Astrodynamics of Interplanetary Cubesats

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Outline

- Interplanetary trajectory design
  - Conventional spacecraft
  - Cubesats
- Main challenges
- Case study: Cubesat mission to Mars
- Proposed strategy
  - Ballistic capture
  - Dual propulsion
- Critical analysis
Interplanetary trajectory design for standard spacecraft

Aim: To find the best path for a conventional spacecraft
  ▶ Fuel-optimal, time-optimal, energy-optimal, etc.

Manoeuvres accomplished through on-board propulsion
  ▶ Small errors in the nominal trajectory zeroed with TCM
  ▶ 6 DoF control usually available (RCS)

Control authority is not an issue
  ▶ S/C designed to cope with off-nominal conditions, unless catastrophic events occur
  ▶ S/C over-actuated
Aim: To find the best solution under much tighter constraints
  - Power generated
  - Propellant stored
  - Thrust exerted

Interplanetary cubesats have much less control authority
  - Capability of executing orbital manoeuvres strongly limited

These features set new challenges in astrodynamics
  - **Arrival**: How to acquire a final, closed orbit about a planet?
  - **Cruise**: How to accomplish the interplanetary transfer?
  - **Departure**: How to leave the Earth?
Case study: Cubesat mission to Mars

Devised strategy involves

- Arrival: Performing **ballistic capture** upon Mars arrival
- Cruise: Using **on-board micro-propulsion**
- Departure: Using **hybrid propulsion** to leave the Earth

Case study: A cubesat mission to Mars
Ballistic capture (in a nutshell)

A massless particle is (temporarily) ballistically captured by a primary if (along the orbit) its Kepler energy ($H$) goes from positive to negative

- The two-body state changes from hyperbolic to elliptic
- Requires n-body dynamics, with $n \geq 3$
- Permanent capture require dissipation
- The opposite behavior is the ballistic escape

![Graph showing temporary ballistic capture](image)

**Temporary ballistic capture**

**Graph showing orbital dynamics**

- Planet
- $H = 0$
- $t_1$, $t_2$
Why ballistic capture

- Saves **propellant**
  - Reduces hyperbolic excess velocity upon arrival
  - Lowers the magnitude of arrival maneuver, or \( \Delta v \)
  - Thus saving propellant, \( \frac{m_p}{m_0} = 1 - \exp\left[-\Delta v/(I_{sp} g_0)\right] \)

- Widens the **launch windows**
  - Target is a point in the space, not the planet

- Increases **safety**
  - Avoids single-point injection failures
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Hyperbolic arrival

Low-energy arrival
Ballistic capture at Mars

- High altitude Mars orbits easily accessible
- Cheaper than Hohmann transfer(s)
- No manoeuvre at arrival needed!

<table>
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<tr>
<th>Point</th>
<th>$r_P$ (km)</th>
<th>$\Delta V_c$ (km)</th>
<th>$\Delta V_2$ (km/s)</th>
<th>$S$ (%)</th>
<th>$\Delta t_{c \rightarrow p}$ (days)</th>
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<td>(D)</td>
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</tr>
</tbody>
</table>
Ballistic capture in the news

- Topputo & Belbruno, arXiv, 2015
- Topputo & Belbruno, CMDA, 2015
Reaching Mars with micro propulsion

**Aim:** target a point in the deep space, $x_c$, to ensure capture using on-board Ion Propulsion

- **Assumptions:** $m_0 = 12$ kg, S/C in parabolic state wrt Earth
  - $T(AU) = 11.312e^{-2.262*AU}$ [mN]
  - $Isp(AU) = 3887.2*AU^2 - 13842*AU + 13445$ [s]
- $TOF = 1179$ days (3.2 years), $mp = 2.79$ kg (mass at Mars = 9.21 kg)
Escaping the Earth

- Cubesats likely launched as **piggy back** payloads
- No control on launch date
- Released in **low-altitude** (LEO, GTO) Earth-bounded orbit
- Escaping with on-board propulsion may be cumbersome
  - **Long duration** needed to escape
    - Pointing, operations, costs, etc. strongly affected
  - **Much radiation** dose accumulate
    - Solar arrays, shielding, etc. strongly affected

Images taken from [http://space.stackexchange.com](http://space.stackexchange.com)
Dual propulsion idea

Both chemical and low-thrust propulsion on-board the system

How it works:

- S/C launched as piggy back in LEO
- Earth escape achieved with chemical, impulsive burn
  - Short duration, less radiation
- Masses involve in chemical propulsion are thrown away
  - Dual-staged S/C, interfaces, complexity
- Cruise accomplished with on-board low-thrust propulsion

- Concept proven in ESA study in 2012
- Implemented by Lisa Pathfinder (for other reasons)
Cubesat achieves escape with its own chemical propulsion system

Cubesat performs Earth-Mars transfer with its own low-thrust propulsion

Upon arrival, ballistic capture is performed (and low-altitude orbit achieved)
Wrap up and conclusions

- Cubesats have been used successfully for Earth observation/communication.
- Wandering in the solar system with extremely low-resources space systems (cubesats) raises a set of completely new challenges in astrodynamics.
- Ideas have been presented to attempt answering these new questions.
- These include:
  - Performing ballistic capture.
  - Having a dual propulsion system.
- More in-depth analyses needed …