A Toolbox for Preliminary Mission Analysis and Design

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Agenda

• Introduction and Motivations
• Structure of the Toolbox
• PAMSIT
• IMAGO
• ATOM-C
• EPIC
• Future Work
Introduction and Motivations

- The design of space trajectories can mathematically be defined as an optimisation problem.
- Traditionally such task has been accomplished resorting to various optimisation method typically based on optimal control theory and gradient method.
- Need of some sort of first guess solution to be initialised.
- Convergence can be deeply affected by this initial guess.
- Local optimisation tools turn out to be quite unsuitable for quick assessments of a large number of possible solution, (pre-phase A studies).
- As an example multiple gravity assist low-thrust transfers make the definition of preliminary solution quite complex. (very few analytical solutions for the motion of a thrusting spacecraft)
- Need for preliminary design tools for complex interplanetary transfer, capable of largely investigating the solution domain, in order to assess the most promising solutions, eventually locating the global optimal one.
Structure of the Toolbox

- The toolbox is composed of 3 main software tools conceived for the solution of specific mission analysis problems:
  - PAMSIT
  - IMAGO
  - ATOM-C

  Plus a global optimisation tool called EPIC

- The 4 main tools are supported by a library of service modules and routines for ephemeris generation, coordinate transformation, graphic output, etc…
PAMSIT

- PAMSIT is a tool for the preliminary design of quasi-ballistic optimal interplanetary trajectories, considering gravity assist and aerogravity assist manoeuvres.
- It is based on a systematic search algorithm (enumerative).
- No propulsive manoeuvres during transfers are considered.
- The software implements a simplified two dimensional model with circular planetary orbits and a linked-conic approximation for GA and AGA.
- The tool allows two basic kinds of analysis: energy-based feasibility study and launch window feasibility analysis.
- Multiple free bound orbits between two subsequent swingbys are allowed.
- Multiple criteria for the selection of optimal sequences, such as departure C3, arrival velocity, time of transfer, or a combination of them are allowed.
**PAMSIT: Main Features**

- **Main characteristics:**
  - systematic global search algorithm;
  - Gravity assist (GA) and Aerogravity assist (AGA) manoeuvres;
  - No propulsive manoeuvres during transfers;
  - Discretisation of the variables that characterise trajectories and minimisation of predefined measures of merit;
  - MATLAB software tool.

**Different analyses:**

(A) **Energy-based feasibility study:** NO phasing considerations; Discretised variables: \( v_\infty L \) (magnitude and direction) and \( \phi \) (both + and -); Resonant transfers and all possible different transfers on the same orbit are considered.

(B) **Phasing feasibility study:** Improved model of Solar System, based on the mean motion of the planets in circular and coplanar orbits; Finite number of bound orbits; Variable launch date; Constraints on the position of the swingby planets and of the spacecraft at the rendezvous dates; Automated trade-offs, choosing suitable measures of merit.

06/09/2004
### PAMSIT: examples

<table>
<thead>
<tr>
<th>AGA+GA Flybys sequence</th>
<th>Launch dd mm yyyy</th>
<th>$v_{\infty,L}$ km/s</th>
<th>ToF s.y</th>
<th>$v_{\infty,A}$ km/s</th>
<th>MM</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>MM1: Low $\Delta V_L$ and short ToF and low $\Delta V_A$</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>$V_{AGA}, M_{AGA}$</td>
<td>23 5 2007</td>
<td>4.25</td>
<td>3.81</td>
<td>5.12</td>
<td>6.74</td>
</tr>
<tr>
<td>$V_{GA}, E_{AGA}$</td>
<td>30 6 2007</td>
<td>3.25</td>
<td>4.24</td>
<td>6.02</td>
<td>6.83</td>
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<td>$V_{GA}, M_{AGA}$</td>
<td>4 2 2009</td>
<td>4.00</td>
<td>3.75</td>
<td>6.95</td>
<td>7.07</td>
</tr>
<tr>
<td><strong>MM2: Low $\Delta V_L$ and short ToF</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$V_{AGA}, M_{AGA}$</td>
<td>19 2 2009</td>
<td>4.00</td>
<td>3.50</td>
<td>8.58</td>
<td>5.68</td>
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<td>$V_{GA}, E_{AGA}$</td>
<td>25 9 2010</td>
<td>3.50</td>
<td>3.83</td>
<td>7.44</td>
<td>5.68</td>
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<tr>
<td>$V_{GA}, E_{AGA}$</td>
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<td>4.00</td>
<td>3.69</td>
<td>7.91</td>
<td>5.78</td>
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<td><strong>MM3: Low $\Delta V_L$ and low $\Delta V_A$</strong></td>
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<tr>
<td>$V_{GA}, M_{AGA}$</td>
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<td>4.00</td>
<td>6.60</td>
<td>4.39</td>
<td>4.61</td>
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<tr>
<td>$V_{GA}, E_{AGA}$</td>
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<td>4.30</td>
<td>5.90</td>
<td>4.69</td>
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<tr>
<td>$V_{AGA}, M_{AGA}$</td>
<td>30 6 2011</td>
<td>3.75</td>
<td>6.16</td>
<td>5.50</td>
<td>4.75</td>
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</table>
The actual feasibility and optimality of PAMSIT solutions has been verified using PAMSIT solutions as first guesses for DITAN.
IMAGO

IMAGO (Interplanetary Mission Analysis Global Optimization) is a tool for the design of:

- Multiple revolution trajectories
- Multiple swingby transfers
- Low-thrust multiple swingby transfers

The solution of the associated two-points-boundary values problem (TPBVP) is solved by:

- An inverse approach for low-thrust trajectories
- A Lambert’s solver for coast arcs

An extended search for optimal solutions is performed using an evolutionary strategy hybridised with an interval branching and evaluation procedure.
IMAGO: Main Features

- **IMAGO** implements a simplified although complete 3D model characterised by:
  - Heliocentric coordinates frame.
  - Lambert solution for coast arcs.
  - Inverse method for low-thrust arcs.
  - Linked conic approximation for swing-bys.
  - Analytical Ephemeris

- **IMAGO** generates a solution in terms of:
  - Launch windows and planetary encounter dates
  - Departure and Arrival velocity at each planet of the sequence.
  - Optimal swing-by altitude
  - Trajectory and Thrust profiles.
  - Corrective deep space manoeuvres
  - Optimal sequence of encounters

- **IMAGO** allows
  - The design of low-thrust gravity assist trajectories combining coast and thrust arcs.
  - The design of multiple swing-by ballistic trajectories with possible deep space maneuvers.
  - The investigation of the best sequence of trajectories to a given target.
**IMAGO: example of low-thrust Earth-Mars Transfers**

IMAGO implements different shape functions for low-thrust arcs. An example is a direct transfer to Mars, compared with the solution found for a CDF study using optimal control theory.

<table>
<thead>
<tr>
<th>Launch Date</th>
<th>2007</th>
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</thead>
<tbody>
<tr>
<td>$C_3$ (km$^2$/s$^2$)</td>
<td>0.38</td>
</tr>
<tr>
<td>Arrival Velocity (m/s)</td>
<td>$\rightarrow 0$</td>
</tr>
<tr>
<td>TOF (days)</td>
<td>500-1000</td>
</tr>
<tr>
<td>Maximum Acceleration (m/s$^2$)</td>
<td>1.5e-4</td>
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</tbody>
</table>

<table>
<thead>
<tr>
<th>Solution 1</th>
<th>Solution 2</th>
<th>Solution 3</th>
<th>CDF solution</th>
</tr>
</thead>
<tbody>
<tr>
<td>Launch Date</td>
<td>06-03-2007</td>
<td>03-03-2007</td>
<td>14-03-2007</td>
</tr>
<tr>
<td>TOF (days)</td>
<td>745</td>
<td>764</td>
<td>751</td>
</tr>
<tr>
<td>Mass ratio</td>
<td>0.168</td>
<td>0.167</td>
<td>0.162</td>
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</tbody>
</table>
**IMAGO: Examples of Earth to Jupiter Transfers**

<table>
<thead>
<tr>
<th>Sequence</th>
<th>EVJ</th>
<th>EVVJ</th>
<th>EVVJ</th>
<th>EMMJ</th>
<th>EMMJ*</th>
<th>EMMJopt</th>
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</thead>
<tbody>
<tr>
<td>$C_3$ (km$^2$/s$^2$)</td>
<td>11.83</td>
<td>12.74</td>
<td>15.9</td>
<td>10.56</td>
<td>10.72</td>
<td>10.7</td>
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<tr>
<td>TOF</td>
<td>3106</td>
<td>2611</td>
<td>2890</td>
<td>2635</td>
<td>2570</td>
<td>2910</td>
</tr>
<tr>
<td>$V_s$ (km/s)</td>
<td>5.5</td>
<td>4.93</td>
<td>5</td>
<td>3.02</td>
<td>4.8</td>
<td>3.92</td>
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<tr>
<td>Mass ratio</td>
<td>0.22</td>
<td>0.37</td>
<td>0.24</td>
<td>0.27</td>
<td>0.35</td>
<td>0.23</td>
</tr>
</tbody>
</table>

- IMAGO solves multiple swingbys problems both with chemical and low-thrust propulsion.
- An example is a multiple swingby transfer to Jupiter.
- A first guess solution obtained with IMAGO is refined with DITAN.
ATOM-C (Astrodynamics Tool for Optimal Manifold Computation)

- ATOM-C is a tool for the preliminary analysis of space trajectories in the Restricted Three-Body and Four-body Problem (R3BP or R4BP).
- The tool is useful for the analysis and design of:
  - optimised transfers between two celestial bodies (ex. Earth-Moon, Earth-Mars, Jovian and Uranus moon tours),
  - transfers to orbits around libration points,
  - periodic and quasi-periodic orbits around stable and unstable equilibrium points.
ATOM-C

- ATOM-C implements efficient algorithms for the generation of stable and unstable manifolds of both Lagrangian points and Halo orbits, as well as transit orbits.

Transfers between Celestial Bodies

- Low-Energy Interplanetary Transfers
- Low-Energy Earth-Moon Transfers
- Low-Energy Moon-to-Moon Transfers

Transfers to Halo Orbits

- L1 and L2 of the Sun-Earth System
- L1 and L2 of the Earth-Moon System

Other Features

- Moon-Assisted Orbital Transfers
- Computation of Periodic Orbits around Libration Points (Lyapunov, Lissajous, Halos, Vertical)
ATOM-C

Transfers between Celestial Bodies
Trajectories defined within the manifolds associated with the periodic orbits around libration points. The manifolds of two different systems are linked together or joined using an intermediate two-body arc and then optimized.

Transfers to Halo Orbits
Trajectories defined on the stable manifold associated to the final orbit. If this stable manifold does not approach the Earth (Earth-Moon system) a three-body Lambert’s arc is used to target a point on this manifold.

The periodic orbits around libration points are computed using semi-analytical methods and then continued to the desired amplitude. The Moon-assisted orbital transfers are based on the solution of a three-body Lambert’s arc.
EPIC

- EPIC is a global optimisation tool conceived for the solution of constrained and unconstrained problems with single and multiple objectives.
- EPIC is based on the hybridisation of an evolutionary strategy and a deterministic branching procedure that cuts the solutions space in subintervals.
- The combined evolutionary-deterministic step exhaustively partitions the domain in order to have an extensive characterisation of complex solution spaces.
- Furthermore, the approach implements a novel direct constraint handling technique allowing the treatment of constrained mixed-integer nonlinear programming problems (MINLP).
EPIC: examples of applications

EPIC has been successfully applied to the investigation of:

- Direct transfers and multiple swingby transfers
- Low-thrust transfers
- Multiple gravity assist low-thrust transfers
- Multiobjective optimisation of combined terrestrial space power plants
EPIC: Characterisation of Earth-Mars Roundtrips

- Final population distributed along launch windows and in the basin of attraction of minima
- Diamonds represent short stay solutions or free re-entry trajectories
- Some regions of the solution space do not present any feasible solution
- In particular between 30 to 200 days of stay time the coast could be significantly high
- This period could extend up to 350-400 days of stay time for some launch dates
EPIC: Characterisation of Mars Free-Return Trajectories
Future Work

• The toolbox will be soon enriched with other tools for:
  – Formation flying
  – Reentry and launch trajectories
  – Aerocapture and aerobraking

• Other alternative optimiser will be included

• Design uncertainties will be included