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

- Twelve 100 lbf Descent Thrusters (On/Off)
- Solid Rocket Motor SRM with Thrust Vector Control
- Twelve 5 lbf Attitude Thrusters (On/Off)
- Rover Offload Ramps

Hypergolic Bipropellant: Monomethyl hydrazine and 25% Nitric Oxide or MON25
Mission Overview

**Launch Vehicle provided Trans-Lunar Injection**

**Flight Phase** | **Delta-V (m/s)**
--- | ---
**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:
Northrop Grumman LN200S IMU
~.07 deg/sqrtthr 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 has never been attempted in space
- For this mission precision landing means landing within 100 meters (3σ) 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

- **Navigation System Architecture**
  - 6 State Kalman Filter (5 Hz)
    \[\omega(3)\; gyro\_bias(3)\]
  - 12 State Kalman Filter (10 Hz)
    \[x(3)\; v(3)\; a\_bias(3)\; a\_SF(3)\]

- **Input Parameters**
  - Sun Sensor: 5 Hz
  - Star Tracker: 5 Hz
  - IMU: 100 Hz
  - NDL: 10 Hz
  - TRN Subsystem: 1 Hz
  - Ground State Update: 1 Hz

- **State Variables**
  - \(r_{sun, sensor}\)
  - \(q_{i2s}\)
  - \(w_{sensor}\)
  - \(a_{sensor}\)
  - \(r_{sun, body}\)
  - \(w_{body}\)
  - \(a_{body}\)
  - \(r_{i2b, body}\)
  - \(w_{bias, est}\)
  - \(r_{corr}\)
  - \(t, range, range-rate_{radial}\)
  - \(t, r_{inertial}\)
  - \(t, v_{inertial}\)
  - \(t, r_{inertial, corr}\)
  - \(r_{i2b, corr}\)
  - \(r, v_{inertial, est}\)
  - \(r, v_{inertial, corr}\)
  - \(r, v_{landing site}\)

- **Output Processing**
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
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

Altitude Time History

- 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
Lateral Position at Touchdown

Land Site Lateral Touchdown Position

Z Position (m)

Y Position (m)

-200 -150 -100 -50 0 50 100 150 200

-200 -150 -100 -50 0 50 100 150 200

100m Requirement

Nominal run

Passes Pos & Vel Req

AAS GNC 2019
Lateral Velocity at Touchdown

Lateral Velocity Magnitude at Touchdown

- Velocity Limit
- Nominal run
- Monte Carlo

Lateral Velocity (m/s)

Run Number

AAS GNC 2019
Vertical Velocity at Touchdown

Vertical Velocity Magnitude at Touchdown

- Velocity Limit
- Nominal run
- Monte Carlo

Vertical Velocity (m/s)

Run Number

0 50 100 150 200
Usable Propellant Remaining

*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?