A graphical tool to design two-ways human Mars missions

G. Genta*, P.F. Maffione
Dept of Mechanical and Aerospace Engineering, Politecnico di Torino, Torino, Italy

ABSTRACT

Human two-way missions to Mars may be of two types: long-stay and short-stay missions. Both require that the crew spends several months in space, with all the problems related with exposure to radiation and microgravity. Using advanced propulsion the travel time may be reduced, but this requires developing nuclear propulsion, either NTP or NEP. Short stay missions also require non-minimum energy trajectories and usually involve quite a short stay on the planet. The aim of the present paper is to develop a graphical tool allowing to choose the most suitable travel dates for a two-ways planetary mission, in a quick and straightforward way. This tool, which can be applied to both impulsive and low thrust propulsion, combines together the well known pork-chop plot – or J-plot or, alternatively, the bacon plot – computed for the two legs of the travel and combines them together after stating the time the crew has to spend on the planet.

1. Introduction

The duration of human missions to Mars is one of the major concern of mission designers, and often one of the reasons which are forwarded to assess that it is impossible to explore Mars with a crewed mission is that the physiological and psychological stress for such a long mission (due to microgravity, radiation, distance from the rest of humankind, long communication delay, etc.) puts human life to excessive risk. Better resorting to robotic exploration [1–3].

The length of a human Mars mission is essentially due to two factors:

- The long duration of the interplanetary travel – 7–9 months.
- The long time the crew must remain on Mars to wait for the optimal conditions for the return journey to occur (long-stay or conjunction missions) – about 17–20 months.

It should be recalled that the environment on Mars is not much better than the space environment, although the first is less hostile: we do not know how much low Martian gravity is better than no gravity at all, Mars has no magnetic field and a very thin atmosphere and hence the radiation environment is anyway severe, as is the psychological stress on the planet.

If the planetary orbits were circular, the conditions for launching an interplanetary mission would repeat with a period exactly equal to the synodic period. In this case there would be a minimum energy impulsive trajectory that would coincide with the Hohmann trajectory [4–8].

In the case of Mars the synodic period is 779.94 days, the duration of the Hohmann trajectory is 258.73 days and its starting and arrival dates are respectively 96.04 days and 162.70 days before and after the opposition. The hyperbolic excess speed at the exit of the Earth sphere of influence is 2945 m/s.

However, planetary orbits are not circular – the orbit of Mars is particularly elliptical – and the Hohmann trajectory is, strictly speaking, unfeasible. Moreover, the various launch opportunities are each one different from the other, even if some regularity can be found, so that the launch windows are different from each other.

In the present study, the positions of the planet has been computed using the JPL solar system ephemerides [9].

The launch windows for an interplanetary mission is fairly narrow and launching outside it involves large energy expenditures. What said above is true both for impulsive and low thrust propulsion, even if the launch windows are not the same for the two cases and, as it will be shown below, the increase in energy for a launch outside the correct window is less severe in case of low thrust.

A short stay mission would take about 550 days, or about 1.5 years, including the journey but, apart from the larger energy, it involves a longer time in space, together with a very short time on the planet – about 30–45 (possibly up to 60) days.

Intermediate choices (for instance a stay of 3–5 months) are practically impossible, since they would require very large quantities of energy (well beyond what is feasible with chemical propulsion and even fission nuclear devices) and, at the same time, long travel durations.
Moreover, if a higher energy trajectory is used to implement a long-stay mission with the goal of reducing the time spent in space, the stay on the planet will be longer, with a total mission time always of the order of about 900 to 1000 days. While trading time in space for time on the planet is anyway an important issue, the advantage in terms of total mission time is not large.

Speaking about ‘fast Mars missions’ there is a large difference between an exploration mission aimed to carry a crew to Mars and back (either a long-stay or a short-stay mission), a one-way colonization mission or a mission whose aim is to change the crew of a permanent Mars outpost. In the latter case the shift would likely be of two years two months on the planet, with a travel time as short as possible.

The present paper concentrates on missions of the first type, which are the most interesting ones in the short term, and its main goal is developing a graphical tool able to choose the best dates for the outbound and the inbound journey once the duration of the stay on Mars has been chosen. Both impulsive and low thrust propulsion is considered.

In case of low thrust propulsion there is not a ‘minimum energy trajectory’: the longer it takes to get to Mars the lower the required energy is. This increases the advantages of a “split mission architecture”, with one or more slow cargo ships carrying all equipment required on the planet and a crew ship carrying the humans on a faster trajectory. Although this strategy has been suggested also in connection with chemical propulsion, when dealing with low-thrust the cargo ships may be much slower and more efficient and the crew ship may be even faster.

Additional advantages of the split mission architecture are that the equipment carried by the cargo ships can be pre-positioned on the planet before launching the crew, and that a slow cargo ship may carry large quantities of propellant to Mars orbit for the return journey, making short-stay missions and fast return journeys easier.

An alternative to refueling in Mars orbit is to put the return vehicle in a highly elliptical Mars orbit, a thing which reduces the quantity of propellant required for the Trans-Earth Injection (TEI), at the expense of the quantity of propellant needed to launch the Crew Ascent Vehicle (CAV) form the planet and thus is made easier by the production of propellant on Mars (ISPP). In this case it is even possible to refuel in Mars orbit with propellant produced on the planet.

2. The pork-chop plot and the J-plot

2.1. Impulsive missions

The most common visual tool for designing a mission to Mars – or better to chose the starting and arrival dates – is the so-called pork-chop plot [10–12]. Usually this term is used to indicate the contour plot of the square of the hyperbolic excess speed $C_\alpha$ required to start the interplanetary trajectory as a function of the starting and the arrival dates. This kind of plot is quite dependant on the launch opportunity, for instance the plot for the Earth-Mars trajectory in the 2035 launch opportunity is reported in Fig. 1a. This choice has been suggested by two reasons: first it is a particularly expedient date – 2035 is a perihelic opposition and thus the planets attain a minimum distance – and, second, because there are several involved actors who suggest the mid-2030s as a good date for the first human Mars expedition.

The same plot but for the return journey is reported in Fig. 1b. It has been obtained for the same launch opportunity, so that the two plots can be used together for a short stay mission performed in 2035. For a long stay mission the plot of Fig. 1a must be used together with a plot for the return journey in the following opportunity – namely that of 2037.

However, the use of the pork-chop plot in the form here shown may be questionable: $C_\alpha$ refers only to the hyperbolic excess speed needed to start the trajectory, while it may be wiser to account for the total energy (or directly the $\Delta V$) to leave the starting orbit, added to that required to achieve the final orbit about the arrival planet in the case the latter maneuver is not performed by using aerobraking.

The data for the minimum energy trajectories are summarized in Table 1 (the dates are referred to the opposition, which in that launch opportunity occurs on Sept. 15, 2035).

A modified pork-chop plot (which could be dubbed $\Delta V$-plot) obtained for a starting circular orbit at 800 km and for an arrival elliptical orbit on Mars with periareion at 320 km and apoareion at 35,000 km from the surface, is reported in Fig. 2a. These values are appropriate for a NTP (Nuclear Thermal Propulsion) spacecraft more than for a chemical spacecraft, for which a lower starting LEO is expedient and aerobraking is usually preferred [13]. The return plot shown in Fig. 2b has been obtained assuming the mentioned elliptical orbit about Mars – the $\Delta V$ required for changing the orbit as required for starting the return journey has been neglected – and the same circular Earth orbit.

The data for the minimum $\Delta V$ trajectories are summarized in Table 2 (the dates are referred to the opposition). Comparing the two tables it is clear that the difference between the optimal trajectories obtained using the two criteria are small (just 2 or 3 days in terms of starting date).

In case of short-stay missions, it may – in some launch opportunity – be expedient to use trajectories involving a gravity assist maneuver at Venus. Usually such trajectories are suggested in the return journey, because it is expedient to use a quick trajectory going to Mars, to reduce as much as possible the exposition of the crew to microgravity in that part of the journey, since the consequences of a long exposure when getting back are less severe (the crew has all the time to recover once at home). However, this is possible not in all launch opportunities and in some cases it may be better to make the flyby while going.

Also in this case it is possible to plot a diagram similar to a pork-chop plot for trajectories with a gravitational assist maneuver.

Pork-chop plots are usually limited to launch dates close to the optimal ones but it is possible to plot it spanning two subsequent launch opportunities, to investigate situations far from those characterized by minimum-energy conditions. A number of cross sections of the surface $C_\alpha(T, \Delta V)$ – regarding the 2035 and 2037 launch opportunities – at constant $\Delta V$ (for 60 days $< T < 240$ days) are reported in Fig. 3. Where a faster trajectory is more convenient than a slower one, only the former is reported.

2.2. Low thrust missions

A plot which can perform the same functions of the pork-chop plot but for electric propulsion is here called J-plot [14]: it is the contour plot of the factor $J$, related to the square of the propellant mass fraction $m_p/m_i$, as a function of the starting and the arrival dates or, more commonly, of the starting date and the travel duration. Also the J-plot can take into account only the interplanetary journey, or also the spiral phases about the starting and arrival planets.

In the ideal case of Variable Exhaust Velocity thrusters with no limitation on the specific impulse, the cost function $J$ is defined as [14–17].

$$J = \frac{1}{2} \int_0^T a^2 dt,$$

(1)

where $a$ is the ratio between the thrust and the mass of the spacecraft. Note that in case of electric propulsion its order of magnitude is roughly about $10^{-3} \text{m/s}^2$, leading to a thrust of the order of 1 N per ton of spacecraft.

$J$ is linked with the propellant mass fraction by the relationship

$$\frac{m_p}{m_i} = \sqrt{a},$$

(2)

where $a$ is the mass/power ratio of the generator, which also accounts for the efficiency of the thruster and the power electronics since the
<table>
<thead>
<tr>
<th>دستگاه</th>
<th>توضیحات</th>
</tr>
</thead>
<tbody>
<tr>
<td>دانلود نسخه تمام متن مقالات انگلیسی</td>
<td>✓</td>
</tr>
<tr>
<td>دانلود نسخه ترجمه شده مقالات</td>
<td>✓</td>
</tr>
<tr>
<td>پذیرش سفارش ترجمه تخصصی</td>
<td>✓</td>
</tr>
<tr>
<td>امکان جستجو در آرشیو جامعی از صدها موضوع و هزاران مقاله</td>
<td>✓</td>
</tr>
<tr>
<td>امکان دانلود رایگان ۲ صفحه اول هر مقاله</td>
<td>✓</td>
</tr>
<tr>
<td>امکان پرداخت اینترنتی با کلیه کارت های عضو شتاب</td>
<td>✓</td>
</tr>
<tr>
<td>دانلود فوری مقاله پس از پرداخت آنلاین</td>
<td>✓</td>
</tr>
<tr>
<td>پشتیبانی کامل خرید با بهره مندی از سیستم هوشمند رهگیری سفارشات</td>
<td>✓</td>
</tr>
</tbody>
</table>