END TO END ARCHITECTURE AND ASSOCIATED TECHNOLOGIES FOR SAFE AND ACCURATE LANDING WITH INCREASED PAYLOAD MASS.

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Introduction: Safe and accurate landing is prominently featured in Challenge Area 2 (Safe and Accurate Landing Capabilities, Mars Ascent, and Innovative Exploration Approaches). This abstract addresses item #7 in that area, "Concepts to navigate and control entry and landing systems to improve landing accuracy from the current state of the art (~10-km semi-major axis or "miss distance") to ≤1 km or lower (<100 m)".

Applicability: The need for safe and accurate landing capability cuts across robotic and future human missions. Drivers for this capability include:

- Landing near a scientifically important site in hazardous terrain to collect a diverse Martian sample
- Landing a "fetch rover" of limited traverse capability close enough to easily collect a previously cached sample
- Landing a future human mission near other previusly landed assets (habitation facilities, cargo, etc.), or landing cargo near a human outpost.

Error sources: MSL represents the current state of the art. MSL deploys its parachute at a target velocity calculated by integrating IMU-sensed acceleration ("velocity trigger"). Figure 1, taken from [1], shows that with a velocity trigger, the largest contributing sources of downrange error at both ignition and touchdown are winds and attitude initialization error.

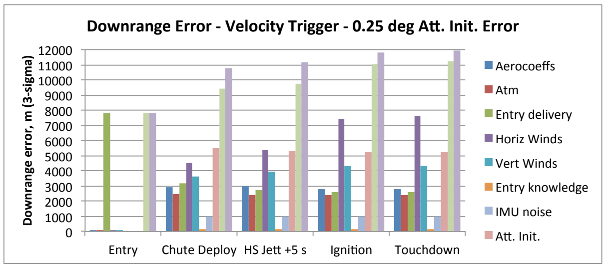

***Figure 1: Individual error source contributions** with 0.25-deg. attitude intiialization error and velocity trigger*

Wind-induced error is not all due to wind drift on the parachute. As the figure shows, >4km of wind-induced error has accumulated by chute deploy. This happens because the target deploy velocity is reached earlier in a headwind and later in a tailwind.

MSL's IMU is initialized with attitude derived from star scanner measurements. The MSL attitude initialization error requirement is 0.25 deg. (3-sigma).

Errors at ignition and touchdown are similar because MSL makes no effort to correct errors in position during powered descent; MSL's powered descent guidance is designed only to avoid the backshell and slow the lander for a soft landing.

Steps to increased landing accuracy: Improving landing accuracy involves a combination of engineering and technology improvements to reduce position error at ignition and "fly out" the remaining error during powered descent.

Attitude initialization error improvement. Engineering improvements can reduce attitude initialization error to 0.06 deg. (3-sigma) [1]. MSL inflight performance shows that addiitonal mitigation options may be available with the MSL baseline design.

Triggering chute deploy on range. Range errors at chute deploy can be significantly reduced by triggering chute deploy at a target downrange distance from the target ("range trigger") instead of using velocity trigger. Figure 2 shows that use of range trigger nearly eliminates wind error prior to chute deploy, leaving drift from horizontal winds on the chute (after deploy) as the largest contributor to downrange error at ignition. **Improving attitude initialization error to 0.06-deg. and using range trigger reduces the landing ellipse semimajor axis to ~4 – 5 km.**

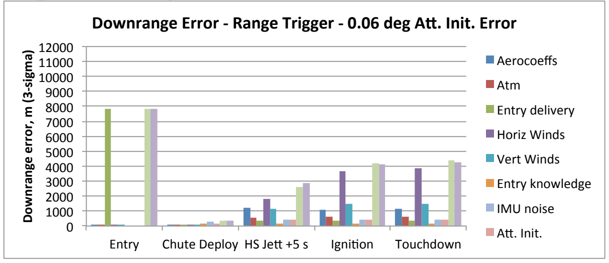

***Figure 2: Individual error source contributions** with 0.06-deg. attitude intiialization error and range trigger*

With range trigger, deployment occurs at the target range but at a speed higher than nominal in a tailwind and a lower than nominal in a headwind. Dispersions (including winds) map predominantly into errors in velocity at chute deploy rather than errors in range. With larger velocity dispersions, care must be taken to avoid deployment at a Mach greater than the upper limit above which the chute could fail. An upper limit on deploy velocity can be imposed with a range trigger ("velocity-constrained range (VCR) trigger"). Deploy occurs on range if velocity is below the constraint; if velocity is above the constraint at the target range, deploy is delayed until slowing to the constraint. Nominal deploy altitude is lowered by ~1 – 2 km in order to allow 3-sigma probability of deploying on range [1].

Implementing range or VCR trigger requires no technology development – this can be accomplished by changing a few lines of code onboard the spacecraft.

Terrain-relative navigation (TRN) with passive imaging. **Previous work has shown that with terrain-relative navigation (TRN) using passive imaging, it is possible to land within < 100m of the target given sufficient fuel to maneuver in powered descent [2].** A TRN algorithm has been developed at JPL leveraging previous experience on MER (DIMES) and other missions. This algorithm has been extensively tested via computer simulation; in a lab testbed; and on thousands of images acquired in airplane testing [3], two sounding rocket flights [4], and parachute drop testing.

Powered descent guidance. Fuel-optimal powered descent guidance has been developed to minimize the propellant required to divert to the target in powered descent [5,6]. This algorithm incorporates constraints on attitude, speed, and glideslope (for terrain clearance). as well as "fuel-limited targeting" capability to fly to the closest point to the target that is reachable if fuel is insufficient to reach the target. It uses robust convex optimization methods and has been tested in a simulation environment over hundreds of thousands of trajectories. Using this algorithm, the propellant cost for a diversion is ~50 kg/km for an MSL-class vehicle.

Neither Apollo nor MSL powered descent guidance was designed to efficiently fly large diverts to the target and are therefore much less fuel-efficient than the convex optimization algorithm for large diverts.

Alternative landing modes: The above discussion shows a progression from the current state of the art to landing within 100m of the center of the landing ellipse (referred to as **Pinpoint Landing**).

For missions where the propellant mass penalty of flying to the center of the ellipse is unacceptably high, **Multipoint Landing** can be used. In Multipoint, the onboard fuel quantity is not sufficient to fly from every point in the landing ellipse to the ellipse center; however enough fuel is available to always reach a site identified as safe. Orbital imagery is used to preselect several safe sites throughout the landing ellipse, to assure that there is always at least one safe site >100m in radius within fuel range at ignition. The number of preselected targets required depends on the amount of propellant carried and the size of the ellipse at ignition. Onboard decisionmaking logic selects a target from the preselected target set after beginning descent imagery.

Realtime hazard detection and avoidance: If the lander design is such that hazards too small to be detectable in orbital imagery pose a threat to the lander, the ability to deliver the lander to an ellipse certified as safe from orbital imagery is not sufficient to guarantee safe landing. In this case, the lander must be able to detect and avoid small hazards in realtime. Flash lidar sensing can be used for this purpose, and has been extensively tested in a laboratory environment and on helicopter test flights [7]. Current state-of-the-art flash lidars can detect small landing hazards at ranges of hundreds of meters, allowing a low-altitude hazard avoidance maneuver of tens of meters which can be accomplished at a propellant cost of a few kg.

Increased payload mass: Payload mass (and propellant mass needed to divert) trades against landing site elevation. Payload can be increased and / or divert distance can be increased by reducing site elevation or by incorporating performance enhancements like high-Isp propellant or advanced aeroassist (lift or drag modulation via inflatable aerodynamic decelerators, trim tabs, retropropulsion or other systems)

Conclusion: Elements of an end-to-end architecture for safe and accurate landing are:

- Use of orbital imagery to select safe landing areas
- Minimization of position dispersions at ignition by improving attitude initialization error and judicious choice of a strategy for triggering the chute or other aerodynamic decelerator(s)
- Use of TRN to achieve position knowledge of tens of meters relative to terrain features
- Optimal-DV powered descent guidance allowing constraints on attitude, glideslope, and speed
- The ability to detect and avoid in realtime hazards to landing that are undetectable in orbital imagery

All of these elements have benefited from several years of development under various programs. This architecture can be used in a wide variety of mission concepts with or without with advanced aeroassist.

References:

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