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Development of a Terrain Sensing Lidar for Precision Navigation and Safe Landing of Space Vehicles

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ABSTRACT

A linear-mode flash lidar sensor employing a resolution enhancement algorithm is being developed at NASA Langley Research Center for enabling precision and safe landing on the Moon, Mars, and other destinations in the solar system. This lidar, referred to Terrain Sensing Lidar (TSL), is a multi-mode sensor capable of hazard detection and avoidance, terrain relative navigation, and long-distance altimetry. The TSL offers a solution for future missions that require landing at pre-designated sites near high value resources or at areas of high scientific value, while avoiding hazardous terrain features, such as escarpments, craters, slopes, and rocks, or pre-deployed assets. TSL can also benefit terrestrial applications such as autonomous aerial vehicles without reliance on signals from Global Positioning System (GPS).

The viability of the TSL for terrain hazard detection and avoidance has already been demonstrated by conducting drone and helicopter flight tests. An upgraded version of this lidar has been recently assembled for additional aircraft flight tests and demonstrating its multi-mode capability.

Keywords: 3D Imaging Lidar, Flash Lidar, Hazard Detection, Precision Navigation, Terrain Relative Navigation

1.0 Introduction

Linear-mode flash lidar offers a viable solution for onboard hazard detection and avoidance required by many landing missions including manned and robotic missions to the Moon, Mars, and other planetary bodies. The main advantage of flash lidar technology over more conventional scanning lidar is the ability to record full 3-D images with a single laser pulse, freezing the scene on every frame by removing all motion of the transmitter/receiver platform. Linear-mode flash lidar records the 3-D image frames by imaging the illuminated scene onto a Focal Plane Array (FPA). Each pixel in the FPA takes independent measurements of the lidar pulse time of flight to the target. Therefore, the flash lidar does not require attitude angle data from external sensors and extensive computation resources and time for compensating vehicle motion during image acquisition. Another advantage is having uniformly distributed pixels with each image frame which simplifies the hazard detection algorithm and reduces the risk of false alarms. Furthermore, its high frame rate allows for timely generation of the 3-D map of the landing area and selection of safe landing locations. Another important feature of flash lidar technology is the ability to perform other key functions during descent which are necessary for precision navigation towards an intended landing site. These essential functions are altimetry, Terrain Relative Navigation (TRN), and Hazard Relative Navigation (HRN), in addition to Hazard Detection and Avoidance (HDA).

We have developed a flash lidar system, refer to as Terrain Sensing Lidar (TSL), for demonstrating the viability of this technology for upcoming landing missions. Figure 1 illustrates operation of our flash lidar in the context of a lunar landing. The lidar begins its operation after a deorbit maneuver at about 70 km above the ground. At this stage, the lidar transmitter beam is focused to illuminate only a few pixels in the center of the detector array to measure range to the ground. Reducing the divergence of the lidar transmitter beam to a fraction of its receiver field of view increases its operational slant range to 70 km from a nominal 1.4 km. The ground-relative altitude measurements provided by the TSL reduces the vehicle position error significantly since the Inertial Measurement Unit (IMU) suffers from drastic drift over the travel time from the Earth. The IMU drift error can be about 1 km for a Moon-bound vehicle and 10 km for Mars. Accurate altitude data reduces position error to a few hundred meters.

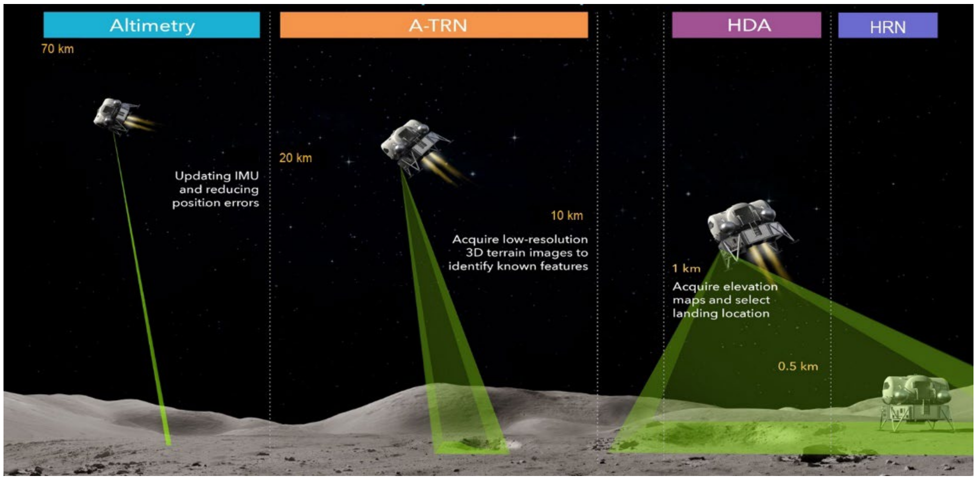


Figure 1. An operational concept of Terrain Sensing Lidar for lunar landing.

When the altitude drops to about 20 km, the lidar beam is expanded to illuminate a section of detector array encompassing more than hundred pixels. In this phase, the flash lidar generates relatively low-resolution elevation data of the terrain which are subsequently compared with stored maps having known surface features such as large craters. This process, referred to as Terrain Relative Navigation (TRN), further reduces the vehicle's relative position error from hundreds of meters to tens of meters.

From about 1 km to 0.5 km altitude, the TSL operates in the HDA mode with its full field of view, generating a high-resolution elevation map of the landing area as described in the next section. This elevation map is then processed to identify hazardous features such as rocks, craters, and steep slopes, and to determine the most suitable landing location. In the case of lunar landing, the flight trajectory angle is about 45 degrees at 1 km altitude which make the slant range to the ground around 1.4 km. The TSL can continue updating the map in order to continuously correct the trajectory toward the selected landing location. This phase of flash lidar operation is referred to as Hazard Relative Navigation. The TSL operation terminates at approximately 50 m above the ground before the vehicle thrusters create a dust plume.

The TSL may also benefit terrestrial applications such as aircraft navigation without reliance on signals from Global Positioning System (GPS). Conventional aircraft Guidance, Navigation, and Control (GN&C) systems combine Inertial Measurement Unit (IMU) data with GPS signals to determine the vehicle position and velocity vector. GPS position (altitude) data is referenced to sea-level and is of limited value when landing on a moving platform or in limited visibility conditions, or when autonomous navigation and landing is required. Furthermore, GPS signal can be blocked or jammed by intentional or unintentional interference causing significant deviation in the navigation solution. TSL, operating as a standalone sensor, provides precise terrain-relative position and velocity data.

2.0 Super-Resolution Technique

Current commercially available linear-mode flash lidar focal plane array has 128 x 128 pixels which is grossly insufficient for mapping the designated landing area with the necessary Ground Sample Distance (GSD) for meeting the HDA requirements. Notionally, the HDA sensor should be able to map a 100 m x 100 m area and detect 30 cm radius hazards from 1 km distance. [1] Adjusting the Field-Of-View (FOV) of this flash lidar to cover 100 m x 100 m area will give a GSD of 78 cm (100 m/128), which is much greater than the 15 cm GSD needed for reliably detecting 30 cm radius hazards. The number of pixels of linear-mode flash lidars is constrained by multiple factors including manufacturing limitations and required laser pulse energy and receiver aperture size for collecting enough returned photons for each pixel to make a range measurement. To overcome this shortcoming, past demonstration flight tests used a mechanical gimbal to scan the target area and stitch individual image frames with sufficiently small FOV and GSD.[2] But accommodation of a mechanical gimbal or scanning mirrors on landing vehicles is very challenging or even impractical. For this reason, we employ a novel Super-Resolution (SR) technique[3,4] to eliminate the need for mechanical scanning.

In SR operation, the lidar FOV is enlarged to cover the whole area of interest and then a sequence of image frames of the same scene, taken from different positions and look angles, are blended to achieve the desired resolution. Our SR algorithm does not require position and attitude (pointing angle) data from an external sensor thus making the flash lidar a standalone instrument. In addition to eliminating the need for a scanning gimbal, the SR has several important advantages over stitching individual image frames. The SR technique lowers range measurement noise, recovers bad pixels, and reduces acquisition time (fewer image frames) for generating the desired Digital Elevation Map (DEM). We have shown 25X image resolution enhancement by processing 20 consecutive flash lidar frames recorded from moving trucks, dynamic testing at NASA LaRC gantry facility, Drone flight tests, and a helicopter flight test.[5,6] The SR algorithm also provides the six-degree-of-freedom (6-DOF) relative state vector (position and attitude) of the host vehicle with higher precision than most inertial measurements.

3.0 TSL DEVELOPMENT AND TESTS

We built a breadboard the of TSL for conducting a series of ground and airborne tests aimed at characterizing our lidar technique for HDA. This lidar used a linear-mode flash lidar camera, consisting of a focal plane array and associated control electronics, developed by Advanced Scientific Concepts (ASC). The lidar was set to acquire range image frames at 20 Hz for the application of the SR algorithm. The algorithm processed the image frames as they were received by the processer producing high resolution DEMs at 1 Hz rate with about 30 msec latency.

We conducted a set of characterization tests at the NASA LaRC's lidar test range and gantry facilities, followed by a drone flight test.[7] The gantry and drone flight tests allowed for pointing the lidar toward the ground and illuminating all pixels as opposed to horizontal tests pointing to targets of limited sizes that do not completely fill the lidar FOV. Figure 2 shows the breadboard lidar on the drone flying over calibrated targets placed in a clear area at NASA LaRC.

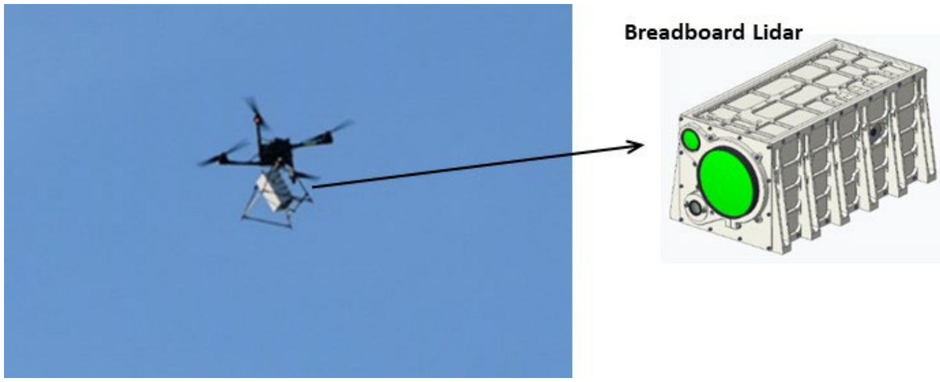


Figure 2. Drone flight test of the breadboard lidar.

After completion of the characterization tests, a helicopter flight test campaign was conducted in 2023 at the Blue Origin's Lunar Terrain Field (LTF) in west Texas that was specifically built for testing landing sensors (see Figure 3). This helicopter flight test allowed for simulating the lunar landing scenarios by flying along different slanted trajectories toward the LTF.

An example of the helicopter flight test data is provided in Figure 4 showing one of the range image frames that are generated at 20 Hz from about 200 m distance and the corresponding DEM generated 1 Hz. As can be seen, some of smaller rock piles are not resolved in the 3-D range image but clearly detected in the DEM created by the SR algorithm.

Figure 3. A view of the Blue Origin's Lunar Terrain Field with rock piles and craters.

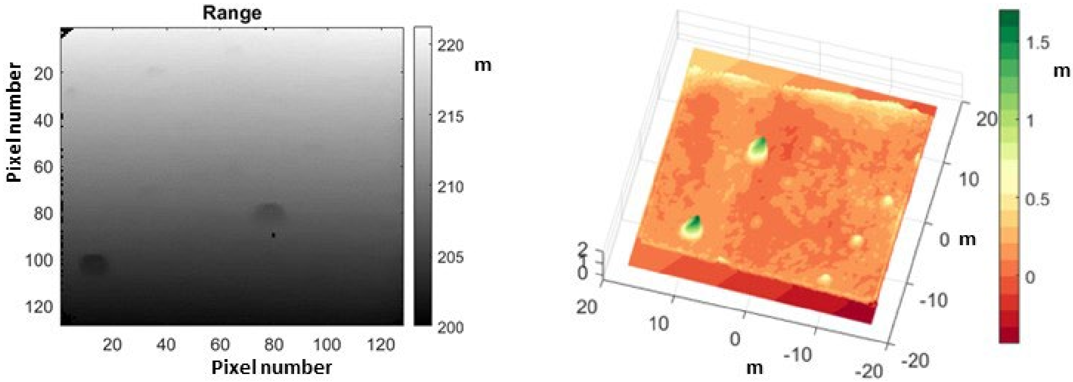
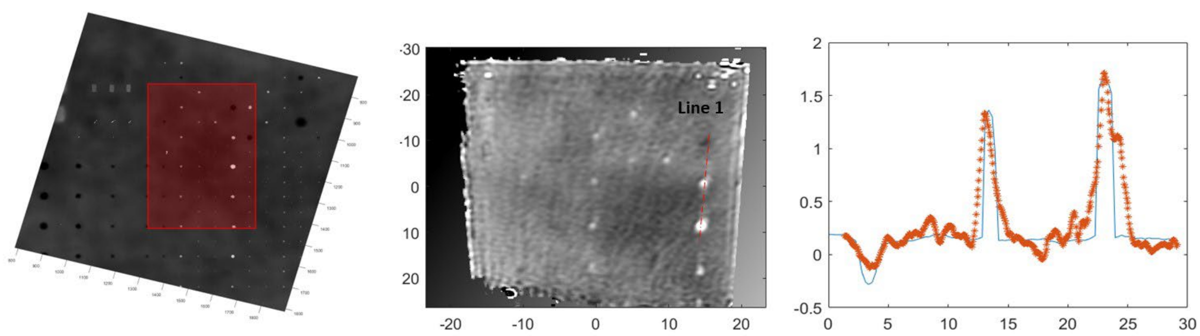


Figure 4. An example of helicopter flight test results, showing a single range image (left) and a high-resolution DEM generated in real-time at 1 Hz by applying SR algorithm to 20 consecutive range image frames (right).

Figure 5 is an illustration of lidar hazard detection performance in which the truth DEM (a) is compared with a lidar-generated DEM (b) by plotting an elevation profile along a line (c) on the generated DEM (b). This data is collected along a 45 degrees trajectory angle which is representative of most lunar descent trajectories. This elevation profile that includes a small crater and two rock piles shows very good agreement between the truth and the lidar generated DEMs to within a few centimeters, part of which is due to the fact that the truth DEM is not an exact representation of the LTF at the time of the flight test. The truth DEM was generated several years earlier, and the field had experienced significant changes due to weather and natural erosions.



(a) **(b)** **(c)**

Figure 5. (a) Truth DEM of a section of the LTF, (b) one of the lidar generated DEMs of the highlighted area on the truth DEM, and (c) elevation profile of the lidar DEM along the line 1.

The results of the dynamic tests described above were used for the design and build of a prototype system. The prototype unit includes several upgrades over the breadboard system to extend the HDA operational range to 1400 m and incorporate multi-mode capability for performing long range altimetry, TRN, and HRN. The prototype system, as shown in Figure 6, has a compact design with a total mass of 6.7 kg which includes the real-time image processor and command/data interface with the host vehicle.

The TSL prototype is suitable for drone, helicopter, and fixed-wing aircraft flight tests and demonstration of its capabilities for landing missions. These flight tests will help to assess the TSL performance for each of the four functions as described above and serve as a steppingstone for the development of spaceflight units.

Figure 6. Terrain Sensing Lidar (TSL) prototype with multi-functional capability.

4.0 Summary

A lidar sensor based on linear-mode flash lidar technology and by utilizing a novel Super-Resolution algorithm is being developed to meet the needs of future landing missions requiring precision safe landing at designated locations on the Moon or other destinations in the solar system. This multi-functional lidar sensor, referred to as Terrain Sensing Lidar (TSL) can enable long distance altimetry, Terrain Relative Navigation, Hazard Detection and Avoidance, and Hazard Relative Navigation. Operating as a standalone sensor, the TSL also provides vehicle relative state vector that can be used by the Guidance, Navigation, and Control system for improved performance. The merits of the TSL have been demonstrated by a series of static and dynamic tests of a breadboard unit including drone and helicopter flight tests. The results of these tests led to the development of a compact and robust prototype system for further flight testing, including high altitude flights, that can pave the path for the development of spaceflight units. The TSL can also benefit terrestrial aerial vehicles requiring autonomous operation in GPS-denied environment.

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