described in section 3 is supplemented with a feature for animating the mission by showing the movement of the spacecraft and planetary bodies linearly with time. A user can also identify the various stages of a mission such as rendezvous, flyby and deep-space maneuvers (DSM) simply by hovering their mouse over the listed itinerary. In addition, a user may rotate the heliocentric trajectory diagram with a simple drag of the mouse, allowing the user to investigate the out-of-plane component of a transfer.

A page with web links is also made available to other existing websites that host resources online relevant to designing trajectories in the Solar System.

5. CONCLUSION

This paper describes a web-based tool for searching for transfer trajectories from Earth to planetary bodies within the Solar System for a variety of mission configurations. It is designed to be a low-fidelity but quick-turnaround method for probing the existence of trajectories during conceptual design phase of a mission. In addition, its education potential is recognized in the context of NASA's participatory exploration initiative.

Although the first iteration of the Trajectory Browser is now complete, there are several additional features that are being considered for a subsequent version. Trajectories to small-bodies other than NEOs can be readily implemented, such as the larger members of the main asteroid belt, Jupiter Trojans and other objects of interest. Additional trajectory configurations are also being considered that utilize more complex gravity assist and deep space maneuvers. Some preliminary work has also been performed to host historical trajectories of past interplanetary missions as references for future mission planning. Finally, the implementation of low-thrust trajectories is also being considered to reflect the availability of electric propulsion technologies for current and planned missions.

ACKNOWLEDGEMENTS

The author wishes to think those who at NASA Ames Research Center that made the development and launch of the Trajectory Browser website possible through their feedback and allocation of resources: BJ Jaroux, Chad Frost, Matt Daniels and Julie Bellerose.

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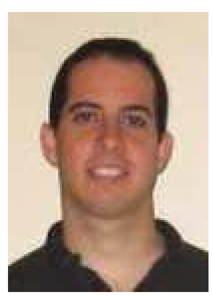
BIOGRAPHY



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