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ADVANCES IN GUIDANCE, NAVIGATION, AND CONTROL FOR PLANETARY ENTRY, DESCENT, AND LANDING SYSTEMS

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Planetary entry, descent, and landing has been performed successfully at Venus, Earth, Mars, Jupiter, Titan, and the moon, producing a wealth of *in situ* data not available from in-space remote-sensing platforms. To achieve such success, entry, descent, and landing systems have been designed to accommodate a wide variety of mission scenarios and environments, from the thin atmosphere of Mars to the thick atmosphere of Venus, from atmospheric entry velocities as low as 4 km/s at Mars to nearly 48 km/s at Jupiter. The history and development of the complex systems necessary to successfully execute entry, descent, and landing is summarized and discussed, with a focus on guidance and control strategies. Improvements to inertial navigation systems and interplanetary approach navigation techniques are highlighted. Mission requirements that drive entry, descent, and landing system design are identified. Lastly, future challenges and goals for entry, descent, and landing systems are enumerated and current technology development efforts are discussed.

INTRODUCTION

Since the early 1960s, entry, descent, and landing (EDL) systems have been used to return payloads to the surface of the Earth and to deliver platforms to planetary surfaces for *in situ* science investigations. Guidance, navigation, and control technology for EDL systems has advanced significantly since that time and continues to be an active area of research. This paper summarizes the development and implementation of guidance, navigation, and control systems for EDL applications since their inception.

Entry, descent, and landing has been successfully performed hundreds of times in the past 50 years. Figure 2 shows a timeline of flights of significant EDL systems. Generally, human EDL systems are flown multiple times; robotic EDL systems are typically unique. Successful entries have been performed at Earth, the moon, Venus, Mars, Titan, and Jupiter. These destinations span a wide variety of environmental conditions. While some EDL systems have flown many times (e.g. STS, Soyuz), most are one-of-a-kind missions (e.g. the Huygens Probe, Mars Pathfinder). However, even one-of-a-kind missions are frequently part of larger families of spacecraft that leverage technologies developed and demonstrated by their predecessors, such as the Soviet Union's Venera Program and the United States' Mars exploration program.

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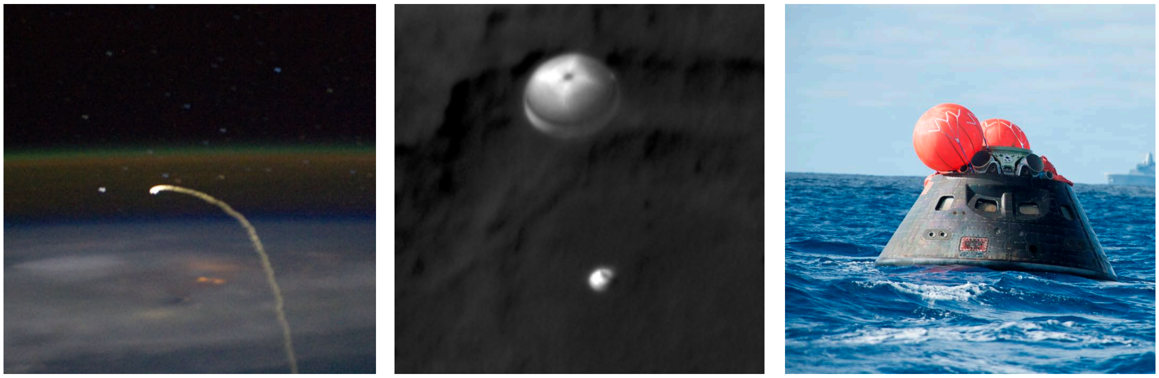
The three parts of EDL trajectories are discussed below. Some missions only perform two out of the three. For example, the Galileo Probe performed hypersonic entry at Jupiter followed by subsonic descent, but did not land.



a) b) c)

Figure 1. Modern entry, descent, and landing systems: a) hypersonic entry of Space Shuttle Atlantis (STS-135), b) parachute descent of Mars Science Laboratory, c) Orion after EFT-1 splashdown; credit: NASA.

Spacecraft may enter planetary atmospheres to change their trajectory with aerodynamic forces. These maneuvers may be used to reduce vehicle energy, change the direction of a vehicle's trajectory, or both, while using only a small amount of propellant, often providing a significant mass savings over equivalent fully-propulsive maneuvers. During entry, a vehicle uses drag generated from flight through the planetary atmosphere to decelerate from hyperbolic or orbital velocity to near-zero planet-relative velocity, allowing the vehicle to land on the surface. After an entry vehicle reaches the top of an atmosphere, hypersonic aerodynamic forces build on the vehicle until they dominate its motion. As atmospheric density increases with decreasing altitude, deceleration and heat rate magnitudes build to peak values. The vehicle then continues to decelerate prior to reaching the planetary surface. Planetary entry maneuvers are accomplished solely through the dissipation of kinetic energy through aerodynamic forces; to do so propulsively requires a propellant mass fraction on the order of that required for launch (near 90% at Earth).

Descent typically begins in the supersonic or subsonic flight regime and is defined to be the portion of the flight during which aeroheating and deceleration are low prior to reaching the surface. With some exceptions, either rocket propulsion or parachute systems have been used for the descent phase.

The landing system is designed to attenuate the impulse from surface impact. Landing system options include retrorockets (Soyuz), legs (Viking), airbags (Mars Pathfinder), and wheels (Space Shuttle Orbiter). The local environment may also be used to attenuate the impact of landing: many missions have relied on ocean landings to eliminate the mass of a landing system.

This paper focuses on civilian EDL systems at large bodies. Munitions delivery systems and small-body rendezvous and landing systems are not discussed.

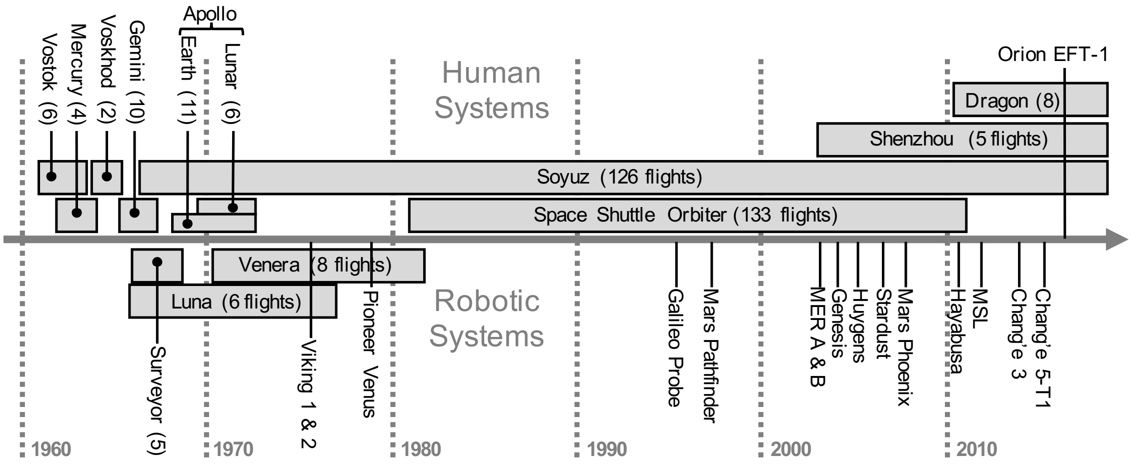
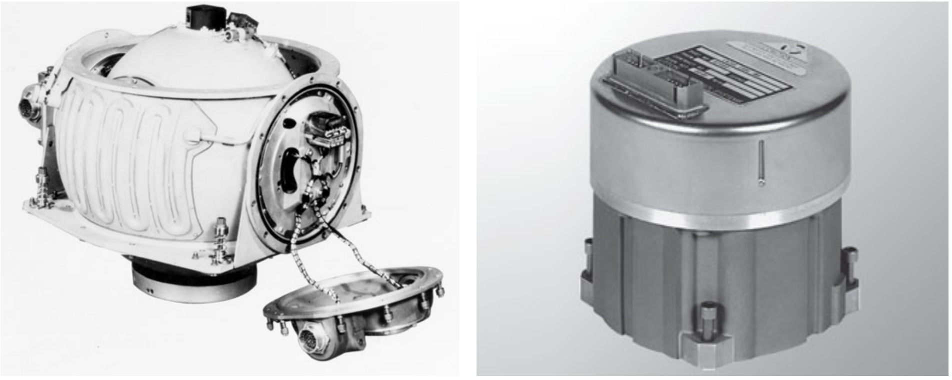


Figure 2. Timeline of Flights of Major EDL Systems.

NAVIGATION

Onboard Navigation

EDL systems typically utilize inertial navigation systems (INS) during flight. During the hypersonic portion of entry, ionization of the atmosphere in the plasma sheath can result in communications blackout, creating the need for a self-contained navigation system. Maneuvering in the atmosphere, coupled with increasing density, makes star trackers and other optical relative navigation sensors infeasible. For planetary missions, communications lag with Earth requires autonomous operation. Final state updates for EDL inertial navigation systems are typically generated by Earth-based ground infrastructure, such as the Deep Space Network.



a) **b)**

Figure 3. Inertial measurement units from a) Apollo and b) Mars Science Laboratory; credit: NASA and Northrup-Grumman.

Early inertial navigation systems utilized stable platform inertial measurement units (IMU). As flight computers improved and reliability became increasingly important, EDL systems transitioned to strap-down IMUs. Figure 3a shows the Apollo stable-platform IMU and Figure 3b the Mars Science Laboratory solid-state strap-down IMU (Northrup-Grumman LN-200S). For comparison, the Apollo IMU was about the size of a basketball; the LN-200S is about the size of a baseball and is fully solid-state. It is difficult to overstate the magnitude of the improvement in performance, reliability, and mass/power requirements.

During descent and landing, EDL systems may once again utilize relative navigation sensors, such as radars and optical terrain tracking. These sensors have been used to provide accurate measurements of altitude and horizontal velocity to improve the ground-relative navigated state for landing. MER DIMES (Mars Exploration Rover Descent Imaging Estimation System) is an excellent example of this. Designed and implemented late in the MER program, DIMES was designed to use optical terrain tracking to estimate the vehicle's horizontal velocity prior to the firing of the retrorockets. It operated successfully for both MER-A and B and was the first use of machine vision for navigation during planetary EDL.[2] MSL demonstrated a high-resolution video descent imager, but the data was only used for landing site context and was not integrated into the navigation filter.

Future systems are likely to make greater use of lidar for ranging during descent. Lider was studied extensively as a part of the Autonomous Landing and Hazard Avoidance Technology (ALHAT) project.[3]

Approach Navigation

Approach navigation, which drives initial state and knowledge errors at the top of the atmosphere, has improved significantly in the past 50 years. In particular, the Deep Space Network has been constructed and continues to be improved. The DSN enables modern deep-space navigation.

Differential Doppler One-way Ranging (ΔDOR), a type of very-long baseline interferometry, has been used to significantly reduce navigation error for interplanetary missions relative to previous methods. ΔDOR uses two out of three DSN stations simultaneously to better determine a spacecraft's position. The reduction is well-illustrated by the approach errors for recent Mars EDL systems. Current system capabilities yield position and velocity delivery errors at Mars of approximately 1 km and 0.75 m/s.[4] This improvement in approach navigation, in conjunction with other strategies, has significantly reduced the size of landing ellipses at Mars (Figure 4).

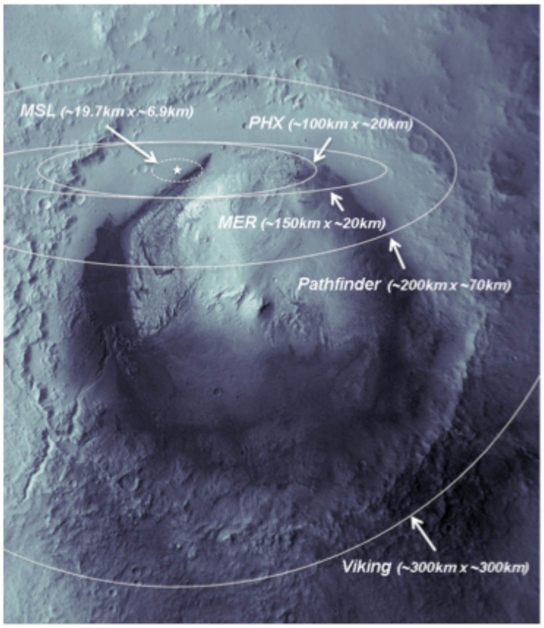


Figure 4. Approximate Landing Ellipse Sizes for Mars EDL Systems.

Future systems may utilize optical navigation and triangulation with existing assets at the planetary destination to further reduce approach navigation error. Further, at Earth, a number of studies have shown the usefulness of GPS at high orbital altitudes; this data can be integrated into navigation filters prior to entry at Earth to improve onboard navigation accuracy.

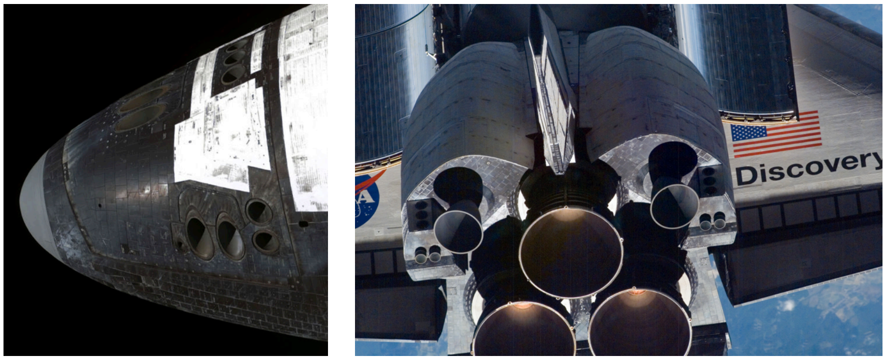
Approach navigation has, and will continue, to play a significant role in EDL mission design and performance. Delivery errors must be actively "steered out" by the vehicle during EDL, consuming control authority. Knowledge errors directly impact the accuracy of the final INS state update: even the most well-designed guidance algorithm can only go where navigation tells it to.

CONTROL AND EFFECTORS

For unguided EDL systems, lifting systems have typically utilized three-axis control to maintain a lift-up orientation (Viking), while ballistic systems utilize a small roll rate (approximately 2 RPM) to null out the integrated effects of any off-nominal lift forces generated by the vehicle.

Without exception, guided EDL systems have utilized lift, coupled with bank-angle steering, to control their trajectories. Bank angle steering takes advantage of most hypersonic vehicles' neutral stability in bank; large hypersonic aerodynamic moments in sideslip and angle of attack directions make maneuvers about those axes infeasible without aerodynamic control surfaces. Reaction control system jets are typically required for maneuvering at low dynamic pressures. However, use of aerodynamic control surfaces at high dynamic pressures been limited due to ablation and modeling concerns. For example, the Space Shuttle Orbiter was able to control its angle of attack via a large body flap, but this capability was used only to maintain a particular angle-of-attack profile and associated L/D, not for steering. Steering was accomplished via the RCS jets and bank-angle steering.[5]

Typical driving requirements for the flight control system are response time and the time required for bank reversals. Because bank-angle steering does not directly control the magnitude of the lift, only its direction, an out-of-plane component of the the lift is generally present. To control out-of-plane motion (crossrange), the vehicle executes a number of bank reversals during the hypersonic portion of entry to maintain the desired heading. For longer entries, such as Orion's at Earth, a slower response time is acceptable (approximately 30 seconds to complete a bank reversal). However, at Mars, where entry timelines are significantly compressed relative to Earth, the control system response time must be much faster, as EDL lasts only 6-7 minutes.



a) b)

Figure 5. Space Shuttle Reaction Control System: a) forward jest and b) aft jets and aerodynamic control surfaces; credit: NASA.

To date, descent systems have consisted of propulsion, parachutes, or a combination of both. Propulsion is used exclusively for landing on airless bodies; atmospheric EDL systems often utilize parachutes at high speed and propulsion for terminal descent. For example, Soyuz capsules deploy a series of parachutes based on pressure sensor data; parachute descent continues until retrorockets are triggered by a radar altimeter just prior to landing (see Figure 6).

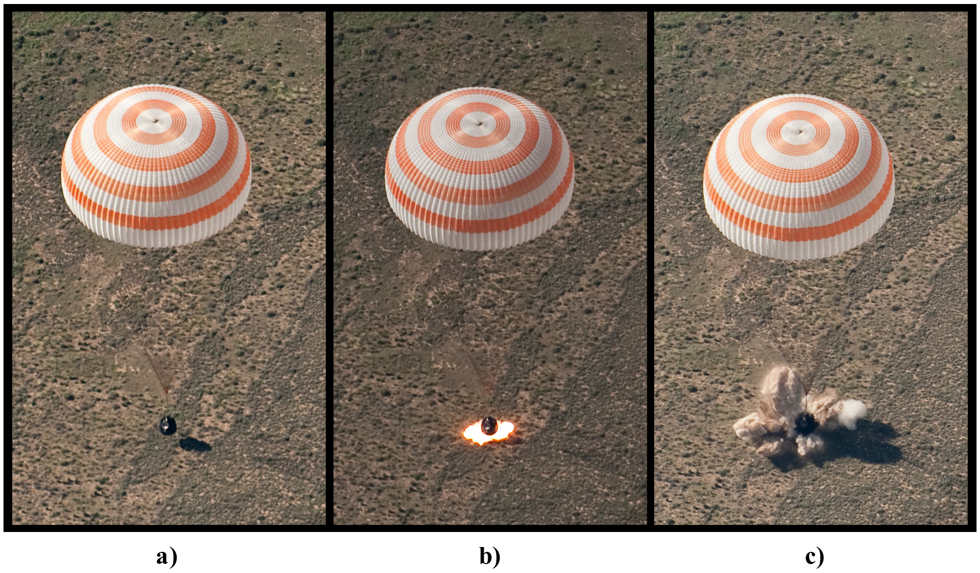

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Figure 6. Soyuz TMA-17 Landing Sequence: a) parachute, b) retrorockets, c) landing.

Parachutes are deployed using different types of triggers, typically based on available onboard navigation data. The simplest system is to use a timer (e.g. Mars Pathfinder); more commonly parachutes are deployed based on altitude (e.g. Orion), velocity (e.g. Mars Science Laboratory), or pressure (e.g. Soyuz). While the triggers may seem simple, state-based triggers often require additional logic and testing to ensure the trigger executes during the correct phase of the mission. A classic example of this gone wrong is the Genesis sample return capsule, which failed to deploy its parachute due to an upside-down accelerometer.

For atmospheric EDL systems, parachutes often also function as stabilizers in the supersonic and subsonic flight regimes. An unfortunate property of aeroshells designed for hypersonic flight is that they are typically unstable at lower Mach numbers.

Landing systems attenuate the impulse from surface impact. At Earth, the earliest systems utilized parachutes or water landing to attenuate the landing impulse. Human systems also included shock-absorbing couches and restraints to further limit peak loads at landing. These systems continue to see use due to their high reliability. To facilitate land landing, the Soyuz landing system uses retrorockets to remove most vertical velocity just prior to surface impact. The U.S. Space Shuttle and Soviet Buran both performed gentle runway landings. Robotic sample return probes have generally been designed without dedicated landing systems: Stardust relied on a shock-hardened design and a relative soft landing surface, Genesis was to be caught during descent by a helicopter to limit forces on its fragile payload.

Planetary landing systems are differentiated by destination. At the moon, propulsion and shock-absorbing legs have been used to achieve a “soft landing” on the planetary surface. Early examples include Surveyor and Luna. No separate landing system is typically required at Venus: the thick Venus atmosphere results in very low terminal velocities. Similarly, at Titan, the Huygens probe required no separate landing system—the Titan atmosphere provided a low terminal velocity and the probe was designed to absorb the landing shock. Mars landing systems have successfully used propulsion with legs (Viking, Phoenix), airbags (Pathfinder, Mars Exploration Rovers), and, more recently, the skycrane (Curiosity), a derivative of propulsive soft landing.

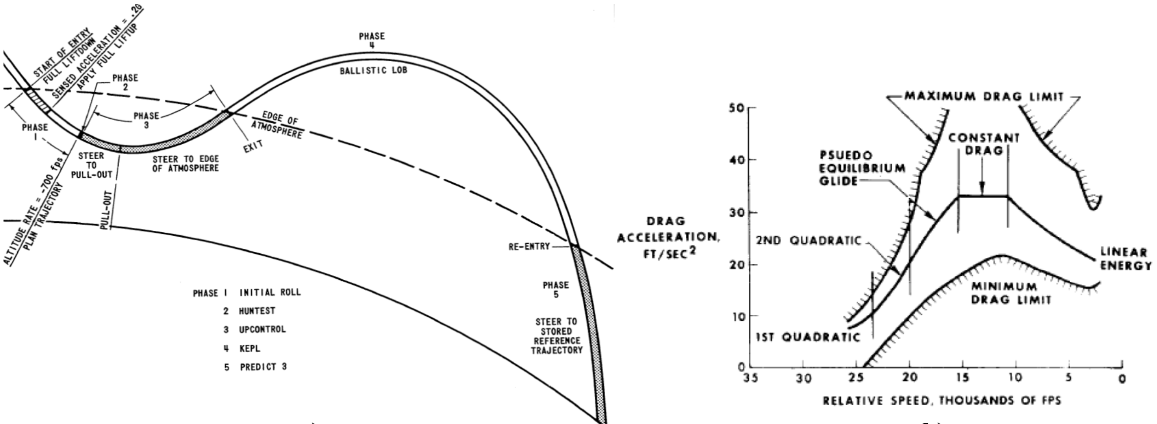
GUIDANCE

Hypersonic Entry

In the hypersonic entry phase, all guided EDL systems to date have utilized bank angle steering. Bank angle steering rotates the lift vector about the atmospheric relative velocity vector to control the amount of lift in the vertical and horizontal directions. The magnitude of the lift is not directly controlled.

Several types of hypersonic guidance algorithms have been developed and flown; software complexity has gradually increased over time as flight processors have improved. In general, these algorithms fall into three categories: terminal-point controllers, reference followers, and predictor-correctors. Most algorithms are broken into discrete phases to meet trajectory constraints and design goals. The Apollo algorithm was a combination of an analytic predictor-corrector and a terminal-point controller (Figure 7a).[6] The terminal-point controller portion is commonly referred to as “Apollo guidance” on its own and formed the basis for the MSL guidance.[7] The Space Shuttle hypersonic guidance was a piecewise reference follower, designed to ensure the vehicle remained inside its performance envelope during flight (Figure 7b).[9] This phased approach has generally led to less complex algorithms and lower computational loads.

Onboard computing capabilities have enabled complexity increase in onboard real-time algorithms and recent development for guidance for EDL systems has focused largely on numeric predictor-corrector algorithms. Orion EFT-1 was perhaps the first flight to use such an algorithm operationally, coupled, in this case, with the Apollo algorithm.[10] Numerical predictor-correctors can provide robust performance across a range of environmental, vehicle, and state parameters. The model-based nature of these algorithms also enables their fidelity to be tailored to available onboard compute power.



a)

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Figure 7. Phased Guidance Algorithms: a) Apollo[8] and b) Space Shuttle[9].

While human systems have typically included hypersonic guidance for all flights, passive systems are more common for robotic systems. Most passive systems are ballistic vehicles that generate no lift and are given a roll rate prior to entry to null out the effects of any off-nominal lift generated during flight (e.g. MER, Stardust).[13] This strategy significantly reduces the uncertainty in the flight envelope and landing ellipse. Other systems have utilized lift, maintained in a vertical orientation through three-axis control, to achieve safe landing (e.g. Viking).[13]

Descent

Descent and landing algorithms fall into two broad classes: propulsive descent and landing algorithms, which are typically designed to optimize propellant usage, and deploy triggers, which utilize discrete events to reduce terminal state error.

The Apollo program utilized powered explicit Guidance (PEG) for the initial breaking phase from lunar orbit;[10] this was followed by an acceleration-based guidance law for terminal descent.[11] However, operationally, the Apollo Lunar Modules were piloted manually during terminal descent. The current state of the art for powered descent guidance is that used by the Mars Science Laboratory, which was designed to target appropriate conditions for the skycrane sequence by following a polynomial reference trajectory.

While still untested operationally, "smart" parachute deploy algorithms can significantly reduce range error at landing for atmospheric EDL systems.[15] Static triggers are simpler to implement, but active, state-based triggers can provide better performance without requiring new hardware. The price of this improvement is a requirement for rigorous development and testing of more complex flight software. Currently, it is anticipated that the Mars 2020 rover EDL system will utilize a range-based parachute deploy trigger.

MODELING

Accurate modeling for EDL systems remains a challenge. While many aspects of EDL are well-understood, the difficulty of obtaining data in EDL-relevant environments makes accurate modeling difficult, especially for nonequilibrium chemically reacting flows, heat shield ablation, and hypersonic aerodynamics. In addition, planetary atmospheres inject a level of uncertainty that, while bounded, can be quite large.

Improvements in computing capabilities (both onboard and on the ground) have alleviated modeling issues somewhat by providing computational data to supplement limited flight-data sets. At Mars, starting with MSL, all missions will now fly instrumented forebodies—this data will hopefully help to reduce mission risk and design margins. Additionally, inexpensive compute power has allowed analysis of performance across entire flight envelopes.[16,17]

Examples of modeling difficulties include the Phoenix reaction control system and recession on the Mars Science Laboratory Heatshield. While Phoenix was to be three-axis stabilized during EDL, no thrusters were fired because engineers could not fully determine the resultant moment on the vehicle from a thruster firing due to complex jet-wake flow interactions.[18] On the Mars Science Laboratory, sensor plugs were placed in the forebody heatshield to measure the amount of recession during entry; each sensor was able to measure 5 different recession depths. Unfortunately, not enough recession occurred to generate a measurement—the recession was less than that of the minimum expected recession.[19]

Recent trajectory reconstruction efforts have shown that the single largest contributor to MSL navigation error at landing was the local gravity model of Gale Crater. This represents both an astounding achievement and a significant challenge: the MSL GNC system performed so well, that further improvements require much more detailed models of the Mars environment. Gathering data to support development of such models may be extremely difficult given current mission cadences and capabilities.

CURRENT CHALLENGES

Significant technology development is required to meet the ambitious goals outlines in recent decadal surveys and recent human exploration plans. At the forefront is the issue of scalability. EDL systems are trending towards the very large and very small and much of the current EDL technology base does not scale well. For example, there is a fundamental limit on landed payload mass imposed by current Mars airbag landing systems; this limit resulted in the development of the skycrane system.

To improve EDL system performance, particularly at Mars, NASA is pioneering a new class of EDL system that utilize deployable aerosurfaces to lower vehicle ballistic coefficient. A lower ballistic coefficient enables EDL systems to decelerate at higher altitudes, an important consideration for more massive vehicles in the thin Mars atmosphere. To date, deployable aerosurfaces have been limited to large drag areas in three classes: inflatable, semi-rigid, and rigid systems. Inflatable systems, commonly referred to as HIADs (hypersonic inflatable aerodynamic decelerator), have been flight-tested and shown good performance in ballistic and lifting configurations.[20] Semi-rigid systems include the ADEPT concept, which utilizes rigid spars and a flexible heatshield.[21] Studies of fully-rigid deployable systems have typically been limited to on-orbit forebody heatshield construction.

While large deployable drag areas are promising, effectors have yet to be developed for steering in the hypersonic phase: complex vehicle geometry and the relative sensitivity of deployable surfaces make RCS jets undesirable, internal moving mass systems may consume a significant portion of total vehicle mass; and aerosurfaces continue to be difficult to implement on deployable structures.

New descent systems are also being explored, including supersonic retropropulsion, supersonic inflatable aerodynamic decelerators, and new parachutes.[22,23] Supersonic retropropulsion has been demonstrated successfully at Earth several times. However, additional development work is required if supersonic retropropulsion is to be used for EDL. While GNC for propulsive descent is well established and understood, that experience is mostly limited to vacuum flight; high-speed atmospheric flight of these systems may require new system configurations and algorithms. Additionally, to maintain stability during the hypersonic phase, design compromises may result in an unwieldly vehicle configuration during propulsive descent. Lastly, the mechanics of exiting the aeroshell at high speed are not well understood. Aeroshell jettison strategies may require coordinated, multibody GNC solutions.

Aerocapture is another mission which has remained on the horizon despite being well within the capabilities of current technology. Aerocapture is a maneuver in which orbital energy is decreased during a single, high-speed pass through a planetary atmosphere. When applied to orbit insertion, aerocapture results in significant spacecraft mass savings relative to all-propulsive or aerobraking methods, and is enabling for certain mission classes.[24] Current technology, developed, tested, and flown on EDL systems, is sufficient to execute aerocapture. What is lacking is a integrated-system flight test. Until this happens, no future program is likely to accept the risk of a new aeroassist maneuver unless no other options exists.

To improve future EDL GNC systems, better knowledge of the EDL environment is required. Modeling improvements for heatshield ablation and recession, chemically-reacting high-enthalpy flows, aerothermodynamics, and hypersonic wake flow are required for detailed analyses pertinent to GNC systems, such as RCS jet placement. Modeling of inflation and deployment of parachutes and other soft-goods-based systems may result in more efficient and better performance designs, as well as improving trigger selection and timeline. Lastly, although it will likely always be a challenge, improved modeling of planetary atmospheres will aid in nearly every facet of GNC system design.

CONCLUSION

The development and flight of entry, descent, and landing systems over the past 50 years has demonstrated significant performance improvements. Much of this performance improvement has come about because of advances in guidance, navigation, and control technology. The miniaturization of GNC hardware and improvements in onboard computing power have significantly reduced costs while improving performance and reliability. However, a challenging EDL mission set remains: there are many more entry, descent, and landing guidance, navigation, and control problems to solve to accomplish current objectives of interest in planetary science and exploration.

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