ASTROBOTIC RESEARCH AND DEVELOPMENT: VISION-BASED NAVIGATION SOLUTIONS FOR SPACECRAFT. Kerry Snyder, Eric Amoroso, Fraser Kitchell, and Andrew Horchler. Astrobotic Technology, Inc. 2515 Liberty Ave, Pittsburgh, PA 15222. *research@astrobotic.com*

Introduction: Astrobotic's Future Missions and Technology department is turning the company's current technologies into products and pursuing novel research focused on space robotics applications. The company's history includes broad technology development for NASA through over 20 contracts. Here we present recent work on GPS-denied vision-based navigation technologies that enable new capabilities in spacecraft autonomy. For entry, descent, and landing applications, Astrobotic has developed a terrain relative navigation (TRN) solution designed for precision lunar landings. For surface exploration technologies, Astrobotic has recently developed AstroNav, a vision and LiDAR-based simultaneous localization and mapping (SLAM) solution for planetary drones.

TRN: In 2014, Astrobotic demonstrated visual terrain relative navigation (TRN) and LiDAR hazard detection to guide a rocket-propelled Masten Xombie to a safe landing (Fig. 1, *https://youtu.be/kK-LwUcj2r8*). The company has continued to refine this navigation system to minimize size, weight, power, and cost by leveraging space-tested COTS parts and hardware accelerated vision processing, for the purpose of providing precision navigation to a robotic lander. As NASA mission planners and Astrobotic's payload customers increasingly express interest in exploring the most challenging destinations on the Moon, Astrobotic sees a growing need for an affordable and effective TRN solution.

TRN provides global spacecraft pose measurements through matching visual features observed from imagery to a priori stored maps. The maps for lunar TRN are produced from imagery and topography data acquired from prior spacecraft, such as Lunar Reconnaissance Orbiter (LRO). To provide a complete lunar TRN solution, Astrobotic has also developed a synthetic physics-based renderer capable of producing TRN maps for any mission targeting the Moon.

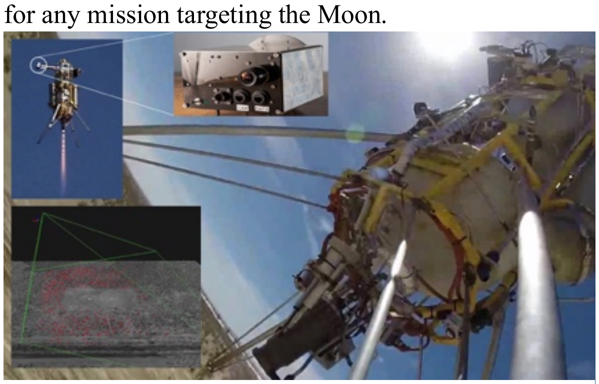

Figure 1. Astrobotic's TRN field test performing precision landing and hazard avoidance in Mojave, CA.

AstroNav: Permanently shadowed regions and lava tubes on the Moon are sites of considerable geological interest and hold the potential for in-situ resource utilization and future human habitation. However, these domains present daunting challenges to exploration and sampling. Free flying vehicles have the mobility to explore such environments but require robust and precise navigation for advanced autonomy. Astrobotic is developing these capabilities under a Phase II NASA STTR contract (NNX16CK16C) to enable high impact science and exploration on the Moon (Fig. 2) [1], [2].

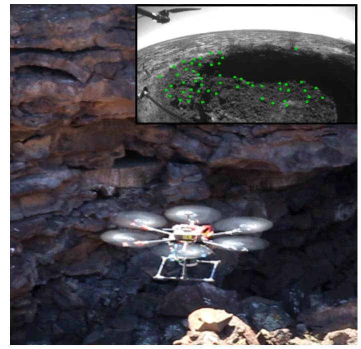

Figure 2. AstroNav operating on a hexacopter within a crater in the Potrillo volcanic field, NM.

Robust, high-rate GPS-denied navigation is required for autonomous exploration of lava tubes and caves and presents unique challenges. On the surface, detailed maps are unavailable, but the surrounding terrain is illuminated and allows for visual navigation. Conversely, underground there is little-to-no light, but the craft will be surrounded by rich geometric surfaces. Astrobotic is developing a solution that fuses LiDAR and visual sensing such that precision navigation is maintained during the transition from light to dark and back. A sensor package combining stereo global shutter image sensors and a Velodyne VLP-16 LiDAR is used to develop and test these capabilities, and sensor measurements are precisely synchronized and collected with a custom sensor interface controller.

With a factor graph-based SLAM formulation, these different navigation modalities are robustly fused. A requirement for drift of < 1% of distance traveled ensures that the free-flyer can safely exit after exploring the cave. Image feature observations are triangulated with stereo cameras and tracked between images with optical flow. LiDAR scan features are registered using LOAM [3] and then processed to generate relative pose measurements. An iSAM2 [4] incremental smoothing backend efficiently fuses these measurements into a coherent, low-drift pose estimate.

References: [1] Snyder K., et al. (2017) *IEEE IPSN*, [2] Sofge E. (2015) *Popular Science*, [3] Zhang J. and Singh S. (2014) *RSS X*, [4] Kaess M., et al. (2012) *IJRR*.