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Engineering Notes

Visualization of the Multidimensional Human Interplanetary Mission Design Space

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Nomenclature

C_3	=	hyperbolic excess (specific) energy, km^2/s^2
$C_{3,1}$	=	C_3 at Earth departure, km^2/s^2
$C_{3,2}$	=	C_3 at Mars arrival, km^2/s^2
$C_{3,3}$	=	C_3 at Mars departure, km^2/s^2
$C_{3,4}$	=	C_3 at Earth arrival, km^2/s^2
$C_{3,\mathrm{tot}}$	=	total mission C_3 ($C_{3,1} + C_{3,2} + C_{3,3} + C_{3,4}$), km^2/s^2
$\mathrm{TOF}_{\mathrm{outbound}}$	=	outbound time of flight, days
$\mathrm{TOF}_{\mathrm{return}}$	=	return time of flight, days
t_{stay}	=	stay time, days
α	=	coefficient for weighting on $\mathrm{TOF}_{\mathrm{outbound}}$
β	=	coefficient for weighting on t_{stay}
ΔV	=	change in velocity, km/s
δ	=	coefficient for weighting on $C_{3,\mathrm{tot}}$
χ	=	coefficient for weighting on $\mathrm{TOF}_{\mathrm{outbound}}$

Introduction

TYPICAL human interplanetary mission design studies to date have had difficulty visualizing the outbound and return transfer data simultaneously. For a round-trip mission, there are too many independent variables to display on two-dimensional plots, such as "pork-chop plots" (contour plots of required C_3 or ΔV for an interplanetary trajectory). The two independent variables on this plot are departure date and arrival date (or time of flight, TOF). However, a complete human mission includes two transfers connected by the surface stay, resulting in four independent variables: Earth departure date, destination arrival date, destination departure date, and Earth arrival date (the latter three can be replaced with outbound TOF, surface stay time, and return TOF). To visualize the design space using two-dimensional plots, many studies eliminate one or more of these variables. However, the mission designer must be able to look at all three segments simultaneously to determine their interactions and to select the overall optimal mission scenario.

A brief look at trajectory analysis studies can show examples of how the design space is visualized [1–4]. Common methods for conditioning the data for visualization are 1) discretizing the outbound and return TOF and then optimizing the departure dates and connecting each with a stay time [1,2] and 2) considering only certain "type I" (transfer angles of less than 180 deg) outbound trajectories and assuming a return on the next available type I return trajectory [3,4]. These visualization techniques do not allow the mission designer to observe the effect of all independent variables on other mission parameters.

To eliminate these deficiencies, a multidimensional design space exploration tool must be used to determine the effect of different mission scenarios on C_3, interplanetary TOF, and other variables of interest. Given a large set of data representing the entire design space, this tool would allow the mission designer to look at the effect of all four independent variables on mission design parameters simultaneously. This paper presents one possible method to visualize this data: the parallel coordinates plot (PCP).

Methodology

To generate the data set used in this visualization technique, the heliocentric trajectories are calculated using the universal variable solution to Lambert's problem. The C_3 at each planetary sphere of influence is then determined using a patched conics approximation [5,6]. The positions of the planets are obtained from the planetary ephemeris using the SPICE toolkit.‡ The C_3 is used in this paper because it does not depend on parking orbit size/shape or arrival method (aerocapture, propulsive, direct entry, etc.). Therefore, no assumptions on the concept of operations must be made in the trajectory analysis.

The results of the trajectory data are viewed using a PCP. This type of plot is used for viewing multidimensional data, such as the mission design problem. The PCP uses a set of parallel axes drawn for each variable. A point in the multidimensional space is a line connecting the coordinate on each axis. A single Earth–Mars human mission scenario is displayed in Fig. 1, which departs Earth on 30 July 2035 with an outbound TOF of 200 days. The Mars surface stay time is 550 days, followed by a return TOF of 180 days. The next axes show the values of C_3 at the four departure/arrival nodes, the total C_3 for the mission, and the total mission duration.

The software package used to visualize the design space is the Pennsylvania State University Applied Research Laboratory Trade Space Visualizer (ATSV), which is capable of visualizing large trade spaces using several multidimensional visualization techniques, including the parallel coordinate plot [7]. Although it is difficult to discern individual points in the PCP when many points are plotted, this tool is very useful in dynamically visualizing multidimensional data sets, for which user inputs automatically update the visualization. To find information on a single point, the user must click on a value along a single axis to open a window containing the data for all points going through that value.

The PCP allows the mission designer to explore all three segments of the human mission (outbound, surface stay, and return) and their effects on other mission parameters simultaneously. A technique known as brushing can be used to place constraints on any variable. Any points (scenarios) in the design space that violate these constraints are removed dynamically from the visualization. Another aspect of the PCP is the ability to determine positive and negative correlation between any two variables. When two variables are placed next to each other, positive correlation has very few line crossings as large values in the first variable correspond to large values in the second variable. Negative correlation has many line crossings as large values in the first variable correspond to small values in the second variable. ATSV allows the user to dynamically

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‡Data about the SPICE Toolkit for FORTRAN (Navigation and Ancillary Information Facility, Jet Propulsion Laboratory) is available online at http://naif.jpl.nasa.gov/naif/ [retrieved 31 July 2009].

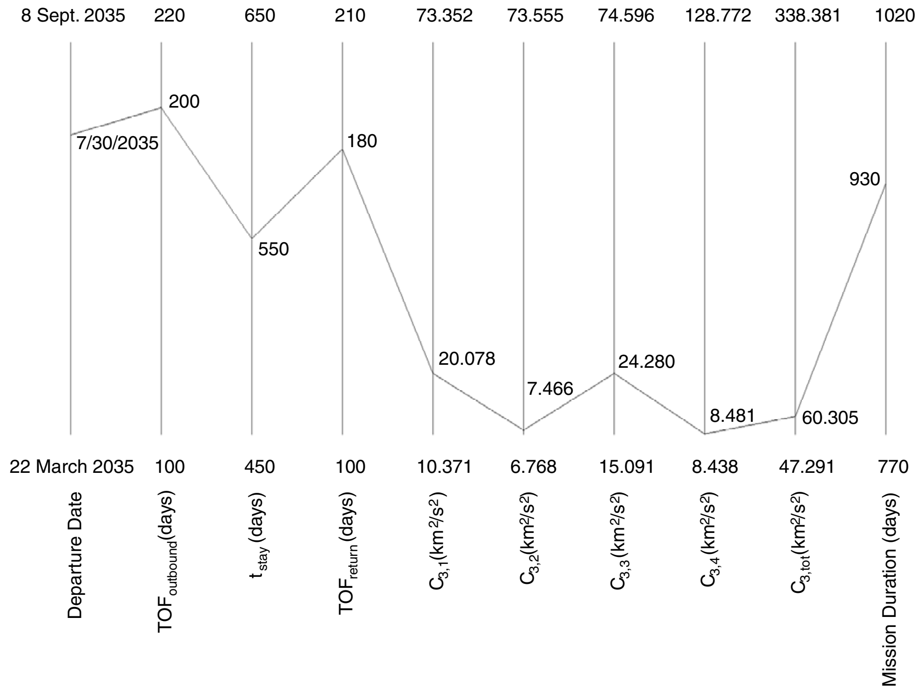

Fig. 1 Point in multidimensional space viewed on a PCP.

move around the locations of axes relative to the others, enabling quick looks at the correlation between two variables [7].

The most useful aspect of this visualization technique to the mission designer is the ability to visualize the design space using a multidimensional Pareto frontier. Points along the Pareto frontier represent the best compromises for the user-specified preferences. In ATSV, the Pareto frontier is developed by selecting the point with the greatest weighted sum and adding it to the frontier (these points are called "nondominated solutions"). Then all points that are inferior to that point in all other variables are considered "dominated solutions" and are not included in the Pareto frontier. This process is repeated for the remaining points until all have been identified as either dominated or nondominated (which make up the Pareto frontier) [8].

Sample Design Problem

Sample Design Space

To show the capability of the parallel coordinates visualization technique for a human Mars mission, a sample design space is created for a human Earth–Mars mission. For instance, with a top level constraint such as "launch in 2035," the design space can be created to explore the available mission scenarios.

The sample design space creates a multidimensional grid containing every possible combination of departure date, outbound TOF, stay time, and return TOF. The Lambert solver runs each point in this grid to determine the required C_3 at each node, and the results are visualized with the ATSV's PCP, as shown in Fig. 2. The axes on this plot are the four independent variables of departure date, outbound

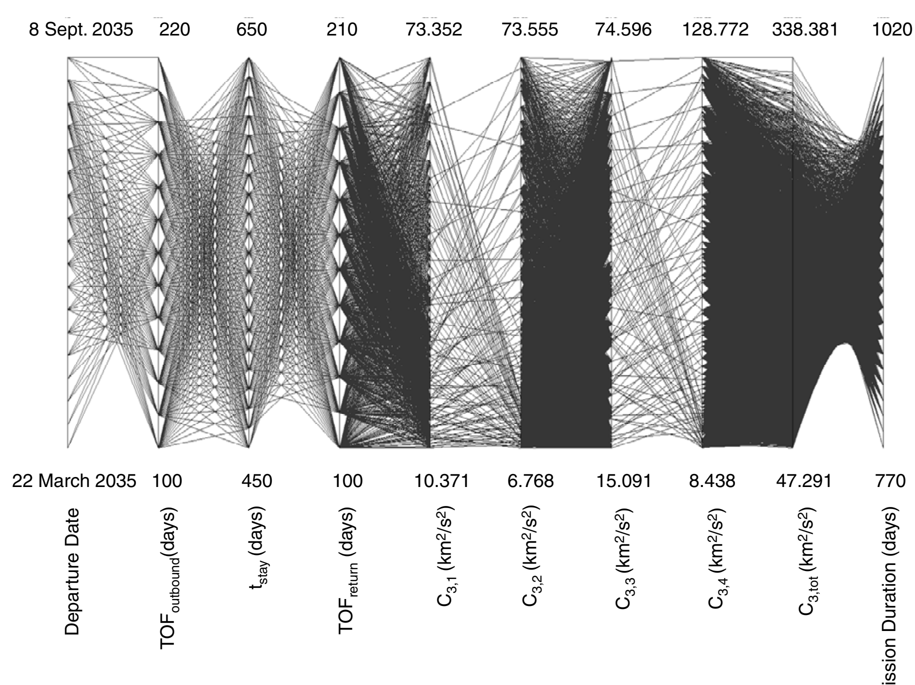

Fig. 2 PCP containing the entire sample design space.

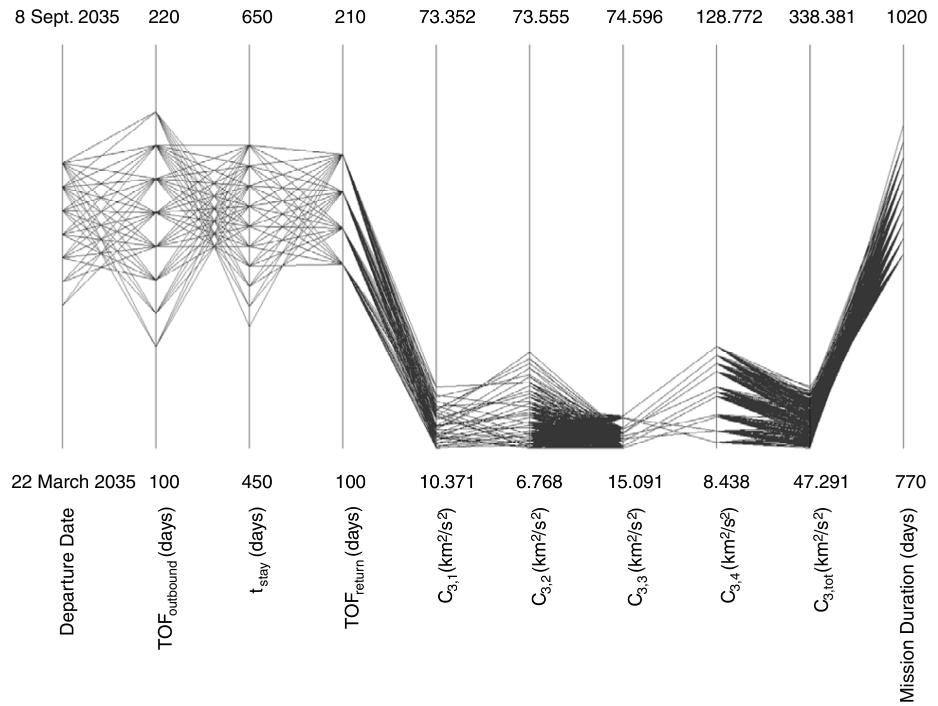

Fig. 3 PCP containing the constrained design space.

TOF, stay time, and return TOF, followed by the dependent variables of $C_{3,1}$, $C_{3,2}$, $C_{3,3}$, $C_{3,4}$, the total C_3 of the mission, and the total mission duration.

Design Space Exploration and Brushing

This design space can be dynamically explored and constrained using the brush tool. The real power of this tool is the ability of the mission designer to visualize the effect of dynamically adding constraints to a given variable (be it independent or dependent) on the rest of the design space instantly.

To illustrate this capability, a sample set of constraints is placed on the overall design space using the brush tool. Restrictions may exist on consumables, radiation exposure, and microgravity affects, which limit the amount of time that the crew can endure interplanetary travel. In this example, the $TOF_{outbound}$ and TOF_{return} are therefore limited to a maximum of 200 days. Also, $C_{3,1}$ and $C_{3,3}$ are limited based on the trans-Mars and trans-Earth injection stages' capabilities, respectively. In this example, assume that both stages are capable of only 20 km^2/s^2, which is a reasonable capability for current propulsive technologies. The stay time is bounded by the consumables available on the surface (defining the maximum stay time) and by the science return of the mission (defining the minimum stay time). In this example, the stay time must therefore lie in the range of 500–600 days. Finally, the entry velocities at the two planets are limited by the current thermal protection technology. To date, this technology allows entry velocities of up to 7.0 km/s at Mars [2] and 12.8 km/s at Earth [9], resulting in a maximum C_3 of 24.6 km^2/s^2 and 43.8 km^2/s^2, respectively.

This new constrained design space is shown in Fig. 3. Notice that, although no constraints were placed on the departure date, several points in the first column were removed, revealing a natural departure "opportunity" that exists for human Mars missions in 2035.

Correlation

The PCP can also be used to visualize the correlation between two variables. Figure 4 reveals the negative correlation between TOF and C_3, meaning that, as TOF increases, C_3 generally decreases (both departure and arrival), which has been shown in previous mission design studies [1]. The pair of black lines connecting the three axes represents two separate transfer opportunities (one with high TOF and one with low TOF). Notice how the line that connects to high TOF has low C_3 values, and the line that connects to low TOF has high C_3 values.

Multidimensional Pareto Frontier

Because the mission designer is concerned with multiple variables (independent or dependent), some of which are conflicting, the

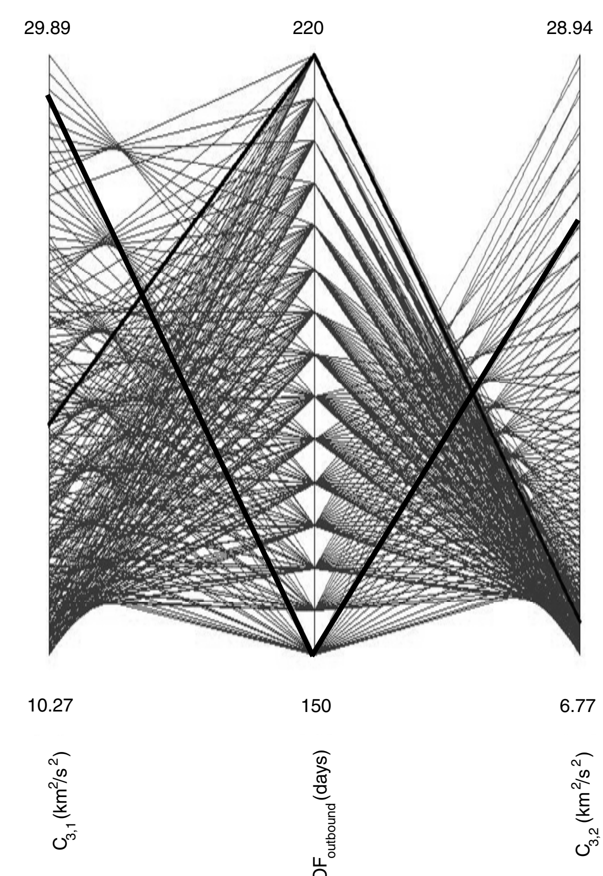

Fig. 4 PCP showing negative correlation between TOF and C_3.

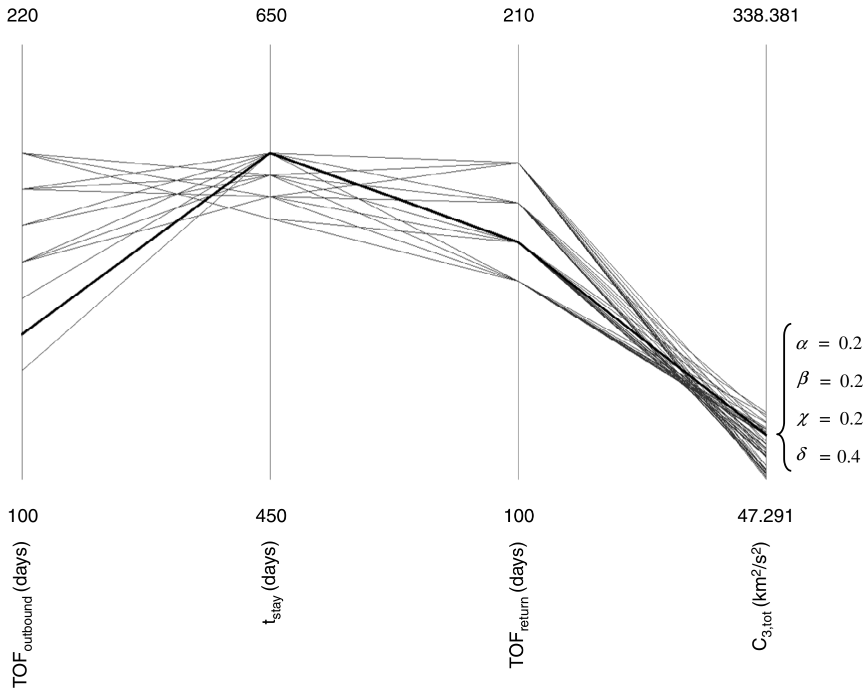

Fig. 5 Multidimensional Pareto frontier.

Pareto frontier shows the best points that form a compromise. When the mission designer selects the "optimal" scenario, it cannot be based on a single criterion because many parameters of the mission design affect the sizing requirements and merit of an interplanetary mission. It has already been shown that reducing TOF increases C_3 due to their negative correlation; therefore, finding a scenario that both minimizes TOF and C_3 is highly unlikely.

Looking at the Pareto frontier using a PCP can give an indication of the ranges in which the optimal solution will lie before that solution is identified. The overall evaluation criterion,

$$\mathrm{OEC} = -\alpha(\mathrm{TOF}_{\mathrm{outbound}}) + \beta(t_{\mathrm{stay}}) - \chi(\mathrm{TOF}_{\mathrm{return}}) - \delta(C_{3,\mathrm{tot}})$$

is a single function that can be optimized to determine the optimal mission scenario. The negative signs in front of α, χ, and δ indicate that these variables should be minimized, and the positive β indicates that this variable should be maximized. In ATSV, the optimization for all cases of coefficients in this OEC will lie within the Pareto frontier.

The Pareto frontier for the constrained design space and a sample optimized solution to the OEC is shown in Fig. 5. The highlighted point in Fig. 5 shows a scenario in which the total C_3 is considered to be twice as important as the other three, but any other weighting scheme will also produce an optimal scenario within this Pareto frontier. Therein lies the importance of the Pareto frontier: for any weighting scheme, the optimal solution will lie on the Pareto frontier. This is easy to see in two or even three dimensions as a curve or surface, but in higher dimensions the PCP is useful in visualizing this frontier.

Conclusions

Because of the high dimensionality of the human mission design problem, typical two-dimensional plots do not allow the mission designer to view the complete trajectory design space at once. To overcome this shortfall, a parallel coordinate plot is a useful tool for visualizing round-trip interplanetary trajectories.

The brush tool can be used to constrain any variable based on certain mission factors or requirements. The visible design space then dynamically updates to eliminate the scenarios that violate those constraints. It also gives the mission designer intuition on how changes in the mission affect other parameters by determining the correlation between any two variables via the number of line crossings between them.

The most useful aspect of the PCP is the ability to visualize a multidimensional Pareto frontier. Any of the available independent or dependent variables may be incorporated into the frontier by defining their preference (minimize or maximize). All optimal trajectory scenarios for a human interplanetary mission will be represented within this frontier.

Although this visualization technique has advantages, it also has disadvantages (such as discerning points in large data sets and finding a "knee in the curve"). It will be a challenge to find one technique that will satisfy the need to visualize the entire design space so that educated decisions can be made about interplanetary missions, and so a combination of PCP with other two-dimensional techniques may be necessary for some applications.

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