Lunar Ascent and Descent of Excavation Resources

Michelle Passmore[1], Anson Biggs[2], Brendan McGeeney[3], Joshua Ku[4], Matthew Robinaugh[5],
Maverick Thigpen[6], Brian Wahlstrom[7]
Embry-Riddle Aeronautical University, Prescott, AZ 86301, USA

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. The key to the design challenge is creating a suitable test environment for a system that can simulate variables such as lunar gravity and a lack of atmosphere while on Earth. Project LANDER endeavored to provide a potential solution by designing a complex simulation utilizing live data from a hardware-in-the-loop system. Unfortunately, due to an abbreviated timetable and low-quality components, LANDER did not meet all its requirements for a successful Operational Demonstration. However, LANDER was a proof-of-concept system, and the team hopes to lay the foundation for future development in this area.

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[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

ConOps   =   *Concept of Operations*

LANDER   =   *Lunar Ascent and Descent* of Excavation Resources

LEM   =   *Lunar Excursion Module*

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 that can act as a general workhorse transporting resources and equipment around the surface will be required. Project LANDER explores the concept of using a thrust vector control (TVC) system to design a vehicle capable of meeting the needs of a lunar transport. The design problem that Project LANDER aims to solve encompasses the vehicle's landing capabilities. A simulation was used to simulate the lunar environment and enabled the design team to test and verify the system on Earth. The results of this project can be used to develop further the control software and TVC system to be used to implement a functional lunar cargo vehicle.

This document provides a brief overview of the proof-of-concept of the LANDER's system and sheds light on what research and existing technology inspired the LANDER's 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. Then, critical requirements, control systems analysis, and LANDER's requirement verification are discussed. LANDER then explains what are believed to be the following 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.

A. 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]. In addition, LANDER benefited greatly from reference systems that have already been on the Moon. Most notably was the Lunar Excursion Module (LEM), the first crewed vehicle to land on the Moon [4]. Although the technology is a far cry from modern capabilities, it is still a great piece of heritage and proof of concept for any project on the lunar surface. However, the engine's thrust is the most significant difference from the system LANDER designed. The LEM burned for a continuous 756 seconds before touching down on the surface, which is far from optimal[5] for a time and propellant expenditure point of view. The engine used by LANDER only burns for 3.5 seconds which is about as close to an instantaneous stop as you can get without imparting massive forces on the landing vehicle.
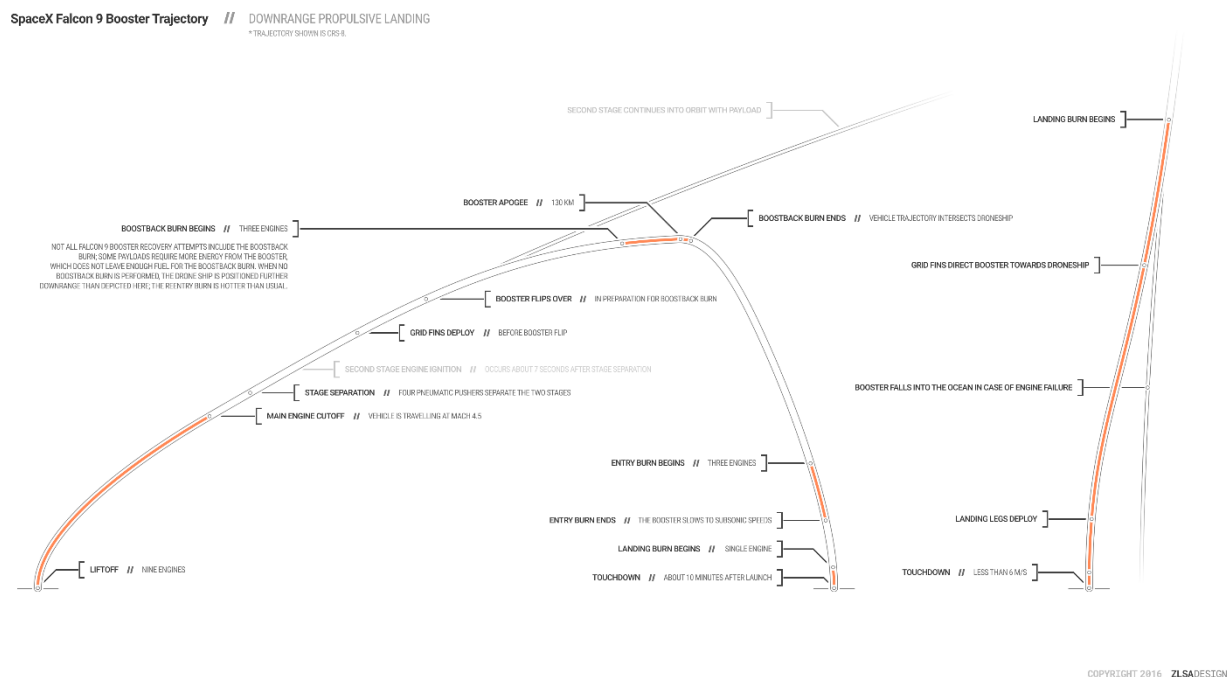
Figure 1: SpaceX Hover Slam Liftoff and Landing ConOps [6]

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 [5]. 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 [6]. The hover slam, pictured above in Figure 1, 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. The major difference between the Falcon 9 and the solution produced by LANDER is that the Falcon 9 only aims to recover the first stage booster from a launch. The LANDER system aims to land and take off with cargo. Other differences from the Falcon 9 include that our system uses only thrust vectoring to change attitude, our engine does not throttle, and being in a vacuum makes the approach to a landing zone much easier.

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 2 provides an image of the assembled system at Test Cell 2 along with a color coded CAD model of the system. All system level requirements are outlined in Table 1.

Table 1: Overview of System Level Requirements

SLR ID	Requirement	Verification Test
SLR_1.1	The vehicle shall not yield under a minimum static load of 60 N.	Static Load Test
SLR_1.2	The simulated vehicle shall control attitude after operation within ±5°.	Operational Demonstration
SLR_1.3	The simulated vehicle shall have a maximum vertical velocity of 1 m/s upon operation's completion.	Operational Demonstration
SLR_1.4	The system shall store thrust data during operation.	Operational Demonstration
SLR_1.5	The system shall process thrust data during operation.	Operational Demonstration
SLR_1.6	The vehicle shall be oriented orthogonal to the ground at the start of operation.	Operational Demonstration

Table 1 lists all system level requirements designed for Project Lander. Success criteria for this project were determined by designing final static load, attitude, vertical velocity, and vehicle orientation thresholds.

The vehicle houses the thrust vector control (TVC) system and the motor as shown in Figure 2 . 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. Finally, the TVC performs corrective gimbaling according to the commands sent by the avionics. A visual concept of operations is provided in Figure 2 to demonstrate the system's functions.
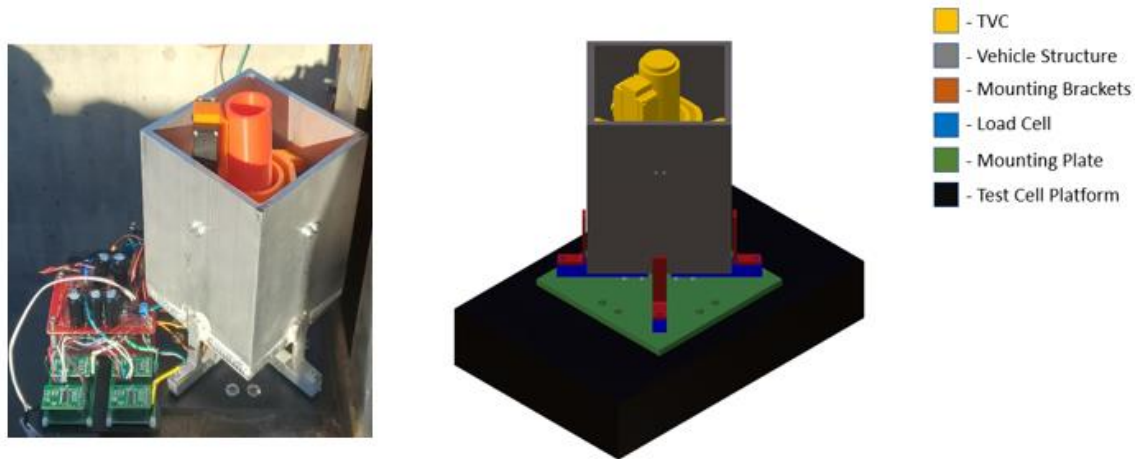

Figure 2: Vehicle Assembly

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 2 the avionics are bolted to the mounting plate, which makes the electronics accessible during testing.

A. Concept of Operations

Figure 3 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.
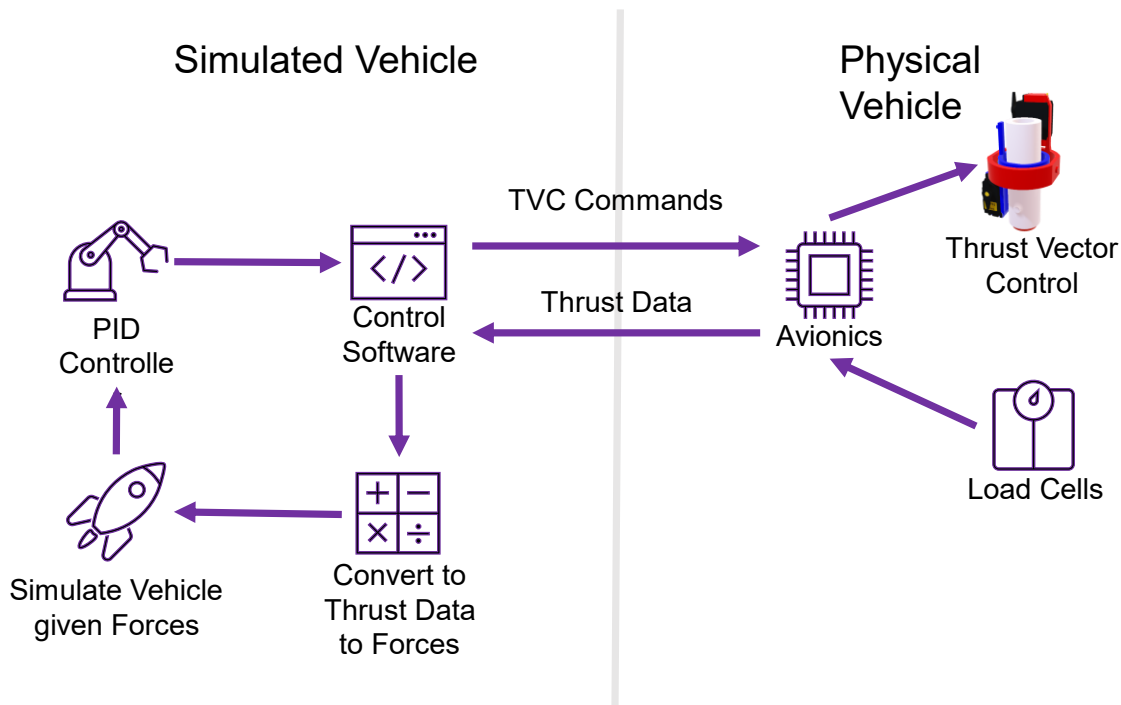
Figure 3: Concept of Operations

The simulated vehicle comprises a feedback loop where the rocket motor causing forces on load cells translates to forces in the simulation. The control system utilizes a PID that gives the simulated vehicle commands; 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 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 majority of the work in the control loop is processing load cell data during the operation of the motor. First, the avionics system must collect data from real-world operations to represent

the simulated vehicle forces adequately. Once the load cell data is translated into the simulation, the simulated vehicles' rigid body dynamics are calculated, feeding the vehicles' current attitude to a PID. The PID determines how the vehicle needs to be maneuvered for a perfect landing. The software then processes those into commands for the physical TVC. Finally, the TVC receives the inputs and points in the corresponding direction, allowing for motor control and the loop repeats.

B. Critical Requirements

Five of LANDER's requirements are 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 cross-subsystem communication capabilities.

The first critical requirement is SLR 1.2, which states that the simulated vehicle shall control attitude after operation within $\pm 5°$ of normal to the ground. 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 $\pm 5°$ tolerance provided by this requirement results in a mission failure. This requirement aids in defining LANDER's unique aspect by specifying that the simulated vehicle must self-correct its attitude landing.

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. This requirement aids in defining LANDER's unique aspect by specifying that the simulated vehicle must start the burn of its F15 motor at the right moment to land with minimal velocity perfectly.

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. This requirement aids in defining LANDER's unique aspect by specifying that the software must communicate with hardware in real-time to provide input to the feedback loop driving the system.

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. Once again, this requirement aids in defining LANDER's unique aspect by specifying that the simulated vehicle must self correct its attitude.

The fifth critical requirement is SSLR 4.2 the Control Mechanisms subsystem shall communicate with the avionics subsystem. This requirement is 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. This requirement aids in defining LANDER's unique aspect by specifying that the simulated vehicle must send real-time commands to the TVC in order to correct the simulated vehicle's attitude.

The five requirements outlined above work together to define the criteria used to judge the success of the various tests performed during the project. Failure of even one of the requirements could lead to a complete mission failure so they must all pass verification for the entire system to succeed.

### C. Analysis & Verification of Requirements

Three main stages of analysis were completed to verify the software-hardware integration. The first stage of analysis addressed the simulated landing. This analysis was conducted to ensure we could meet the requirements of SLR 1.2 (Attitude Control) and SLR 1.3 (Maximum Velocity). The team's initial step 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. The initial PID gains were derived from estimating the capabilities of the TVC and the desired behavior of a low settling time and overshoot percentage.
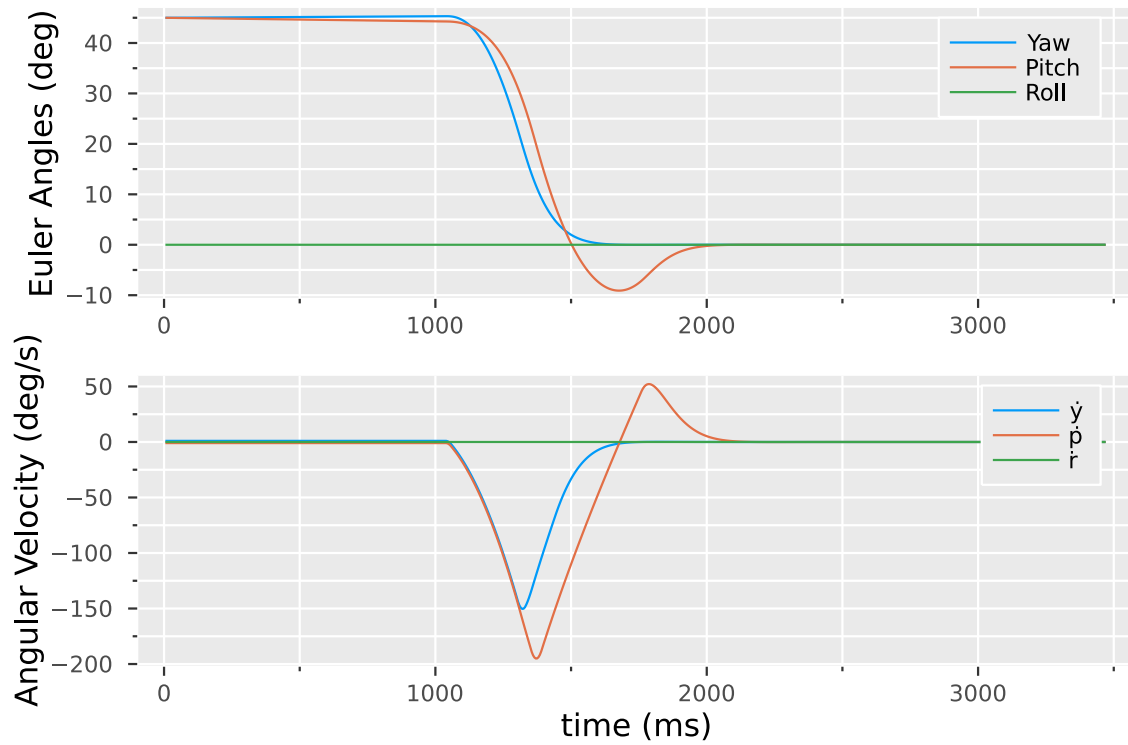
Figure 4: Simulated Vehicle Deflection

A low settling time was desired as it would allow for a limited effect on the vertical thrust throughout the flight since the motor would be pointed mostly vertical after the attitude correction. The team also wanted to leave room to implement throttling using the TVC possibly, but that was deemed unnecessary early in testing. Instead, the initial overshoot percentage used was chosen to allow for quick corrections in attitude while remaining within the limits of the TVC without saturating the available thrust. These gains were then used in the initial Simulink model of the control system and tweaked based on the actual behavior exhibited by the model. Figure 4 shows that the designed PID is able to reduce the vehicles deflection to 0° within 1 second. 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 (Maximum Velocity). 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.
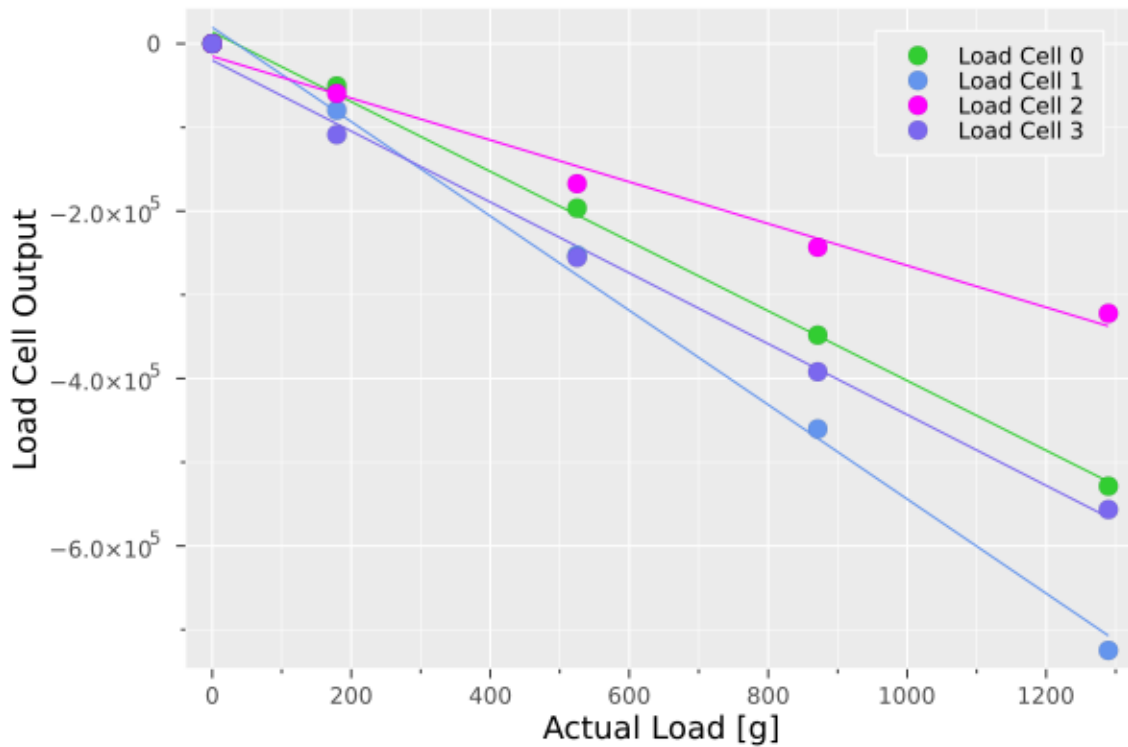
Figure 5: Load Cell Calibration Curve

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. The resulting load cell calibration curves can be seen in Figure 6.

The curves seen in Figure 6 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.

D. State of Requirements

One system level test and three subsystem level tests were performed to attempt to verify a total of 20 requirements. Table 2 provides an overview of the results from LANDER's formal qualification test event.

Table 2: State of Requirements

Test Name	Test Pass/Fail Status	Requirements Tested	Requirement Description	Verification Method	Requirement Pass/Fail Status
Operational Demonstration	Fail	SLR 1.2	Attitude Control	Demonstration	Fail
		SLR 1.3	Maximum Velocity	Demonstration	Fail
		SLR 1.4	Data Storage	Demonstration	Pass
		SLR 1.5	Data Processing	Demonstration	Fail
		SLR 1.6	Vehicle Orientation	Demonstration	Pass
		SSLR 1.2	Equipment Containment	Demonstration	Pass
Static Load Test	Pass	SLR 1.1	System Yielding	Test	Pass
		SSLR 1.1	Bracket Deformation	Test	Pass
		SSLR 2.1	Test Stand Integration	Test	Pass
		SSLR 5.1	Thrust Measurement	Test	Pass
		SSLR 5.2	Avionics Communication	Test	Pass
Avionics Integration Test	Pass	SSLR 2.2	Control Mechanisms Integration	Test	Pass
		SSLR 2.3	Software Integration	Test	Pass
		SSLR 3.1	Program Size	Inspection	Pass
		SSLR 3.2	Software Processing	Test	Pass
		SSLR 3.3	Software Outputs	Test	Pass
		SSLR 3.4	Response Time	Test	Pass
		SSLR 3.5	Input Rate	Test	Pass
		SSLR 4.2	Servo Commands	Test	Pass
TVC Test	Fail	SSLR 2.2	Control Mechanisms Integration	Analysis	Pass
		SSLR 2.3	Control Software Integration	Test	Pass
		SSLR 3.3	Software Inputs	Test	Pass
		SSLR 4.1	Deflection Accuracy	Inspection	Fail
		SSLR 4.2	Servo Commands	Demonstration	Pass

The Avionics and Software Integration and Static Load tests passed all associated requirements. The Operational Demonstration failed to verify three critical requirements: SLR 1.2 (Attitude Control), 1.3 (Maximum Velocity), and 1.5 (Data Processing). This failure was due to a software bug in the vehicle dynamics and thrust acquisition functions. Given another 2 weeks, LANDER is confident that the software bug could have been fixed, and another test could have been run to demonstrate the system's ability to gimbal the F15 motor.

The TVC test aims to demonstrate the capabilities of the Thrust Vector Control (TVC) system. The TVC is mechanically very complex, and it is vital that the servo movements accurately rotate the rocket motor to the correct angle. The TVC test was a success except for the deflection accuracy. The results of the TVC test are limited to the experimental angle values used in the test. This limitation impacts the overall system during the Operational Demonstration since the TVC could gimbal in other angles that were not tested during the TVC test. LANDER is

confident that the equations derived for turning gimbal deflections into servo movements are correct, so the complete system's performance impact should be minimal.

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.

During the development of LANDER, 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.
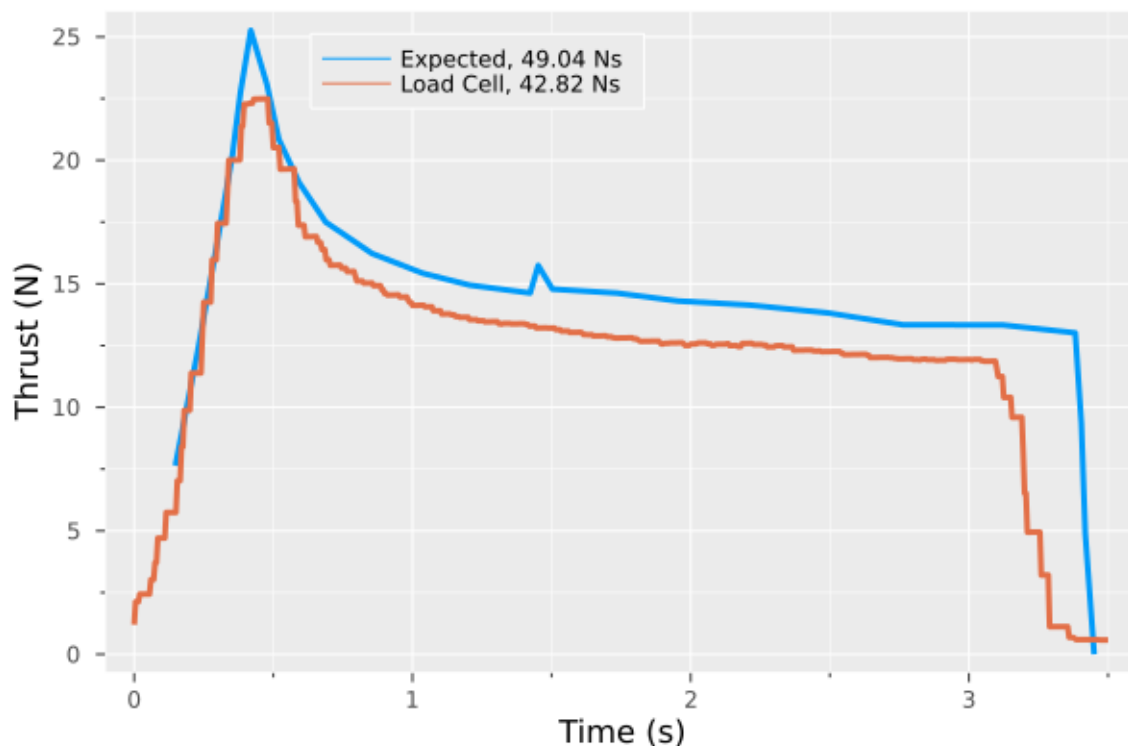
Figure 6: Operational Demonstration Thrust Curve

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. As can be seen in Figure 6 in the end the team was able to come up with a remarkably good thrust curve using the load cells. The thrust curve from the load cells gathered during the operational demonstration are only 13.6% from a nominal expected value. Although the much time spend on the load cell integration could have been avoided with even slightly more expensive load cells, in the end the team was able to engineer a solution.

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.