Full-scale Static Testing of the Lidar-based Autonomous Planetary Landing System (LAPS)

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Abstract

Future targeted exploration missions to the lunar or Martian surfaces will need an intelligent landing sensor system that can detect hazards and guide the lander to a safe site identified during the descent. Lidar-based approaches enjoy many advantages over competing hazard detection technologies, such as active illumination and high spatial resolution. A technical overview of the Lidar-based Autonomous Planetary landing System (LAPS) operational concept and design reference mission is provided. The effects of motion on the imaging capabilities of the sensor, and the consequent need for compensation, are detailed. Recent full-scale static tests using the ALHAT target at NASA Langley have been used to validate the imaging performance model of the lidar sensor. Based on the validated model, the flight baseline should be able to resolve features down to 2 cm depth and 12 cm width.

1. Introduction

Prior planetary exploration missions have selected landing areas with relatively flat, hazard-free terrain over the uncertainty ellipse of the landing spacecraft in order to maximize the likelihood of successful landing. However, future exploration missions to the lunar or Martian surfaces will seek to land in a particular region of interest, either for targeted scientific study, identification of in situ resources, or establishment of a manned presence. For example, the south pole of the moon is an area of key scientific interest [1][2][3]. Desirable landing areas will almost certainly have terrain that does not meet the flatness and hazard-free criteria used in prior mission planning.

Orbiters will have the ability to perform mapping and hazard detection at approximately 2 m scale [4]; however, landers will likely need to avoid hazards at the 30 – 50 cm scale [5][3]. Consequently, there is a clear need for an intelligent landing sensor system which can measure the terrain with sufficient resolution to generate a cost map which provides an assessment of the terrain in terms of its local slope, roughness, and reachability. The location of the site with the least cost is then used as an input to the lander’s guidance function such that it can touch down safely. As an additional capability, if the sensor can localize itself with respect to a map generated from orbit, then terrain-relative navigation can be performed which allows the lander to control its position with respect to a fixed location on the planetary surface. The lander can then touch down, subject to the hazard avoidance constraints, at a desired site which has been preselected from orbit. This capability is referred to as pinpoint landing [6]. Pinpoint and hazard avoidance landing will therefore be enabling technologies for whole classes of missions.

This paper presents the results of continued development of the Lidar-based Autonomous Planetary Landing System (LAPS). Section 2 describes the advantages of using a lidar-based system for planetary landing. The key role played by a priori and a posteriori motion compensation is also highlighted. The operational concept of a LAPS-equipped descent scenario is detailed in Section 3. The results of full-scale tests performed at NASA Langley are presented and compared with the performance model in Section 4. Conclusions and future development directions are discussed in Section 5.
2. Time-of-flight lidar

The Lidar-based Autonomous Planetary landing System (LAPS), as its name implies, is intended to be a guidance, navigation, and control (GNC) system for planetary landers [7][8][9][10][11]. The primary sensor is a time-of-flight lidar unit which has several advantages for planetary landing:

- **Operational range:** The lidar has an operational range from a few kilometres (depending on the reflectivity of the target object) down to a few metres.

- **Illumination invariance:** The lidar is an active illuminator with performance invariant to ambient lighting conditions, unlike a camera-based system. LAPS can therefore be applied to landing on the dark side of planetary bodies, or within the basins of permanently shadowed craters. The pulse duration, and therefore the exposure time, is approximately 1 nanosecond.

- **Feature invariance:** The lidar works equally well on terrain which does or does not contain any visual features, unlike an optical correlator system [12].

- **Imaging capability:** The lidar can create a high-resolution three dimensional image of the surface, unlike a radar-based system [13].

The system measures the time of flight of a short duration (~1 ns) laser pulse which reflects off of a surface and returns to the sensor. Using the speed of light, the time of flight is converted into the path length of the laser pulse, and hence, the range from the sensor to the surface can be measured. By steering the beam, the lidar is able to “paint” an object with laser pulses at high rate (~10 kHz) to form a three-dimensional image of the object.

The LAPS hardware architecture consists of three items: the Optical Head Unit (OHU), the Avionics Unit (AU), and the cable harnesses connecting them. This architecture follows that used in the current space lidar design, shown in Figure 1. The XSS-11 lidar was launched in April 2005 and operated successfully throughout the spacecraft’s mission life. In addition to the sensor, the LAPS includes onboard GNC software to perform state estimation, generation of guidance references, and generation of feedback control signals which can be used to drive the lander actuators.

Unlike a camera, which acquires all of its data in parallel, the lidar sequentially acquires scan points as the beam is steered over the object. The time required to complete a scan is therefore a major design driver in the use of lidar in a planetary landing system. Motion of the sensor frame while the scan is occurring necessitates the use of a motion compensation scheme, which is discussed in the following subsection.

2.1. Motion compensation requirements

As mentioned above, the lidar scanning mirror requires some time to trace out the scan pattern and to acquire an image. However, during a planetary descent, the lidar itself is moving with respect to the terrain being scanned. This lander motion has two effects on the acquired data:

- **Scan pattern distortion:** The lander motion distorts the scan pattern on the terrain. This distortion degrades the spatial sampling and affects the ability to detect hazards.

- **Data distortion:** Since each point is measured with respect to the lidar frame, the data will be distorted (or “smeared”) by the lander motion.

These distortions can be mitigated through the use of a motion compensation scheme. First, the scan pattern distortion must be removed at the mirror level using a priori compensation (also called platform stabilization, as it makes the lidar behave, in effect, like a stable platform). This ensures that the correct region of the terrain is scanned with the correct spatial sampling. Second, the data distortion is removed as the points are returned using a posteriori compensation (also called post-processing motion correction). This enables all of the data to be expressed in a frame that is stationary with respect to the terrain. Both schemes must be applied in order to realize the desired imaging of the terrain.

As an example, consider the exaggerated two-dimensional case shown in Figure 2. The lidar acquires data while it is both translating and rotating. The acquired data, as expressed in the lidar frame, is distorted in two ways: it covers more of the terrain than desired, and appears to slant upward (Figure 2A). If the same descent and scan is performed using only platform stabilization, the correct region of the terrain will be scanned, but the data will be distorted (Figure...
2B). Conversely, if only motion correction is applied, the data will all be expressed in a meaningful frame, but the spatial sampling of the desired landing site will be less than desired (Figure 2C). Only by applying both motion compensation schemes does the lidar acquire and report the desired image data (Figure 2D).

Error analysis becomes critical when motion compensation is considered. The ability to correctly image a landing site is only as good as the ability to compensate for the motion of the spacecraft. By extension, the effectiveness of motion compensation depends on the accuracy of the dynamic state knowledge of the lander. Contributions to the imaging error budget of the lidar arise from linear velocity and angular rate knowledge errors, latency in the state estimates, range resolution and beam divergence, and mirror pointing accuracy.

3. The LAPS operational concept

The LAPS operational concept has been described in detail in [14]; a summary is provided below.

3.1. Definition of a safe landing site

The definition of a safe landing site is strongly influenced by the type of lander, its size, structure and design. The definition summarized in Table 1 is based on inputs from [5] and [14].

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Area of interest</td>
<td>100 x 100 m²</td>
<td>The lander will land within this area.</td>
</tr>
<tr>
<td>Lander size</td>
<td>2.5 m Ø</td>
<td>Viking-sized lander</td>
</tr>
<tr>
<td>Size of safe landing site</td>
<td>5 m Ø</td>
<td>Twice the size of the lander</td>
</tr>
<tr>
<td>Maximum local slope</td>
<td>15°</td>
<td>Over the extent of the landing site, a Viking and Phoenix requirement</td>
</tr>
<tr>
<td>Maximum sampling step for slope</td>
<td>1 m</td>
<td>Sufficient for measuring local slope within the landing site</td>
</tr>
<tr>
<td>determination</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Maximum allowed boulder size</td>
<td>30 cm</td>
<td>Phoenix lander requirement</td>
</tr>
<tr>
<td>Minimum resolution for roughness</td>
<td>10 cm</td>
<td>Sufficient for measuring roughness within the landing site</td>
</tr>
<tr>
<td>determination</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

3.2. Design reference mission

Given the definition of a safe landing site, the hazard avoidance landing sensor must determine safe sites sufficiently ahead of touchdown so that the lander can be redirected to the best of the safe sites. In this context it fulfils the role of a guidance sensor.
With the addition of terrain-relative navigation (currently in development by NGC Aerospace [16]), the sensor can be used for pin-point landing and as a low-bandwidth closed-loop navigation input. LAPS is intended both for fully autonomous operations on unmanned descent vehicles, or in a supervised autonomy scheme for manned missions.

In order to more clearly define the LAPS concept, it is useful to subdivide the descent phase of the operation into the stages illustrated in Figure 3. The LAPS is used primarily in the Safe Site Search stages as described below:

**Safe-Site Search (SSS-1) – Slope Detection**
The goal of this mode is to search for and identify a number of safe site candidates (e.g., five) in a landing area of a certain size (e.g., 100 m × 100 m). The potential safe sites are identified based upon an assessment of the local slope, which is found by placing a specified density of points within a lander-sized region (e.g., 25 points per 5 m × 5 m area) and fitting an intelligent mean plane through the points. A cost map can be generated based on the local slope, roughness, and fuel usage information (see Figure 4). The landing area is scanned several times (at least three times) for reliability. This mode ends when the safe site candidates have been identified and the lidar has sufficient spatial resolution to detect roughness hazards.

**Safe Site Search (SSS-2) – Hazard Detection**
This operational stage starts at the altitude where the lidar resolution allows roughness assessment, and ends at the altitude where the lander must commit to a landing at a selected site (either due to fuel budgets or candidate safe sites leaving the lidar’s field of view). The goal of this mode is to identify any hazards within any of the candidate safe sites based on the roughness
assessment, which is performed by placing a certain density of points within a hazard-sized region (e.g., 10 points per 30 cm × 30 cm area). Each candidate site is scanned several times (at least three times) for reliability.

In both safe site search stages, both a priori and a posteriori motion compensation must be used in order to produce meaningful scan data (see Section 2.1).

A natural tradeoff exists when defining the altitude and duration budgets for the stages of the descent. Designing the descent for minimum fuel use results in a fast descent, but less certainty about the safety of the eventual landing site. Slowing down the SSS-1 and SSS-2 stages to allow the sensor more time to repeatedly image the site increases the certainty of safety, but incurs an additional fuel cost. The LAPS design reference mission seeks to find a balanced design point in the tradeoff. Obviously, to make the lidar-assisted safe landing an attractive option, the goal is to alter the nominal descent trajectory as little as possible. In that way, the design reference mission has the smallest possible impact on the fuel budget while still maintaining credible operating conditions for the lidar.

Details of the design of the reference descent can be found in [14]. Here it is sufficient to note that the time to perform the necessary scans and the effective spatial resolution of the lidar are used to determine the altitude ranges for SSS-1 and SSS-2. A piecewise-continuous form of the gravity turn guidance law [9] is used to generate the descent, shown in Figure 5. The guidance law implicitly accounts for the gravity of the body, therefore the trajectory will be the same for Moon and Mars, given the same initial conditions. Note that even though the LAPS trajectory is slower than the nominal gravity turn, it is still significantly faster than the Apollo moon landing trajectories [17], as shown in Figure 6. The Apollo landings are significant because they represent the only prior hazard avoidance landing missions, albeit with a human in the loop.

3.3. LAPS flight baseline

The flight lidar for use as a safe landing sensor has not yet been built and tested; however, a development path has been established for the landing lidar based on the XSS-11 flight lidar heritage. Table 2 compares the flight specification with the XSS-11 lidar and the terrestrial ILRIS-3D system used in the LAPS test facility. The major areas of improvement are the mirror
acceleration, mirror controller bandwidth, and the range and bearing resolution. The improved performance specifications have been used to derive the timing and imaging error budgets, and thereby show that a credible design reference mission can be established.

### Table 2. Specifications for the flight lidar

<table>
<thead>
<tr>
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<tbody>
<tr>
<td>Mirror Acceleration</td>
<td>920 rad/s²</td>
<td>230 rad/s²</td>
<td>&gt; 145 rad/s²</td>
</tr>
<tr>
<td>Controller Bandwidth</td>
<td>240 Hz</td>
<td>80 Hz</td>
<td>60 Hz</td>
</tr>
<tr>
<td>Controller Damping</td>
<td>0.5</td>
<td>0.3</td>
<td>0.3</td>
</tr>
<tr>
<td>PRF</td>
<td>10 kHz</td>
<td>10 kHz</td>
<td>2 kHz</td>
</tr>
<tr>
<td>FOV</td>
<td>+/- 20º</td>
<td>+/- 10º</td>
<td>+/- 20º</td>
</tr>
<tr>
<td>Range Resolution</td>
<td>2 cm, 3 σ</td>
<td>5 cm, 3 σ</td>
<td>1 cm, 3 σ</td>
</tr>
<tr>
<td>Beam Divergence</td>
<td>170 µrad</td>
<td>500 µrad</td>
<td>170 µrad</td>
</tr>
</tbody>
</table>

### 4. Static tests using the ALHAT target

In August of 2007, the LAPS team had the opportunity to perform static tests of the lidar unit in a landing sensor capacity using the Autonomous Precision Landing and Hazard Detection Avoidance Technology (ALHAT) target located at the NASA Langley Research Center [18]. The ALHAT Sensor Test Range (STR) consists of a three dimensional calibrated test target, located at a 250 m standoff range from the sensor platform. The target board uses variations in reflectivity, slope, width, and depth of its features (see Figure 7) in order to test the resolution and sensitivity of candidate hazard avoidance sensors. Further details of the facility can be found in [18]. The tests were performed using both the Engineering Model (EM) of the XSS-11 lidar and the ILRIS-3D terrestrial lidar. A sample dense scan of the target board is shown in Figure 8.

The XSS-11 lidar was designed for orbital rendezvous rather than planetary landing, and does not have either the acceleration or the imaging performance of the LAPS baseline (see Table 2). Further, the EM unit has downgraded performance with respect to the XSS-11 flight unit, and therefore the test data is not directly representative of the LAPS performance. However, the test data was used to validate a performance model of the EM unit, which was based on the Average Modulation Transfer Function (AMTF) of the optical system [19]. The AMTF describes the average sensitivity of the lidar to different spatial frequencies, given a commanded scan density.

Using the ALHAT target board geometry as an input to the performance model, the average response of the XSS-11 EM unit was predicted (Figure 9). The experimental data was processed by extracting the range and bearing signals from a sparse scan (Figure 10) and averaging the depth values as a function of the distance along the target board (Figure 11). Note the close agreement in terms of the edge distortions, and attenuation of the depth of the 12.5 cm width features.

Having validated the model, the LAPS baseline parameters were used to predict the performance of the LAPS sensor under the same conditions (Figure 12). Note that the edges are less distorted and that the LAPS can resolve the 12.5 cm features without any depth attenuation.

The tests were repeated at night, with no loss of performance since the lidar is an active illuminator. Tests were also repeated with a cloud of smoke between the lidar and the target board, after range gating out returns from the smoke cloud, the imaging performance was unchanged.
5. Conclusions and future work

The LAPS research and development projects have established a credible design reference mission for a lidar-based hazard avoidance landing system. The required lidar performance was specified, using a realizable development path from the existing flight heritage.
Full scale static tests of the XSS-11 Engineering Model rendezvous lidar using the Autonomous Landing and Hazard Avoidance Technology (ALHAT) target have been used to validate the LAPS sensor performance model. Based on these results, the LAPS flight unit will be able to statically resolve hazards down to ~ 2 cm in depth and ~ 12 cm in width. This performance meets the mission requirement to detect hazards of 30 cm or larger (Table 1).

A companion paper describes the hardware-in-the-loop facility recently commissioned for testing motion compensation and safe site search in a dynamic environment at TRL-4/5 [14]. In the near future, the facility will be used to perform dynamic validation of the fuel cost map generation. Velocity determination and terrain-relative (i.e., absolute) navigation algorithms, critical for the development of pin-point landing capability, will also be tested using this facility.

Future missions, both manned and unmanned, will require safe and accurate landings [20][21][22]. This mission critical element is being addressed by MDA, NGC Aerospace, and Optech through the LAPS technology program.

6. Acknowledgments

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7. References


