

Analysis of Entry, Descent, and Landing Systems and Outcomes

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Entry, descent, and landing systems (EDL) have been evolving since their inception to enable missions to access more scientifically interesting areas with increasingly precise landing requirements. Originally targeting large basins or plains, EDL architecture has developed to enable landing on crater floors and near mountainous terrain. This paper explores the development of EDL systems over several decades, focusing on key design parameters that have resulted in successful missions to a variety of target bodies. It also examines EDL system failures, identifying faults in navigation sensors as the most common cause of mission failure during the EDL phase. Finally, this paper compares mission cadence and spread across different target bodies by various space agencies and countries, evaluating program performance in terms of first arrivals and landing accuracy. By reviewing the history of EDL design, success, and failures, this review aims to identify lessons learned across all target bodies and design spaces that could improve the success rates of future missions.

I. Nomenclature

EDL = entry, descent, and landing

II. Introduction

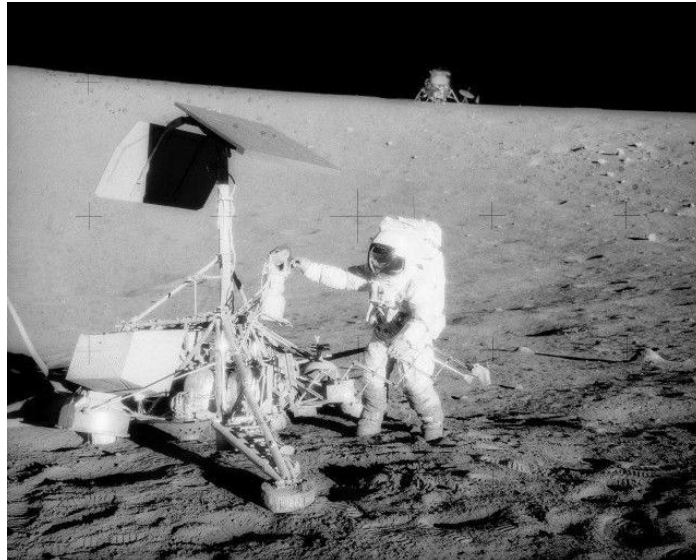


Fig. 1 Apollo 12 astronaut exploring Surveyor 3 landing site with lunar module and its landing site in background. [1]

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Entry, descent, and landing (EDL) is often the last propulsive or dynamically challenging aspect of a vehicle's mission but also commonly marks the beginning of the vehicle's major scientific contributions.

Figure 1 shows where Apollo 12 landed in 1969, 160 m from Surveyor 3 [2]. Apollo 12's mission was, in part, to recover pieces of Surveyor 3 to study the effects of space. NASA had instructed the lunar pilots to avoid landing closer than 152 m to prevent the engine from damaging the probe [2]. In 1971, Apollo 14 landed 50 m from its targeted location [3]. Robotic vehicle engineers would not surpass this level of accuracy until the late 2010s with comet and asteroid sample-collection missions. Of course, the mass of the probes was considerably less than that of the Apollo lander, demonstrating that autonomous pinpoint landing of large payloads has yet to be accomplished. As EDL technologies evolve, space missions are demanding greater and greater precision in landing to enable the next era of landing vehicles and the scientific discoveries that will accompany them.

Many literature review and synthesis papers in the EDL field either focus primarily on algorithm review or comparisons of certain mission techniques on a specific body. This paper extracts trends of space vehicles that have successfully completed the EDL phase of flight on various bodies. This paper also identifies trends or exceptions that may aid in pinpoint landing development and prevent the repetition of errors that have led to failure in the EDL portion of flight.

The sections in this paper describe and justify an EDL classification scheme, review historical EDL trends, study the improvement in EDL accuracy, and review mission failures.

III. Classification and Methods

In this section, the method for selecting missions to include in the data set is explained as well as the parameters used in classifying the guidance architecture, autonomy level, and accuracy level.

Because the focus of this paper is evaluation of EDL mission structures against their intended landing targets, only missions that reached the EDL stage are considered here. Missions in which a landing was planned but could not be achieved because the missions failed before the EDL stage are not included. For example, a lunar lander that failed in Earth orbit is not considered in this study. Similarly, intentional body impacts for decommissioning or a rocket stage that was impacted into a body are not included. However, dedicated impactor probes are included in this analysis.

Several plots rely on EDL success or mission success as a data point. Mission success is primarily based on Asif Siddiqi's mission success data. Where his data are not available, similar criteria are used to determine mission success. EDL is considered successful if the EDL portion of the mission enabled the vehicle to accomplish its mission goals. If mission reports indicate that a fault in the EDL sequence, like impact velocity, kept the vehicle from accomplishing all aspects of its mission regardless of how accurate the final resting point of the lander, the EDL portion is considered a failure.

Because primary source and even secondary source data are not directly available for all missions for all categories, the plots do not all have the same number of data points. Some space agencies are transparent about their algorithms and their accuracy capabilities, while others are not. Similarly, private space companies do not release much information on their probes' EDL architecture or capabilities due to intellectual property rights and the current competition for commercial lunar payload contracts. Every effort was made to find pertinent EDL information for every mission. Key parameters used in this paper are as follows:

- 1) Autonomy level
- 2) Body type (planet/moon/asteroid/comet)
- 3) Crewed (yes/no)
- 4) EDL computer capabilities
- 5) EDL descent portion successful (yes/no)
- 6) EDL sensor suite
- 7) Final velocity
- 8) Guidance architecture
- 9) Initial descent velocity
- 10) Initial EDL descent height
- 11) Miss distance
- 12) Landing targeting error ellipse
- 13) Launch country or agency
- 14) Launch date
- 15) Mission name

- 16) Mission objective achieved (yes/no)
- 17) Notable firsts
- 18) Peak load
- 19) Probe mass
- 20) Target body

Details on the classification of guidance, autonomy, and accuracy are shown in Tables 1, 2, and 3.

Table 1 EDL guidance architecture

Guidance type	Guidance explanation
Ballistic	Vehicle does nothing to reduce descent velocity.
Atmospheric	Vehicle relies on the atmosphere for descent using parachutes, aerobraking, or both.
Propulsive	Vehicle relies on engines, either solid rocket or throttleable, for descent.
Hybrid	Vehicle relies on both atmospheric and propulsive guidance methods to manage descent.

In this paper, descent guidance refers to the method used to bring a vehicle to a stop on the target body. This definition allows for a comparison of techniques for descent guidance across agencies and timelines where specific guidance architecture data are not usually available.

Table 2 EDL autonomy classification

Autonomy type	Autonomy description
Ballistic	Vehicle does no guidance maneuvers to slow down in descent.
Preprogrammed	Vehicle relies on a preprogrammed sequence, either timed or with sensors, to effectuate the EDL sequence.
Human	Vehicle relies on a human to control the entire or terminal descent onto the target body.
TRN/Hazard avoidance	Vehicle relies on a terminal terrain relative navigation or a hazard avoidance maneuver to effectuate the EDL sequence.

The classification scheme defined in Table 2 focuses on the terminal aspect of the EDL sequence, which is key for unlocking pinpoint guidance.

Table 3 EDL accuracy binning

Bin	Bin description
Multi 100 km	Distance to target is 100 km plus from landing point.
Multi 10 km	Distance to target is between 10 km and 99 km from landing point.
Multi km	Distance to target is between 1 km and 9 km from landing point.
100 m to 1 km	Distance to target is between 100 m and 1 km from landing point.
20 m to 100 m	Distance to target is between 20 m and 100 m from landing point.
10 m to 20 m	Distance to target is between 10 m and 20 m from landing point.
1 m to 10 m	Distance to target is between 1 m and 10 m from landing point.

Table 3 shows the accuracy binning for EDL descent classification. Accuracy data are not the same as the error ellipses but rather the distance between the landed position and the intended landing point. Most multi-100 km landings were on Venus. The 1 m to 10 m category is considered to be the pinpoint landing target.

IV. Historical Trends in Landing Accuracy

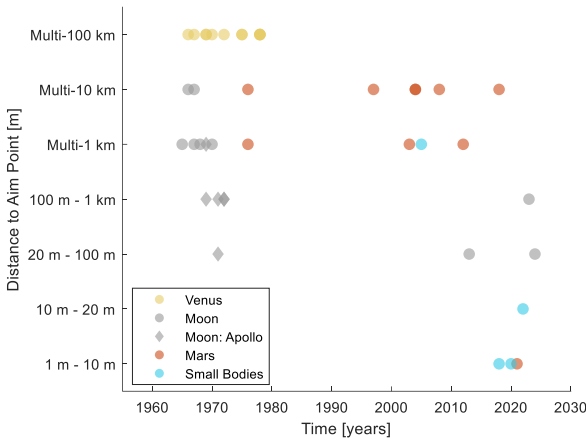


Fig. 2 Published landing distance to aim point.

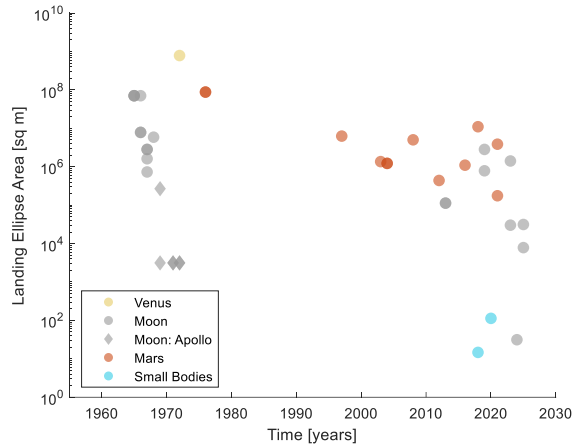


Fig. 3 Published target landing ellipse.

Figures 2 and 3 show what can be considered an early era of variability, the 1960s and 1970s, where missions had a wide range of miss distances. Of note is how exceptionally accurate the manned Apollo missions were relative to their time. Also, of note is how, occasionally, probes would significantly overperform their published target ellipse. The ellipse area was larger in the 1960s and 1970s compared to that of the 2000s, but occasionally probes would land very close to their target location. Landing accuracy remained a challenge on Venus. Both American and Soviet attempts were only successful in putting probes within hundreds of kilometers of their intended aimpoints. Often the error estimate of the reported landed position is only known within a hundred kilometers due to atmospheric conditions [4]. Relative to lunar and Martian EDL environmental conditions, conditions on Venus are the hardest for vehicles to survive.

The Mars missions shown in Figs. 2 and 3 clearly provide a bridge to autonomous precision landings. As payloads have become more expensive and landing requirements for scientific activities more precise, EDL technology has evolved. An example is the desire to study the small, irregular bodies of comets and asteroids. Figure 4 shows a rolling 10-year average of EDL landing success.

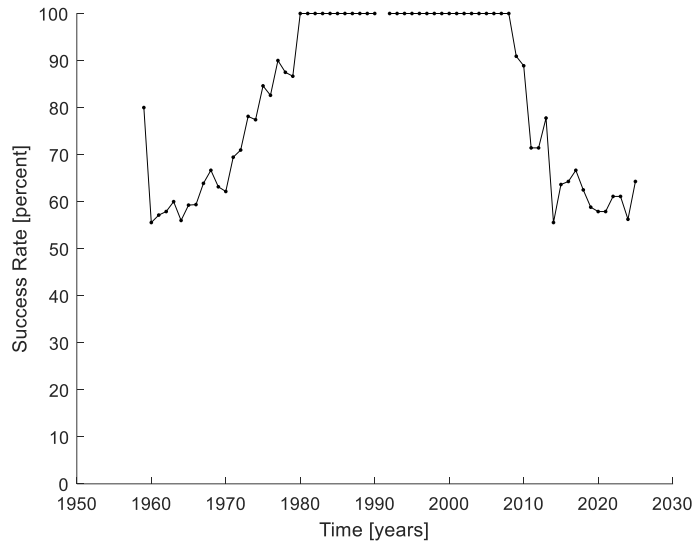


Fig. 4 Rolling 10-year landing success rate.

As the space race drew to a close, both the United States and the Soviet Union were mastering the EDL technology of their time. Apollo 12, 14, and 15 landed within 160 m [2], 50 m [3], and 550 m [5] of their aim points, respectively. On the Soviet side, the Luna 21 probe landed within a 50 km crater and included a rover [6]. The Soviets Luna program culminated with Luna 24, which was an autonomous sample return mission that returned successfully [6]. However, after a multi-decade break from missions requiring EDL sequences, the landing success rate decreased from 2000 through 2010. Now, with more and more missions slated for exploration, technology is maturing and the success rate is improving. However, success rates do differ between government-designed landers and privately funded or contracted landers. In 2019, the Israeli SpaceIL Beresheet lander failed during descent due to a glitch that caused its descent engine to malfunction [7]. In 2023, the Hakuto R Mission 1, developed by iSpace failed when the altitude filter incorrectly gave an altitude reading that triggered an early descent [8]. In 2025, Intuitive Machines IM2 failed, landing on its side outside its target ellipse; investigations to date point to faulty altimetry data [9]. Figure 4 illustrates that landing a vehicle on a target body remains a challenge, even with advances in technology.

V. Drivers of Accuracy

The classification described in Section III is further elaborated in Figs. 5 and 6. The key insight highlighted by the data in these figures is that autonomy is driving the increased precision and is the future for improvements in EDL precision. Decoupling the vehicle from preprogrammed ground instructions is paramount for either or both of these reasons: (1) ground control does not have better sensor and image data from orbit than a vehicle does in terminal descent to direct the EDL sequence to land in a safe (flat, large, boulder-free) location, and (2) the communication delay is so long that ground instructions reflecting new transmitted terminal data would not be delivered until after the descent had been completed.

Mars missions have the greatest offset from the $y = x$ line, an expected finding due to the effect of the atmosphere on the entry part of the EDL sequence and the factor of the orbital speed in the downrange direction. Moon and comet missions are primarily on the line $y = x$ or just off the line, indicating just the contribution of the orbital speed in the downrange direction.

VI. Engineering Insights

Designing a vehicle to be successful in the EDL sequence is paramount for a complete science mission. Although vehicle landing missions can gather scientific data on their transfer and descent, their primary data-gathering potential is on the surface of the target body. Detailed reviews of EDL failures are presented in the next section, but overall engineering insights and design choices about landing are shown in Figs. 8 and 9.

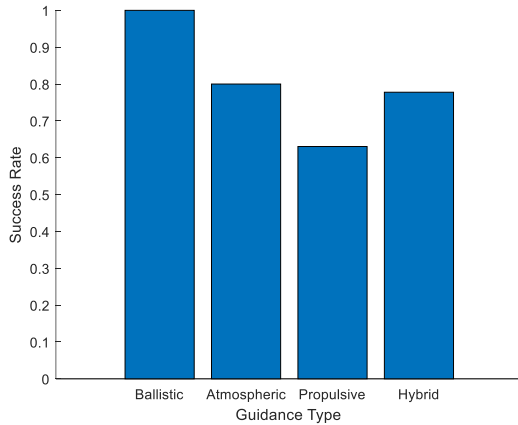


Fig. 8 Guidance type vs success rate.

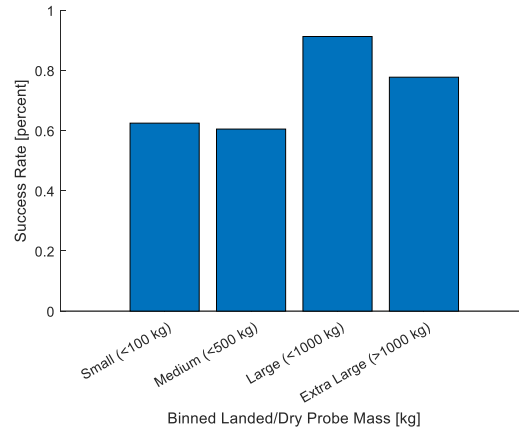


Fig. 9 Vehicle mass vs success rate.

Interestingly, propulsive is the least successful guidance type, whereas atmospheric is the most successful, excluding ballistic. Atmospheric and hybrid both rely on drag, which offers a form of near guaranteed descent speed reduction, whereas propulsive landing is more susceptible to a critical failure capable of crippling the entire EDL strategy. The distribution of vehicle mass vs success rate is interesting. It does not increase directly with size, indicating bigger probes are not inherently more reliable. Medium-mass vehicles may experience a Catch-22, having enough mass to require advanced EDL strategies but not enough weight budget to have the more robust and redundant EDL systems found on larger vehicles. Extra-large vehicles could carry extra risk due to their extreme complexity.

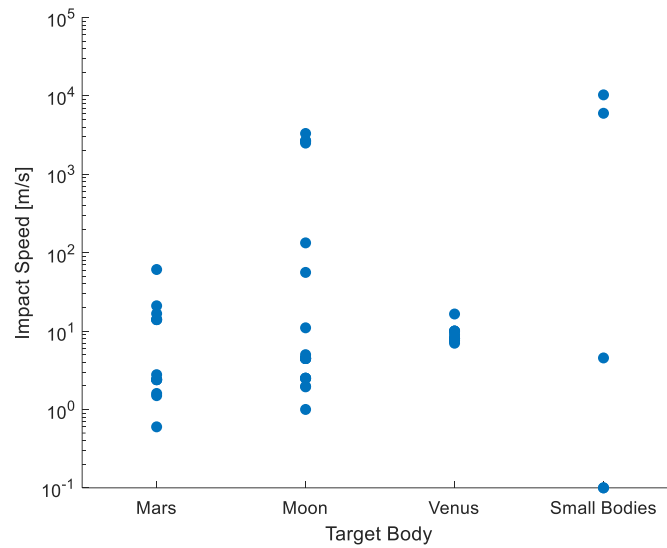


Fig. 10 Impact speed vs target body.

As shown in Fig. 10, impact speed varies significantly across all bodies; however, vehicle landings on Venus have a very small distribution, most likely due to the dense atmosphere. The small bodies have the highest distribution, due in part to being subjected to both high speed impact missions as well as very precise sample collection missions requiring minimal speed. The minimum impact speeds on the Moon and Mars are quite similar, but the maximum is higher for the Moon, reflecting the possibility of higher speed descents in the absence of atmospheric braking.

Understanding the initial environment of the EDL sequence is also important. Figure 11 is a plot of the different starting velocities for EDL sequences. The starting velocity is effectively the minimum amount of velocity the EDL sequence must remove through different deceleration methods for a safe landing. The initial velocity occurs either: (1) when the landing vehicle separates from the main spacecraft bus, which may enter into an orbit as its own satellite mission; (2) when a probe crosses the atmospheric interface for bodies with atmospheres; or (3) when the EDL sequence starts for bodies in vacuum.

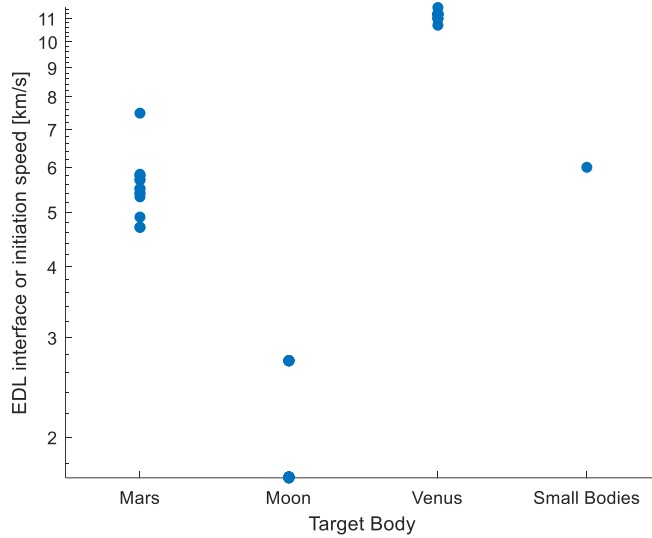


Fig. 11 Initial speed at interface or descent start.

Venus missions have the highest entry speeds followed by a Mars mission then the Huygens probe, which landed on Titan, then the remaining Mars missions in quick succession. Of note is the order of atmospheric densities from greatest to least: Venus, Titan, and then Mars, which is the same order as the initial speeds from greatest to least. The lunar missions start at lower altitudes, as shown in Fig. 12, and have the lowest entry speeds as shown in Fig. 11.

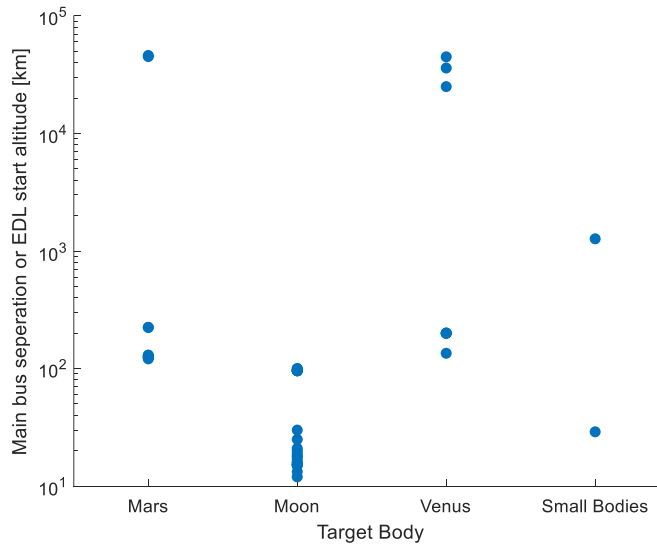


Fig. 12 Initial altitude at interface or descent start.

The distribution of starting altitudes on Venus and Mars guidance schemes is mostly due to differences in guidance architectures. For example, during the Soviet Mars program, Mars 3 and Mars 6 separated from their bus at 46,000 [11] and 45,000 [12] km respectively. This starting altitude is in contrast with dedicated missions like Pathfinder and Curiosity, which started their EDL sequences at 130 km [10] and 125 km [13], respectively. A similar trend can be seen on Venus with Venera 6 starting its descent at 25,000 km [13] and the Pioneer probes separating from the main bus at 200 km [14].

The difference in velocities and atmospheric density or lack of atmosphere is also visible as a defining parameter in landing vehicle design as seen in Fig. 13, which depicts the peak g loading of different missions.

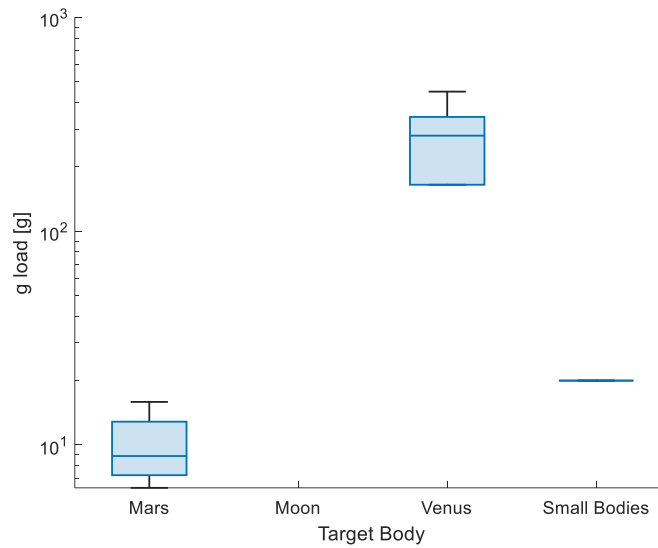


Fig. 13 Max g load across target bodies.

Max g loading is most commonly reported for atmospheric entry, so no lunar data are present. As mentioned above, the greater Venetian atmospheric density combined with the higher speeds causes significantly higher g loads on the Venetian-bound vehicles than those descending to Mars. The aggregated missions to Venus have a median max g load of 280 g while the Martian missions have a median of 8.875 g. The sole mission to land on Titan, classified as a small body, experienced a max g load of 20 g.

A critical component of the engineering of a lander is its computer. Without a computer, no sensor data can be interpreted, and no guidance commands can be issued. Table 4 shows the development of the main computers where data are available for landing vehicles.

Table 4 Evolution of landing computer capability

Year	Mission	Brand	Computer	Memory	Clock Speed [MHz]	MIPS	FLOPS	RAM [mb]	Notes
1969	Apollo 11-17	MIT/Dra- per [15]	AGC Block II [15]	76 kb [15]			14245 FLOPS [15]		
1976	Viking 1 and 2	Honeywell [16]	HDC 402 x2 [16]	18000 x2 words [17]					
1997	Pathfinder	BAE [16]	RAD6000 [16]	128 mb [18]	20 [18]	22 [18]			
2003	Beagle 2	ESA [19]	ERC32 [19]		15 [20]	10 [20]	2 MFLOPS [20]		
2004	MER-A (Spirit) and MER-B (Opportunity)	BAE [21]	RAD6000 [21]		33 [16]	35 [16]			
2012	MSL (Curiosity)	BAE [22]	RAD750 [22]	2 gb [22]	200 [22]	260 [22]		256 [22]	
2016	ExoMars Schiaparelli lander	Atmel [23]	AT697F Leon2 [23]	4 gb [23]	100 [24]	100 [24]			
2018	Insight	BAE [25]	RAD750 [25]		115.5 [25]	260 [26]			
2021	Perseverance	BAE [27]	RAD750 [27]	2 gb [27]	200 [27]	260 [27]		256 [27]	Also includes: computer vision acceleration card (1GB DDR2 RAM) [27]

For reference, the current latest base iPhone model, an iPhone 17, has 8 gb of RAM [28] and an A19 processor that is capable of speeds of up to 4260 MHz on select cores [29]. The iPhone 17 comes with a minimum storage capacity of 256 gb [30]. The 256 gb of memory dwarfs the mere 76 kb the Apollo astronauts had when landing on the Moon. The iPhone specifications are also far above the specifications that enabled the Perseverance rover to autonomously land within an 8 km x 7 km ellipse, using 256 mb of RAM, a 200 MHz processor and 2 gb of storage. Also of note is that the Apollo missions were able to land with a processor that had 14,245 FLOPS; in 2003, Beagle 2 attempted to land on Mars, and had a computer with 2,000,000 FLOPS of computing capability.

Of similar interest is the evolution of guidance algorithms. The USSR’s Luna 2 mission was only spin stabilized and did not have any propulsion [31]; its sole objective was simply to impact the Moon. Following this mission, the United States’ early Ranger spacecrafts used midcourse corrections [31]. The Ranger 9 mission in 1965 included a terminal maneuver to align the velocity vector with the impact angle of the craft, a first for planetary descent guidance [31]. At the time, midcourse corrections were used on Venus missions, and crafts that could survive descent through the harsh conditions were under development. Venera 3, which descended in 1966, used midcourse corrections that were computed from ground stations using doppler radar and interplanetary reference points like the Sun and Canopus [32]. Without these course corrections the probe would have missed the planet [12]. The uncorrected miss distance was 60,550 km; the Soviets did 13,000 calculations to correct the course [12].

Surveyor 1 landed on the Moon in 1966 and was equipped with several technological advancements in EDL technology. It used a doppler radar system called the RADVS and had throttleable vernier engines to manage descent speed. The Radar Altimeter and Doppler Velocity System used four beams to sense the velocity and range vector informing the guidance system of key parameters [33].

Viking 1 followed this trend of evolving EDL techniques and landed on Mars in 1976. Viking 1 used doppler sensing to measure horizontal velocity, throttled vernier engines for vertical velocity control, and throttleable pitch for horizontal velocity control [34]. During descent the probe also used a center of mass offset lift control scheme [35].

Computer vision was first leveraged by the MER-A and MER-B missions, commonly referred to as Spirit and Opportunity, which landed in 2004. These landers were equipped with a system called DIMES. The Descent Image Motion Estimation System combined real time imaging data, radar altimeter data, and IMU data, to robustly estimate the horizontal velocity of the landers [36]. Terrain relative navigation EDL schemes were first seen on the Hayabusa program. Similar to the MER rovers, Hayabusa, which landed in 2005, used imaging to help null the horizontal velocity

but also included the ability to drop a terrain marker while 30 m above the surface to further help improve its navigation solution [37]. Hayabusa 2, which landed in 2018, built on the success of the terrain markers.

Before Hayabusa 2, in 2013, the Lunar Chang’e 3 probe executed the first hazard avoidance maneuver at 100 m in altitude using its throttleable engines [6]. The Chang’e series of probes used an adaptive explicit guidance descent scheme [38]. Later, the Chandrayaan series lunar probes also used a hazard avoidance maneuver at 100 m for safe landing [39]. The use of hazard avoidance is the latest EDL development, and now the focus is moving to leveraging it to produce reliable pinpoint landings. NASA is also seeking to leverage these guidance schemes that worked on Perseverance, which weighed 3.3 metric tons [40], for human-scaled landers that are projected to weigh from 49 to 65 metric tons [40]. Missions that occurred after the terrain relative navigation and hazard avoidance breakthroughs are included here for their navigational techniques, which improved the accuracy of these missions. The OSIRIS-REx mission in 2020 used a form of natural feature tracking to assist in producing a navigation solution accurate enough for the tight safe zones on the target body [41]. The Mars Perseverance mission may be the most famous case of hazard avoidance, safely landing the Mars rover within its ellipse in 2021 using its landing vision system and safe target selection algorithm [42]. The DART asteroid redirection mission, which impacted in 2022, used a DRACO camera system. The Didymos Reconnaissance and Asteroid Camera for Optical navigation was needed for precise and fast navigation and targeting since the probe impacted at 6.1 km/s [43]. To hit the asteroid at this speed, the SMART navigation system was employed. The Small-body Maneuvering Autonomous Real Time Navigation system was able to image the two asteroids (Didymos and Dimorphos) and command the spacecraft to impact Dimorphos based on the relative body position in the imagery [43].

The SLIM lander made by JAXA executed a very precise EDL descent onto the lunar surface using hazard avoidance in 2024. To execute the first pinpoint landing (within 100 m of the target) SLIM used vision-based navigation and its obstacle detection and avoidance scheme that ran at an altitude of 50 m [44]. The Firefly Aerospace Blue Ghost M1 lunar mission, which landed in 2025, also used vision navigation combined with the polynomial D’Souza guidance to land within its error ellipse [45].

VII. Failure Analysis

Figure 14 shows the distribution of failures during the EDL sequence. Further detail on each failure is provided in Table 5. The most common failures were navigation sensor faults, followed closely by thruster and landing faults.

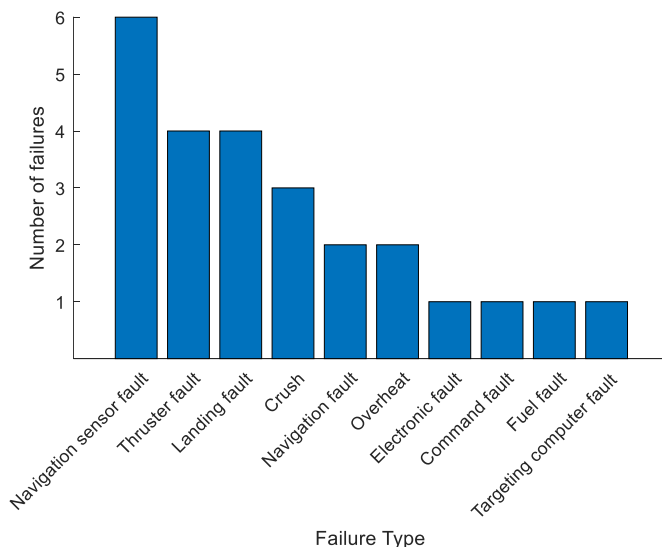


Fig. 14 Distribution of failures during EDL sequence.

Table 5 Descriptions of EDL failures

Mission	Target	Year	Fault Classification	Fault Description
Ranger 4	Moon	1962	Electronic	Failure of onboard computer, leading to solar panel and navigation failure [6]
Luna 5	Moon	1965	Navigation sensor	Failure of flotation gyro on the guidance computer [6]
Luna 7	Moon	1965	Navigation sensor	Attitude sensor failure caused loss of Earth lock [6]
Luna 8	Moon	1965	Landing	Unrecoverable spin caused by metal fragment piercing a landing airbag [6]
Venera 3	Venus	1966	Overheat	Loss in orientation due to overheating from atmosphere [6][32]
Surveyor 2	Moon	1966	Thruster	Failure of thruster to ignite for course correction [6]
Venera 4	Venus	1967	Crush	Crushed from atmospheric pressure [6]
Surveyor 4	Moon	1967	Thruster	Explosion of thruster in descent [6]
Venera 5	Venus	1969	Crush	Crushed from atmospheric pressure [6]
Venera 6	Venus	1969	Crush	Crushed from atmospheric pressure [6]
Luna 15	Moon	1969	Navigation sensor	Navigation sensor error in pitch axis [46]
Venera 7	Venus	1970	Overheat	Melted parachute lines [12]
Mars 2 Lander	Mars	1971	Targeting computer	Targeting computer failure to update with correct coordinates [6]
Luna 18	Moon	1971	Fuel	Insufficient fuel for descent thrusters [46]
Mars 6 Lander	Mars	1974	Landing	Suspected radio failure or landing in rough area [6]
Luna 23	Moon	1974	Landing	Severe damage during landing with premature halt in altitude and high descent speed. Later imaging showed lander on side [6]
Rosetta	Churyumov–Gerasimenko 67P	2014	Landing	Landing failure, failure of ice screws to penetrate hard surface, failure of thruster due to seal, failure of harpoon anchor to fire due to electrical failure [6]
ExoMars Schiaparelli Lander	Mars	2016	Navigation sensor	Incorrect reading from inertial measurement unit causing premature landing sequence activation [6]
Beresheet	Moon	2019	Command	Engine fire command glitched by manual command from ground control; unable to recover in time before crash landing [7]
Chandrayaan-2	Moon	2019	Navigation	Over-constrained navigation target, overpowered engines, and software glitches [47]
Hakuto R Mission 1	Moon	2021	Navigation	Incorrect sensor measurement included by navigation filter, leading to free fall [8]
Luna Glob (Luna 25)	Moon	2023	Thruster	Failure of thruster to stop during midcourse burn, causing impact [48]
SLIM	Moon	2024	Thruster	Failure of one of two main engines causing incorrect landing attitude [49]
IM-2 Athena	Moon	2025	Navigation sensor	Noisy laser altimeter; vehicle landed on side [9]
Hakuto R Mission 2	Moon	2025	Navigation sensor	Deterioration of performance in rangefinder [50]

Some comments on Table 5: The Soviet Venera missions were the first to attempt the descent through the Venetian atmosphere, eventually leading to a very successful program with many firsts in interplanetary robotics. NASA leveraged the Soviet atmospheric data and was able to land its first Venus vehicles, the Surveyor large probe, day probe, night probe, and north probe, successfully. The Hakuto R Mission 1 failed due to incorporation of an incorrect measurement; a similar failure occurred five years earlier with the ExoMars lander. Navigation sensor failures are by far the most common failure mode found in this analysis. Two recent missions, IM-2 and Hakuto R Mission 2, both reported sensor anomalies after investigating their landing failures.

VIII. Cross Space Program Synthesis

Finally, missions by country or launch agency and target body over time are shown in Figs. 15 and 16 to capture the state of the modern space race.

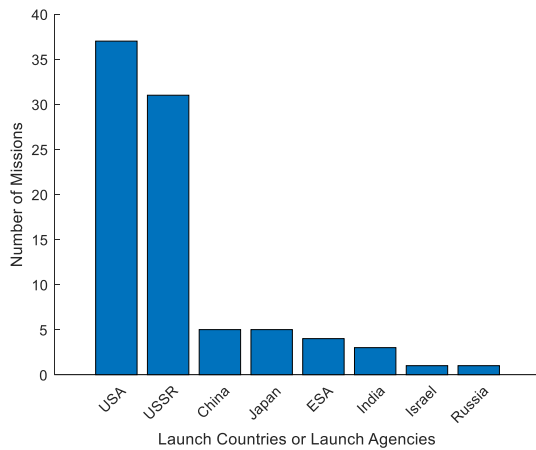


Fig. 15 EDL missions by country or launch agency.

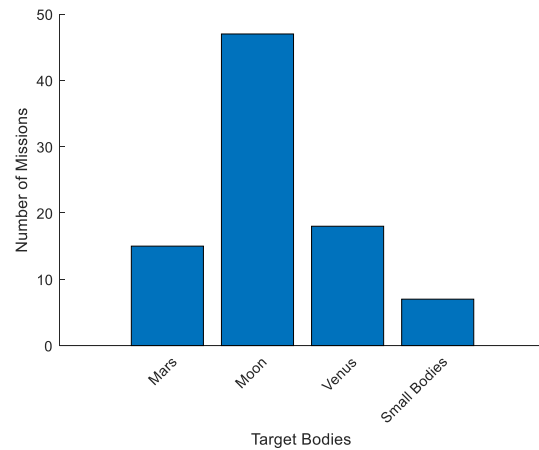


Fig. 16 Number of missions to different target bodies.

Not surprisingly, the most well-traveled countries are the USA and the USSR, who have launched the majority of planetary and small body vehicles. Russia has failed to capitalize on the USSR pedigree of EDL technology, launching only one lunar lander, which failed in lunar descent. The most visited body is Earth’s nearest neighbor, the Moon, with Venus taking the second spot, largely as a result of the Soviets’ prolonged campaign to land a probe after losing several in the severe Venetian atmospheric conditions. Figure 17 provides a timeline showing the Soviets’ Venus campaign as well as the rise of global participation in space exploration in the 21st century after domination in the 20th century by the USA and the USSR. Japan, which started landing probes 40 years after the USA and the USSR is credited with some of the most precise small body landings as well as the most precise lunar landing. As shown in Table 6, Hayabusa and SLIM were both launched by JAXA, and Chang’e 3 was launched by the Chinese. All other vehicles were launched by NASA. The table lists missions whose published miss distance from the final aimpoint was less than 100 m.

Table 6 Data on current EDL descents with 100 m or less miss distance

Mission	Year	Autonomy	Miss Distance [m]	Notes
Hayabusa 2	2018	TRN-assisted	0.59 [51]	Touch and go
OSIRIS-REx	2020	TRN-assisted	1 [41]	Touch and go
Mars 2020, perseverance	2021	TRN-assisted	5 [52]	Hazard avoidance
Smart Lander for Investigating Moon (SLIM)	2024	TRN-assisted	10 [53]	Measurement taken before start of hazard avoidance scheme
DART (Double Impact Redirection Test)	2022	TRN-assisted	17 [54]	Impactor
Apollo 14	1971	Human	50 [3]	Human pilot
Change 3	2013	TRN-assisted	89 [38]	First autonomous hazard avoidance

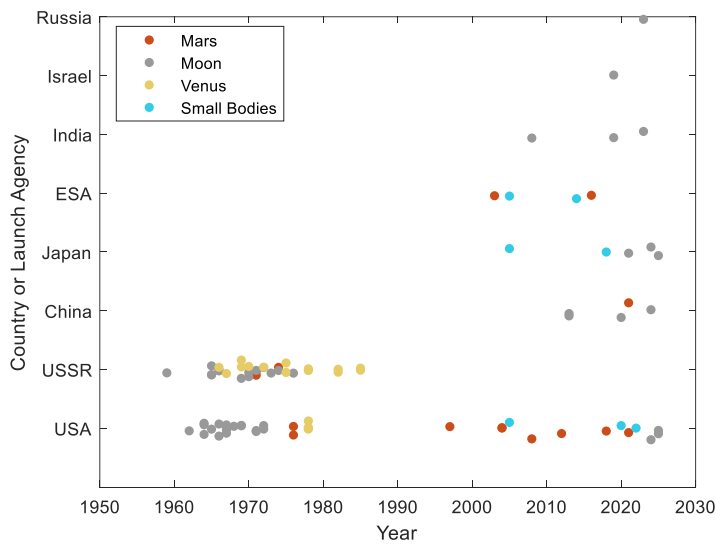


Fig. 17 Target body landing mission timeline.

For legibility, in Fig. 17, slight y-axis jitter is applied so multiple missions occurring in the same year are all visible. Six countries have landed on target bodies since the early 2000s, ending the decades-long exclusivity of the US and the USSR in terms of successful landings on target bodies. Table 7 (adapted from data in Asif Siddiqi’s *Beyond Earth: A Chronicle of Deep Space Exploration, 1958–2016*) [6] shows notable firsts; as space becomes more accessible, future versions of this table are bound to include more countries and target bodies.

Table 7 Notable Firsts

	Absolute Firsts	Moon	Venus	Mars	Saturn (system)	Comets	Asteroids
USA	1	2	0	1	0	2	0
USSR	7	3	5	1	0	0	0
ESA	0	0	0	0	1	2	0
Japan	0	0	0	0	0	0	1

Although the initial absolute firsts and the first visits to Earth’s nearest neighbors were achieved primarily by the USSR and occasionally by the US, more recent first successful landings on farther target bodies, such as asteroids and comets, have been achieved by ESA and JAXA.

In closing, landing on target bodies remains a challenge, one that is complicated by the desire for pinpoint accuracy. With more agencies and countries working on solving precision and advanced guidance problems, reliability is improving. Because of the number of catastrophic failures caused by navigation sensor or filter faults, these elements should remain an area of focus for improving robustness. As these hurdles are conquered with unmanned probes, human landers can use this pedigree of reliability to add to the noticeable firsts shown in Table 7.

Appendix

Appendix table: Sources used to develop plots

Mission	Source						
	Accuracy	Mass	Ellipse	Landing Speed	Initial Speed	Initial Altitude	Peak Load
Venera 3	[4]	[6]					
Venera 4	[4]	[12]			[10]	[12]	[12]
Venera 5	[4]	[12]			[12]	[12]	[10]
Venera 6	[4]	[12]			[6]	[12]	[10]
Venera 7	[4]	[10]		[10]	[6]	[6]	[12]
Venera 8	[4]	[12]	[12]		[12]		[6]
Venera 9	[4]	[12]		[12]	[12]		[12]
Venera 10	[4]	[12]		[10]			[12]
Pioneer Day Probe	[55]	[10]		[10]		[14]	[14]
Pioneer Night Probe	[55]	[10]		[10]		[14]	[14]
Pioneer North Probe	[55]	[10]		[10]		[14]	[14]
Pioneer Large Probe	[55]	[10]		[10]		[14]	[14]
Venera 11		[10]		[6]	[6]		[10]
Venera 12		[10]		[12]	[6]		[10]
Venera 13		[10]		[12]	[12]		[10]
Venera 14		[10]		[10]			[10]
VEGA 1 Lander		[10]		[56]	[56]		[10]
VEGA 2 Lander		[10]		[56]	[56]		[10]
Mars 2 Lander		[10]					
Mars 3 Lander		[10]		[10]	[11]	[11]	
Mars 6 Lander		[10]		[12]	[12]	[12]	
Viking 1 Lander	[56]	[10]	[40]	[10]	[35]	[57]	
Viking 2 Lander	[56]	[10]	[40]	[10]	[35]	[57]	

Mission	Source						
	Accuracy	Mass	Ellipse	Landing Speed	Initial Speed	Initial Altitude	Peak Load
Pathfinder	[6]	[10]	[40]	[10]	[58]	[58]	[59]
Beagle 2	[60]	[10]	[61]	[10]	[61]		
MER-A Spirit	[6]	[10]	[40]	[10]	[62]		[62]
MER-B-Opportunity	[6]	[10]	[40]	[10]	[62]		[62]
Phoenix	[63]	[6]	[40]	[10]	[64]	[64]	[64]
Mars Science Lab (Curiosity)	[65]	[6]	[40]	[13]	[13]	[13]	[66]
ExoMars Schiaparelli lander		[23]	[67]	[68]	[68]	[68]	[69]
insight	[70]	[70]	[71]	[10]	[70]	[70]	[70]
Mars 2020, perseverance	[52]	[40]	[40]	[72]	[72]	[73]	[72]
Tianwen-1		[74]	[75]	[76]	[76]	[76]	
Luna 2		[46]		[10]			
Ranger 4		[10]		[10]			
Ranger 6		[6]					
Ranger 7		[6]		[77]			
Ranger 8		[6]		[77]			
Ranger 9	[6]	[6]		[6]			
Luna 5	[6]	[10]	[46]	[78]			
Luna 7		[10]	[46]				
Luna 8		[10]	[46]				
Luna 9		[10]	[46]				
Surveyor 1	[6]	[6]	[79]	[79]	[79]	[79]	
Surveyor 2		[6]	[79]	[79]	[79]	[79]	
Luna 13		[46]					
Surveyor 3	[80]	[6]	[80]	[79]	[80]	[80]	
Surveyor 4		[10]	[81]	[79]	[79]	[79]	
Surveyor 5		[10]	[82]	[79]	[79]	[79]	
Surveyor 6	[83]	[10]	[83]	[79]	[79]	[79]	
Surveyor 7	[6]	[10]	[84]	[79]	[79]	[79]	
Apollo 11	[85]	[85]	[86]	[85]	[87]	[85]	
Luna 15		[10]		[6]		[46]	
Apollo 12	[2]	[88]	[41]		[87]	[87]	
Luna 16	[89]	[10]		[6]	[46]	[6]	
Luna 17 (Lunohkod 1)		[10]		[6]	[46]	[46]	
Apollo 14	[3]	[88]	[41]		[87]	[87]	
Apollo 15	[5]	[88]	[41]		[87]	[87]	
Luna 18		[10]		[6]	[46]	[46]	
Luna 20		[10]		[6]	[46]	[46]	
Apollo 16	[90]	[88]	[41]				
Apollo 17	[91]	[88]	[41]				

Mission	Source						
	Accuracy	Mass	Ellipse	Landing Speed	Initial Speed	Initial Altitude	Peak Load
Luna 21(Lunohkod 2)		[10]		[10]	[46]	[46]	
Luna 23		[10]		[6]	[46]	[46]	
Luna 24		[10]		[10]	[46]	[46]	
Chandrayaan 1 <i>impact probe</i>		[6]				[6]	
Change 3	[38]	[6]	[38]	[38]		[6]	
Change 4		[6]	[38]				
Beresheet		[92]	[92]		[92]	[92]	
Chandrayaan 2		[39]	[47]		[39]	[39]	
Change 5		[93]				[94]	
Hakuto R Mission 1		[95]					
Luna 25 <i>luna-glob</i>		[53]	[53]				
Chandrayaan 3	[96]	[97]	[53]		[98]	[98]	
Smart Lander for Investigating Moon (SLIM)	[53]	[53]	[53]				
IM 1 Odysseus		[99]					
Change 6		[100]					
Blue Ghost M1 <i>TO 19D</i>		[45]	[101]	[45]	[45]	[45]	
IM 2 Athena		[102]	[9]				
Hakuto R Mission 2		[95]					
Hayabusa		[6]		[103]			
Hayabusa 2	[51]	[104]	[51]				
OSIRIS-REx	[41]	[6]	[41]	[105]			
DART <i>Double Impact Redirection Test</i>	[54]	[43]		[43]			
Deep Impact		[6]		[6]			
Rosetta		[106]				[6]	
Huygens probe	[6]	[6]		[107]	[10]	[107]	[10]

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