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Soft Landing on the Moon: The Ups and Downs of Robotic Lunar Landers

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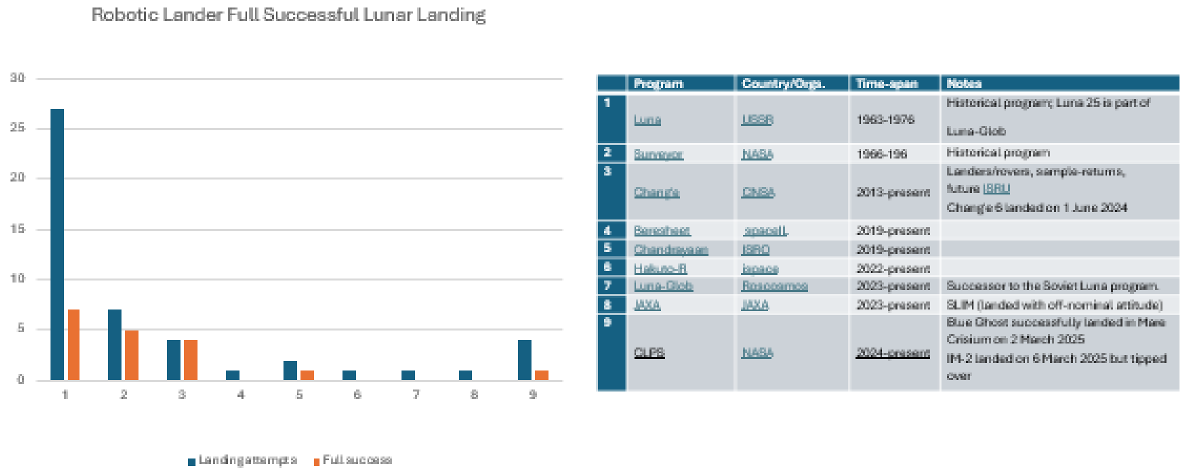
Abstract

The primary emphasis in the past two years has been to establish anchor nodes of the International Lunar Network (ILN), a network of lunar science stations envisioned to be emplaced by multiple nations. This network will consist of multiple landers carrying instruments to address the geophysical characteristics and evolution of the Extensive risk reduction design and testing have advanced the design of the lander system and reduced development risk for flight projects. However, the landing safety assessment is an integral element of the planning of a planetary landing mission. A legged landing platform is used as a study object. Legged landers are designed to touch down in a defined attitude on their landing legs. Energy dissipation and load attenuation is realized by absorber elements inside or attached to the stroking struts. The lunar surface is highly variable with terrain features such as slopes, rocks, and craters which the landing legs must accommodate. Non-linear kinematic math models have been produced for the flight lander to predict the behavior of the lander at landing and optimize the design. The root causes of these can be both intrinsic (landing instability can be caused by excessive touch down velocities) or extrinsic and are here terrain-related (e.g. steep slopes). A failure to land is thus not assessed as a matter of the system's technical reliability but to terrain-related failures as a consequence of an operational decision for a certain landing site. This paper utilizes a qualitative analysis method aims to investigate the performance capabilities and limitations of robotic landers successfully landing on the Moon's surface for payload mission operations.

Keywords: International Lunar Network, lunar lander leg, precision landing

Background

During the so-called Space Race during 1958-1976, the Soviet Union's Luna program was a series of robotic impactors and landers that achieved a total of seven successful soft landings out of 27 landing attempts. Luna 9 was the first spacecraft to achieve a soft landing on the Moon (February 3, 1966), after 11 unsuccessful attempts.
The United States' Surveyor program first soft-landed on the Moon June 2, 1966, followed by four additional successful soft landings. The Apollo program completed six successful lunar soft landings from 1969 until 1972.
The Chinese Lunar Exploration Program included robotic lander, rover, and sample-return components; the program realized an initial successful lunar soft-landing with the Chang'e 3 spacecraft on 14 December 2013. As of 2023, the CLEP had achieved three successful soft landings. India's Chandrayaan-2 robotic lunar lander attempted a soft-landing but crashed on the Moon's surface. On 23 August 2023, the program's follow-up Chandrayaan-3 lander achieved India's first robotic soft-landing and later conducted a brief hop on 3 September 2023 to test technologies required for Indian lunar sample return mission called Chandrayaan-4. Japan's Smart Lander for Investigating Moon made a successful lunar landing with wrong attitude, bleak signal bandwidth, even after losing one of its engines during descent within 100 m of its landing spot (19 January 2024). In January 2024, the first mission of the NASA-funded CLPS program, Peregrine Mission One, suffered a fuel leak several hours after launch, resulting in losing the ability to maintain attitude control and charge its battery, thereby preventing it from reaching lunar orbit. The second CLPS probe *Odysseus* landed successfully on the Moon (22 February 2024), marking the United States' first unmanned lunar soft-landing in over 50 years. This mission was the first private-NASA partnership to land on the Moon and the first landing using cryogenic [1]. However, the mission experienced some anomalies, including tipping-over on the lunar surface due to a non-functioning landing LIDAR instrument, and apparently low communication bandwidth [2]. Later it was revealed that one of the lander's legs broke upon landing on a slope [3]. Firefly Aerospace's lunar lander Blue Ghost Mission 1, carrying NASA-sponsored experiments and commercial payloads as a part of Commercial Lunar Payload Services program to Mare Crisium, launched with Hakuto-R Mission 2 on a Falcon 9 launch vehicle, and successfully landed on the Moon's surface 2 March 2025. On March 6, 2025, Intuitive Machine's lunar lander IM-2 transported NASA-sponsored experiments and payloads to Mons Mouton. Landing was intact after touchdown but rested on its side, thereby complicating its planned science and technology demonstration mission. This outcome was similar to what occurred with the company's IM-1 *Odysseus* spacecraft in 2024. On March 13, Intuitive Machines shared that *Athena*'s altimeter had failed during landing, leaving its onboard computer without an accurate altitude reading. As a result, the spacecraft struck a plateau, tipped over, and skidded across the lunar surface, rolling once or twice before settling inside the crater [4].



	Program	Country/Orgs.	Time-span	Notes
1	Luna	USSR	1963-1976	Historical program; Luna 25 is part of Luna-Glob
2	Surveyor	NASA	1966-196	Historical program
3	Chang'e	CNSA	2013-present	Landers/rovers, sample-returns, future ISRU Chang'e 6 landed on 1 June 2024
4	Beresheet	SpaceIL	2019-present	
5	Chandrayaan	ISRO	2019-present	
6	Hakuto-R	ispace	2022-present	
7	Luna-Glob	Roscosmos	2023-present	Successor to the Soviet Luna program.
8	JAXA	JAXA	2023-present	SLIM (landed with off-nominal attitude)
9	CLPS	NASA	2024-present	Blue Ghost successfully landed in Mare Crisium on 2 March 2025 IM-2 landed on 6 March 2025 but tipped over

Figure 1. Robotic Lander Successful Lunar Landings

I. Introduction

The CLPS mission experienced some anomalies, including a non-functioning landing LIDAR instrument. Moreover, one of the IM-1's lander's legs broke upon landing 18° due to landing on a slope. NASA's Multi-center Lander Tech Office in a short study of cryogenic lunar lander concepts in Summer of 2017 defined a trade space that conceptualized landing cargo on the moon and recommended improvement in the lander legs provide more stable landing [5]. IM-1 mission aimed to test precision landing technologies and measure the quantity of liquid propellant in Nova-C propellant tanks in the zero gravity of space [6]. The US Vision for Space Exploration (VSE) outlined planned stages for the post-2010 timeframe and subsequent robotic landing missions under NASA's Lunar Precursor and Robotics Program (LPRP). The first robotic lunar landing mission recommended, characterized surface environment at one of the lunar poles and provided operational experience demonstrating automatic/semi-automatic landing capability. Secondary mission objectives included determining the distribution of obstacles smaller than those resolvable with radar/ LIDAR. Terrain properties potentially hazardous to the landing platform include the terrain slope and its roughness. They significantly influence the mechanical contact at touchdown between the planetary surface and the landing system. Slope is hereby defined by de Rosa et al. 2012 as "the inclination relative to the local horizontal of the mean plane" [7]. The mean plane is thereby the least error fit to the terrain surface underneath the landing system footprint. Roughness is defined as "the deviation from the mean plane and as such is a property of each point of the terrain below the lander …" [8]. Intuitive Machines' Nova-C lander carried a Navigation Doppler Lidar (NDL) payload as a backup to its primary navigation systems to provide precise altitude, speed, and direction to the guidance, navigation, and control (GNC) subsystem that enabled the lander to land safely on the lunar surface. Originally developed at NASA's Langley Research Center in Hampton, Virginia, NDL used a laser to measure altitude to within a few feet and relied on the Doppler effect – frequency changes to radiated energy that occur as the source moves – to determine direction and speed to within a few centimeters per second. NASA planetary landers traditionally rely on radar, using radio waves for this function, but NDL technology is more accurate and weighs far less, a major benefit for cost and space savings on planetary missions [9]. IM executives suggested that issues with Athena's laser altimeters contributed to the bad landing, similar to the previous mission when Odysseus came in too fast and toppled over. Specifically, the Terrain Relative Navigation laser, designed to provide altitude and velocity readings, returned "noisy" data that could not be fully trusted, while the Hazard Relative Navigation sensors transmitted intermittent signals. Athena, like Odysseus, had a tall, slender build, standing 15.6 feet (4.8 meters) in height, raising stability concerns. But CEO Steve Altemus insisted that the lander's weight distribution kept the center of gravity low, and the company remained confident in its design [10]. More often than not, private sector attempts to visit the moon have resulted in failure. Intuitive Machines experienced its second moon setback in March 2025. Its lander, Athena, was off target by about 800 feet, touched down in a crater, then tipped over. It snapped and sent some photographs and activated a few experiments before going silent about 24 hours later. The Moon's lack of atmosphere rules out parachutes, and forces spacecraft to rely on precise thrusts and navigation over hazardous terrain [11]. NASA Marshall Space Flight Center (MSFC) and The Johns Hopkins University Applied Physics Laboratory (APL) conducted mission studies and performed risk reduction activities for NASA's robotic lunar lander flight projects. Fig. 2 shows the descent phase for the single solar /battery lander, similar for the other missions.

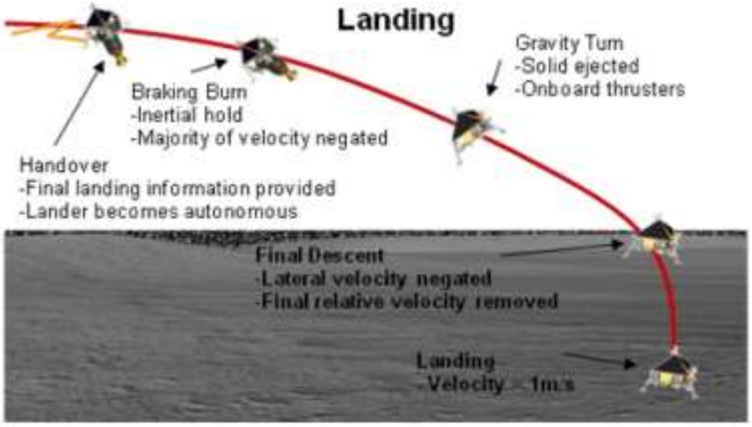


Fig. 2. Landing phase

Since 2005, the team has been supporting NASA’s Exploration Systems Mission Directorate and Science Mission Directorate designing small and medium lunar robotic landers for diverse missions. The primary emphasis in the past two years has been to establish anchor nodes of the International Lunar Network (ILN), a network of lunar science stations envisioned to be emplaced by multiple nations. This network will consist of multiple landers carrying instruments to address the geophysical characteristics and evolution of the moon [12]. Extensive risk reduction design and testing have advanced the design of the lander system and reduced development risk for flight projects. Candidate missions described in the lunar lander concept include 1) International Lunar Network – anchor nodes for a geophysical mission 2) Lunar Polar Rim – rapid mission architecture for quickly demonstrating technology and landing on a polar rim, and 3) Lunar Polar Volatiles Stationary (LPVS) – single point lander to study volatiles in a Permanently Shaded Region (PSR). The payload and concept of operations were guided by the science objectives outlined in the Scientific Context for Exploration of the Moon [13]. A rapid mission to a nearly permanently lit polar rim would contain an instrument suite to interrogate the radiation environment. And the particle energies would provide knowledge about the local environment. Additional features include attitude control system (ACS) thrusters for precision landing and thrust vector control (TVC) to control the lander’s attitude or angular velocity for precision landing. Optical terrain relative navigation (TRN) is also included for this mission to allow precision landing [14]. The landing should occur at a predetermined and relatively obstacle free location utilizing an optical TRN for a safe landing. Communication opportunities within a PSR are particularly challenging and pose the primary landing site constraint. Since there is no available lunar orbiting communications asset, direct line of sight between the lander and Earth is required in order to provide data communication. A direct communication path can only be obtained in a PSR when the landing site is permanently shadowed from the sun but visible from earth, resulting in “earthshine” conditions which also supports optical TRN. The LPVS lander in the surface operations configuration is shown in Figure 3.

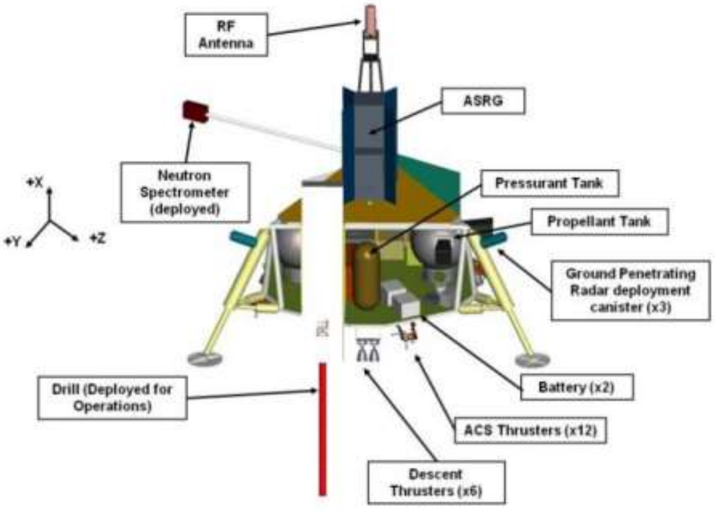


Figure 3. LPVS lander in surface operations configuration

The landing concept showed optical cameras and lit landing sites for control of lateral velocities. A least squares optical flow (LSOF) algorithm would image the lunar surface during the descent phase and compare the sequential images to determine lateral velocity completion. A navigation filter with inputs from a RADAR altimeter and LSOF enabled the terminal descent phase's autonomy, and the vertical and lateral velocities reduced to less than 1 m/s to allow a soft landing. High fidelity end-to-end simulation, field testing, and testing in an earth-based hover/descent lander test bed demonstrated the technique and reduced the landing risk [15].

Purpose

This paper utilizes a qualitative analysis method aims to investigate the performance capabilities and limitations of robotic landers successfully landing on the Moon's surface for payload mission operations.

II. Methods and Results

The study employed a grounded theory approach to investigate use of robotic landers soft-landing on the Moon. Twelve web news accounts reporting on robotic landers landing on the Moon were reviewed about their operations. Consistent with a grounded theory angle, there was no hypothesis to be tested. Rather, several common themes emerged out of the analysis process. The findings revealed that the respective lander organizations recognized primarily the importance of lander leg stability. Other issues included laser altimeters, laser range finders, and laser navigation. Additionally, few landers needed structural redesigns, algorithms reworked, and descent velocities slowed. Appendix A presents the raw data from which summary of the sample findings is presented in Table 1.

Problematic issues per lunar landing	Reported frequency of problematic issues (sample size=12)	Problematic issues per lunar landing	Reported frequency of problematic issues (sample size=12)
Lander leg broke	5	Engine malfunction	2
Laser altimeter	3	Design-related stability	1
Laser range finder	2	Cost-related performance	1
Laser navigation	2	Limited direct to Earth communication	1
Technical, software glitch	2		

Table 1

Five of the twelve web articles reviewed cited lander leg stability as a critical factor for a successful soft landing on the Moon which justifies a literature review to study the issue.

Lander leg stability for successful lunar landings.
The tiny gravity and unknown properties on the Moon surface, like ground shape (i.e. craters, boulders, etc) and grain size, make the robotic lunar lander prone to bouncing, tumbling, and tipping over [16]. Collisions and upside-down of the lander may damage instruments or disrupt their work. In practice, the landing leg's nonlinearity, the lander's attitude error, and rough terrain cause the lander to rebound. The thruster at the body's top generates a downward propelling force that suppresses rebound motions. Since the contact forces between the footpads and the ground surface are discontinuous and unpredictable [17], it is challenging to analyze the lander's stability using the stability criteria in control theories. From simulation results, a lightweight thruster possibly provides a proper thrust force value that ensures the lander's stability. The inertia sensor of the lander measures the body's vertical acceleration. Meanwhile, force sensors of the landing footpads measure the ground contact forces. The lander's onboard computer starts the thruster when it detects a contact force, indicating the lander collided with the ground. A simple control strategy recommends that thruster outputs a constant propelling force of F_{thr} and does not stop until the lander achieves stability or has anchored on the surface [18].

Although some landers have successfully landed on the moon [19], landing is still an immature field and requires further research to improve its success rate. Buffer legs [20] may accomplish a soft landing. The main body of the lander is equipped with three or four buffer leg mechanisms, composed of struts and footpads. When footpads touch down the ground, buffer materials fill in the struts and absorb part of the shock energies to protect the main body from damage. During the landing process, intricate connections between the struts, nonlinear buffer materials, and the interactions between the footpad with complex shape and irregular ground, result in complex dynamics responses, which are worth studying thoroughly to ensure the safety and stability of a landing.

A dynamical model for the soft landing of a space lander consists of a main body and four sets of buffer mechanisms. Each buffer mechanism includes one primary strut and two secondary struts. The primary strut is linked with the main body through a cantilever beam and fixed with the footpad. The secondary strut is made up by an outer tube jointed with the main body and an inner tube jointed with the footpad. Between the outer and inner tubes, buffer materials are filled to absorb the shock energy. Degrees of freedom of the main body and four footpads are generalized as coordinates. Generalized coordinates describe motions of the struts in the buffer mechanisms, such as the offset displacement of the primary strut and the compression lengths of the secondary struts. Therefore. the interaction force between the primary strut and the main body and the compression force between the inner and outer tubes in the secondary struts may be calculated. The contact force between the footpad and the ground can be obtained by applying the Archimedes law for granular media to the discrete elements of the footpad [21].

III. Discussion

Like throwing a dart and hitting the bullseye on a moving target in the next city over: that's what it's like trying to land a spacecraft on the moon. With an inhospitable surface of steep craters and inconvenient boulders, there are no landing pads, no GPS, no air traffic control, and no one to help if things go wrong. Without the benefit of GPS to give accurate positioning, or astronauts on board to look out the window, a spacecraft must slow itself from traveling at a mile per second to an eventual landing speed of just one meter per second and accurately calculate its own location with meter-level accuracy. Kevin Scholtes, Firefly's Future Systems Architect, explains "A hundred kilometers up, one kilometer up, or 10 meters up — when you look at the surface, you see craters." That means that even with ideal navigational data, it's still hard to tell how far away the surface is as you get closer to it. With modern technology and cameras on spacecraft like NASA's Lunar Reconnaissance Orbiter, that imagery is invaluable for picking a landing site, but at a resolution of a few meters per pixel, images can't show all of the hazards that a lander needs to avoid [22]. "That's a pretty low resolution for detecting a big rock that you're about to land on," Scholtes adds.

The lander is used to absorb the impact energy of the landing process. The cushioning capacity is limited. The traditional landing gear does not have an active cushioning capacity, so it is impossible to ensure that each landing leg starts working at the same time and this leads to redundancy in design. In addition, the tilted posture of the lander after landing has an adverse impact on subsequent operations. The detection range is limited. Terrain properties potentially hazardous to the landing platform include the terrain slope and its roughness. Although the lander can expand the detection range, due to the constraints of volume, energy, communication, and trajectory, its detection range is still limited. The landing site of the lander is mostly selected from flat terrain due to the limitation of landing capacity [23]. To achieve high precision position and attitude control, a vision-based relative navigation system is also needed, along with advances in sensor capability for surface feature detection. To account for possible contingencies and ensure the possibility of real-time trajectory recalculation, a safety margin may be required for the mission, lengthening and shortening the downrange from a certain initial position. Increasing the distance of the landing site may not pose any problems in finding the optimal solution, but at a small additional cost, the trajectory could be correctly adjusted.

IV. Conclusion

The primary emphasis in the past two years has been to establish anchor nodes of the International Lunar Network (ILN), a network of lunar science stations envisioned to be emplaced by multiple nations. This network will consist of multiple landers carrying instruments to address the geophysical characteristics and evolution of the moon. Extensive risk reduction design and testing have advanced the design of the lander system and reduced development risk for flight projects. The primary emphasis in the past two years has been to establish anchor nodes of the ILN lunar science stations envisioned to be emplaced by multiple nations. This network will consist of multiple landers carrying instruments to address the geophysical characteristics and evolution of the moon. Extensive risk reduction design and testing have advanced the design of the lander system and reduced development risk for flight projects. However, the landing safety assessment is an integral element of the planning of a planetary landing mission. In addition to the position dispersion around the nominal landing site it has to consider the topographic characteristics of that place, which might endanger the landing system. A legged landing platform is used as a study object. Its touchdown dynamics is represented by a high-fidelity numerical multibody simulation which is validated by experimental data from a dedicated test campaign. Legged landers are designed to touch down in a defined attitude on their landing legs. Energy dissipation and load attenuation is realized by absorber elements inside or attached to the stroking struts. The touch down velocities are well below 10 m/s for which reason these landing systems are also sometimes dubbed “soft” landers. Since the descent and ACS propulsion systems use pulsed thrusters, the vertical touchdown velocity and the tilt angle and rates may not be completely nulled at touchdown. The lunar surface is highly variable with terrain features such as slopes, rocks, and craters which the landing legs must accommodate. Non-linear kinematic math models have been produced for the flight lander to predict the behavior of the lander at landing and optimize the design. The root causes of these can be both intrinsic (landing instability can be caused by excessive touch down velocities) or extrinsic and are here terrain-related (e.g. steep slopes). A failure to land is thus not assessed as a matter of the system’s technical reliability but to terrain-related failures as a consequence of an operational decision for a certain landing site.

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Appendix A.

Source	Publication Author/Title	Publication Date	Publication Website	Spokesman	Statement
IM	Ahmed, I./ "Oops, we tipped it again: Mission over for sideways"	03-08-25	www.phys.org	S. Altemus, CEO	Issues with Athena's laser altimeters; Stability concerns with Athena and Odysseus per tall, slender design.
IM/NASA	Miller, H./" Athena lunar lander declared dead after landing sideways"	03-07-25	www.yahoo.com	NASA	Before the landing, they knew going in, that some of the low-cost missions would fail; Laser navigation system began acting up.
	Dunn, M./" Private lunar lander may have fallen over while touching down near the moon's south pole"	03-06-25	www.apnews.com		Hourlong descent appeared to go well until the final approach when the laser navigation system began acting up.
	Whittington, M./ "Opinion - Failure is more than an option in rocket science — it's a necessity"	03-16-25	www.yahoo.com		Laser range finders of the vehicle failed, placing it 250 meters away from its intended landing site, in the midst of a sloped crater.

	Kuthunur, S./ "Everything has changed since Apollo': Why landing on the moon is still incredibly difficult in 2024"	03-01-24	www.livescience.com		Odysseus broke one of its six legs upon landing and had ended up toppled on its side. Japan's SLIM ending up upside down on the lunar surface due to an engine malfunction during descent.
	Kuthunur, S./ "Everything has changed since Apollo': Why landing on the moon is still incredibly difficult in 2024"	03-01-24	www.livescience.com		Several high-profile missions have failed due to technical glitches that led to fatal judgments of speed, altitude and orientation.
	Kuthunur, S./ "India lands on moon! Chandrayaan-3 becomes world's 1st spacecraft to land near lunar south pole"	08-23-23	www.livescience.com		In September 2019, failed when the Chandrayaan-2 lander crashed into the moon due to a software glitch.
Physical Research Laboratory (India)	Kuthunur, S./ "India lands on moon! Chandrayaan-3 becomes world's 1st spacecraft to land near lunar south pole"	08-23-23	www.livescience.com	Bhardwaj, A., Director PRL	Onboard algorithms that calculate spacecraft speed in real time during descent were reworked to allow for "more freedom to deviate" from protocol "but still do the landing,"
Physical Research Laboratory (India)	Kuthunur, S./ "India lands on moon! Chandrayaan-3 becomes world's 1st spacecraft to land near lunar south pole"	08-23-23	www.livescience.com	Bhardwaj, A., Director PRL	Other changes that helped facilitate the mission's success include a larger target landing zone, stronger legs for Chandrayaan-3's Vikram ("valor") lander to withstand higher landing speeds and dynamic engines that adjusted the spacecraft's velocity for a smoother touchdown.
IM/ NASA	Kaufman, M./ "Moon photo reveals how lunar landing	03-07-25	www.mashable.com	Nickola Fox, NASA's Science	Southern pole region is lit by harsh sun angles and limited direct communication

	just went wrong. The mission is over.”			Mission Directorate	with the Earth. Area has been avoided due to its rugged terrain.
IM	Thomson, I./ ”Athena Moon lander officially FOADs – falls over and dies – in crater”	03-07-25	www.theregister.com		Odyssey probe, tried a landing in February last year but was travelling too fast and broke a leg on landing,
IM	Quach, K./ “The batteries on Odysseus, the hero private Moon lander, have run out.”	03-02-24	www.theregister.com	Steve Altemus, CEO	Odysseus onto the Moon, it came down too fast and smashed at least one of its six legs in the process
IM/NASA	Malik, T./ “Private Intuitive Machines moon lander declared dead after falling on its side in crater at the lunar south pole.”	03-07-25	www.space.com	Tim Crain, CTO	Stressed that the rugged nature of south pole region of the moon, with its harsh sunlight angles and difficulty to reach. Proud of how well our crater tracking system, …in this very unusual lighting condition.
IM	AFP/ “US company says Moon mission over after landing sideways again”	03-07-25	www.fox28spokane.com		Issues with Athena’s laser altimeter — which provide altitude and velocity readings
IM	Roulette, J. & Sriram, A./ “Intuitive Machines' Athena lander appears to be on its side on moon - just like first time”	03-06-25	www.msn.com		Issues involving a laser range finder causing landing problems. Faulty laser altimeter used to judge its distance from the ground - broke a lander leg.