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GUIDANCE, NAVIGATION, AND CONTROL FOR NASA LUNAR PALLET LANDER

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The NASA Lander Technology project is leading the development and integration of the Lunar Pallet Lander (LPL) concept. The objective is to demonstrate precision landing by delivering a payload to the lunar surface within 100 meters of a landing target. Potential landing sites are selected near the lunar pole where water may be present in permanently shadowed regions that could enable future in-situ resource utilization. The LPL is part of a sequence of missions aimed at maturing the necessary technologies, such as lunar precision landing sensors, that will enable the next generation of multi-ton lunar payloads and human landers. This paper provides an overview of the Mission Design, Guidance Navigation and Control (GNC) algorithms, and sensor suite. The results show the LPL simulated trajectory and landing precision performance under nominal and dispersed conditions. The landing precision simulation confirms the need to rely on high-accuracy navigation techniques and sensors such as Terrain Relative Navigation (TRN) and the Navigation Doppler Lidar (NDL), currently being developed for space applications. The results also demonstrate the ability of the guidance and control system to perform a soft lunar touchdown by combining thrust vector control during the solid rocket motor deceleration phase, and pulse engine control, for the liquid powered descent phase.

INTRODUCTION

In preparation for future robotic missions to the lunar surface, NASA has performed a number of concept studies to identify technology needs for upcoming lunar missions. These studies have spawned development efforts in advanced propulsion, navigation and landing, and various other lander subsystems. NASA has also independently developed and terrestrially flown lander test beds: Morpheus (led by NASA Johnson Space Center) and Mighty Eagle (led by NASA Marshall Space Flight Center).[1] Morpheus and Mighty Eagle demonstrated vehicle-level integration capabilities using different propulsion architectures, navigation and landing systems, ground and flight software, and avionics. The success of these efforts led to the establishment of an integrated, cross-agency lander community that now supports industry through several funded efforts under NASAôs Advanced Explor Project.

In one of the recent studies, the Lunar Pallet Lander (LPL) concept was introduced, as illustrated in Figure 1. The LPL is a lander capable of delivering a 300kg rover payload to the polar regions of the Moon. The rover would be able to perform science or be equipped with an In-Situ Resource Utilization (ISRU) demonstration payload. This lander was designed to minimize cost and schedule, with its mission terminating once the surface payload was delivered. While still emphasizing simplicity and affordability, this

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lander design has been further evolved to investigate features potentially extensible to future human landers. Also, the LPL will provide power and communications to the payload from transit to lunar landing. Finally, lander is not intended to survive the lunar night.

This paper provides an overview of the LPL mission design, guidance, navigation, and control system. The paper is divided into five main sections. The first section, provides an overview of the mission design. Section two, defines the guidance, navigation and control algorithms. Section three, describes the multi-body dynamics generalized lander simulation tool. In addition, section four, describes the lander simulated performance during a lunar descent. Finally, section five summarizes the key findings and future work.

MISSION DESING

The LPL uses a combination of liquid propulsion and solid propulsion. The solid stage, composed of an ATK Star 48AV Solid Rocket Motor (SRM), is used for the breaking burn, and it is jettisoned after SRM burnout. The liquid propulsion consists of twelve pulsed thrusters descent engines, 100 lbf each, three on each of the four corners of the vehicle, as shown in Figure 1 below. The liquid engines use a hypergolic bipropellant: a Monomethylhydrazine (MMH) as fuel, and 25% nitric oxide (MON25) as oxidizer.

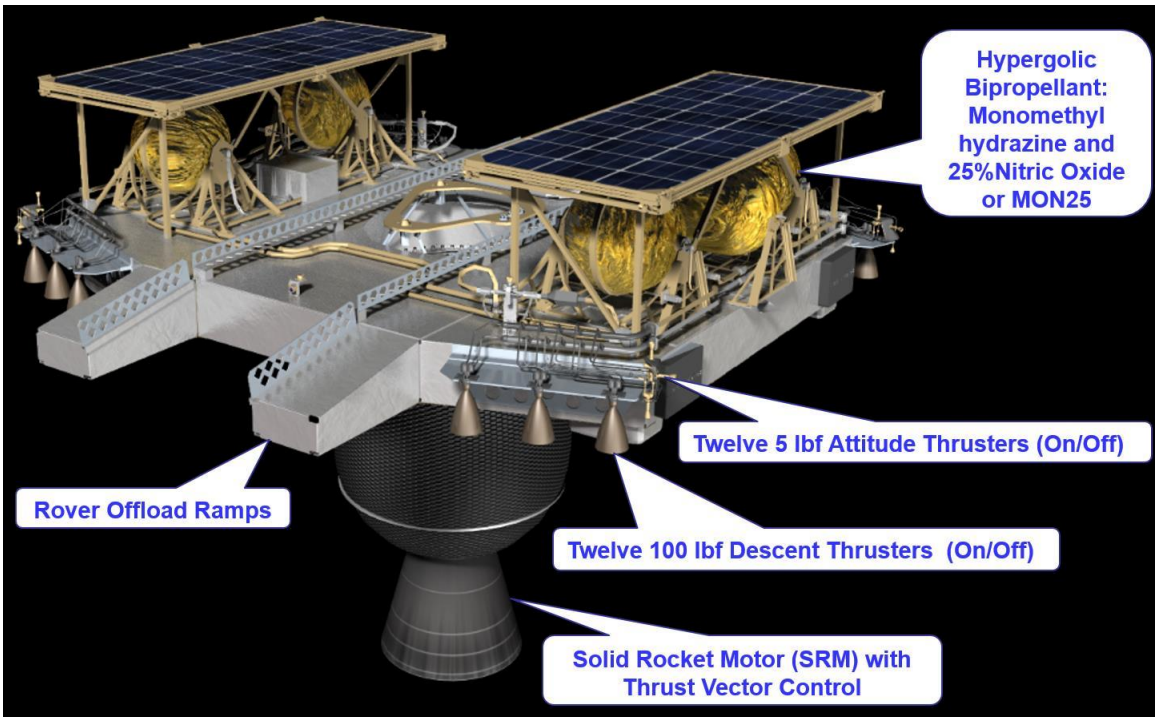
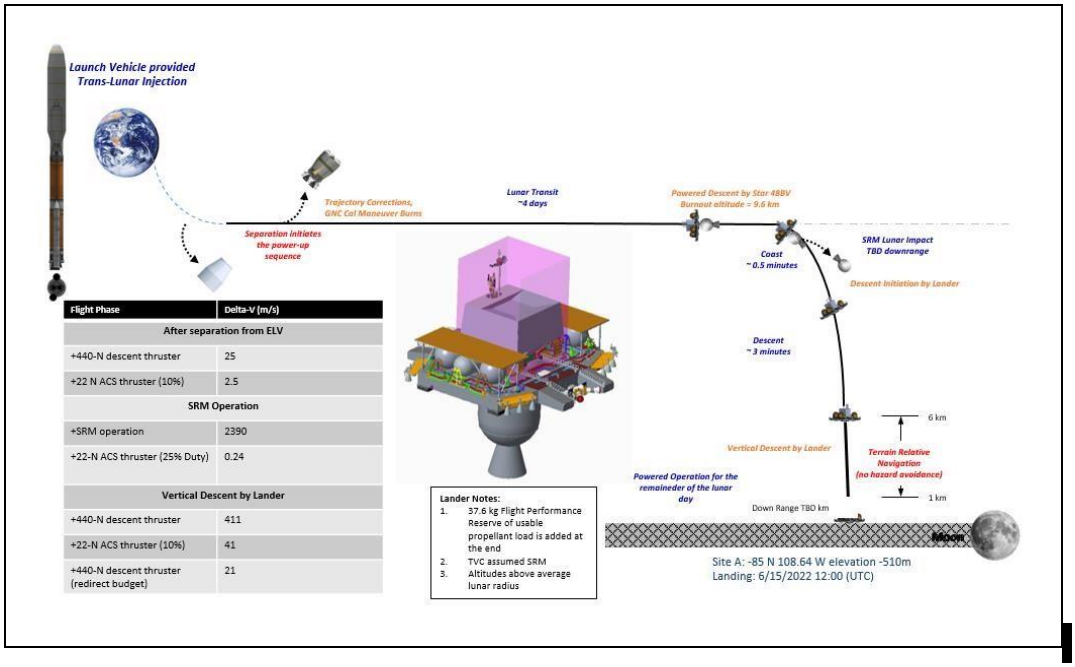


Figure 1. Lunar Pallet Lander Configuration, without Payload.

The LPL mission design assumes a ride on an Evolved Expendable Launch Vehicle (EELV) class vehicle. With the LPL as a primary payload, the mission design is greatly simplified, since the lander can fly into a direct descent to the lunar surface. Therefore, after the Trans Lunar Injection TLI burn, provided by the EELV, the LPL separates from the upper stage of the launch vehicle, as shown in the mission summary Figure 2. After system checkout and sun-pointing, the LPL will perform Trajectory Correction Maneuvers (TCMs) to ñcleanò any TLI insertion dispersions. The

for all TCMs. After TLI, and any needed TCMs, the LPL cruises for approximately 4 days before initiating the breaking burn with the SRM. The LPL trajectory is optimized, to account for SRM performance variations due to solid propellant temperature, Figure 3, and navigation uncertainties during the SRM burn that could bias the trajectory as much as +-6 km in crossrange and downrange. [2,3] After the solid burn is completed, a short coast of 30 seconds allows the vehicle to maneuver to its optimal liquid descent burn orientation. The final liquid burn is decomposed on three phases. The first phase use optimal guidance with a target at 200 meters above the lunar surface, and a descent velocity of 10m/s.[4] Then, the second phase is a vertical descent from 200 meters down to 10 meters, with a linear ramp down in descent velocity to 1 m/s. A final descent phase is performed at a constant velocity of 1 m/s until touchdown.



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

Figure 2. Lunar Pallet Lander Mission Summary.

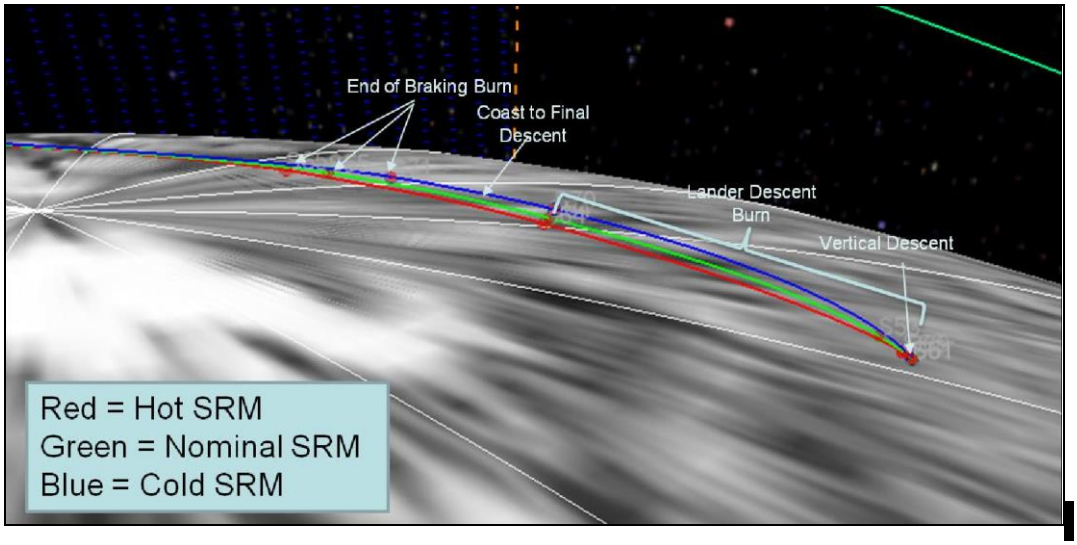


Figure 3. Lunar Pallet Lander Final Descent with SRM Temperature Dispersions

GUIDANCE, NAVIGATION AND CONTROL

GUIDANCE

The Guidance systemôs function is to command attitu
to the liquid engines) so that the guidance targets are achieved without violating design constraints. The Guidance system depends on navigated inertial position, inertial velocity, attitude, and the current time from the Navigation subsystem. The Mission Manager supplies the Guidance system with inputs for event notifications and engine status. The remaining inputs to the Guidance algorithms are mission-dependent data and constants, which are loaded onto LPL in the form of loadable parameters. Outputs from the Guidance system passed to the Control system include the estimate of liquid propellant remaining, as well as commanded attitude and angular velocity. Additionally, the Guidance system outputs the recommended shutdown command to the DCS engines. Another study[14] provides a detailed summary of Powered Descent Algorithms.

The Guidance system is divided into four main areas: Coast Guidance, Braking Guidance, Powered Descent Guidance, and Vertical Descent Guidance. Coast Guidance is firstly used in the Pre-SRM mission phase, which starts at the time of separation from the ELV upper stage and ends at the beginning of Solid Rocket Motor (SRM) ignition. There are also two Post-SRM Coast Guidance phases: one between SRM shutdown and ignition of the DCS engines, and one right before the Vertical Decent phase. Braking Guidance occurs during the SRM burn. Powered Descent Guidance, using pulsed liquid engines, occurs after the Post-SRM Coast and lasts until the LPL has achieved a specified target above the landing site. Lastly, the Vertical Descent phase begins at the specified target above the lunar surface and lasts until the LPL touches down at the target site. During each phase, an appropriate guidance scheme is used, with some phases containing multiple guidance schemes to be used for trade studies. Table 1 lists the current choices of guidance algorithms to be used through each phase.

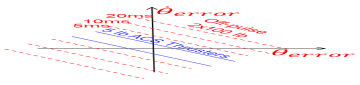
Table 1: Guidance Algorithms by Phase

Phase of Flight	Guidance Routine Option
Pre-SRM Coast	LVLH Hold ï adjusts attitude to pre-determined LVLH pitch angle
	MEDeA ï runs MEDeA descent algorithm, predicts starting LVLH pitch angle
SRM Burn	LVLH Hold ï holds pre-determined LVLH pitch angle through duration of burn
	MEDeA ï closed-loop SRM guidance for adjusting commanded LVLH pitch
Post-SRM Coast	Fixed time coast
Powered Decent	An Optimal Guidance Law for Planetary Landing[6]
	Augmented Apollo Powered Decent Guidance[16]
Vertical Alignment	Optional mode to pitch vehicle vertically
Vertical Decent	Linear velocity ramp-down, then linear position-velocity controller logic

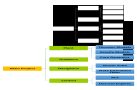
In the Pre-SRM Coast phase, either a fixed known pitch angle relative to Local Vertical Local Horizontal (LVLH) frame is commanded, or a predicted required attitude at the start of the SRM burn is calculated and commanded by running the Moon Entry Descent Algorithm (MEDeA). The MEDeA, a predictorcorrector algorithm for the SRM burn developed by Ellen M. Braden NASA-JSC, is an integrated closedloop guidance algorithm that accounts for the variations in the SRM thrust profile while staying within the liquid propellant budget. The SRMôs thrust profile is estimated using temperature thrust profiles and an on-board calculated burn time. Using this estimated thrust profile, the SRMôs pitch angle is adjusted using a numeric predictor-corrector method to achieve a pre-determined distance from the desired landing site. At the end of the SRM burn and SRM disposal, a second predictor-corrector determines the minimum coast time needed for the vehicle to reach the desired landing site within the liquid propellant budget. The liquid thruster guidance is chosen by the trajectory designer to steer out state errors from the SRM burn and meet the mission constraints. For example, either a minimum acceleration guidance or the Apollo guidance could be used for the liquid powered descent portion.

No guidance attitude is commanded in the Post-SRM Coast phase, and the vehicle is allowed to coast freely either using a fixed time or a time calculated by MEDeA. After the Post-SRM Coast, the liquid Powered Descent phase starts. In the Powered Decent phase, two analytical algorithms are chosen. The first algorithm,[6], is an optimal closed-loop feedback law which was analytically derived using the Euler-Lagrange equations, and assumes a linear acceleration profile. The second algorithm, Augmented Apollo Powered Decent Guidance (A2PDG[16]), is also analytical and allows for a wider range of acceleration and trajectory profiles.

An Optimal Guidance Law for Planetary Landing[6], starts with Euler-Lagrange theory and solves an analytical expression for optimal control. The Cost index function is defined to minimize given by following equation



Which is subjected to:



Where is a constant gain and is the final time. , and are components of acceleration expressed in the landing site frame. and are position and velocity, respectively. For the above problem, the flat earth assumption is applicable and , the gravity vector, constant. If the objective is to target a final state and , a linear form of analytical control is found given be following equation:

In the above equation, is the difference between current and the final time. can be found by solving the following quartic equation, as referenced in DôSouza:

A2PDG, developed by Ping Lu[16], assumes that the acceleration over the course of the burn takes the form of a quadratic, which is not necessarily optimal but adds an additional degree of control and is near optimal. For example, with DôSouza the final position and final linear form of velocity. However, a quadratic form of control enables the control of the final acceleration as well. This feature is useful to control the orientation of the lander at the end of the Powered Descent phase. If the