Lander Vision System for Safe and Precise Entry Descent and Landing A. E. Johnson[1] and M. P. Golombek[2], [1]aej@jpl.nasa.gov, , [2]golombek@jpl.nasa.gov, Jet Propulsion Laboratory, California Institute of Technology, 4800 Oak Grove Drive, Pasadena, CA 91109.

Introduction: The Lander Vision System (LVS) concept is a tightly integrated bolt-on smart sensor system that provides real-time terrain relative position, velocity, attitude and altitude while also detecting landing hazards. The LVS would increase access to scientifically rich landing sites and could be a low mass, volume and cost replacement for the Terminal Descent Sensor (TDS) on Mars Science Laboratory (MSL). Currently, a prototype LVS is being built from commercial components that have a defined path to flight implementation. The sensor suite includes a camera for the landmark recognition required for terrain relative position estimation and image-to-image feature tracking for horizontal velocity estimation. A dual use flash lidar is used for near surface hazard detection as well as measuring range through the entire descent. An inertial measurement unit (IMU) propagates vehicle motion between image and lidar measurements so that high rate state information can be provided to the spacecraft. The sensors are tightly integrated with a high performance computer that performs all required processing. After field testing next year the LVS will be at technology readiness level 4.

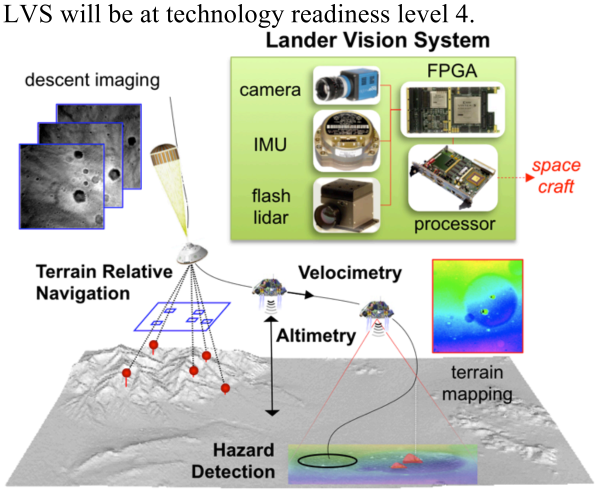

Figure 1. Lander Vision System.

Mars Science Need: Landing site selection is restricted by the need to find a safe site that is also scientifically interesting. Reducing the size of the landing ellipse and increasing the mechanical hazard tolerance of the lander are two methods employed by MSL to increase the number of selectable landing sites. However, even with these improvements over past Mars missions, many of the sites desired for Mars Sample Return (MSR) are not accessible by MSL. The science goals of MSR are to return a suite of samples to earth from diverse geological contexts. Geological diversity is correlated with hazardous landing sites due to the need to have stratigraphy and outcrops in the sampled terrain. To date robotic planetary landers cannot "see" hazards or landmarks for navigation. In this sense they have all landed blindly. Fortunately, there are two complimentary technologies that can fill this gap: Terrain Relative Navigation (TRN) for avoiding large known hazards and Hazard Detection (HD) for avoiding small unknown hazards.

During HD the lander would build a terrain map around the landing zone from on-board sensor data and diverts the vehicle to a safe site within the terrain map. By providing multiple possible safe sites to choose from HD dramatically improves the probability of safe landing. In contrast, during TRN the lander would recognize landmarks and computes a map relative position, which could be used in two different ways. First, if there is enough fuel, the lander would be guided to a pin-point landing (within 100m of the target). If the vehicle is limited on fuel, then the landing ellipse is populated with safe landing sites and the lander would be guided to the safest reachable site. This multi-point safe landing strategy would enable selection of landing ellipses with large distributed hazards.

Table 1 shows seven reference landing sites selected by the MSR End to End International Science Advisory Group [1]. These sites were chosen to span the set of desirable sites for a future MSR mission. Each site is stressing to the landing system in some way and most of them show the need for multi-point TRN or HD. Based on detailed high resolution analysis of the hazards covering the ellipse, TRN is would definitely be required at 4 of the 7 sites landing ellipses. Once additional reconnaissance is available, is it probable that analysis will show that TRN would be required for Mawrth Vallis 0. Northeast Syrtis and East Margaritafer were considered for MSL based on their high science content, but were later discarded due to the presence of too many landing hazards.

Based on rock abundance maps from orbital imagery [e.g., 2] it has also been shown that HD would be required for Jezero crater and Nili Fossae. Once additional reconnaissance is available analysis will probably show that HD is needed for Ismenius Cavus. These sites would have been accessible to MSL had a mature TRN and HD capability been available.

Besides enabling access to future MSR sites the LVS would be needed for MSR architectures that require pin-point landing to pick up the sample cache. It could also be used to place a science platform near very high priority localized science targets like seepage features or a methane source yet to be discovered.

Table 1 MSR Reference Sites

Site	**Challenge**	**TRN?**	**HD?**
Gusev Crater	14.5°S	No	No
Jezero Crater	Rocks	No	**Yes**
Nili Fossae	-0.6 km elev	**Yes**	**Yes**
Mawrth Vallis 0	Rough	Probably	Maybe
East Margaritifer	Inescapable Hazards	**Yes**	Probably Not
NE Syrtis	Scarps	**Yes**	Maybe
Ismenius Cavus	33.5°N	**Yes**	Probably

Concept of Operation: As shown in Figure 2, The LVS processing would occur in phases. The LVS would have a low bandwidth interface to the spacecraft computer which runs the guidance and control functions that respond to the LVS measurements. The spacecraft would propagate attitude from entry using its own IMU. This attitude estimate would be passed to the LVS to initialize attitude in the LVS navigation filter [3]. The LVS would begin propagation of attitude from that point forward using its own IMU. After the heat shield is ejected (by 5km), the flash lidar would begin collecting range measurements in its narrow beam mode. Altitude is estimated from these ranges and attitude estimates. After the altitude has converged the camera would begin taking images. Matches between descent image and the map (landmark matches) would provide position measurements [3] while matches from one image to the next (feature tracks) would provide velocity measurements. Both image processing functions are derived from the successful Mars Exploration Rovers Descent image Motion Estimation System software[4].

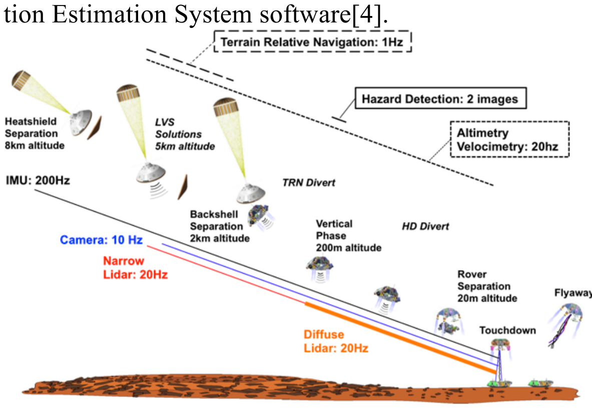

Figure 2. LVS Concept of Operation.

Once the position estimate has converged it would be passed to the spacecraft so that a divert to the target could be calculated and begin immediately at the start of powered descent (around 2km).The lander diverts to a point above the TRN target. During the divert and all the way to touch down feature tracking and ranging are used to estimate altitude and velocity. At the end of the divert (around 240m) , the lidar would be reconfigured to the wide illumination mode for ranging and HD. Two 12 m x 12 m flash lidar range images would be taken and processed to identify hazards. The safest reachable site that appears in both images would be selected as the landing site. The spacecraft would then execute a small divert to place the lander above the safe site prior to final descent and touchdown.

Benefits: The LVS design is optimized to generate robust and accurate measurements from a minimal suite of sensors. Each sensor serves multiple purposes, which reduces mass, volume and development costs. The flash lidar is the ideal sensor for hazard detection because it can generate all the data required with a single low noise range image taken at long range. By decreasing the width of the laser illumination the flash lidar can also be used to measure range at high altitude thereby removing the need to add a separate altimeter. The camera provides landmark matches for position estimation and provides image-to-image feature tracks for velocity estimation, which eliminates the need for a separate velocimeter. Finally, the IMU provides the attitude, propagated from the cruise phase, needed to start TRN and it provides high rate updates of the navigation state required for closed loop guidance.

Another advantage of the integrated LVS sensor suite is that there are multiple ways to cross validate the results produced by each sensor. For example, camera 3D position estimates are compared to the flash lidar range while camera velocity is compare to integrated accelerations from the IMU. This cross checking creates a system that robust to bad sensor measurements and incorrect processing results.

The LVS would also have mass, volume and cost benefits. The MSL Doppler radar TDS measures altitude and velocity. The TDS is 25 kg and consumes 100 watts of power. It does not perform TRN or HD. It also must be mounted on a large 'proboscis' to separate the radar antenna from the spacecraft to minimize the effect of multi-path interference. In contrast the LVS would be on order 10 kg and consume 100 W and would not require a special mounting structure due to the narrow beam of the lidar and the passive nature of the visible camera. The LVS would meet the accuracy and update rate requirements of the TDS in a lower mass and volume package. The LVS cost could also be potentially lower because it would built from commercial components that are already being space qualified.

References:[1] McLennan S. M. et al. (2011) Final Report MSR E2E iSAG, http://mepag.jpl.nasa.gov/, 1151–1154. [2] Golombek, M. P. et al. (2008) *JGR* 113, A09, [3] Mourikis, A. I. et al., (2008) *IEEE TRO*, 25, 2, [4] Johnson, A. E. (2007) *IJCV* 74, 3.