

Multi-Functional Flash Lidar for Precision Safe Landing in Challenging Terrains

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A Flash Lidar utilizing a novel Super-Resolution (SR) technique has been developed for providing Terrain Relative Navigation and Hazard Avoidance capabilities onboard landing vehicles. Processing algorithms for precision navigation and safe landing location identification take advantage of the uniform fixed pixels property of generated high resolution Digital Elevation Maps (DEMs) to achieve high reliability operation in near real-time. This paper describes the current and next generation breadboard units, report the results of recent dynamic tests, and explain the operational concept as envisioned for future landing missions.

I. 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 [1,2]. 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 [3,4]. Unlike scanning imaging lidar systems that generate 3-D images by scanning the laser beam across the scene and measuring the time of arrival for each returned laser pulse, a flash lidar records a full 3-D image frame by

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illuminating the scene with a single laser pulse and imaging the scene onto one 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) [5], and Hazard Relative Navigation (HRN), in addition to Hazard Detection and Avoidance (HDA) [6,7].

We have built a flash lidar system using the linear-mode flash lidar camera developed by Advanced Scientific Concepts (ASC) which has 128 x 128 pixels. Fig. 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 30 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 well over 30 km from a nominal 1.0 km. The ground-relative altitude measurements provided by the flash lidar 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.

When the altitude drops to about 20 km, the lidar beam is expanded to illuminate approximately hundred detector pixels out of 16,384 pixels. In this phase, the flash lidar generates relatively low-resolution elevation data of the terrain below 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 flash lidar operates 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 (HDA function). The flash lidar can continue updating the map in order to establish a trajectory toward the selected landing

location. This phase of flash lidar operation is referred to as Hazard Relative Navigation (HRN). The flash lidar operation terminates at approximately 100 m above the ground before the vehicle thrusters create a dust plume.

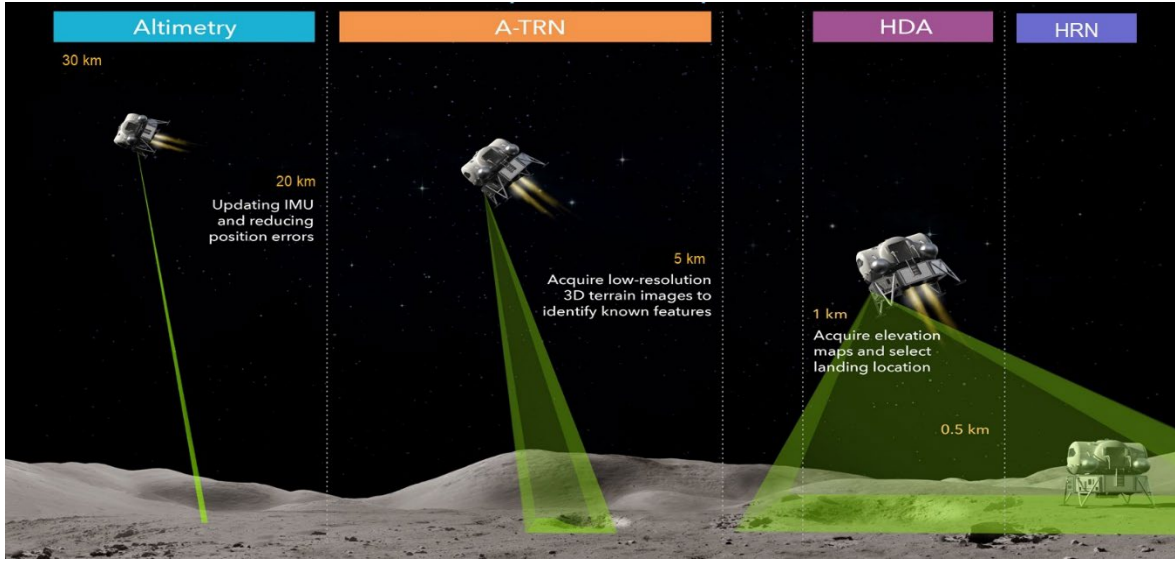


Fig. 1 An operational concept of our multi-functional flash lidar for lunar landing.

II. Super-Resolution Technique

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 measurement. The camera has a 128 x 128 pixels detector array which is grossly insufficient for mapping the designated landing area with sufficient Ground Sample Distance (GSD) to meet most HDA requirements. Adjusting the Field-Of-View (FOV) of this flash lidar to cover a 100 m x 100 m area will give a GSD of 78 cm ($100 \text{ m}/128$), which is much greater than the 15 cm GSD needed for reliably detecting 30 cm diameter hazards required by most landing missions. 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 [7]. However, accommodation of a relatively large mechanical gimbal on landing vehicles is very challenging or even impractical. For this reason, we employ a Super-Resolution (SR) technique [8,9] to eliminate the mechanical gimbal.

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 [9,10], and a recent helicopter flight test. 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.

III. Performance Characterization and Demonstration Tests

A breadboard lidar system has been developed with an integrated real-time SR algorithm for conducting a series of static and dynamic tests to demonstrate the capabilities of the flash lidar technology for hazard detection and avoidance. These tests included operating the lidar from a moving platform at NASA LaRC's gantry facility and onboard a drone. Recently, a helicopter flight test campaign was conducted to demonstrate the hazard detection capability of the lidar for lunar landing missions. Results of this helicopter flight test campaign will be described in detail in a separate publication in the near future. To our knowledge, this was only the second successful HDA demonstration with a lidar sensor in a simulated lunar approach environment, i.e., moving platform with a simulated lunar approach/landing trajectory profile. The first demonstration was the closed-loop rocket-powered NASA Morpheus flight in 2014 for which our flash lidar was mounted on a mechanical gimbal to scan the scene such that the individual image frames can be stitched together covering the targeted area [7]. In this latest flight test, the real-time SR algorithm allowed for generation of the DEMs without the use of a gimbal. This flight test showed very reliable hazard detection performance with no or minimal false alarms depending on the range to the ground.

The gantry and drone flight tests allowed for characterizing the performance of the lidar and quantifying the quality of the Digital Elevation Maps (DEMs) generated by the SR algorithm. As shown in Figs. 2 and 3, several rectangular and hemispherical objects with different sizes, from 5 cm to 1 m, were placed on the ground as targets. The reflectivity, shape, size, and the spacing of these targets for each test were selected so that the primary performance parameters, including resolution, range precision, and hazard detection threshold could be determined. For the gantry experiments, the lidar and the associated support instruments were placed in a basket suspended by tethers (Fig. 2). The basket was lowered by the tethers while some random lateral motions are introduced. The lidar sensor head was mounted to the side of the basket such that it had a clear view of the ground and the calibrated targets. The gantry test was limited to a vertical travel path at a very low velocity with a maximum range of 65 m.

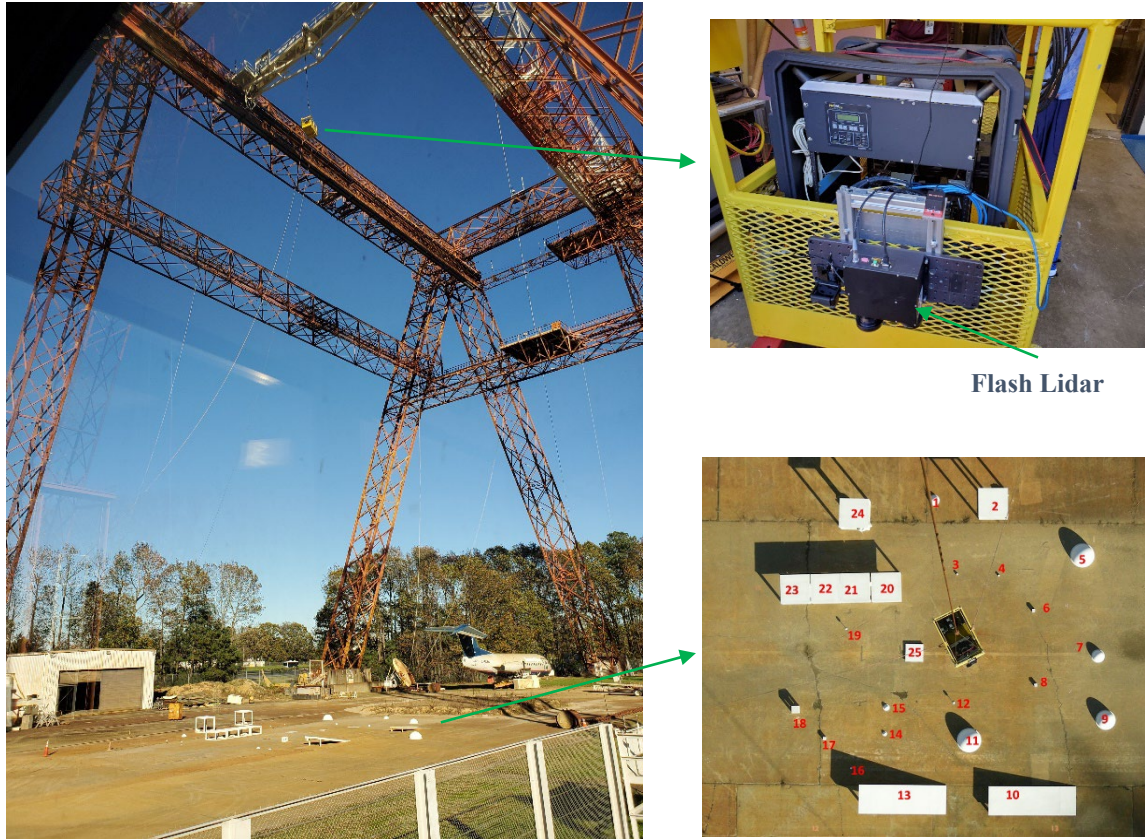


Fig. 2. Dynamic test of flash lidar breadboard system at NASA Langley Landing and Impact Facility (LandIR) or Gantry.

The drone flights expanded the operational envelope of the test compared with the gantry tests. The longer operational range and flight along the slanted trajectories allowed for better characterization of the lidar. The lidar was canted for it to be pointed towards the ground with 30 degrees look angle (Fig. 3). The drone flights conducted at LaRC were limited to 120 m altitude due to proximity to an Air Force Base Runway. Despite this operational altitude limitation, the drone flight proved highly valuable in assessing the SR algorithm and quantifying most lidar performance parameters.

An example of the drone flight test data is provided in Fig. 4 where a single image frame, generated at 20 Hz, and a SR DEM generated at 1 Hz are shown. The DEMs were generated in real time with less than 40 msec latency. These tests showed that our breadboard flash lidar with integrated real-time SR algorithm achieves 0.4 M pixel DEMs per second with 3 cm range precision. These dynamic tests also proved very useful for assessing and fine tuning a hazard detection and safe landing location identification algorithm [11] that has been developed for real-time implementation in our next breadboard unit.

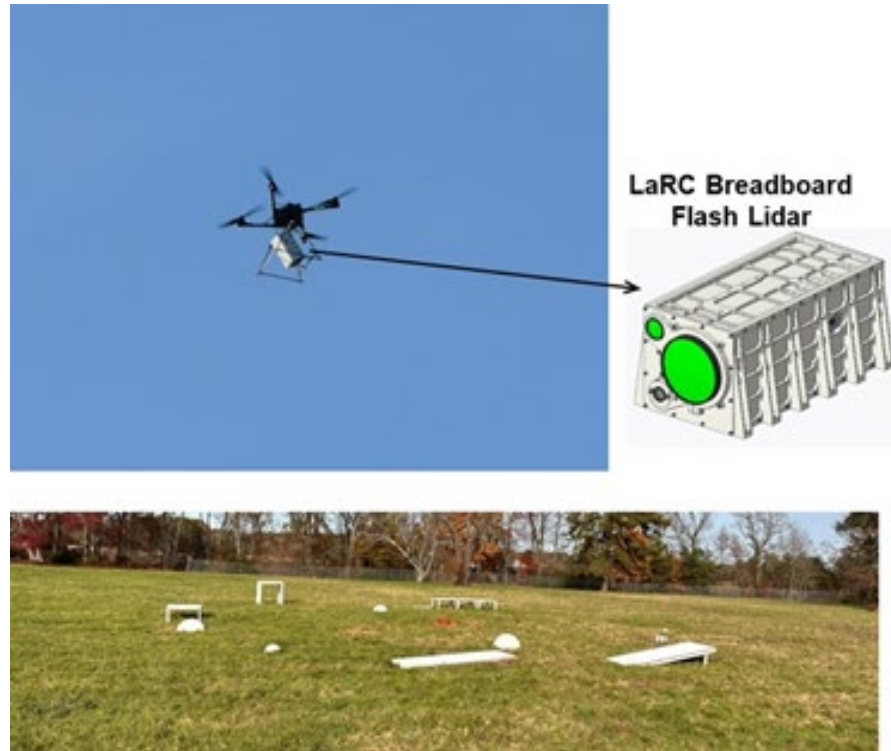


Fig. 3 Drone flight tests of flash lidar breadboard lidar at NASA LaRC.

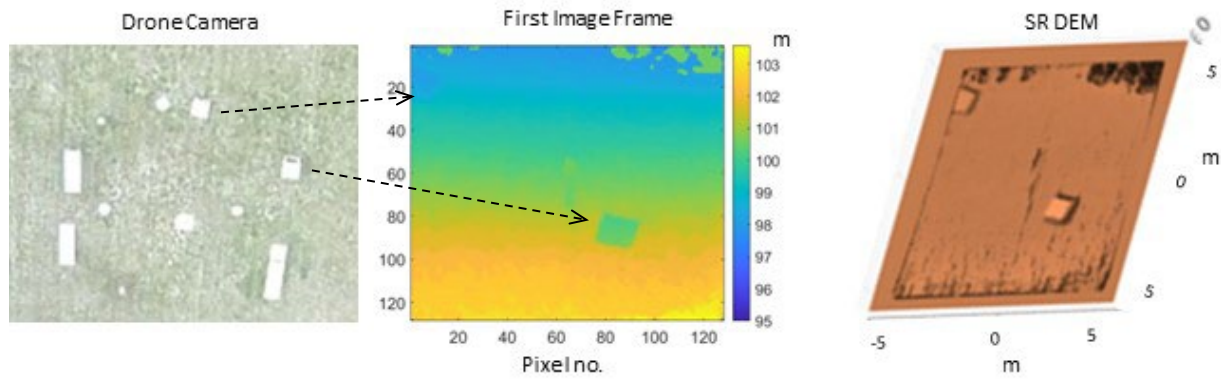


Fig. 4 Example of drone flight test results.

IV. Multifunctional Flash Lidar

The results of the dynamic tests described above have proved invaluable for designing the lidar and particularly for improving the real-time image enhancement and processing algorithms. We also implemented several lessons-learned from the recent helicopter flight test campaign into our next lidar breadboard. The upgrades over the current lidar include higher transmitted pulse energy ($> 5X$), and implementation of a real-time hazard detection and safe

landing areas identification algorithm. This new breadboard unit, which is currently being built (Fig. 5), will be capable of performing all four descent and landing functions of Fig. 1 as described earlier. Table 1 summarizes the specifications of the multi-functional breadboard lidar.

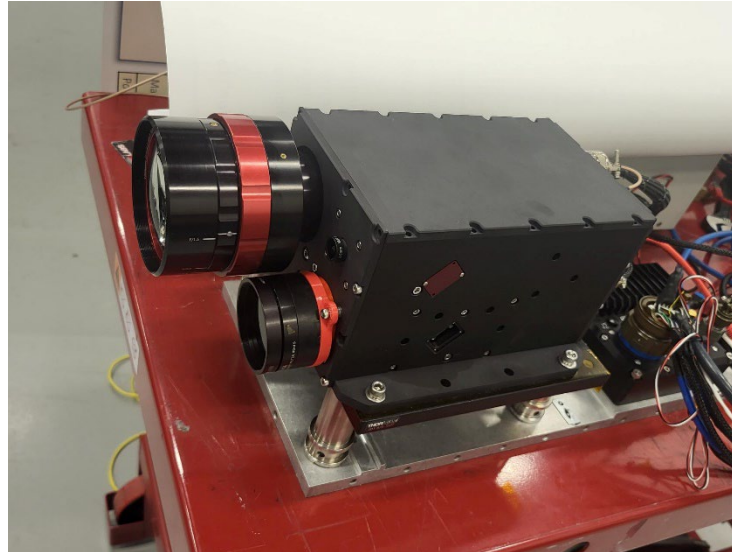


Fig. 5 New flash lidar breadboard with multi-functional capability.

Table 1. Multi-functional breadboard specifications

Parameter	Multi-functional Breadboard Flash Lidar
Altimetry Operational Range	30 km – 30 m
TRN Operation Range	20 km – 15 km
HDA Slanted Operational Range	1 km – 0.7 km
Range Image Frame Rate	20 Hz
HDA Update Rate	1 Hz
Frame Rate	20 Hz
Weight	14.0 lb
Power	55 W

This lidar will be suitable for drone, helicopter, and fixed-wing aircraft flight tests demonstrating multi-functional operation for landing on the Moon, Mars, and other destinations in our solar system. These flight tests will help to further improve the real-time image enhancement and processing algorithms and provide a path to the development of spaceflight units.

V. Conclusion

A multi-functional flash lidar sensor utilizing a Super-Resolution algorithm is being developed for performing altimetry, Terrain Relative Navigation, Hazard Detection and Avoidance, and Hazard Relative Navigation thus meeting the needs of future landing missions requiring precision safe landing at designated locations on the Moon or other destinations in the solar system. A breadboard system has already been developed for demonstrating the Hazard Detection and Avoidance capability and has undergone a series of dynamic tests including drone and helicopter flight tests. The results of these tests have helped to design a multi-functional breadboard flash lidar that is currently under the development. This flash lidar meets the performance requirements for a wide range of lunar landing missions including crewed missions. The compact and robust design of the new flash lidar will allow for flight tests onboard drones as well as helicopter and fixed-wing aircraft platforms. This flash lidar and the results of the flight tests will be the groundwork for the design and build of future spaceflight units.

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