Trajectory Analysis for OMOTENASHI Mission

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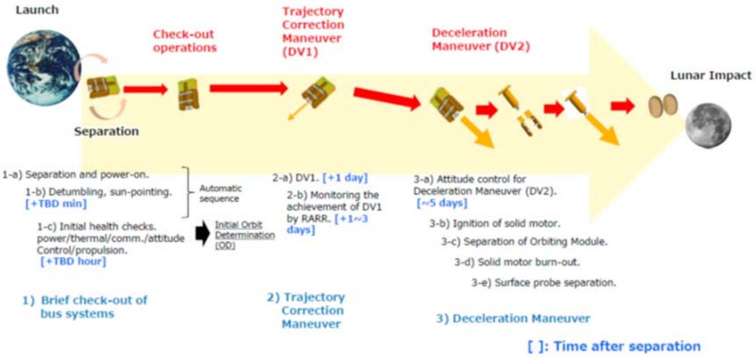
Introduction

- OMOTENASHI is **one of thirteen 6U CubeSats of NASA SLS/EM-1**
- OMOTENASHI will be **the world first micro-Lunar lander**
- OMOTENASHI will reach the Moon with **short period** (about 4.7days)
- OMOTENASHI has a **solid motor** to decelerate itself just before the Lunar impact and land on the Moon (semi-hard landing)
- The impact velocity is constrained under 30 m/s (TBD), but it is **strongly affected various sub-system and navigation errors**.

Robust trajectory design is a major requirement for OMOTENASHI mission



1-a) Separation and power-on.
1-b) Detumbling, sun-pointing. [+TBD min]
Automatic sequence
1-c) Initial health checks. power/thermal/comm./attitude Control/propulsion. [+TBD hour]
Initial Orbit Determination (OD)

2-a) DV1. [+1 day]
2-b) Monitoring the achievement of DV1 by RARR. [+1~3 days]

3-a) Attitude control for Deceleration Maneuver (DV2). [~5 days]
3-b) Ignition of solid motor.
3-c) Separation of Orbiting Module.
3-d) Solid motor burn-out.
3-e) Surface probe separation.

1) Brief check-out of bus systems

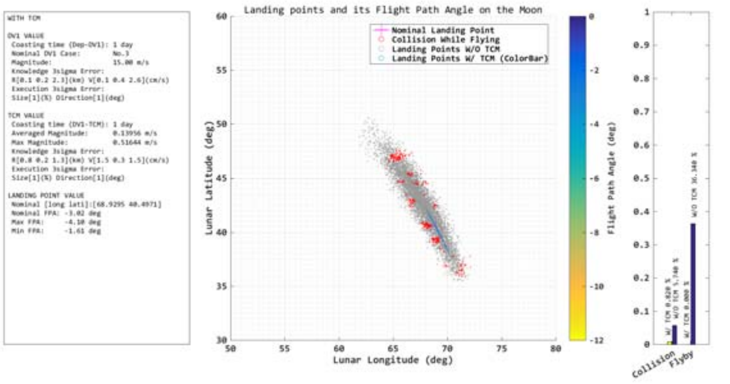
2) Trajectory Correction Maneuver

3) Deceleration Maneuver

[ ]: Time after separation

Earth-Moon Transfer Phase

- Transferring from SLS's nominal flyby trajectory to shallow flight-path-angle landing trajectory with DV1 at 1day after coasting.
- How to determine the DV1 and coasting time:
  - Structural restriction on velocity increment magnitude(< 20m/s)
  - Trade-off analysis between fuel consumption, size of the feasible landing region and Orbit Determination (OD) constraints
- Error analysis with fixed nominal DV1 profile at DV1 event:
  - With fixed knowledge error at DV1 and fixed execution error of DV1
  - Mapping these supposed errors with State Transition Matrix
  - Evaluating failure cases (flyby and collision on the moon terrain while flying)
  - High failure rate with performing DV1 only
- Adding Trajectory Correction Maneuver (TCM) scenario
  - Profile of TCM is determined by fixing the arrival time and position
  - With fixed knowledge error at TCM and fixed execution error of TCM
  - Significantly reduce failure rate with adding TCM



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WITH TCM

DV1 VALUE
 Coasting time (Dep-DV1): 1 day
 Nominal DV1 Case:        No.3
 Magnitude:               15.00 m/s
 Knowledge 3sigma Error:
 R[0.1 0.2 2.3](km) V[0.1 0.4 2.6](cm/s)
 Execution 3sigma Error:
 Size[1](%) Direction[1](deg)

TCM VALUE
 Coasting time (DV1-TCM): 1 day
 Averaged Magnitude:      0.13956 m/s
 Max Magnitude:           0.51644 m/s
 Knowledge 3sigma Error:
 R[0.8 0.2 1.3](km) V[1.5 0.3 1.5](cm/s)
 Execution 3sigma Error:
 Size[1](%) Direction[1](deg)

LANDING POINT VALUE
 Nominal [long lati]:[68.9295 40.4971]
 Nominal FPA: -3.02 deg
 Max FPA:     -4.10 deg
 Min FPA:     -1.61 deg
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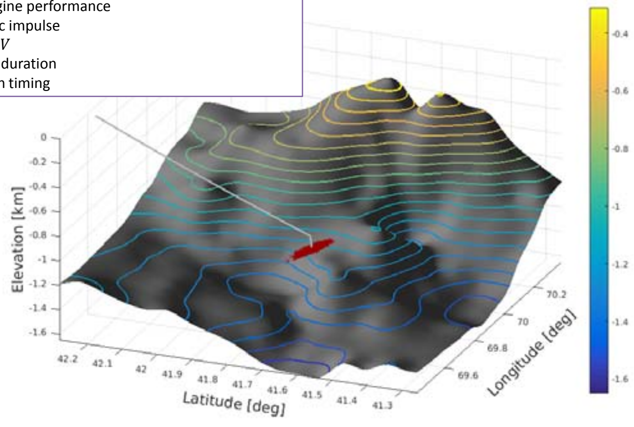
Landing Phase

- Incoming shallow flight-path-angle
  - Robustness to timing errors
  - Robustness to velocity changes. Braking maneuver direction can be adjusted to minimize vertical landing velocity
- Structural limit: $V_{landing} < 30$ m/s
- Braking maneuver DV2 determined by fixing:
  - Fixed altitude
  - Zero vertical velocity
- Error analysis
  - Thrust-local horizontal angle, position, and thrust duration errors have the greatest impact
- Failures include $V_{landing} > 30$ m/s and premature landings during braking maneuver
  - Decreasing final altitude decreases $V_{landing}$
  - However it leads to more premature landings
- High-fidelity Moon topography is used to assess the lunar terrain
  - SELENE mission data

Error sources
- Position and velocity at ignition (Orbit Determination)
- Thrust pointing (attitude)
  - Angle with local horizontal
  - Angle with local vertical
  - Spin axis nutation
- Rocket engine performance
  - Specific impulse
  - Total ΔV
  - Thrust duration
  - Ignition timing



Summary and Future Work

- Earth-Moon transfer phase
  - Error sensitivity is evaluated. Especially, velocity knowledge error, delta-V execution error could make the spacecraft miss the Moon.
  - The use of TCM is currently considered. However further study is still needed.
  - The knowledge at DV2 is the most critical since the DV2 should be conducted at hundred of meters of altitude. DDOR is essential.

- Landing phase
  - Robustness is evaluated considering various errors, high-fidelity Lunar topography.
  - Current analysis shows reasonable success rate.
  - Further study is needed to improve the dynamical system.