Lunar CubeSats

Low Cost Lunar Exploration

Willem van der Weg and Massimiliano Vasile
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- Introduction
- ESMO Concept
- CubeSat Concept
- Results
- Concluding Remarks
Why the Moon?

- Recent Lunar Exploration
  - Smart 1 2006
  - SELENE 2007
  - Chang’e 1 2007
  - Chandrayaan-1 2008
  - LRO 2009
  - LCROSS 2009
  - Chang’e 2 2010
  - GRAIL 2011

12-10-2012

Low Cost Lunar Exploration
Paradigm Shift

- Paradigm shift from large-scale expensive missions to small-scale risk tolerant cheap missions
  - Lower cost, faster development, cheaper production outweigh the higher risks of losing individual spacecraft

- Goals of our research:
  - Facilitate Low Cost Lunar Exploration
  - Create small budget missions feasible for Universities and small industry

- Science
  - Splitting of instruments across multiple vehicles
  - Reverse design philosophy: see what we can achieve at a certain level of cost
European Student Moon Orbiter

- ESA sponsored European project with 20 University teams participating
- ASCL is lead team for both Mission Analysis and Flight Dynamics
- Preliminary Design Review closed successfully last year
- Mission Analysis Challenges
  - Secondary payload (no control over exact launch date and orbit insertion)
  - Long waiting period in GTO
  - Low cost (COTS components, flight spares, low ΔV budget)
  - Launch window analysis of 2014 and 2015
ESMO Transfer

- Weak stability boundary transfer uses Sun’s gravity to raise perigee of the orbit and to change the orbit plane such that conditions are suitable for lunar capture.
- Saves propellant compared to traditional transfer, thus lowering cost.
Launch Window Analysis

12-10-2012

Low Cost Lunar Exploration
Lunar Orbit

- Research into orbits with low propellant cost that satisfy payload requirements and mission cost budgets
- Find ideal balance between cost and performance
Design Robustness

- Research into contingencies, such as lunar capture manoeuvre failure
  - Spacecraft inserted into orbit using attitude thrusters or main engine at a later date
  - Made possible by weak capture as a result of the Weak Stability Boundary transfer

*Complete LOI failure*

- 3 maneuver recovery
  - 55 m/s extra $\Delta v$
  - 4.4 days before 1$^{st}$ maneuver
ESMO Budget

- ESMO had a budget of 4M+ Euros
- Launch cost reduced by piggy-backing
- Operation cost reduced by use of single ground-station and limiting complexity
- Further low cost measures
  - Use of flight spares and commercial-off-the-shelf components
  - Highly elliptical lunar orbit
  - Transfer with low propellant cost
- ESMO is a potential S class mission (below 50M Euros)
  - Preliminary Design Review completed
  - British Primary Contractor SSTL
Why not go even smaller?

- ESMO is small at 200+ kg, but we can go even smaller towards the design of <10 kg systems
- Rapid development of new micro-propulsion systems that can be fitted onto Nano-spacecraft
- Nano-spacecraft require deployable arrays/antennae to operate farther from the Earth, leading to higher area to mass ratios than is typical
- Project becomes small enough for single universities or companies
- Initial investigation sponsored by UK Space Agency
**3U CubeSat**

- 3 unit CubeSat with weight of 4~5 kg
- Trajectory to Moon exploits natural perturbations and makes effective use of solar radiation pressure
- Area to mass ratios from 0.5 ~ 4 m²/kg
- Engines allow high Δv budgets
  - MiXI can achieve up to 7 km/s for a 3 unit CubeSat

<table>
<thead>
<tr>
<th>Engine</th>
<th>Thrust (mN)</th>
<th>Engine Mass (kg)</th>
<th>Isp (s)</th>
<th>Power (W)</th>
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</thead>
<tbody>
<tr>
<td>MiXI</td>
<td>0.01-1.5</td>
<td>0.2</td>
<td>2500-3200</td>
<td>13-50</td>
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<tr>
<td>Colloid</td>
<td>0.03-0.3</td>
<td>0.3</td>
<td>~3000</td>
<td>1.5-15</td>
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<td>CHT</td>
<td>3-6</td>
<td>&lt;1</td>
<td>1200-2000</td>
<td>50-170</td>
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</table>
CubeSat to Halo Orbit

Example
- 72 manoeuvres
- ~ 2.251 km/s Δv cost
- 701 day transfer time
CubeSat to Lunar Orbit

- Achieving lunar capture or quasi-capture

Example
- 64 manoeuvres
- \( \sim 2.213 \text{ km/s } \Delta v \text{ cost} \)
- 1023 day transfer time
- Ideally suited for magnetosphere study
Science Opportunities

- Magnetosphere studies
- Lagrange L1 and L2 missions
  - Low propellant cost of heteroclinic connections allow for multiple switches between L1 and L2 with different orbit shapes
- Lunar surface studies
  - Multiple cheap spacecraft allow for effective full surface observation
- Lunar impact studies

- The cost of these missions only vary in terms of payload coast
  - Same bus
  - Same launch
  - Similar operations
  - Similar transfer
Future Development

- Further study is sponsored by ESA
- Look into faster transfers with higher associated $\Delta v$ cost
- Investigate possibility of WSB transfers for Nano-spacecraft
- Low thrust capture around the Moon in a variety of orbits
- Expand system design of the CubeSat
- Port software packages from ESMO to Nano-spacecraft concept (navigation, orbit determination, manoeuvre simulator, etc.)
Thank you!
Questions?
Lunar Capture Tools

Key:
- Green: pass by L1
- Red: pass by L2
- Blue: lunar Impact
- 250 $t= \sim 3$ years

Spacecraft placed at
- $x = x_{L1}, z = 0$
- $v_y = 0, v_z = 0$
- $y$ and $v_x$ sampled
Fixed Orientation Database (1)

- Ariane 5 launches at fixed times during the evening (white lines)

- All solutions include 3 apogee raising maneuvers prior to departure
Robustness

Complete LOI failure

2 maneuver recovery
50 m/s extra $\Delta v$
3.5 days before 1$^{st}$ maneuver

3 maneuver recovery
55 m/s extra $\Delta v$
4.4 days before 1$^{st}$ maneuver

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Contingency procedure
- - No maneuver performed
★ Maneuver
Previous Study

- ‘CubeSat Lunar Mission Using a Miniature Ion Thruster’
  Ryan W. Conversano and Richard E. Wirz
- Constant thrust spiral up to Moon
- CubeSat with miniature ion thruster
  - MiXI thruster capable of of 1.5 mN at $I_{sp}$ over 3000 s
  - 0.35 m² solar array satisfactory for power
- High ΔV capability (up to 7 km/s)

- We use a different strategy of thrusting arcs modelled as small impulses and experiment with reflective surfaces
  - Goal to save further propellant and increase payload mass
ESMO Flight Dynamics

- Complete mission simulator constructed

**Orbit Determination**
Simulates non-exact determination of spacecraft state

**Manoeuvre Simulator**
Simulates a manoeuvre taking into account full environmental and mechanical model

**Navigation Module**
Allocates Correction Manoeuvres