Lunar Ascent and Descent of Excavation Resources

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As interest in colonizing the Moon increases, developing a sustainable method of transporting equipment and resources to and from the lunar surface will be necessary. LANDER's approach to this problem is a system that uses one thruster capable of vectoring thrust to control vehicle attitude and perform propulsive landings with minimal fuel use. However, key to the design challenge is creating a suitable test environment for such a system that can simulate variables, such as lunar gravity and a lack of atmosphere. Project LANDER endeavored to provide a potential solution by designing a complex simulation utilizing live data. Due to an abbreviated timetable and low-quality components, LANDER did not meet all of its requirements for the Thrust Vector Control Test and Operational Demonstration. However, while LANDER was a proof–of-concept system, the team hopes to lay the foundation for future development in this area.

[1] Team Lead and Vehicle Structure
[2] Control Mechanisms and Control Software
[3] Control Software
[4] Avionics
[5] Vehicle Structure
[6] Test Stand
[7] Test Stand

Nomenclature

(Nomenclature entries should have the units identified)

LANDER = Lunar Ascent and Descent of Excavation Resources

PID = *Proportional – Integral – Derivative*

SLR = *System Level Requirement*

SSLR = *Subsystem Level Requirement*

TVC = *Thrust Vector Control*

I. Introduction

As lunar mining and colonization missions are on the rise, the importance of a multi-purpose space vehicle becomes more obvious. Project LANDER explores the concept of using a thrust vector control (TVC) system to design a vehicle capable of transporting mining equipment and resources between the lunar orbit and lunar surface. The design problem that Project LANDER aims to solve encompasses the vehicle's landing capabilities. To successfully design a system with landing capabilities, a complex simulation with hardware in the loop was designed. The simulation enables the design team to test and verify the system by simulating a lunar environment on earth. The results of this project can be used to further develop the control software and TVC system to be used in a functioning equipment transferring vehicle.

This document provides a brief overview of the proof-of-concept LANDER system and sheds light on what research and existing technology inspired the LANDER system. Next, a more detailed system overview is provided, including system objectives and the concept of operations. Subsequently, the unique aspect of LANDER and its performance is explored. Next, critical requirements, control systems analysis, and LANDER's requirement verification are discussed in detail. Additionally, LANDER explains what are believed to be the next steps to take LANDER from a proof-of-concept system to a field-capable design. Finally, in reflection of the past academic year, Project LANDER looks inward and identifies valuable lessons learned throughout the project.

Existing Systems The project taken on by LANDER comes from the imminent need for a vehicle capable of doing propulsive landings on the Moon to transport mining equipment and resources around the Lunar Surface. With the growing capabilities of private companies and increased interest by nations to visit the Moon, it is becoming more evident every day that the Moon will be a significant part of Earth's economy in the coming decades [1,2]. The scale of operations on the Moon will likely be small compared to Earth, but given the cost of getting propellant and hardware off Earth's surface, even small operations could be wildly profitable [3]. Explain how this section will cover the research you conducted in prelim to find preexisting models to inflect your own system design.

SpaceX Falcon 9 Hover Slam Maneuver

Before there is a significant amount of infrastructure on the Moon, the most valuable resource will be propellant. Therefore, a minimum fuel approach is required when calculating an optimal landing trajectory on the Moon [4]. In the case of the Moon, where there is no atmosphere, a minimum fuel approach utilizes a "hover slam" maneuver, which the SpaceX Falcon 9 has successfully utilized since 2015 [5]. The hover slam involves letting the vehicle free fall towards to surface of the Moon until the last available moment, then igniting the engine and ideally reaching 0 velocity at the instant that the vehicle contacts the surface of the Moon. The hover slam is the optimal solution to landing while minimizing fuel and time. (How is your own design different from the SpaceX Falcon 9?)

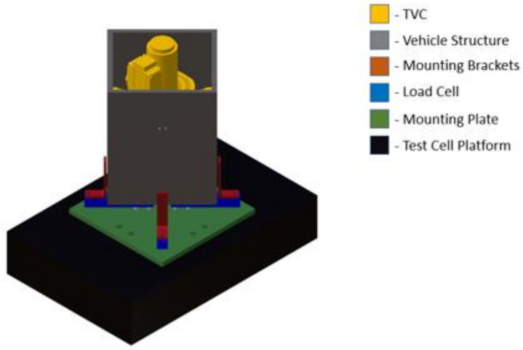
Any other pre-existing systems for subsequent paragraphs here?

Transition

II. System Overview

Project LANDER's objective is to create a system that demonstrates controlled propulsive landing capabilities. The results of project LANDER could be used to design a model landing vehicle for use in a real drop flight test. The system is comprised of a test stand and vehicle. Figure 1 provides an image of the assembled system at Test Cell 2.

The vehicle houses the thrust vector control (TVC) system, the motor, and the avionics, as shown in Figure 1. The control software sends simulated flight data to the avionics. The simulated flight data is then converted to commands which are sent to the TVC system. The TVC performs corrective gimbaling according to the commands sent by the avionics. A visual concept of operations is provided in Section A Figure 2 to demonstrate the system's functions.



As shown in Figure 2, the TVC is the yellow assembly mounted inside of the rectangular vehicle. The red mounting brackets of the vehicle are screwed into the blue load cells. The load cells are bolted to the green mounting plate, which connects the vehicle assembly to the black test stand. As shown in Figure 1, the avionics are bolted to the mounting plate, which makes the electronics accessible during testing.

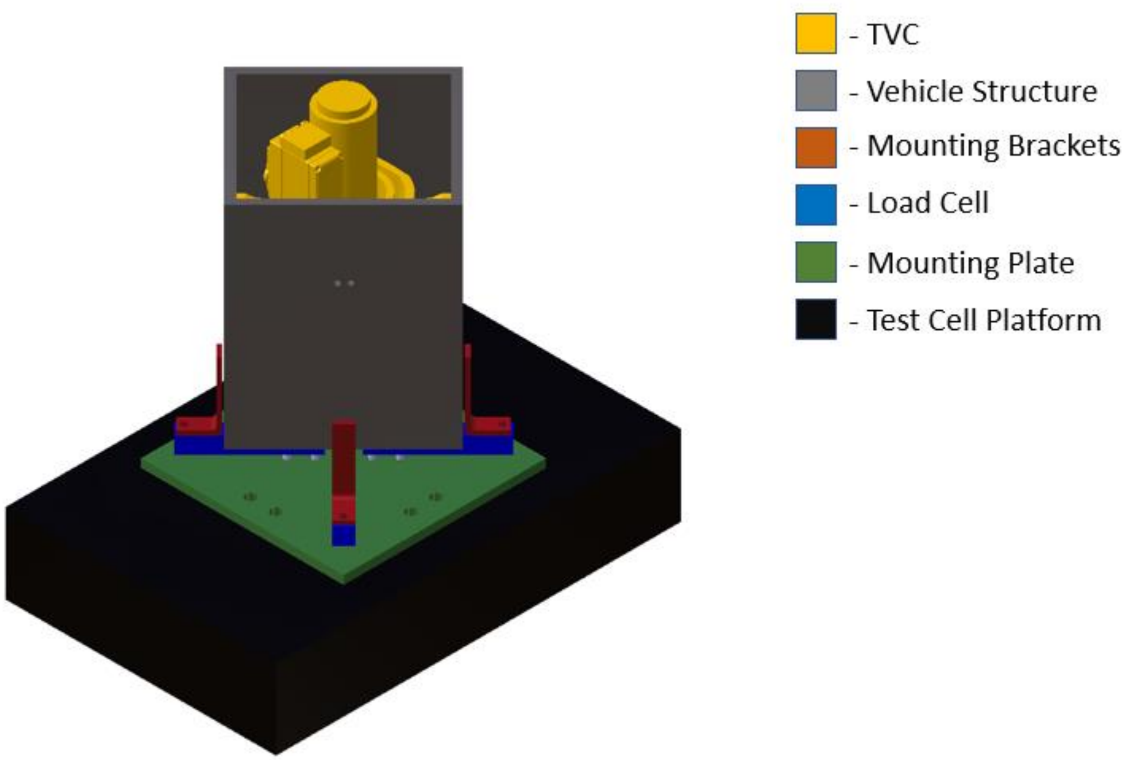


Figure 2: Color Coded Vehicle CAD

Transition

A. Concept of Operations

Figure 2 depicts a graphical concept of operations for Project LANDER. A critical concept to understand is the difference between simulated and physical vehicles. The simulated vehicle is found in the control software, which is used to create simulated flight data to send to the avionics subsystem. The simulated flight data is converted to commands to “trick” the physical vehicle into moving as if it were under real flight conditions. These movements occur in the TVC system.

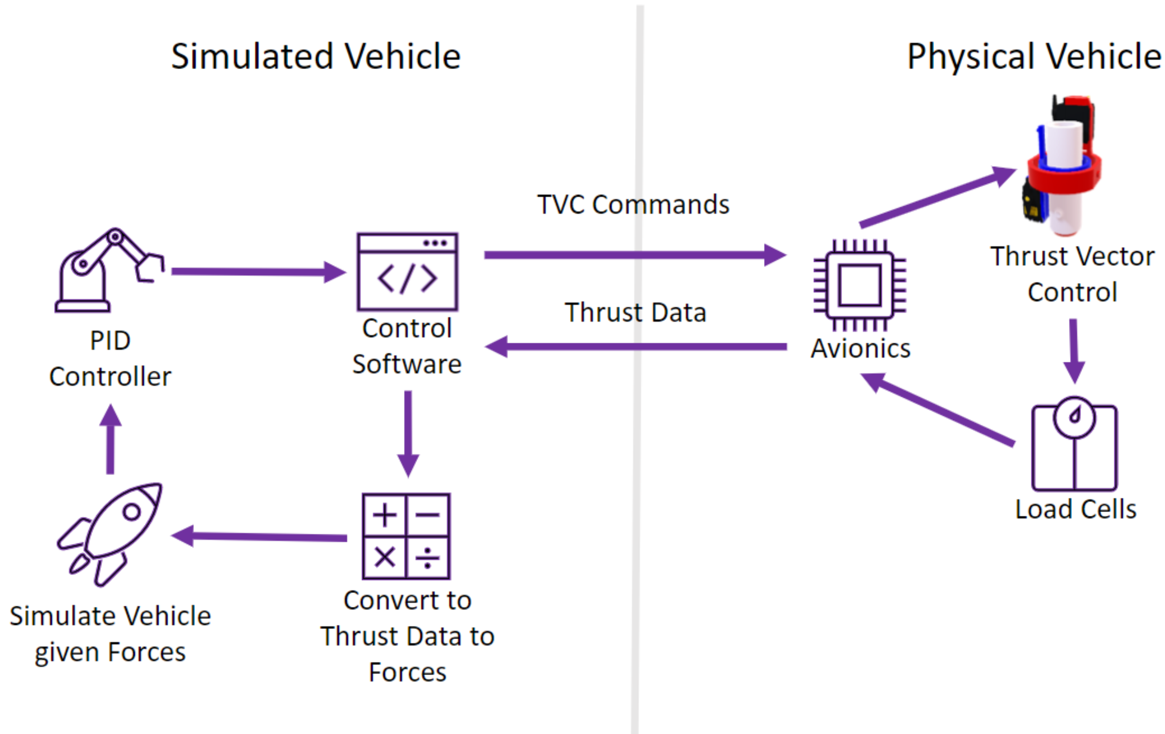


Figure 3 1: Concept of Operations

The simulated vehicle comprises a feedback loop where the rocket motor causing forces on load cells translates to forces in the simulation. A PID ? on the simulated vehicle then gives commands to the simulated vehicle; the commands are then translated back into hardware as TVC commands. The physical vehicle encompasses the avionics, TVC, and load cells. The physical vehicle receives commands from the simulated vehicle and returns real, calculated thrust data back to the control software.

III. Unique Aspects of LANDER

The control software showcases a rigid-body dynamic simulation using hardware in the loop, making it an incredibly complex and unique portion of the LANDER project. The following section provides an overview of the dynamic simulation by describing the system confirmation, critical requirements, analysis, and verification outcomes.

A. System Configuration

The avionics system is a loop process that consists of three basic procedures: 1) processing load cells, 2) turning load cell data, and 3) commanding the TVC. The first major process is processing load cell data during the operation of the motor. To adequately represent the simulated vehicle's forces, the avionics system must collect data from the real-world operation. (how is this completed?) While the data is being collected, the next process can occur: turning load cell data into forces on the simulated vehicle. This data will be acquired by taking the data and converting the data into numbers a computer can understand. (how?) After the computer receives the data, the final process can execute: commanding the TVC. The TVC receives the inputs and points in the corresponding direction, allowing for control of the motor.

A. Critical Requirements

Five of LANDER's requirements are deemed critical based on their governing of system integration and mission success. Three of the critical requirements are system-level requirements. The fourth and fifth are subsystem requirements taken from the control mechanisms subsystem. All critical requirements define mission success through the outcome of measured values or the system's cross-subsystem communication capabilities.

The first critical requirement is SLR 1.2, which states that the simulated vehicle shall control attitude at the conclusion of operation within ± 5°. This requirement ensures that the system will drive the simulated vehicle's attitude to 0° by using the integrated PID controller in the control software to command the TVC. Any final attitude outside of the ± 5° tolerance provided by this requirement results in a mission failure.

The second critical requirement is SLR 1.3, which states that the simulated vehicle shall have a maximum vertical velocity of 1 m/s upon operation completion. This requirement ensures that the system will drive the simulated vehicle's vertical velocity to 0 m/s by burning the onboard solid-propellant motor at the correct time. Any final vertical velocity outside of the 1 m/s tolerance provided by this requirement results in a mission failure.

The third critical requirement is SLR 1.5, which states that the system shall process thrust data during operation. This requirement specifies that the system will read thrust data from the four load cells on the test stand and the process is such that it can be used as an input to a physics simulation for testing purposes. Failure to process thrust data properly results in an inaccurate physics simulation, thus rendering the test a failure.

The fourth critical requirement is SSLR 4.1 the Control Mechanisms subsystem shall be capable of gimballing seven degrees. This requirement is taken from the control mechanisms subsystem and ensures that the system will drive the simulated vehicle's attitude to 0° by using the TVC to produce torque. SSLR 4.1 works with the previously mentioned SLR 1.2 to define how the system corrects the simulated vehicle's orientation.

The fifth critical requirement is SSLR 4.2 the Control Mechanisms subsystem shall be capable of gimballing seven degrees. This requirement is once again taken from the control mechanisms subsystem and ensures that the system sends commands from the avionics subsystem to the servos in the control mechanisms subsystem. SSLR 4.2 works in conjunction with the previously mentioned SSLR 4.1 to define the relationship between the control mechanisms and the rest of the system.

The five requirements outlined above work together to define the criteria used to judge the success of the various tests performed during the project.

B. Analysis & Verification of Requirements

Three main stages of analysis were completed to verify the software-hardware integration The first stage of analysis addressed the simulation of the landing. This analysis was conducted to ensure we were able to meet requirements SLR 1.2 descriptive phrase and SLR 1.3 descriptive phrase. The initial step the team took was to calculate the gains required for the PID controller used in the control software. The PID gains were found using an analysis of the behavior of the simulated vehicle, ideal settling times, overshoot percentage, and the limits of the TVC. A low settling time was desired as it would allow for minimum effect on the total vertical thrust which creates a more consistent velocity at impact. The overshoot percentage used was tweaked to allow for quick corrections in attitude while remaining within the limits of the TVC without saturating the available thrust. (was this risky?) The initial values were derived from ideal settling times and overshoot percentages. These gains were then used in the initial Simulink model of the control system and tweaked based on how the actual behavior exhibited by the model. After the PID gains were found, the next step was to find the ideal theoretical drop height to meet the velocity target in SLR 1.3 descriptive phrase. Since throttling of the motor is not possible as it is a solid propellant motor, finding the drop height was essential to ensure the landing would be predictable.

The next stage of analysis was to ensure that the physical systems were functioning as expected. This included the avionics system, load cells, and TVC system. Due to the high current demands of the igniter, the team had to determine the size of the capacitor bank required to provide sufficient current and voltage for the ignitor to be set off. The next big step in the analysis was to create a calibration curve for the load cells being used. These curves are needed to ensure that the data being sent to the avionics during the operational demonstration is processed into forces and moments properly. The last step of the analysis before full integration testing was to convert the desired TVC angles into servo angle inputs.

The last stage of analysis was done after the full operational demonstrations were conducted. The team used the collected data from the simulation to adapt our load cell calibration.

C. State of Requirements

No bueno ?

Were any requirements unable to be verified?

IV. Conclusion and Lessons Learned

The LANDER team designed and manufactured a functioning thrust vector control system, control software, a test stand, and corresponding avionics. The LANDER system allows the vehicle to use control software to instruct the TVC to take corrective action to allow the vehicle to complete a simulated landing.

Amidst the tremendous hurdles that LANDER encountered, many lessons were learned that will be carried forth into the future. First, LANDER encountered many problems, such as difficulty handling load cells and faulty communication between the microcontroller and servos, which could have been appropriately mitigated had the team started prototyping and integrating the system early. LANDER would have also significantly decreased the number of days that were cut out of the testing schedule due to prolonged integration failures or setbacks?.

As mentioned previously, the four load cells on the test stand were unreliable and caused integration of the test stand and avionics to slip into the testing schedule timeline. Had LANDER re-evaluated the project's hardware needs when changing scope, more care would have been spent choosing load cells to get load cells less prone to dropouts and failures. Additionally, with the leftover budget gained from not purchasing an entire sensor suite needed for a flight test, a significant amount of money could have been put into higher quality load cells.

Another issue that arose during the manufacturing phase of the system was improper fabrication of the L-brackets connecting the vehicle to the load cells. The final iteration of these L-brackets placed the load cells under a tremendous amount of stress, making it incredibly difficult to calibrate the load cells properly. This significantly impaired the software's ability to determine the thrust direction, thus rendering the PID controller ineffective. Seeking out experienced personnel to fabricate critical components like the L-brackets could have alleviated many of these problems encountered in this scenario.

While many issues were encountered and many lessons were learned throughout the project, a significant amount of progress was made towards the final goal of a flight test of a propulsion-controlled landing system. Projects in the future will be able to use the knowledge gained from LANDER to further this progress and achieve this final goal.

Appendix

A. Budget

A breakdown of Lander's budget is provided in Table 1. The breakdown includes the allotted budget provided by the college of engineering, the projected total cost, total amount spent to date, and the current budget available.

Table 1: Current Budget for LANDER

Budget Category	Amount
COE Allotted Budget	$1,150.00
Projected Total Cost	$649.52
Total Amount Spent to Date	$698.25
Current Budget Available	$451.75

Of the $1,150.00 provided, Lander has spent $698.25, which leaves $451.75 available for spending. Lander is finished with all fabrication and testing; thus no further spending is anticipated. A breakdown of the total amount spent to date by subsystem is provided in Table 2.

Table 2: Breakdown of LANDER's Expenditures by Subsystem

Subsystem Breakdown	Amount
Structure	$108.06
Avionics	$162.26
Control Mechanisms	$289.82
Test Stand	$138.11

Insert commentary

B. Timesheet – to be added when everyone updates the spreadsheet
Text

Acknowledgments

An Acknowledgments section, if used, **immediately precedes** the References. Individuals other than the authors who contributed to the underlying research may be acknowledged in this section. The use of special facilities and other resources also may be acknowledged.

References

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