

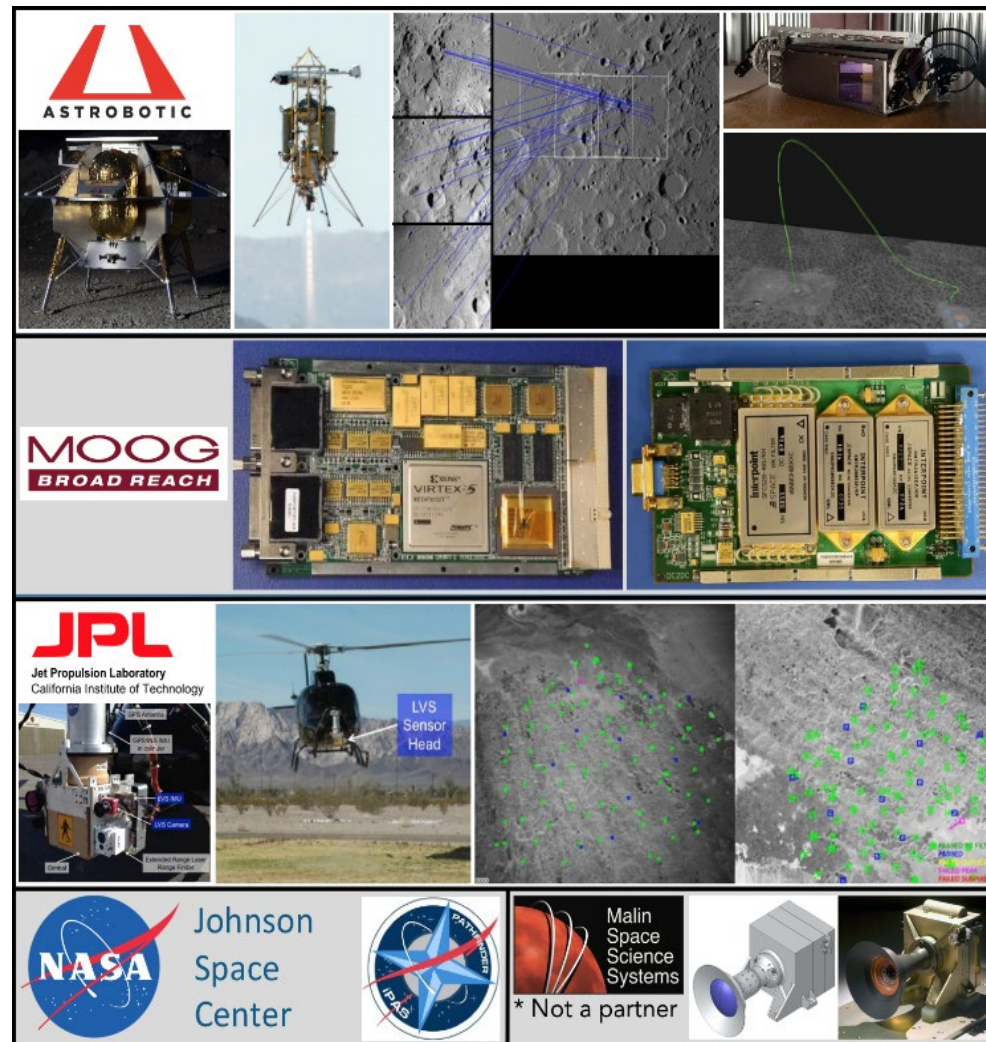


Space Technology Mission Directorate Game Changing Development Program

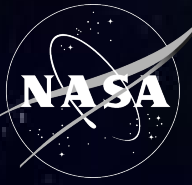
Project Overview



- **Technology Product Capability**
 - Commercial bolt-on Terrain Relative Navigation (TRN) sensor system to enable 100-m precision planetary landing by estimating spacecraft pose relative to an onboard map
 - Builds on Astrobotic's and JPL's prior TRN systems
- **Technical Capabilities**
 - Enables robust 100-m precision planetary landings
 - Unique signature-based algorithms facilitate lander integration
 - System includes:
 - High-performance standalone TRN sensor
 - Hardware-accelerated TRN algorithms that work on Moon, Mars, Earth and beyond
 - Accurate lunar map generator and tools for TRN analysis
 - Fast, high-fidelity lunar simulator for hardware-in-the-loop testing
- **Exploration & Science Applicability**
 - Vision-based precision planetary landing technology
 - Algorithms demonstrated to work at Moon and Mars
 - Enabling capability for science and business objectives
 - First Astrobotic TRN sensor will fly on Astrobotic's Peregrine lunar lander in 2022



Mission Infusion & Partnerships

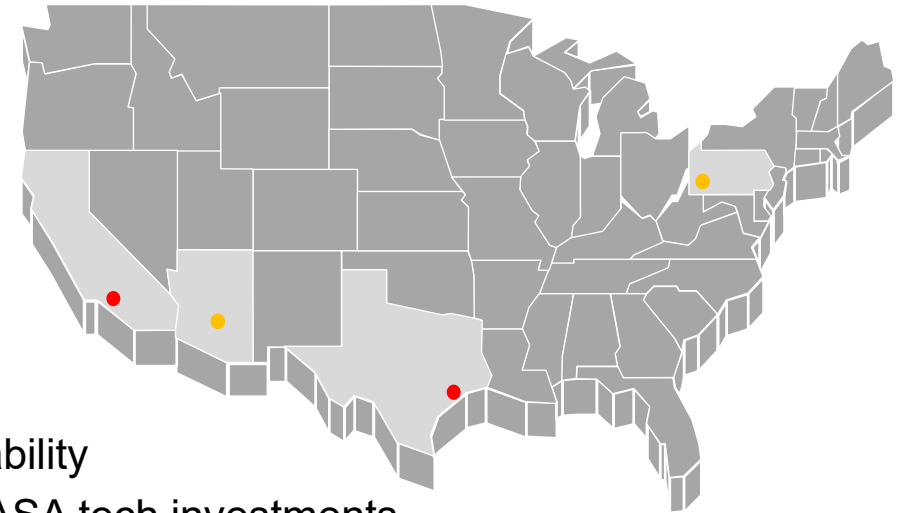


➤ Contributing Partners and/or Stakeholders

- Astrobotic Technology, Inc.
- Moog, Inc.
- Jet Propulsion Laboratory
- NASA Johnson Space Center

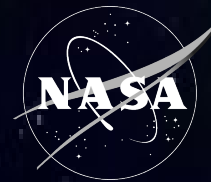
➤ Infusion/Transition Plan

- Goal: Develop a product and a complete toolchain, not just an internal capability
- Leveraging Public-Private Partnerships via Tipping Point to capture prior NASA tech investments
- Transfer Mars 2020 LVS + Feature Descriptor IP Implementation to Industry
- JPL Consulting on software approaches based on Mars 2020 LVS expertise
- Flying TRN Sensor on Astrobotic Peregrine Mission 1, the Griffin-VIPER mission to the South Pole, and on future commercial missions
- OPAL Sensor's high reliability design suitable for missions beyond the Moon
- Partnering with other companies to provide TRN capabilities
- Pitching to DoD agencies and primes to adapt technology for defense applications
- Internal R&D program supported by Phase II SBIR (GSFC) to port Astrobotic's TRN software to lower SWaP-C hardware



Standalone Sensor for High Precision Planetary Landing

Technology Goals & Project Objectives



Technology Goals

| | |
|----------------|---|
| Goal #1 | Develop a TRN sensor (and supporting systems) and raise it to TRL 9. TRL 9 is interpreted as “flight-proven” through a successful demonstration of the OPAL Sensor in a flight to the Moon. |
| Goal #2 | Provide the capability to estimate and log absolute spacecraft pose from the initiation of powered descent to the initiation of terminal descent in order to enhance the absolute position knowledge of the spacecraft. The goal is a final touchdown accuracy of 100 m during future closed-loop lunar landings for realistic lunar trajectories (sufficiently lit surface, pointed at surface, spacecraft capable of divert maneuvers, etc.). |

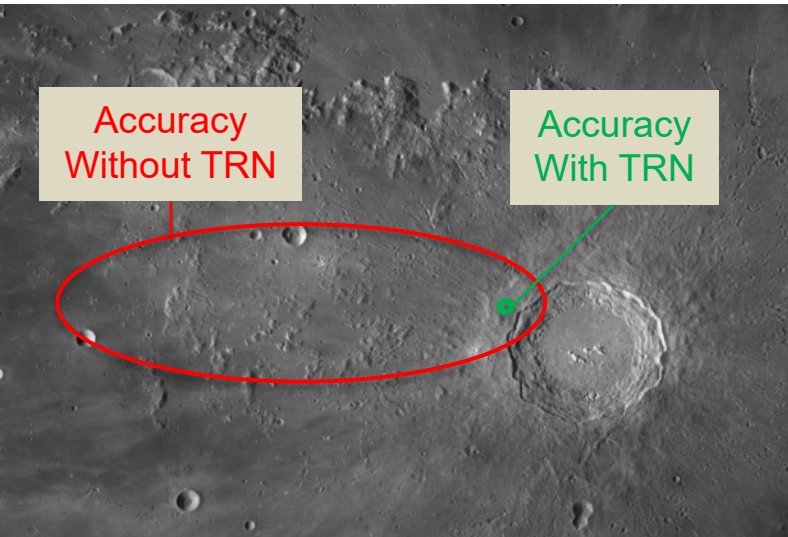
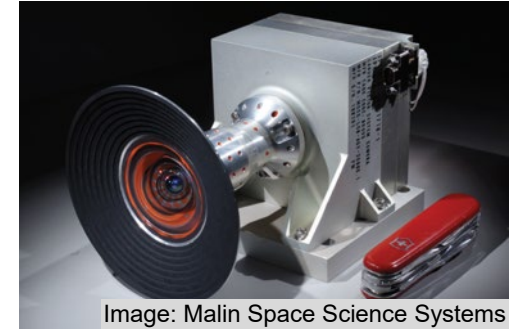
Project Objectives – Technology Demonstration Mission

| | |
|---------------------|--|
| Objective #1 | Integration – The OPAL Sensor shall be integrated with the Peregrine lander (referred to as the spacecraft herein) no later than three months prior to launch. |
| Objective #2 | Functionality – The OPAL Sensor shall estimate and log absolute spacecraft pose from the initiation of powered descent to the initiation of terminal descent. |
| Objective #3 | Performance – The OPAL Sensor shall enhance the spacecraft absolute position knowledge. |

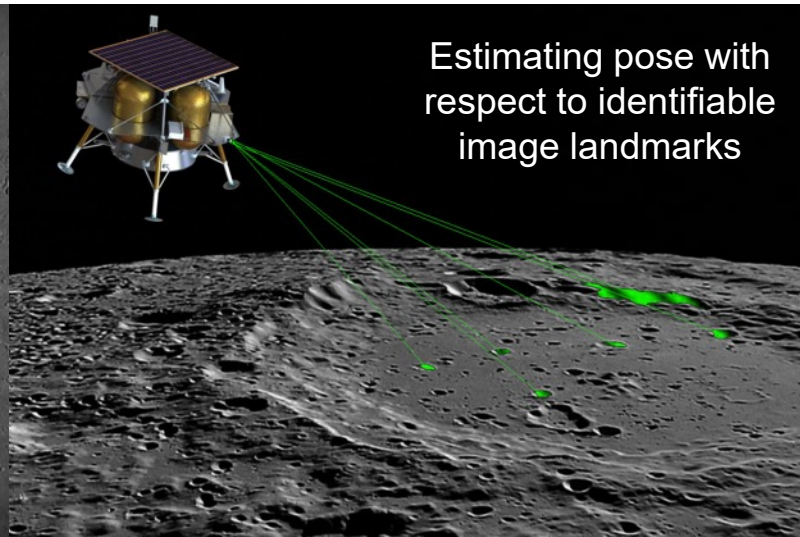
Astrobotic TRN – Technology Overview



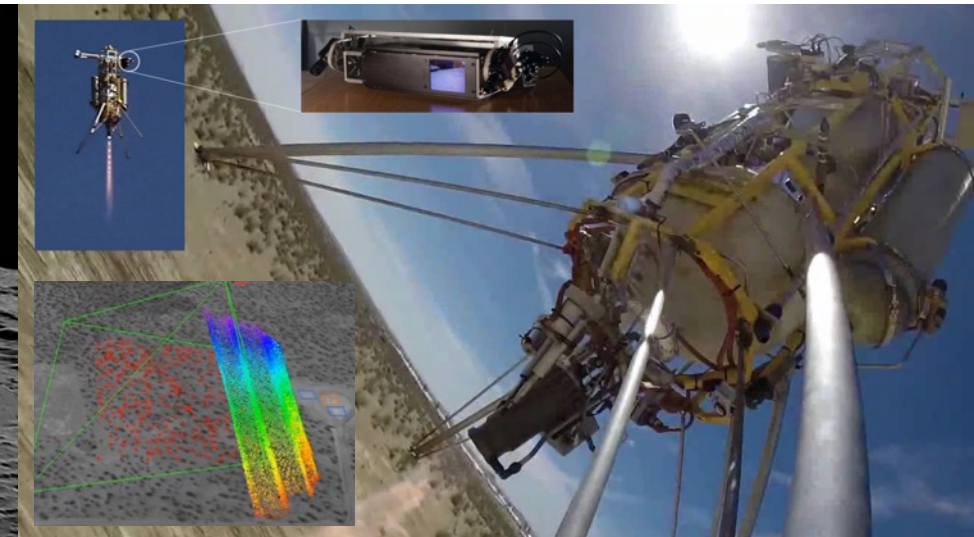
- “GPS” for lunar landers – visual feature detection for pose determination
- Determines absolute pose relative to a map with just a camera image
- Visual feature descriptor matching for robustness
- Developing for Moon, but applicable in Earth orbit or at Mars
- Enabling capability for science and business objectives



100-m lunar landing precision
(~100x improvement)

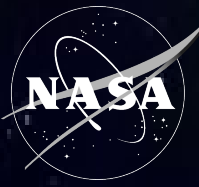


Estimating pose with respect to identifiable image landmarks



Testing use for precision landing of a vertical takeoff, vertical landing rocket

Astrobotic TRN – Technology Overview

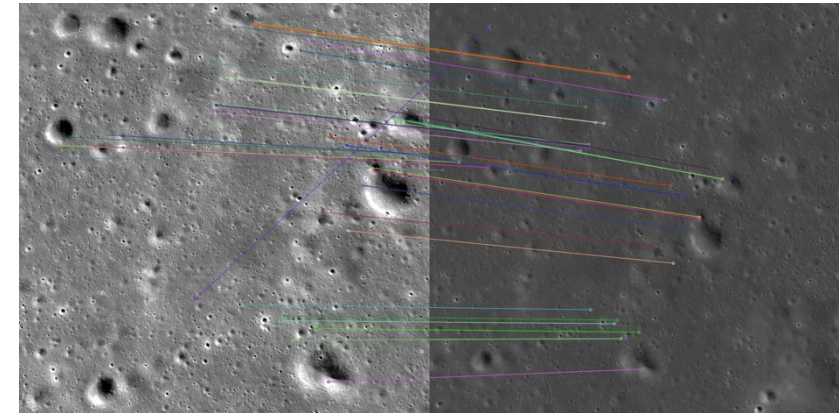


Mars 2020 Lander Vision System (LVS) TRN:

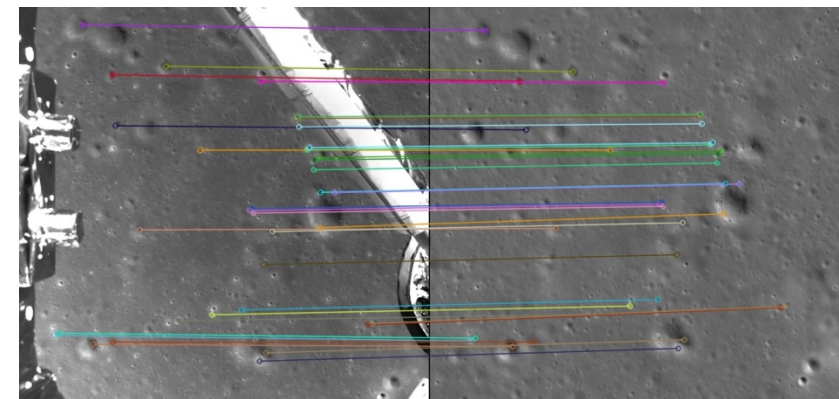
- Image correlation-based algorithms
- Requires spacecraft navigated state
- Requires raw IMU data

Astrobotic's OPAL TRN:

- “Lost in space” acquisition (like star tracker)
 - Does **NOT** require spacecraft navigated state
 - Does **NOT** require IMU data
 - **Operates on images only**
 - Potential storage reduction
 - Less reliance on image warping
- Feature descriptors to match to map
 - Camera must be pointed towards mapped surface
- Limitations:
 - Increased reliance on outlier rejection schemes
 - Scale and rotation differences between image and map

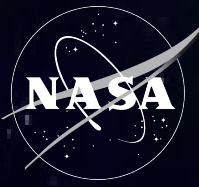


Feature extraction and matching with illumination difference



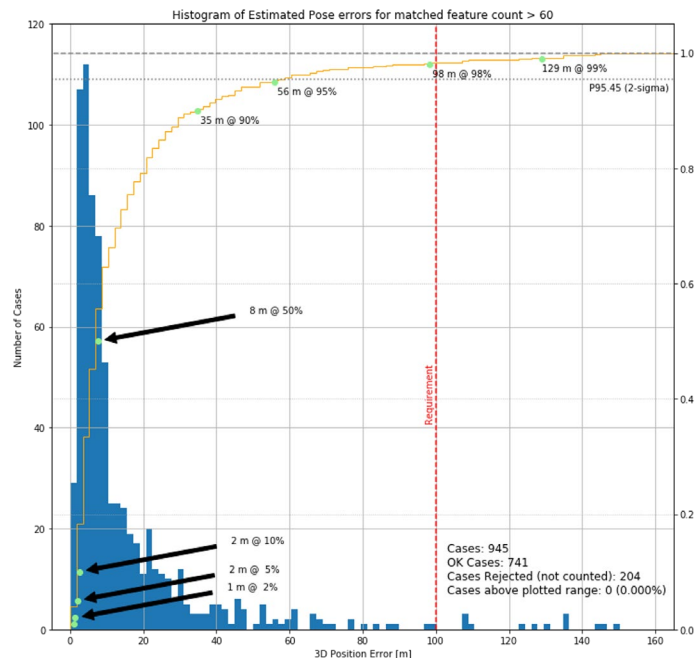
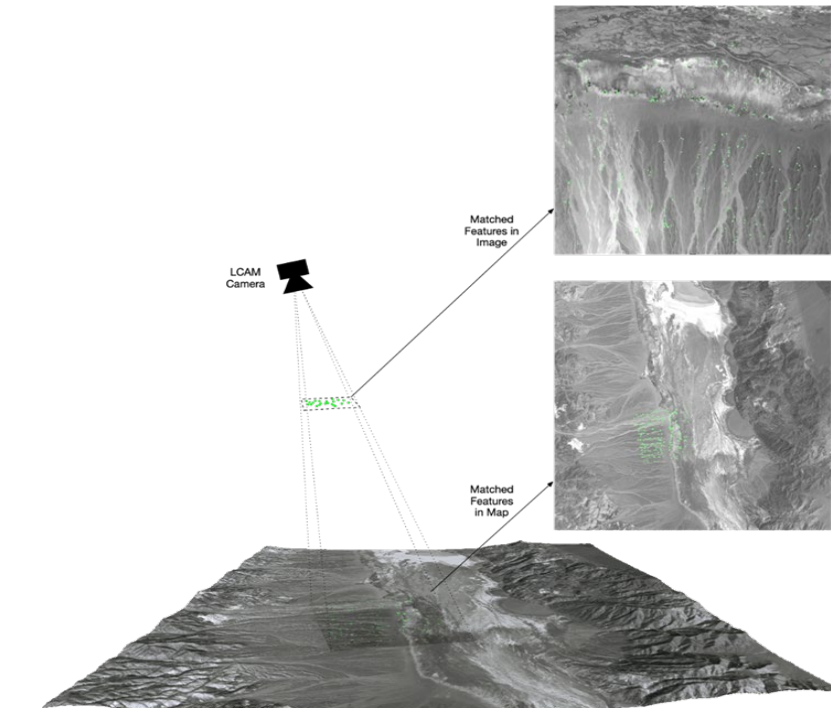
Feature extraction and matching a generated scene from Astrobotic DEMs

Accomplishments (1 of 8)

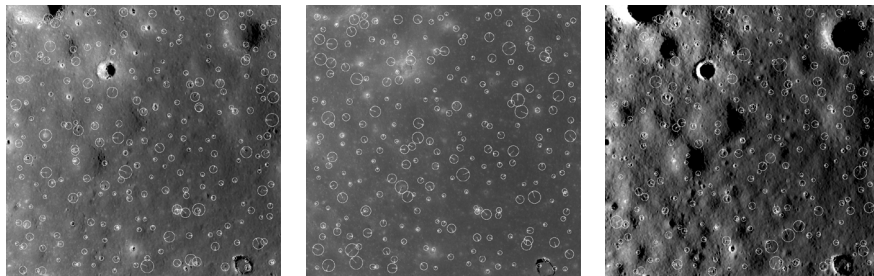


- TRN algorithm preliminary performance analyzed and presented at AIAA SciTech 2021...

TRN detects features in images taken during descent and matches them to an onboard map to estimate location



TRN algorithm performance analyses show strong potential to provide robust position estimate accuracy much better than 100 m



Development of a Signature-based Terrain Relative Navigation System for Precision Landing

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Erik Bailey, Yang Cheng, Dan Clouse, Carlos Y. Villalpando,
Ashot Hambardzumyan, Andrew E. Johnson
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Astrobotic, Pittsburgh, PA, 15233, USA

Abstract – Astrobotic’s OPAL (Optical Precision Autonomous Landing) system, developed under public-private partnership, is a stand-alone, bolt-on commercial terrain relative navigation (TRN) sensor enabling pose estimation over a wide range of altitudes, off-nadir angles, and velocities. TRN enables spacecraft to land at more challenging sites through pinpoint landing and *a priori* hazard avoidance. OPAL builds on Astrobotic’s previous work on TRN sensor systems that have been deployed in suborbital rocket and helicopter field tests as well as JPL’s Lander Vision System (LVS) for Mars 2020. The OPAL system will fly aboard Astrobotic’s Peregrine Mission One that will touch down near Lacus Mortis in 2021 as part of the first NASA Commercial Lunar Payload Services (CLPS) missions. OPAL’s signature-based TRN algorithms, simulation tools, and testing approach are overviewed.

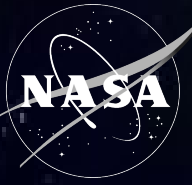
I. Introduction

Landing on planetary bodies presents fundamental challenges for mission design and execution. The lack of GPS requires spacecraft to be equipped with other means to aid dead reckoning strategies based on inertial measurement units (IMUs) for sufficient trajectory determination. Terrain relative navigation (TRN) is a computer vision technique and guidance, navigation, and control technology for precise landing for planetary exploration missions and reduces navigation uncertainty from the order of kilometers to the order of meters [1]. Reducing the dependency on IMU performance may also enable this technology to be deployed in smaller scale, lower budget missions in the future.

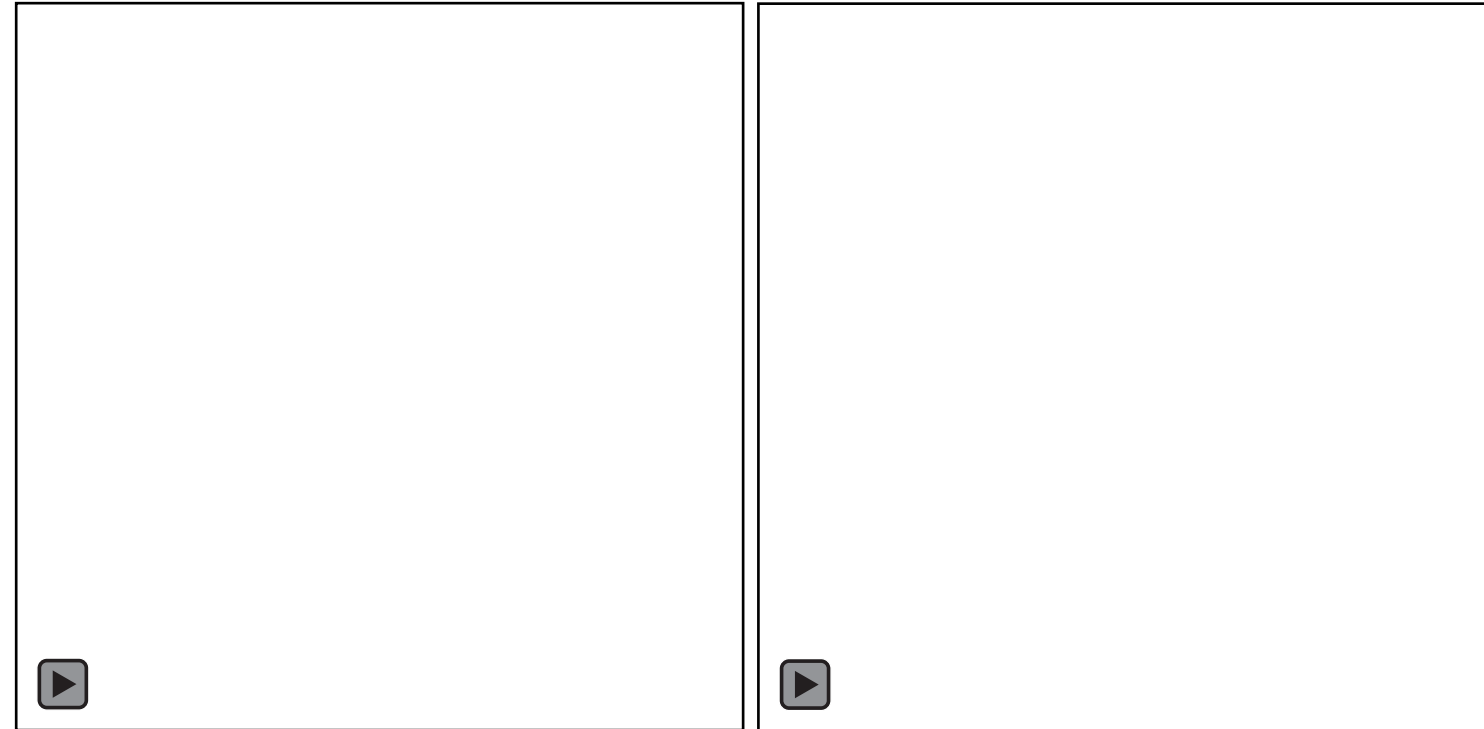
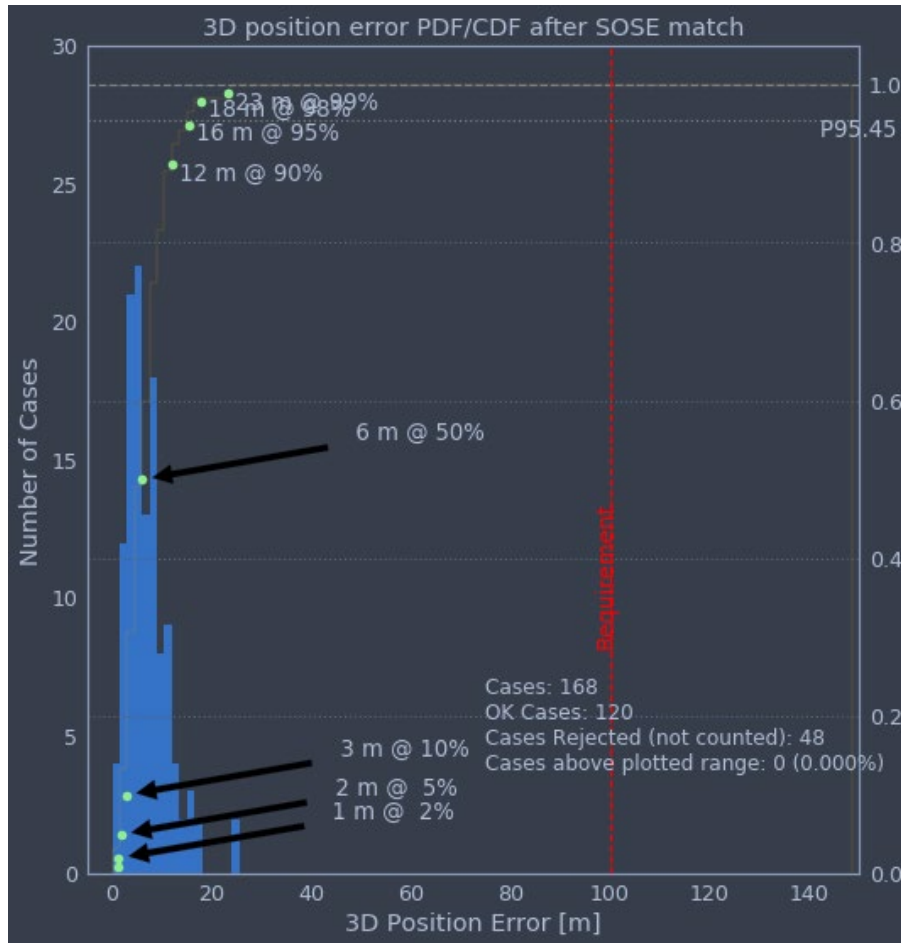
Using camera measurements (real-time image processing) to bound drift from dead reckoning for space missions has roots from the Mars Exploration Rover Descent Image Motion Estimation System (MER DIMES) [2], where three images were captured and compared as a sequence to lower uncertainty in spacecraft horizontal velocity to reduce landing risk. TRN adds another component to this processing: an onboard reference map created in advance from orbital imagery of a target landing site. Captured images from a camera are used to produce pose measurements that are “terrain relative” because they are relative to the *a priori* map data. TRN approaches are not monolithic [3]; there are a number of approaches that differ in the map information representation, the techniques used to compare images to the map, and how position and attitude (pose) information are integrated into an overall guidance, navigation, and control (GNC) solution. JPL, Astrobotic, and several other teams [4,5] have independently developed TRN systems. However, here we detail the development of a novel TRN system led by Astrobotic with members of the JPL team responsible for the Mars 2020/Perseverance TRN system. The result of this collaboration will be a system that is designed to fly on missions to the Moon, Mars, and beyond.

Paper on Astrobotic’s TRN Approach Published and Presented at AIAA SciTech 2021

Accomplishments (2 of 8)



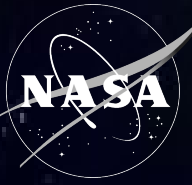
➤ TRN algorithm performance enhanced...



Testing feature detection and matching across image scales (altitudes).

Updates to TRN algorithm match performance of Mars 2020 TRN algorithms, well within 100-m requirement.

Accomplishments (3 of 8)



➤ All flight hardware qualified and delivered...

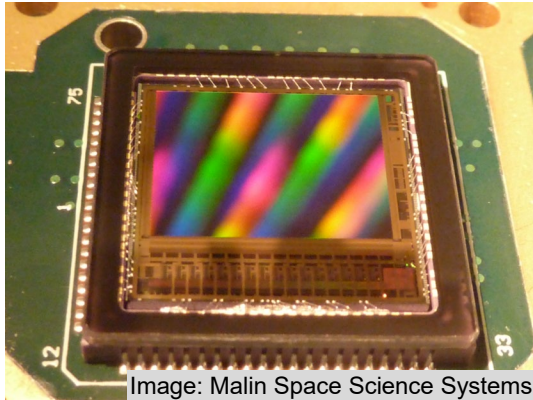
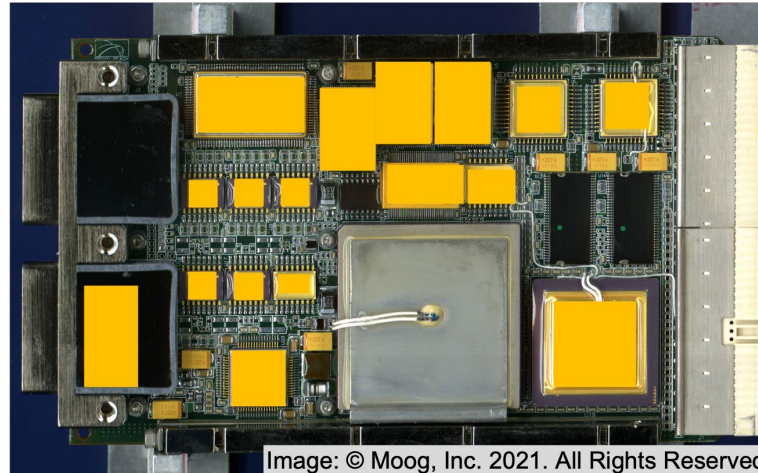


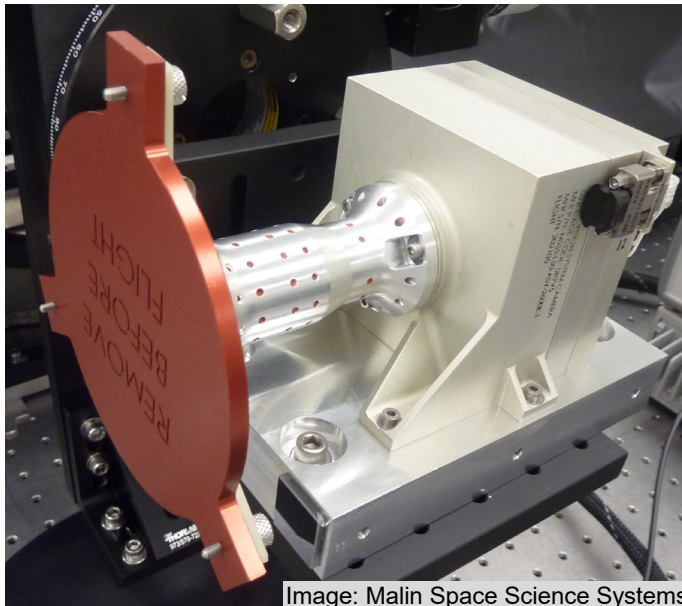
Image sensor of Flight Model TRN Camera Before Assembly

Image: Malin Space Science Systems



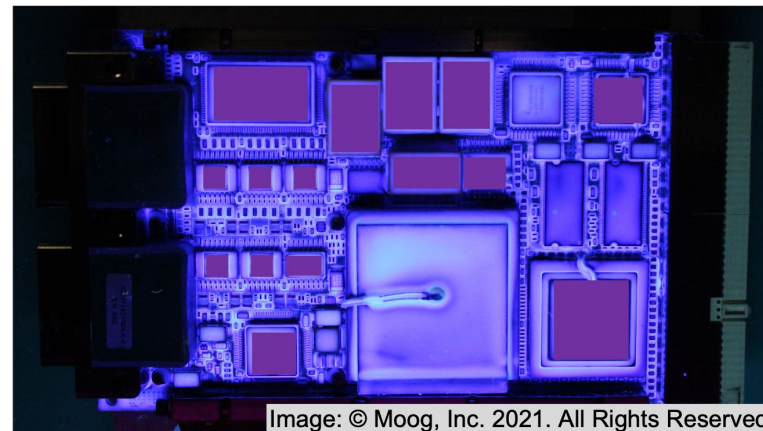
Flight Model TRN Processor Board – integrated OPAL Compute Element currently undergoing environmental qualification

Image: © Moog, Inc. 2021. All Rights Reserved.



Qualified Flight Model TRN Camera Delivered to Astrobotic – build-to-print of Mars 2020 landing camera

Image: Malin Space Science Systems



UV image of TRN Processor Board Showing Conformal Coating

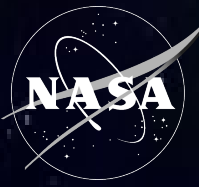
Image: © Moog, Inc. 2021. All Rights Reserved.



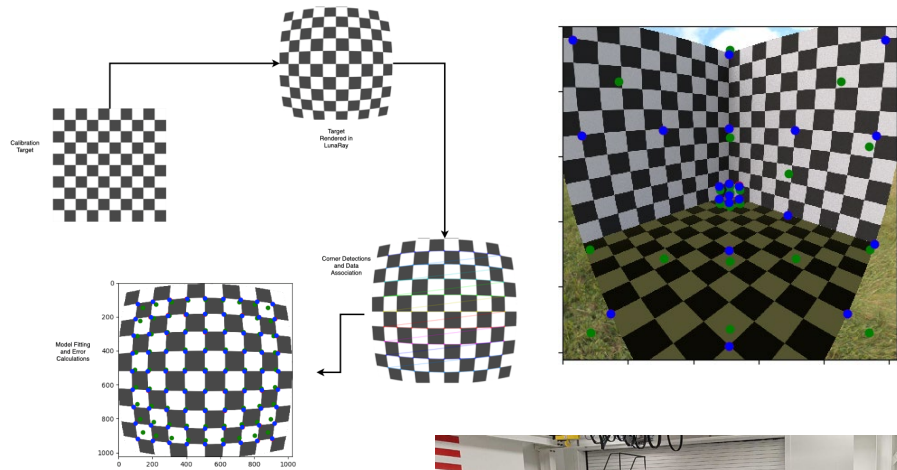
Qualified Flight Model TRN Compute Element Delivered to Astrobotic

Image: © Moog, Inc. 2021. All Rights Reserved.

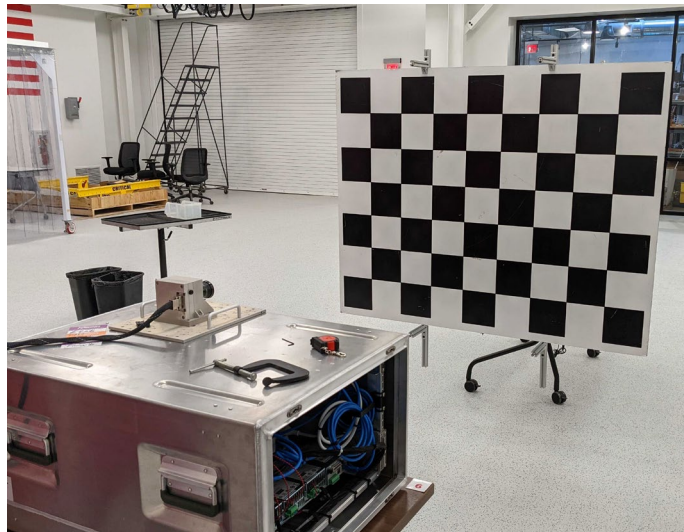
Accomplishments (4 of 8)



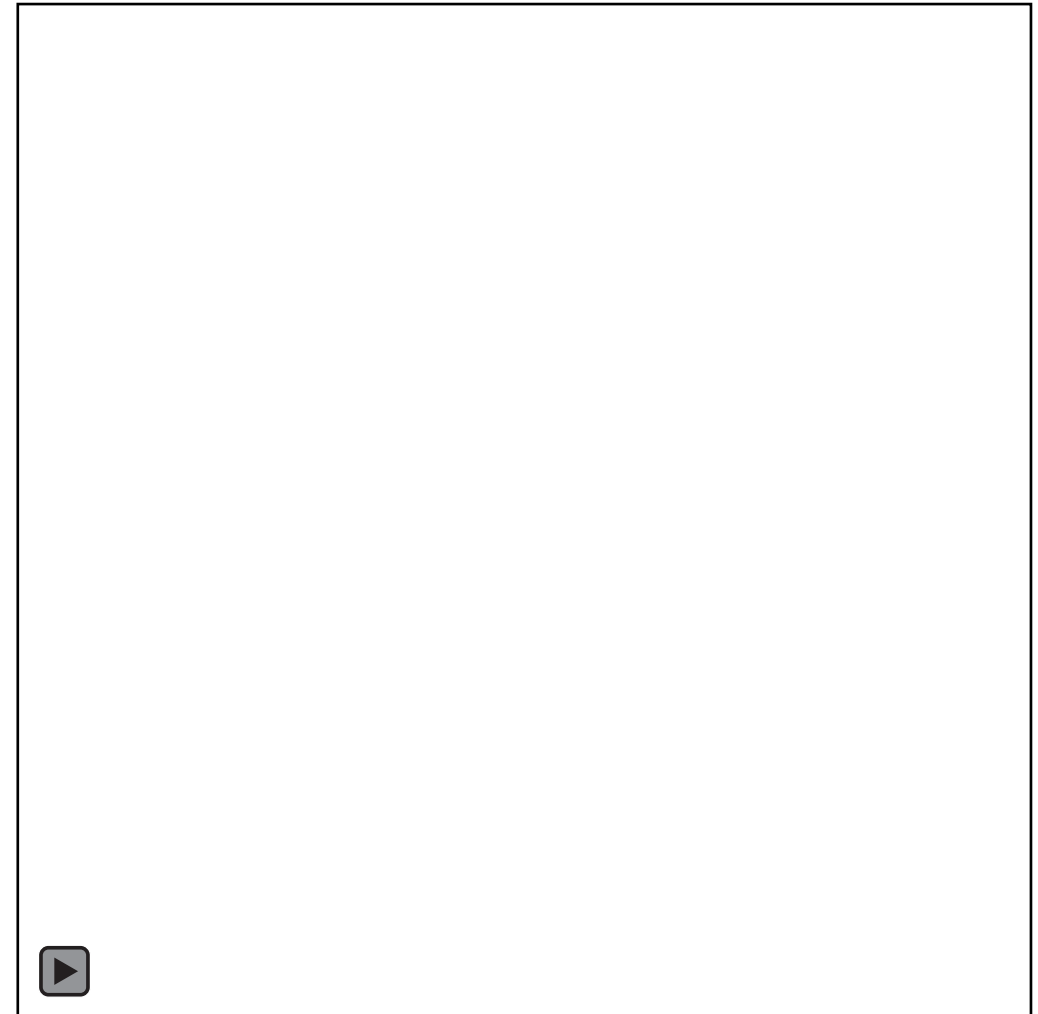
➤ TRN Camera calibrated and simulated...



TRN Camera calibration process and tools developed and demoed



Optical calibration of EM TRN Camera



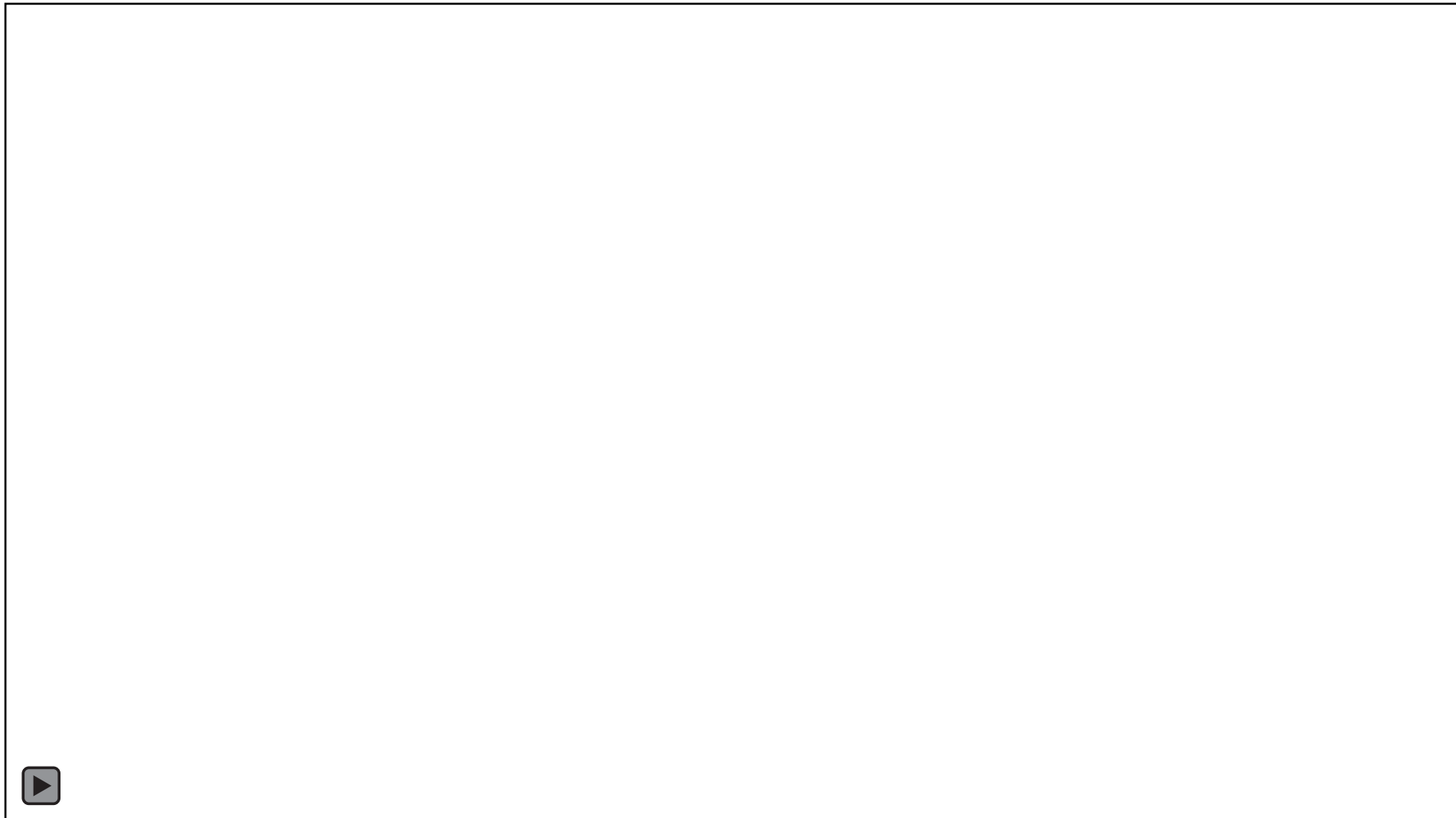
Full trajectory rendered in LunaRay of simulated TRN Camera images. (Note: full fidelity terrain models not used in this video.)



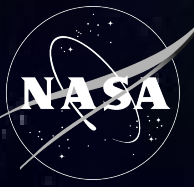
Accomplishments (6 of 8)

- LunaRay simulation of full lunar descent trajectory...

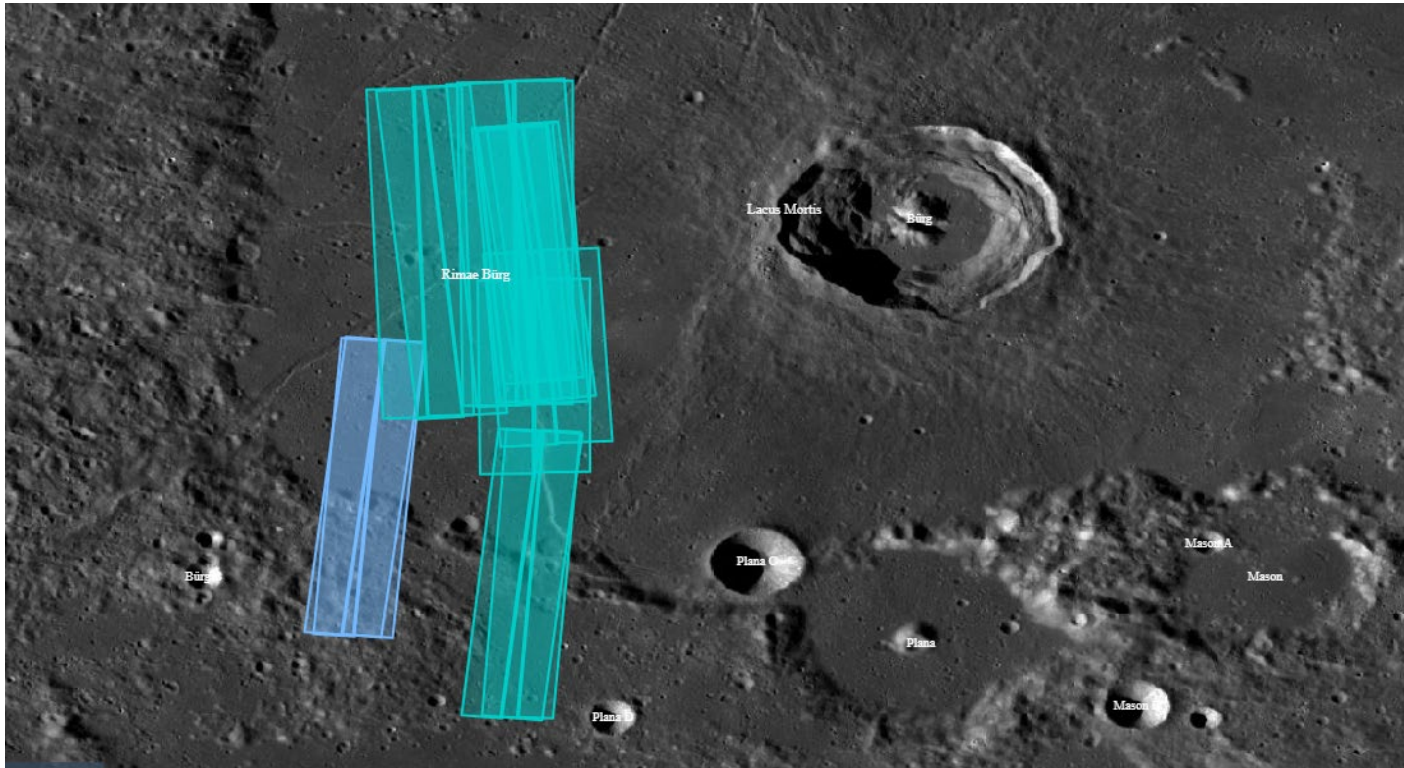
Simulated TRN
Camera Images inset.
(Note: video is not real
time. Lander model is
representative.)



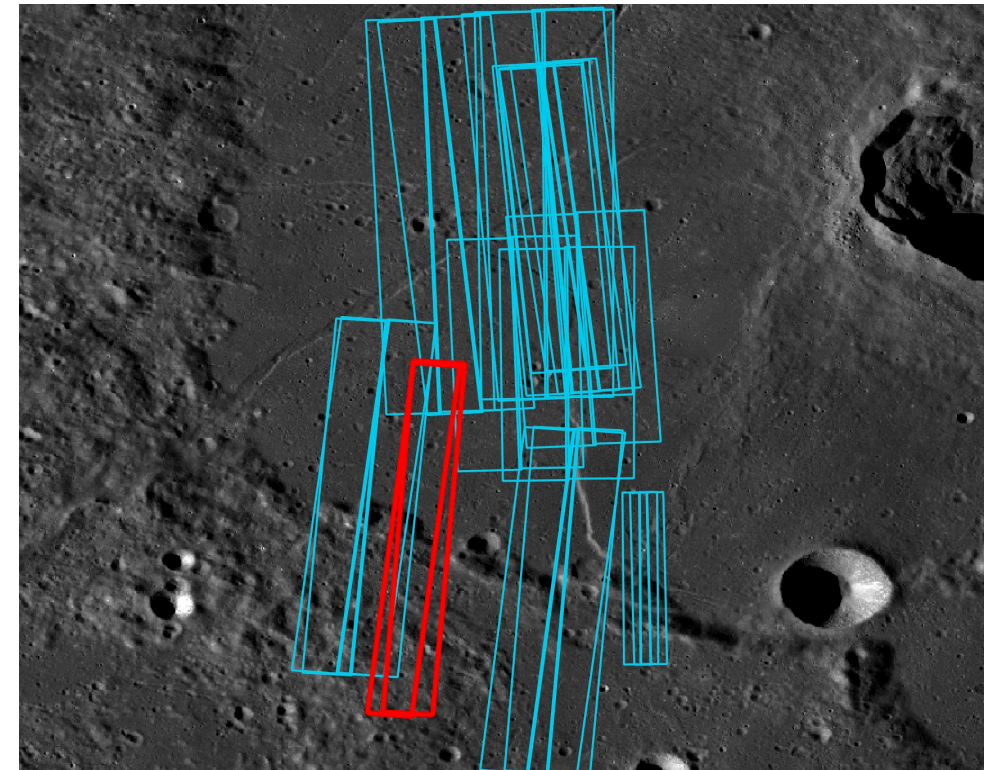
Accomplishments (7 of 8)



- New LRO stereo images of landing site requested, acquired, and released...



New LROC NAC stereo image pair (light blue) of PM1 landing region (Feb 12); Existing stereo pairs (cyan). Such data is critical to creating accurate 3D maps of the surface used by Astrobotic's TRN system.

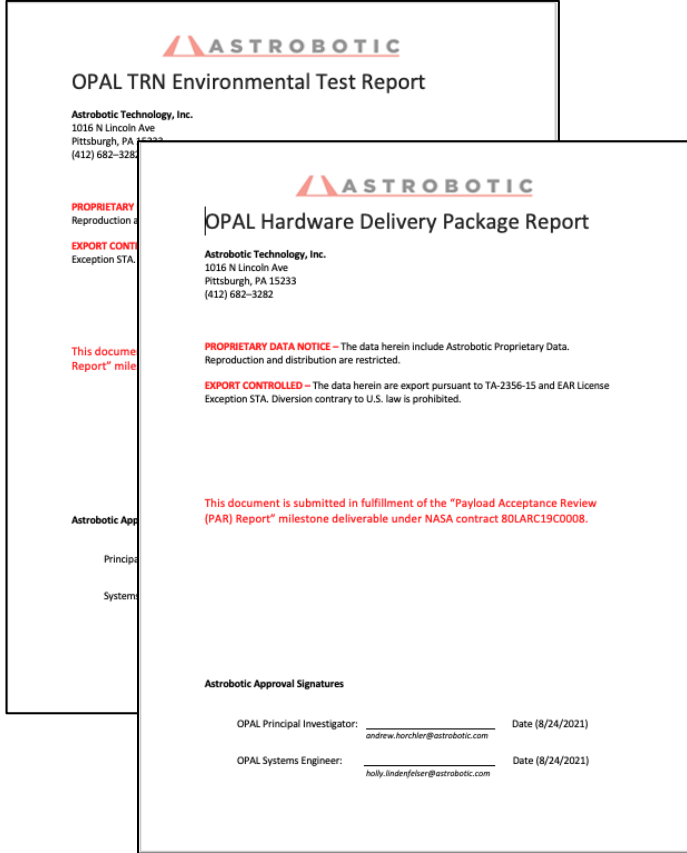


Second LROC NAC stereo image pair (red) of PM1 landing region delivered (Jun 2); Existing stereo pairs (cyan). We continue to work with LRO/LROC team to task them for future data collection in support of terrain data needs.

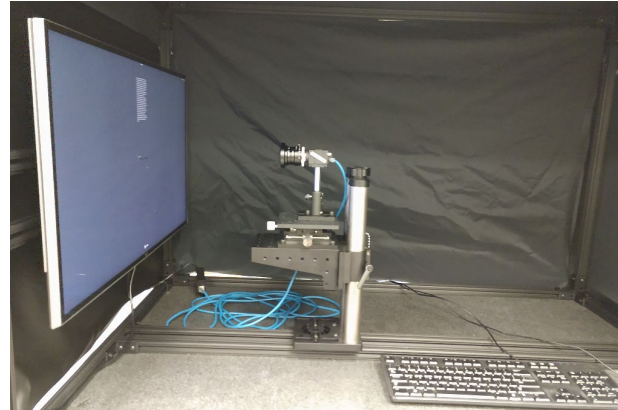


Accomplishments (8 of 8)

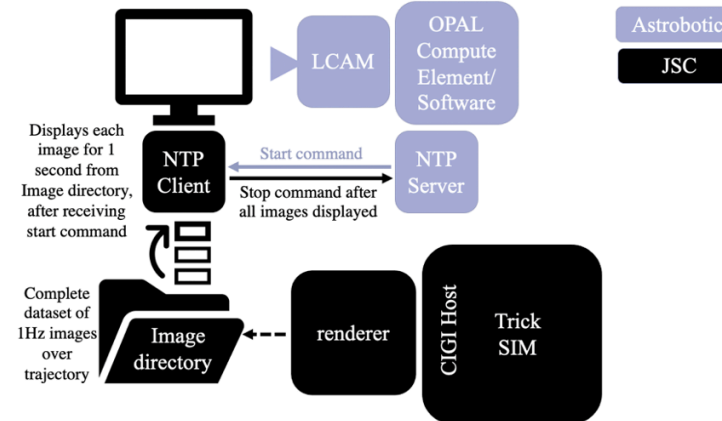
➤ Contract deliverables submitted and working toward IV&V at JSC...



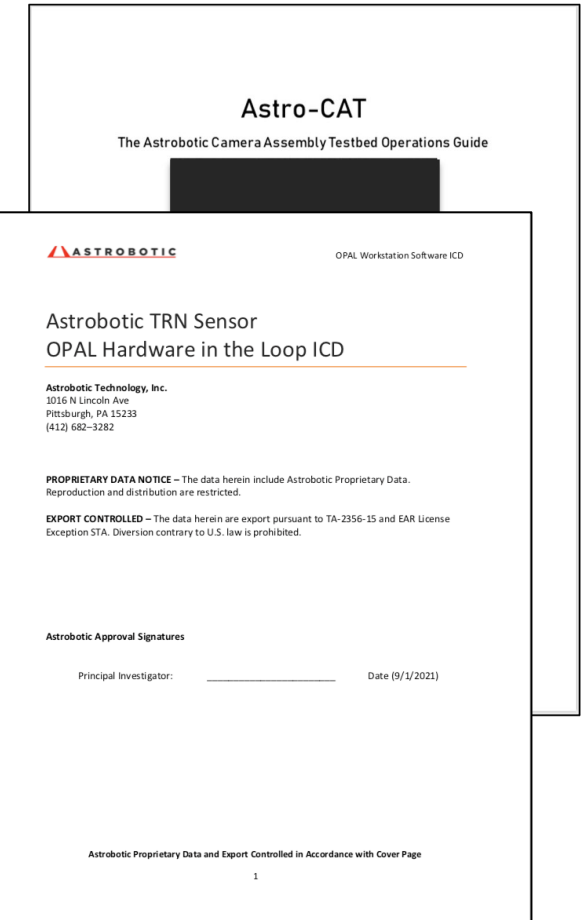
OPAL TRN Environmental Test Report and Hardware Delivery Package Report delivered to NASA. OPAL approved for integration.



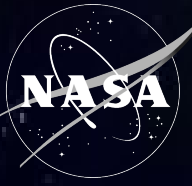
JSC Optical Test Bench where Astrobotic's TRN system will undergo IV&V testing.



Astrobotic/JSC ICDs and test plans developed.



Astrobotic TRN TRL Advancement



- CDR – Nov 2021
- Overall system currently at TRL 5 (some components at 8)
- Successful IV&V testing at JSC in October 2021 will raise TRL to 6
- A successful terrestrial flight test in February 2022 will raise TRL to 7
- A successful lunar tech demo later in 2022 will raise TRL of sensor to 9

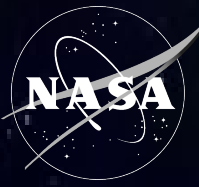
Technical Assessment



| Technical Capability Elements | TRL | | | TRL Verification |
|---------------------------------|-------|------|----------------------|--|
| | Entry | Exit | Current ¹ | |
| OPAL TRN Compute Element | 8 | 9 | 8 | Hardware has previously flown in GEO. Environmental qualification of FM complete. Lunar Tech Demo Mission (TDM) will raise hardware to TRL 9 for lunar environment. |
| OPAL TRN Camera | 6 | 9 | 8 | Build-to-print camera performed successfully for Mars 2020 TRN. TDM will raise hardware to TRL 9 for lunar environment. |
| OPAL TRN Flight Software | 4 | 9 | 5 | Software (and TRL 9 FPGA modules) fully running. IV&V testing will raise flight software running on compute element to TRL 6. Terrestrial flight test will raise this to TRL 7. Lunar TDM will raise OPAL TRN software/algorithms to TRL 9. |
| LunaRay Simulation | 4 | 9 | 5 | Map generation and real time scene rendering software fully functional. IV&V testing will raise simulation software to TRL 6. Terrestrial flight test will raise map generation software to TRL 7. Lunar TDM will raise TRN map generation software to TRL 9 |

¹Date of last TA was February 28, 2021

Astrobotic TRN Key Performance Parameter (KPP) Status

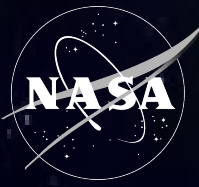


| Parameter | Units | State of the Art (SOA) ⁽¹⁾ | Threshold Value | Project Goal | Current Value To Date | Current Value: Technical Basis of Estimate | Expected Exit Value | Exit Value: Technical Basis of Estimate |
|--|------------|---------------------------------------|-----------------|---------------------|-----------------------|--|---------------------|--|
| Landing Precision (at 2 km, Moon) | m (radius) | 40 ⁽²⁾ (at 4 km, Mars) | 100 | <100 ⁽³⁾ | <40 | Estimated via CDR analysis with JPL ⁽⁴⁾ | <100 | Substantiated via Tech Demo Mission ⁽⁵⁾ |
| TRN Rate | Hz | 1 (after init.) | 2 | 1 | 1 | Estimated via similarity to LVS | 1 | Verified via flatsat testing |
| Mass (including chassis and harness) | kg | 7.0 | 5.5 | 5.0 | 4.9 | Verified via mass of EM hardware | <5.0 | Verified via final flight hardware mass values |
| Nominal Power Draw | W | 32 | 38 | <35 | 32.8 | Estimated via Moog heritage programs | <35 | Verified via flatsat testing |

Notes:

- ⁽¹⁾ SOA comparison to JPL Mars 2020 Lander Vision System (LVS).
- ⁽²⁾ JPL requirement for Mars 2020 mission to Jezero Crater; includes cross-correlation “fine match” step.
- ⁽³⁾ Astrobotic target for lunar TRN Sensor product; assumes “coarse match” only.
- ⁽⁴⁾ Predicted performance using JPL tools based on Peregrine Mission concept of operations; assumes “coarse match” only.
- ⁽⁵⁾ Verified by analysis of reconstructed flight trajectory and closed-loop simulation.

Project Assessment Summary



| Project Name | Performance | | | | Comments |
|--------------|-------------|--------|-------|-------|--|
| | C | S | T | P | |
| Mid Year | Green | Yellow | Green | Green | <p>Technical –</p> <p>Cost –</p> <p>Schedule – Some schedule impact due to COVID-19 and hardware delays. Assessing path to IV&V at JSC and terrestrial flight test in late 2020. Planning for 4 to 6-week delay in delivery of flight hardware (within margins).</p> <p>Programmatic –</p> |
| Annual | Green | Yellow | Green | Green | <p>Technical –</p> <p>Cost –</p> <p>Schedule – HW/SW integration and testing has taken longer than anticipated, due to FPGA challenges, HW limitations/availability, and SW bugs. This has delayed IV&V testing at JSC, CDR, and terrestrial flight testing. Two milestone deliverables (HW Acceptance Report, Environmental Test Report) submitted and accepted out of order. Schedule has been re-baselined and communicated to COR and CO. HW is approved for and on track for lander integration and schedule still has acceptable margin for Lunar Tech Demo with new 2020 launch date.</p> <p>Programmatic -</p> |

EPO Update (Upcoming)



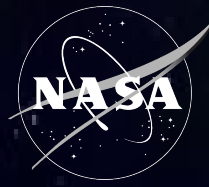
- In touch with LRO/LROC on press release and/or web feature on the Peregrine Mission 1 landing site (LROC has acquired new stereo images for TRN).
- In touch with GCD and NASA PA on photos/video of upcoming flight testing activities for possible use in a NASA.gov feature.
- Will submit full paper and present on performance and testing of TRN system at AIAA SciTech 2022.
- Interviewed with NASA Spinoff for an upcoming article on the technology behind Peregrine Mission 1 and TRN (release date TBD)



Demonstrating OPAL TRN hardware and LunaRay simulation software to Dr. Thomas Zurbuchen (June 2021)



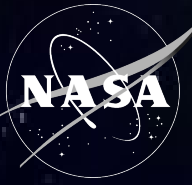
Discussing the Peregrine lander in front of the lander's structural test model. Peregrine passed SIR in Q2 2021.



Plans Forward and Infusion Plan

- Astrobotic's TRN system will be demonstrated aboard our Peregrine lunar lander in 2022 as part of this Tipping Point.
- The TRN system will be employed to safely and precisely land our Griffin lander and NASA's VIPER at the lunar South Pole in 2023. The system will undergo further flight testing before launch and is being developed along with a hazard detection sensor.
- Astrobotic has sold and is on contract to deliver our lunar TRN system (HW, SW, maps, simulation tools) to another space company. Looking to support more missions.
- Astrobotic's TRN sensor was baselined as the precision landing system by one of the three HLS teams
- Under a Phase II NASA SBIR, Astrobotic is developing next generation vision-integrated compute HW to provide lower SWaP-C and higher performance TRN (and other advanced visual navigation applications). The system will be tested at JSC's STAR Lab.
- LunaRay engine being used and marketed for landing site analysis and orbital simulation.

Summary



➤ Accomplishments for the Year-to-Date

- All flight hardware has been environmentally qualified and delivered to Astrobotic
- Flight hardware and documentation has undergone review and is accepted for lander integration
- TRN algorithm performance exceeds performance requirements across a wide range of test cases (Moon, simulated Moon, Mars, and Earth)
- LunaRay renderer and terrain modeling tools meet all requirements; Full lunar descent simulation
- Two contract milestone deliverable documents submitted
- Astrobotic's lunar TRN system commercialized – sold to another space company

➤ Forward Work

- Completion of HW/SW integration testing, IV&V testing, CDR, terrestrial flight testing
- Lander integration and integrated acceptance testing
- Finalization of TRN flight software and TRN flight maps
- Lunar Tech Demo and post-mission analysis

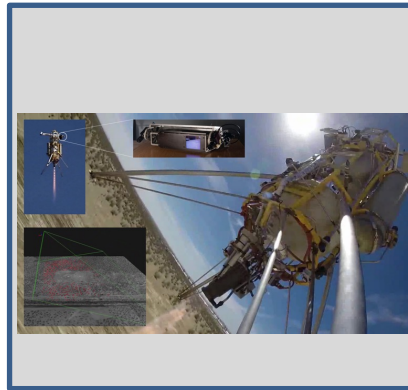


BACKUP

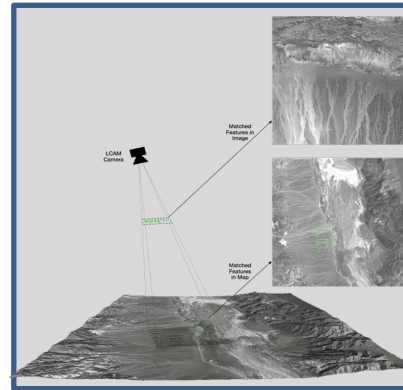
Astrobotic TRN – Annotated Cover Pictures

Annotated Cover Slide Images

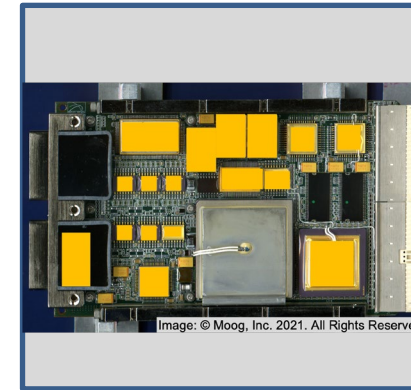
**** Please NO ITAR/SBU Images ****



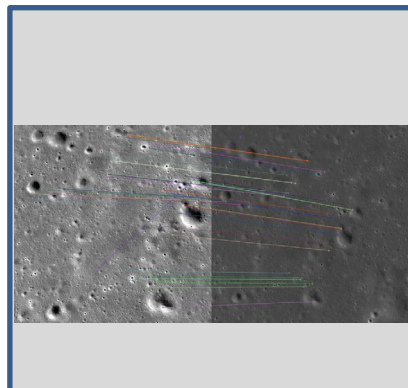
2014 Flight Testing



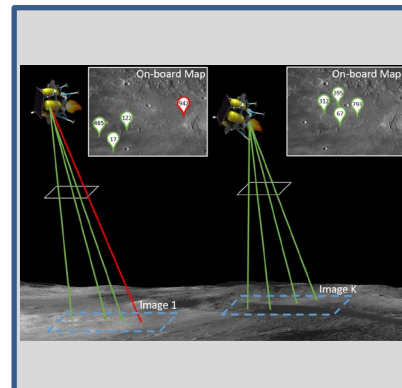
TRN Map Matching



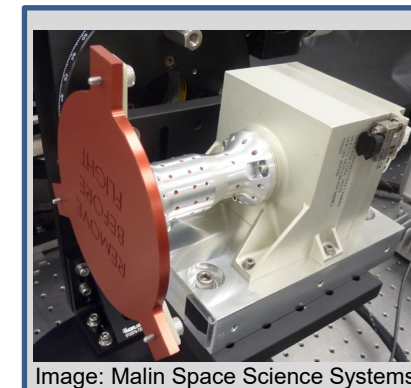
OPAL TRN FM Processor



TRN Feature Matching



Astrobotic TRN ConOps



OPAL TRN FM Camera