

Robotic Lunar Lander Field Trial Avionics

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Justin Thomas, Jay White, Dorian Seagrave, Robert Davis, David Edell and David Artis
Johns Hopkins Univ. Applied Physics Lab

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ABSTRACT

The NASA Robotic Lunar Lander Development Project is a joint effort between NASA's Marshall Space Flight Center and the Johns Hopkins University Applied Physics Laboratory (JHU/APL) to create a new generation of autonomous robotic landers to achieve scientific and exploration goals on both the lunar surface and other airless celestial bodies, including near-Earth asteroids. In mission concepts, the Entry, Descent, and Landing phase relies on optical navigation algorithms to provide precise spacecraft state corrections using real-time imagery. JHU/APL recently completed helicopter-based navigation field trials in southern California to collect representative descent imagery of terrain types that have some similarity to foreign bodies. This imagery will further demonstrate optical navigation algorithm readiness in addition to prior validation with artificially-rendered lunar surface imagery. This paper provides background and discusses the detailed design of the field trial avionics system used to collect flight data.

generation of robotic landers. MSFC and APL engineers are currently conducting studies and test activities to aid in the design of these multi-use landers for future robotic space exploration as illustrated in Fig. 1.

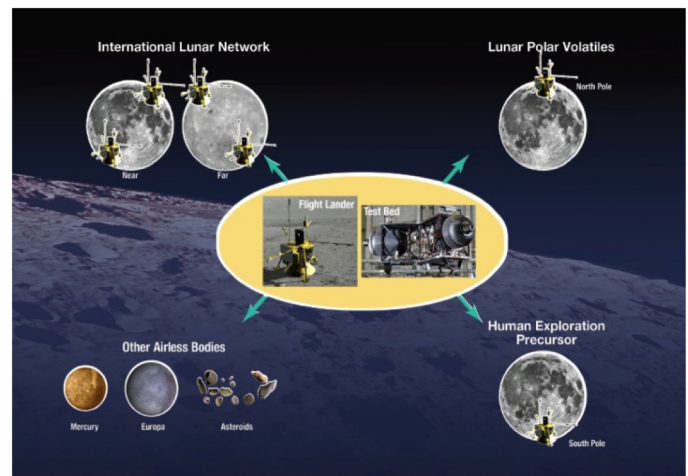


Figure 1. The Robotic Lunar Lander Development Project - NASA MSFC and JHU/APL are enhancing lunar lander capabilities that apply to a variety of robotic scientific missions.

INTRODUCTION

ROBOTIC LUNAR LANDER DEVELOPMENT PROJECT

NASA's Marshall Space Flight Center (MSFC) and the Johns Hopkins University Applied Physics Laboratory (JHU/APL) are creating a new generation of small, smart, versatile robotic landers [1] to achieve scientific and exploration goals on the surface of the moon and other airless celestial bodies, including near-Earth asteroids, under the Robotic Lunar Lander Development Project (RLLDP). The lander capability being developed will pave the way for many exciting robotic scientific missions. NASA's Robotic Lander Test Bed conducts test activities to prove the design of this new

OPTICAL NAVIGATION ALGORITHMS

Real-time optical imagery combined with on-board image processing algorithms provide enhanced sensory information for autonomous precision landing on the surface of the Moon and other airless bodies. The following algorithms are in use for the RLLDP and are undergoing evaluation in increased levels of representative environments.

- Least-Squares Optical Flow (LSOF) - This algorithm [2] provides optical velocity estimation as a low mass and low cost alternative to Doppler velocimeters. It serves to aid in nulling lateral motion during terminal descent. Under RLLDP, this algorithm has been demonstrated in the GN&C Software Testbed (APL's guidance, navigation, and control (GN&C) closed-loop simulation environment) and integrated into the MSFC Warm Gas Test Article [3]. Future Warm Gas Test Article test flights will provide further evaluation using the terrestrial environment.

- Terrain Relative Navigation (TRN) - TRN algorithms use on-board terrain knowledge to provide surface-relative positional knowledge. The JHU/APL Autonomous Precision Landing Navigation (APLNav) TRN algorithm [4,5,6] uses image correlation between camera images and images rendered in real-time using on-board Digital Elevation Maps. A prototype of the algorithm has already been demonstrated in a representative flight environment [7]. Current work involves integrating APLNav into the GN&C Software Testbed for full closed-loop simulation on a representative flight processor.

Another area of interest for the RLLDP is a Passive Hazard Detection (PHD) algorithm based on optical cameras. The development and evaluation of the PHD algorithm remains future work.

NAVIGATION FIELD TRIALS

The RLLDP Navigation Field Trials (NavFT) were successfully completed in March 2011 and built upon experience from prior field trials [7-8]. One of the main NavFT objectives was to collect images, altitude data, and truth data representing flight profiles, terrain variations and various lighting conditions for use in verifying and refining velocity determination, hazard detection and precision landing navigation algorithms (e.g., LSOF, PHD, APLNav, etc). Desired imagery consisted of varying combinations of flight profiles that include low altitude TRN and final lunar descent trajectories (below 10,000 feet Above Ground Level (AGL)), terrain that includes low/no vegetation areas representative of the lunar landscape (nominal and extremes), and lighting conditions that include low and high sun elevations.

Another significant objective was to collect radar altimeter data in support of passive optical velocity determination algorithms, such as LSOF, and to verify the operation of a flight-like radar altimeter in real-world conditions and altitude ranges.

The NavFT approach was to fly a custom avionics system with an array of sensory devices on-board a MD 500D helicopter. After considering an array of factors, the NavFT team decided on southern California as the test area. The final test sites (Fig. 2) were in surrounding areas centered at Brawley, California:



Figure 2. Navigation Field Trials Locations - The pictured locations contain terrain representative of the lunar surface (when viewed in grayscale) for verifying and refining optical navigation algorithms.

NAVIGATION FIELD TRIALS AVIONICS

For NavFT, the Optical Camera Controller (OCC) is the sole avionics processor. The original Optical Camera Controller (OCC) concept was strictly for a device that provides the same functional flight camera interface we envision on a lunar lander mission. A direct interface from the avionics processor to the optical cameras would add an additional processing load not representative of a true flight system, skewing flight software (FSW) performance.

The additional OCC responsibilities to support NavFT were to directly interface with all flight sensors (optical cameras, Radar Altimeter (RA), and Inertial Navigation System (INS)), support two camera pairs (one pair for TRN imagery, and one pair for final descent (LSOF) imagery), record all imagery, altitude, and vehicle state data in real-time, and provide a Command & Data Handling (C&DH) interface to an in-cabin flight operator via a PC laptop.

REQUIREMENTS

The primary requirements for the NavFT Avionics system included:

- Acquisition of simultaneously exposed camera images at 1 Hz from camera pairs (2 pairs desired, 1 pair required)
- Acquisition of altitude measurements from a Radar Altimeter

- Acquisition of vehicle state and orientation from an INS that combines a Global Positioning System (GPS) receiver with a Inertial Measurement Unit (IMU)
- Archival of sensor and run-time data to persistent storage (2 camera pairs desired, 1 pair required) for ground-based post-processing
- Providing highly-accurate time knowledge using a common time base across all sensor data
- Providing an in-flight operator with monitoring and command capabilities, including imagery to assist the pilot's awareness
- Operating in the target environment (altitudes up to 10,000 feet AGL, helicopter shock and vibration, etc...)

DESIGN CHALLENGES

The requirements drove the following primary design challenges:

- Meeting the desired data bandwidth for data acquisition and storage (32 MB/sec desired, 16 MB/sec required)
- Ensuring synchronized exposure of camera images
- Providing accurate, same reference source time knowledge for all sensors
- Keeping costs low and within a short schedule (around 6 months)

The resulting high-level system design is illustrated in [Fig. 9](#) (at the end of this paper) and now discussed in detail.

DESIGN RESULTS

All objectives and requirements were met with the following additional capabilities:

- Support for 4 cameras. Two more than required. This allowed for simultaneous collection of imagery for camera orientations expected for LSOF and APLNav.
- Support for 32 MB/sec real-time storage. This allowed for the archival of 4 camera images per second in addition to all other vehicle state data (GPS position and IMU orientation/rates from the INS and altitude from the RA).
- Timestamp accuracy within ± 0.5 milliseconds for INS samples, ± 0.5 microseconds for camera images, and ± 20 nanoseconds for RA samples.
- The last minute addition of a Light Detection And Ranging (LIDAR) sensor as a technology demonstration.

We will now discuss the avionics design details: the sensors, avionics electronics, avionics software, and flight operator software.

Sensors

The array of flight sensors included the following:

- Cameras (4 total in several orientations) - Illunis RMV 4021 (2048×2048 resolution, 62° field-of-view, 12-bit grayscale) matched with a Fujinon HF12.5SA-1 lens
- INS - NovAtel SPAN-SE RT2-G-S-I, which includes the following components:
 - GPS Receiver - NovAtel OEMV-3
 - IMU - Honeywell HG-1700 AG58 (100 Hz)
- RA - Honeywell HG-8508DA02 (50 Hz)

The cameras were selected to provide a high field-of-view angle with sufficient pixel bit depth. The resolution is higher than what is expected in near-term spaceflight applications, but imagery can be post-processed via image pixel binning and region of interest selection to decrease the resolution to flight levels while retaining sufficient field-of-view. Capturing raw imagery at high resolutions provides potential use in aerial applications and ensures long-term data set applicability by retaining additional detail for future spaceflight applications. The INS and RA provide state data to determine camera position (GPS position and RA altitude) and orientation when images are taken.

The NavFT team placed the cameras, IMU, and GPS antenna on an external mounting plate ([Fig. 3](#)) connected to a strut assembly extending forward from the aircraft. The primary design motivators were to give the cameras an unobstructed view of the ground and to obtain the most accurate camera state information (GPS and IMU rigidly fixed with respect to cameras). The NavFT team placed two RA antennas on a separate mounting plate ([Fig. 4](#)) installed under the aircraft body, facing directly nadir. The primary design motivators were to meet the antenna requirements and provide an unobstructed view of the ground. The INS receiver unit (includes the GPS receiver) was placed in a rack with the avionics, located in the rear of the helicopter cabin. The RA electronics unit was placed in-cabin, under the passenger floor. As both the INS receiver and RA electronics did not require external mounting, it was easiest to install them in-cabin.