 Guidance, Navigation, and Control for NASA Lunar Pallet Lander

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Overview

- Mission Concept
- Mission Requirements and Navigation Sensor Selection
- Vehicle Guidance Navigation and Control Overview
- Simulation Architecture
- Vehicle Landing Performance
- Future Work and Next Steps
Lunar Pallet Lander

- Hypergolic Bipropellant: Monomethyl hydrazine and 25% Nitric Oxide or MON25
- Twelve 100 lbf Descent Thrusters (On/Off)
- Solid Rocket Motor SRM with Thrust Vector Control
- Rover Offload Ramps
- Twelve 5 lbf Attitude Thrusters (On/Off)
Mission Overview

Launch Vehicle provided
Trans-Lunar Injection

Flight Phase | Delta-V (m/s)
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After separation from ELV
+440-N descent thruster | 25 (TCMs)
+22 N ACS thruster (10%) | 2.5
SRM Operation
+SRM operation | 2390 (Braking Burn)
+22-N ACS thruster (25% Duty) | 0.24
Vertical Descent by Lander
+440-N descent thruster | 411 (Liquid Descent)
+22-N ACS thruster (10%) | 41
+440-N descent thruster (redirect budget) | 21

Lander Notes:
1. 37.6 kg Flight Performance Reserve of usable propellant load is added at the end
2. TVC assumed SRM
3. Altitudes above average lunar radius

Site A: -85 N 108.64 W elevation -510m
Landing: 6/15/2022 12:00 (UTC)
Driving Requirements & Sensor Selection

- **Touchdown position and velocity requirements drive GNC sensor selection**
- **Precision landing requirement of 100 meters**
  - To achieve the above precision landing, good measurement of position and velocity are needed:
  - Terrain Relative Navigation (TRN) position sensor is used, which takes images of lunar surface during descent and updates lander location within < ~10m accuracy
  - Navigation Doppler Lidar (NDL) altimeter and velocity sensor for high accuracy altitude and 3-axis velocity measurements with ~0.17 cm/s velocity error
- **Touchdown requirements of 2m/s maximum vertical & horizontal velocities**
  - To meet this requirement, analysis shows that the NDL and a medium grade IMU suffice
Attitude and Attitude Rate Requirements:

- Max vertical attitude at touchdown of 5 deg
- Max angular rate at touchdown of 2 deg/s
- Max attitude error at touchdown +/-10 deg
  - Sun pointing or Communications pointing
- Sun pointing during cruise +/-10 deg

The above requirements can be met with medium grade IMU, Star Trackers, and Sun Sensors.

Candidate sensor:
Northrup Grumman LN200S IMU
~.07 deg/sqrt hr angle random walk

Candidate sensor:
2-NST Blue Canyon Star Tracker
Cross-boresight Accuracy 6 arcsec, 1-sigma
Around-boresight Accuracy 40 arcsec, 1-sigma

Candidate sensor:
6xNewSpace Fine Digital Sun Sensor
.1deg accuracy with 140deg FOV
Precision Landing Requirement

- Precision landing has never been attempted in space
  - For this mission precision landing means landing within 100 meters (3\(\sigma\)) of a prescribed target
  - Mars 2020 will employ autonomous TRN for the first time (primarily for hazard avoidance)
- Previous lunar missions targeted large, flat areas which are largely devoid of hazards
  - Most science missions, however, want to land near craters and outcrops
- Without lunar GPS, precision landing requires Terrain Relative Navigation (TRN)
- TRN measures position by correlating images taken by an on-board camera with stored imagery of the lunar/planetary surface
- Combining TRN with NDL significantly improves the Navigation knowledge to achieve precision and soft landing
Guidance

- **SRM burn**, uses a fixed pitch angle w.r.t. LVLH is used,
  - Based on a *Moon Entry Descent Algorithm by Ellen M. Braden – NASA/JSC/EG5*
  - Employs a predictor-corrector, predicts vehicle location down to descent and landing
  - Uses an estimated SRM thrust profile based on PMBT
  - Attempts to ensure a good initial state for liquid burn
  - Can be ran during pre-SRM coast to calculate initial LVLH pitch angle

- **Liquid Descent**, several guidances are currently traded
  - Apollo (baseline), Tunable Apollo, and Quadratic guidances
    - With quadratic formulation of the commanded acceleration
      \[ a_c = c_0 + c_1 t_{go} + c_2 t_{go}^2 \]
    - Differences lie in the commanded acceleration coefficients and the targets
    - All target a final position, velocity, and acceleration vector
    - By targeting acceleration, the desired final attitude of the vehicle can be specified
  - The Minimum Acceleration (D’Souza) guidance only targets the final position and velocity vectors
    - The final attitude of the vehicle cannot be specified
    - A pitch-over maneuver is needed for the vehicle to achieve the desired final attitude
Navigation Architecture

6 State Kalman Filter (5 Hz) \([\omega(3) \text{ gyro\_bias (3)}]\)

12 State Kalman Filter (10 Hz) \([x(3) \text{ v}(3) \text{ a}_{\text{bias}}(3) \text{ a}_{\text{SF}}(3)]\)

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**Navigation System Architecture**

- **Sun Sensor**
  - Inputs: \(r_{\text{sun, sensor}}\)
  - Frequency: 5 Hz

- **Star Tracker**
  - Inputs: \(q_{\text{i2s sensor}}\)
  - Frequency: 5 Hz

- **IMU**
  - Inputs: \(w_{\text{sensor}}\), \(a_{\text{sensor}}\)
  - Frequency: 100 Hz

- **NDL**
  - Inputs: \(t, \text{range, range-rate}_{\text{radial}}\)
  - Frequency: 10 Hz

- **TRN Subsystem**
  - Inputs: \(t, r_{\text{inertial}}\)
  - Frequency: 1 Hz

- **Ground State Update**
  - Inputs: \(t, r_{\text{inertial}}, v_{\text{inertial}}\)
  - Frequency: 10 Hz

- **Output Processing**
  - Inputs: \(r, v_{\text{landing site}}, t, r_{\text{inertial}}\)
  - Frequency: 100 Hz

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**Processing Blocks**

- **SS Processing**
- **ST Processing**
- **IMU Processing**
- **Attitude Integration**
- **State Integration**
- **State Estimation Filter**
- **Attitude Estimation Filter**

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**Formulas**

- \(r_{\text{sun, body}}\)
- \(q_{\text{i2b,ST}}\)
- \(q_{\text{i2b, prop}}\)
- \(w_{\text{bias, est}}\)
- \(r, v_{\text{inertial, est}}\)
- \(dX_{\text{corr}}\)
- \(t, r_{\text{inertial, corr}}\)
- \(r, v_{\text{landing site}}\)
SRM - Control

• Control operates at 50Hz
• SRM stage uses thrust vector control
  – Proportional Integral Derivative (PID) linear control law
  – Roll control via the Attitude Control System (5lb-ACS)
  – SRM is sized for the specific mission/landing site
Pulsed Liquid Engine Control

- Descent Engines (DE): 12 x 100 lb
  - Pulsed On/Off to minimize axial velocity error
  - “Water Hammer” effects:
    - All engines On/Off simultaneously causes high-pressure waves on propellant lines and valves
    - Mitigate through staggering the number of DE engines turned On/Off and at a given time
- Attitude Control System (ACS) Engines: 12 x 5 lb
  - Phase-Plane control: On/Off pulsing if attitude or rate error is outside “deadbands”
  - “Off-Pulsing” - Augment ACS control authority by turning Off pairs of DE engines:
    - To counter large torques e.g. due to C.G. offsets
    - Off-Pulsing requires fast-acting propulsion system/valves performance, ~5ms On/Off cycles
    - Off-Pulsing for 5, 10, or 20ms depending on magnitude of control error/disturbance torque

![Phase Plane Diagram](image)
Generic LAnder Simulation in Simulink (GLASS)

- Lunar Pallet Lander is modeled in the Generic LAnder Simulation in Simulink (GLASS) developed by MSFC
  - Uses Mathworks Simscape Multibody dynamics tool for spacecraft and planetary bodies
  - GLASS is used to develop and autocode GNC software in C language
  - Uses Simulink Projects for high modularity and version control capability
  - Highly focused on Model Based Design approach
  - Interfaces with Core Flight Software cFS

- Using GLASS a 200-Case Monte Carlo dispersed analyses has been conducted to evaluate the lander soft touchdown performance

- Dispersed mass properties, propulsion performance, and sensor error parameters
Monte Carlo Results: Altitude

- SRM Ignition (71.8km)
- SRM Burnout (~9 km)
- TRN Starts ~9 km
- Liquid Engine Starts ~7km
- NDL Starts ~2km
- TRN Ends ~500m
- NDL Ends ~30m
- IMU only below ~30m
- NDL+IMU

Altitude Time History

0  50  100  150  200  250  300  350  400
\(10^4\)
\(9\)  \(8\)  \(7\)  \(6\)  \(5\)  \(4\)  \(3\)  \(2\)  \(1\)  \(0\)

Altitude (m)

0  20  40  60  80  100  120  140  160  180  200

Time (s)

260  280  300  320  340  360

Altitude (m)

NDL+IMU

IMU only below ~30m
Lateral Position at Touchdown

Land Site Lateral Touchdown Position

- **100m Requirement**
- **Nominal run**
- **Passes Pos & Vel Req**
Vertical Velocity at Touchdown

**Vertical Velocity Magnitude at Touchdown**

- **Velocity Limit**
- **Nominal run**
- **Monte Carlo**

**Axes:**
- Vertical Velocity (m/s)
- Run Number

**Values:**
- Vertical Velocity: 0 to 2.5
- Run Number: 0 to 200
*26.9 kg of unusable propellant remaining onboard*
Future Work

Working towards PDR in the Spring:

• Finalize TRN sensor requirements
• Finalize Nav. trades including lunar “touchdown” detection sensor selection
• Analyze Plume Surface Interaction effects
• Finish evaluation of different Guidance algorithms
• Evaluate alternative control algorithms
• Incorporate vehicle flexible body dynamics and mature propulsion models
• Include SRM separation analysis/effects
• Include Launch vehicle performance into dispersed analysis
• Finalize system-level requirements
Thank you

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Any questions?