ITT 6791 – Hybrid Propulsion Transfer Strategies

Executive Summary

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Motivations

Low energy transfers have shown that it is possible to reduce the Δv cost (and therefore the propellant mass) for a number of transfer types. This is possible by exploiting the natural *n*-body dynamics characterizing the spacecraft motion within the Solar System. In particular, the concept of ballistic capture makes it possible to reduce the hyperbolic excess velocity upon moon/plant arrival, and allows the spacecraft to perform few orbits at zero cost. Low energy transfers are designed by using impulsive maneuver, and therefore they inherently use chemical propulsion (Figure 1). On the other hand, solar electric propulsion (or SEP for brevity) entails considerable savings in the propellant mass thanks to its high specific impulse. Nevertheless, fully SEP interplanetary and lunar transfers suffer from the long durations needed to achieve escape, which may even lead, in some cases, to discard this option.

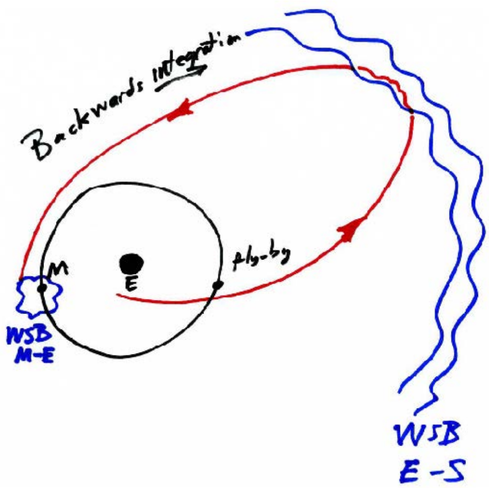

Figure 1: A sketch of an exterior low energy transfer to the Moon.

A way to circumvent the disadvantages of fully SEP solutions, while still preserving its points of strength, is to combine solar electric and chemical propulsion together. This gives rise to hybrid propulsion transfers. The transfer is intended hybrid as both chemical and SEP are mounted on the same platform. Hybrid transfers use chemical propulsion to achieve Earth escape and SEP in the remaining part of the transfer, up to the final orbit acquisition. At arrival, ballistic capture is performed, so reducing further the overall cost of the mission.

Objectives

Preliminary solutions using hybrid propulsion had already been observed for both transfers to the Moon and to Mars. However, previous works had only presented the concept from a preliminary trajectory design perspective, and in-depth analyses in real scenarios were still missing. As the concept of hybrid propulsion transfer is brand-new, a thorough investigation was necessary to assess the validity of these preliminary studies when realistic mission constraints and consequences at system level are taken into account.

The main objective of the present study is to contemplate the effects that the hybrid propulsion transfers have on the spacecraft subsystems, and therefore on the overall spacecraft design. As, on the one hand, it may be proven that hybrid propulsion transfers outperform both patched-conics and low-energy transfers from the propellant consumption standpoint, so, on the other, the implications on the system design are not obvious. In summary, the objectives of the ITT 6791 were:

- to analyze in detail the hybrid propulsion options from GTO to 1) low lunar polar orbits, 2) low Mars orbits, 3) NEO orbits, and to compare the achievable gains with conventional propulsion transfers;
- to perform a preliminary sizing of the spacecraft equipped with hybrid propulsion, and to define subsystem requirements deriving from hybrid transfers.

Main Results

In this study the hybrid propulsion transfers have been studied under the perspective of a dual-stage spacecraft. This are defined by two detachable units: the Chemical Propulsion Stage (CPS) and the Mission Platform Bus (MPB). The CPS embarks all the equipment associated with the chemical propulsion (engine, propellant, tanks, feeding lines, etc.), whereas the MPB is made up by the mission payloads and all the necessary subsystems. The MPB uses solar electric propulsion. With this configuration, the CPS is fired a number of times right after the launch to achieve escape. The CPS is then jettisoned from the MPB. This avoids carrying all the inert masses associated to the chemical propulsion for the rest of the mission, and increases the thrust-to-mass ratio of the SEP phase (and therefore the efficiency and controllability). This solution has been deemed more appropriate than the single-staged one (Figure 2).

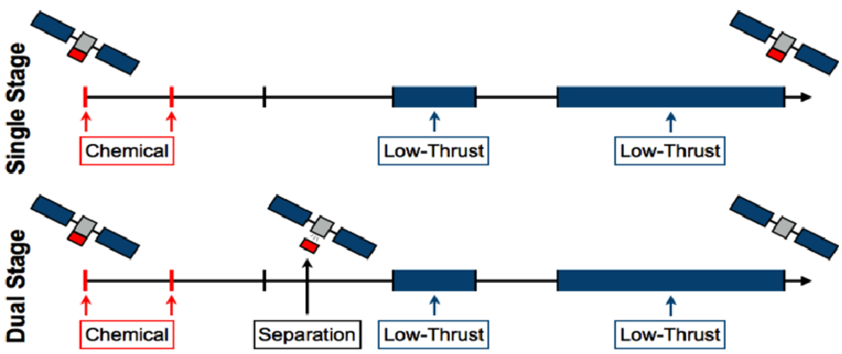

Figure 2: Conceptual view of single- and dual-stage hybrid spacecraft.

Hybrid solutions have been obtained for all of the three application cases (Moon, Mars, NEO). As these solutions exploit the highly nonlinear dynamics typical of the n-body models, their derivation is not trivial, especially when an end-to-end optimal control problem is solved (Figure 3). In these solutions the optimal balance between the two propulsion types has been found. Preliminary solutions have been later refined. The refinement process implements the subsystem models for the CPS and SEP. In particular, three iterations have been performed between the trajectory design and system sizing phases.

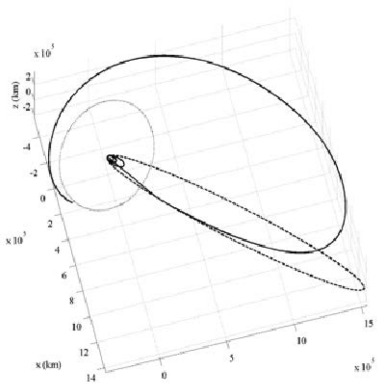

Figure 3: Hybrid lunar transfer

One of the ultimate goals of the present study was to arrive at the definition of a standard platform for the possible future ESA's mid-sized missions. From the preliminary results it had been found that all the three applicative scenarios analyzed required about the same propellant mass (red bars in Figure 4). Thus, a common CPS has been designed for lunar, Mars, and NEO hybrid mission. A sketch of the CPS can be seen in Figure 5. Moreover, all the analyzed cases share the same electric thruster, too (Snecma Hall effect PPS.5000, nominal Isp of 1735 s and maximum thrust of 276 mN). Both the CPS and MPB embark also a number of common components (RCS system, thruster PPU, etc.) and, when different, these are modular.

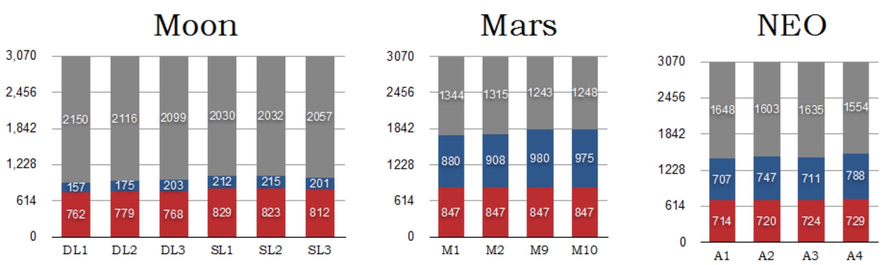

Figure 4: Mass breakdown for the three applicative cases (red: chemical propellant mass, blue: Xenon propellant mass, grey: remaining useful mass).

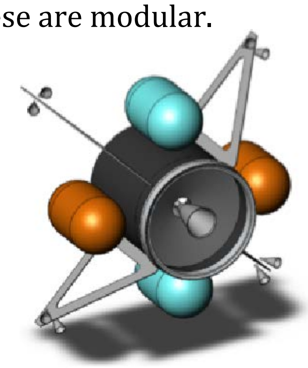

Figure 5: The CPS.

Comparison with Conventional Propulsion

The hybrid spacecraft preliminary sized have been compared to those associated to the reference missions using conventional propulsion. Existing ESA studies have been exploited to derive the Δv costs for the reference cases (Lunar Lander, ExoMars, and MarcoPolo). Based on that, the chemical subsystem of the reference mission has been sized and therefore it has been possible to extract the Useful Mass At Target (UMAT). This figure has been then compared to that of the hybrid spacecraft. Beside the UMAT, the comparison has been done also in terms of Final Spacecraft Mass (i.e., the mass injected into the final mission orbit). In the case of the NEO sample return, the Earth Return Mass (ERM) is used in place of UMAT.

The measure of efficiency of hybrid transfers is assessed in terms of:

- average advantage (relevant performance measure - FSM, UMAT or ERM - averaged across the conventional and hybrid solutions)
- best advantage (lowest achievable performance measure of the conventional solutions vs highest achievable of the hybrids; i.e., best-case hybrid vs worst-case conventional).

	Lunar		
Equipment	Total Mass (kg)	Margin (%)	Total Mass incl. margin (kg)
Mission Payload	874.13	5.00	917.84
AOCS	5.00	5.00	5.25
Power	20.00	5.00	21.00
Solar Arrays	162.00	10.00	178.20
Comms	20.00	5.00	21.00
OBDH	20.00	5.00	21.00
Environment	30.00	5.00	31.50
Structure	100.00	5.00	105.00
Harness	60.00	5.00	63.00
SEP Dry	253.65	16.54	295.61
CPU Dry	181.73	18.18	214.77
Total Dry	1726.51	1.09	1874.17
System Margin		20%	374.83
Total Dry with margin			2249.00
SEP Xenon Propellant			166.00
CPU Propellant & Pressurant			655.00
Total Wet Mass			3070.00
Launch Mass			3070.00

Figure 6: Composite S/C mass budget for lunar case.

	Avg FSM	Avg UMAT	Best FSM	Best UMAT
Moon	+247 kg (+14%)	+396 kg (+27%)	+323 kg (+19%)	+480 kg (+33%)
Mars	+450 kg (+52%)	+236 % (+27%)	+453 kg (+47%)	+460 kg (+62%)
NEO	+437 kg (+34%)	+880 kg (+109%)	+700 kg (+67%)	+1143 kg (+205%)

Table 1: Summary of comparison of hybrid vs conventional prop.

It has been found that in all cases hybrid spacecraft outperform conventional propulsion ones (Table 1). In particular, two-digit gains can be achieved in the case of missions to the Moon and Mars, while even three-digit saving can be get in case of NEO sample return mission (in Table 1, ERM is used in place of UMAT for the NEO).

Conclusions

The concept of hybrid propulsion spacecraft has been assessed in this study in terms of preliminary sizing of the CPS, the SEP, and the Solar Arrays. Preliminary trajectories found in the first part of the study have been refined by considering the devised models for the CPU and the SEP. Detailed comparisons have been carried out and a critical analysis on the hybrid concept has been performed, as well as with some recommendations.

As outcome of this study it can be said that the hybrid propulsion concept outperforms the conventional propulsion cases. In particular, considerable savings have been found for all three applications cases. However, the concept of hybrid propulsions needs further analyses and investigations, which have been clearly identified throughout the study.