The SPLICE Project: Continuing NASA Development of GN&C Technologies for Safe and Precise Landing

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Guidance, Navigation and Control (GN&C) technologies for precise and safe landing are essential for future robotic science and human exploration missions to solar system destinations with targeted surface locations that pose a significant risk to successful landing and subsequent mission operations. These Entry, Descent and Landing (EDL) technologies are a part of the NASA domain called PL&HA (Precision Landing and Hazard Avoidance) and are considered high-priority capabilities within NASA space technology development roadmaps to promote and enable new mission concepts. The SPLICE (Safe & Precise Landing – Integrated Capabilities Evolution) project is a multi-center, multi-directorate NASA project focused on continuing the decade-plus of NASA investments and projects focused on PL&HA technology development and infusion. This paper highlights the GN&C technologies in development within SPLICE, along with the simulation and field test plans for validation of the capabilities and Technology Readiness Level (TRL) maturation toward infusion into potential near-term robotic lunar landing missions.

I. Overview

NASA Technology Roadmaps[1,2] and the NASA Space Technology Mission Directorate (STMD) EDL investment strategy deem precision landing and hazard avoidance (PL&HA) technologies as critical capabilities for future robotic science and human exploration missions to the Moon, Mars, icy bodies and other solid-surface destinations. The PL&HA suite of technologies includes multiple sensors, algorithms, and avionics components that when integrated together enable a spacecraft to safely land in close proximity to specified surface locations. Such locations include landing within topographically diverse terrain consisting of lander-sized hazards (e.g., high slopes and/or large rocks), as well as in regions in close proximity of pre-positioned surface assets (e.g., cached science samples or human mission infrastructure). These technologies support the NASA Strategic Plan to enable exploration of new solar system destinations and allow access to new surface regions of scientific interest that are currently unreachable with current landing capabilities.

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The SPLICE (Safe & Precise Landing – Integrated Capabilities Evolution) Project has been initiated with the STMD Game Changing Development (GCD) Program as a three-year project from government fiscal year (FY) 2018 through FY 2020. The project objective is to develop, mature, demonstrate and infuse PL&HA (Precision Landing and Hazard Avoidance) technologies into NASA and potential US commercial spaceflight missions. The SPLICE project is the focal PL&HA project within the agency and is the direct successor of the prior NASA ALHAT (Autonomous precision Landing and Hazard Avoidance Technology)[3] and COBALT (CoOperative Blending of Autonomous Landing Technologies)[4] Projects that ended in FY 2015 and FY 2017, respectively. The project also continues the multi-center partnerships within the agency PL&HA community, including contributions from JSC, LaRC, GSFC, Jet Propulsion Laboratory (JPL), Armstrong Flight Research Center (AFRC), and Marshal Spaceflight Center (MSFC). Additionally, the SPLICE project is closely aligned to other agency focal projects in High Performance Spaceflight Computing (HPSC)[5] and Entry Systems Modeling (ESM) for synergy in both infusion timelines and mission architectures.

SPLICE is developing multiple focal technologies in PL&HA sensing, computing, and algorithms. The SPLICE sensor developments include a NDL (Navigation Doppler Lidar) Engineering Test Unit (ETU) for ultra-precise velocity and range measurements and a HD (Hazard Detection) Lidar Engineering Development Unit (EDU) for high-resolution terrain imaging and safe landing site identification. Additionally, the project is developing a PL&HA DLC (Descent & Landing Computer) EDU that is incorporating a surrogate processor for the in-development NASA HPSC processor. The DLC and surrogate work are focused on preparation of PL&HA algorithms and computational architectures for accelerated migration to the flight HPSC processor once it is completed in the 2022-2023 timeframe. The NDL ETU will achieve TRL 6 by the end of FY 2019, and the HDL and DLC EDUs will achieve TRL 5 by late FY 2020.

The SPLICE project is also conducting robotic and human mission Concept of Operations (ConOps) studies to understand the relevance of the focal technologies (and to identify the capability gaps) for NASA near-term and long-term missions to the Moon, Mars, and elsewhere. Performance characterization and TRL maturation of the technologies are being accomplished through ground, airborne, and suborbital testing of the component and integrated technologies, as well as in Hardware-in-the-Loop (HWIL) Simulation-based testing. Fundamental GN&C and PL&HA algorithms research is also being performed in SPLICE between the supporting NASA centers and through partnerships with multiple US universities.

II. Mission Concept Analyses and Requirements

SPLICE is conducting detailed modeling and ConOps analyses of GN&C and PL&HA systems and multiple candidate mission EDL architectures for robotic and human landings on the Moon, Mars, and other solar system bodies. The work is in partnership with the STMD ESM project. The analyses are utilizing multiple reference landers, combinations of GN&C and PL&HA sensors, and different EDL trajectories to develop a PL&HA Requirements Information "Matrix" (RIM). The purpose of the RIM is to establish applicability of existing PL&HA technologies to near-term missions, as well as to identify capability gaps that require future NASA investments into next-generation PL&HA technologies. In addition, the results of the analyses are helping to refine the implementation of some of the current SPLICE focal technologies, such as the HD Lidar. The ConOps studies will be ongoing during the SPLICE project and continue afterward to inform the PL&HA RIM and drive future mission architectures and EDL and PL&HA technology investments.

The SPLICE ConOps studies are leveraging two simulation and analysis toolsets, along with PL&HA and EDL expertise from across the agency. The toolsets are LinCov (Linear Covariance)[6] and POST2 (Program to Optimize Simulated Trajectories II).[7] LinCov is a powerful tool for conducting rapid architectural trade studies of sensor selection, quality, and phasing during EDL to determine design points to consider in higher-fidelity, computationally expensive Monte Carlo simulations. POST2 is a high-fidelity, six-degree-of-freedom (6-DOF) simulation tool, developed at NASA LaRC, for conducting detailed analyses of atmospheric ascent and entry flight. These tools are used in complementary ways to provide a complete and thorough approach to EDL mission studies, and their independent results provide valuable cross comparisons and validation of performance against anticipated mission requirements. LinCov is well-suited to quickly analyzing a large combination of sensors and sensor performance, the results of which are used to select a subset of cases for more detailed analyses within POST2 simulations. POST2 includes detailed GN&C models and algorithms and solves the full equations of motion, whereas LinCov uses a linearization assumption to propagate states.

Medium-to-high fidelity models are in development for the each of the PL&HA sensor systems, and both heritage and research GN&C algorithms are being put into the simulation software for studying the benefits or drawbacks to the mission architectures. Figure 1 provides a notional PL&HA EDL or DDL (Deorbit Descent and Landing) highlighting representative GN&C phases and the sensor systems during each of the phases. The PL&HA sensing capabilities under evaluation in the studies include Terrain Relative Navigation (TRN), Hazard Detection (HD), Hazard Relative Navigation (HRN), NDL and/or optical velocimetry for velocity, and NDL or other altimeters for ranging. TRN uses a passive optical camera and a reconnaissance map to determine a global navigation state. HD utilizes an optical sensor to determine landing hazards and safe landing sites from either a camera image or a lidar-generated map: SPLICE technologies are focused on active lidar-based HD. HRN utilizes the lidar-generated map from HD to perform a subsequent TRN-like function.

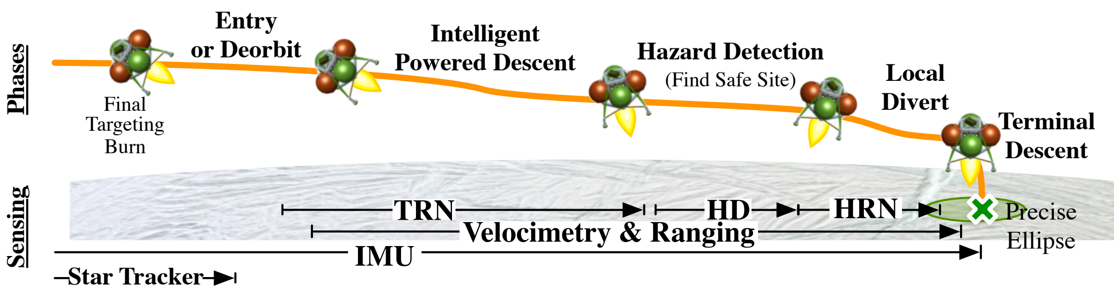

Figure 1. Notional PL&HA ConOps.

III. Focal Technologies

III.A. Navigation Doppler Lidar

The NDL, in development at NASA LaRC, provides ultra-precise and direct velocity measurements, as well as range measurements.[8–10] The NDL measurements are utilized within a lander GN&C subsystem to minimize navigation error in velocity and position (minimize the landing ellipse) and to tightly control vertical and lateral velocities during terminal descent to ensure a soft and/or controlled touchdown. NDL has been in development within NASA for more than a decade and will be at TRL 6 at the end of 2019, following completion and testing of an Engineering Test Unit (ETU).

The NDL ETU consists of an electronics chassis and a fiber-coupled optical head (Figure 2). The electronics chassis incorporates a custom command and data handling (C&DH) board, seed laser, fiber optic amplifier, and other electro-optical components. The optical head contains three fiber-coupled, transmit/receive telescopes that are rigidly mounted to the vehicle with a clear field of view to the ground.


Figure 2. NDL ETU electronics chassis (left) illustration and example optical head (right).

The NDL uses a customized laser waveform and optical homodyne detection to obtain both velocity and range measurements along each telescope line of sight (LOS). The NDL ETU is designed to achieve LOS velocity and range performance of 200 m/s and 7+ km (lunar), respectively, with accuracies on the order of 2 cm/s and 2 m, respectively. The Size, Weight, and Power (SWaP) for the NDL ETU are as follows: chassis size 35cm x 24cm x 17cm, chassis mass under 10 kg, optic head mass under 4 kg (customizable), power ∼85W.

The NDL ETU is designed for spaceflight, incorporating spaceflight and path-to-spaceflight components, conductive cooling, and provisions to minimize electromagnetic interference (EMI). The telescopes can be separated for packaging advantages with spacecraft design and integration. The low divergence of the NDL laser beams further facilitates packaging options. Environmental tests of the NDL ETU will include thermal, vacuum, vibration, and EMI tests, along with radiation testing of select components. In addition, a high-speed NDL test will be conducted to validate the velocity performance of the sensor.

III.B. Descent and Landing Computer

The DLC, in development at NASA JSC, is designed as a stand-alone EDL GN&C computer to offload the computationally expensive processing of PL&HA algorithms from the host vehicle (HV) flight critical functions running on the primary flight computer. The design has been done in partnership with the STMD HPSC Project to develop a surrogate processing platform in preparation for the forthcoming NASA HPSC processor.[5] The architecture also leverages design elements of the HD compute element developed during the former ALHAT project.[11]

The DLC manages and time stamps all Input/Output (I/O) data from the EDL GN&C and PL&HA sensors, communicates with the HV flight computer, and provides a hardware-based method for time synchronization between the DLC and the HV time. See the illustration in Figure 3. The DLC incorporates commercial-off-the-shelf (COTS) Xilinx Multi-Processor System on a Chip (MPSoC) devices as surrogates for the in-development NASA HPSC multicore processor. Each MPSoC is hosted on a custom baseboard. Also included are a path-to-spaceflight Field-Programmable Gate Array (FPGA) card for I/O data interfacing, management and time stamping, as well as a path-to-spaceflight DLC power card and a solid state drive (SSD). The MPSoC devices include a quad-core ARM A53 processor cluster, dual ARM R5 real-time processors, and FPGA fabric. The MPSoC FPGA is used for implementing high-speed serial interface firmware to the standalone FPGA, as well as for MPSoC-to-MPSoC inter-board communication for PL&HA applications requiring additional A53 clusters for data and algorithms processing.

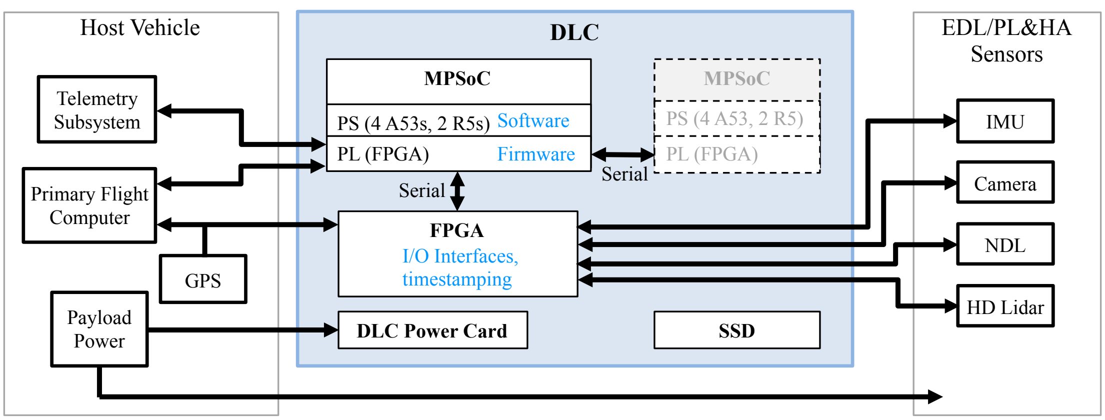

Figure 3. Illustration of the DLC architecture with interfaces to PL&HA sensors and terrestrial host vehicle testbeds.

Software development within SPLICE is leveraging the NASA core Flight System (cFS) framework, which has been ported to the 64-bit multicore HPSC surrogate and is running native within the DLC. The DLC EDU is being designed toward spaceflight, including all path-to-spaceflight or equivalent electronics and a path-to-spaceflight chassis enclosure. The DLC EDU will be put through functional and environmental testing relevant for spaceflight environments, as well as through HWIL simulation-based testing, to achieve TRL 5+ within the timeline of the SPLICE project.

III.C. Hazard Detection Lidar

The HD Lidar, in development at NASA GSFC, is a scan-array lidar system that couples an optical beam steering mechanism with a small detector array to generate a precise three-dimensional terrain map within seconds. The HD Lidar measures millions of ranges per second, each with $\sim$1 cm accuracy, and can accommodate a wide range of return signal intensities. These range measurements are merged onboard in real-time with inertial measurements of position and attitude to create an accurate digital elevation map (DEM) of the landing area. This DEM is then assessed to identify the safe landing sites.

The HD Lidar has the capability to produce medium- and short-range, high-resolution terrain maps, as well as long-range altimetry measurements. The terrain map size, range precision, ground sample distance (GSD), and slant range at execution are customizable to meet the needs of multiple mission scenarios. The configuration for the SPLICE HD Lidar EDU is in active architectural trades through the project ConOps studies of potential near-term robotic lunar lander missions. The targeted specifications are slant ranges on the order of 500 m to 1+ km, map diameters on the order of 50-100 m, GSD of 5-10 cm, and cm-level range precision. A detailed HD Lidar performance simulator has been developed to predict the accuracy and coverage of the DEM over a range of environmental conditions (e.g., position and angular changes during data collection), surface conditions (slope, roughness, distinct features/"hazards", etc.), and sensor performance characteristics (e.g., range precision, pixel size, false detections, pixel dropouts, etc.). A simulated lunar example of an anticipated HD Lidar DEM is provided in Figure 4.

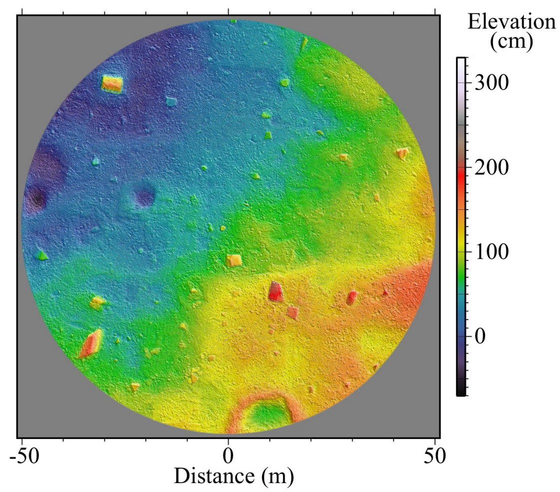

Figure 4. Simulated HD Lidar lunar DEM.

The components within the HD Lidar EDU are primarily high-TRL, spaceflight heritage components, or derivatives of subsystems, that have flown on multiple missions, such as the Lunar Orbiter Laser Altimeter (LOLA) that flew on the Lunar Reconnaissance Orbiter (LRO) and the Global Ecosystem Dynamics Investigation (GEDI) Lidar set to fly on the International Space Station (ISS). The steering mechanism is the only mid-TRL component, and it is in active development and testing within the project. The HD Lidar EDU will be tested to TRL 5+ within the timeline of the SPLICE project.

III.D. PL&HA Algorithms

Safe and precise landing requires complex algorithms and high-performance computing to fuse sensor data and plan intelligent maneuvers that are subsequently executed with the vehicle propulsion system. The SPLICE project is investing new and novel methods for onboard HD for safe site identification, terrain-relative sensor fusion for improved navigation, and 6-DOF guidance. In addition, SPLICE is leveraging existing NASA and US Government investments into TRN algorithms.

III.D.1. Hazard Detection and Safe Site Identification

Identification of safe landing sites is accomplished with an HD algorithm that analyzes the HD Lidar terrain DEM to determine candidate surface sites with high probability for safe landing (i.e., acceptable slopes and low probability of lander-size hazards). The algorithm considers lander geometry, hazard tolerances, touchdown orientations, and lidar and navigation uncertainty in the determination of a safety probability for each candidate location within the generated terrain map. The identified safe landing sites are then utilized within higher-level GN&C logic to plan and execute a hazard avoidance divert to accomplish a safe and precise landing. The HD phase of PL&HA is time critical, so the HD algorithm must process the HD Lidar map and identify safe landing sites rapidly in real time. The SPLICE HD algorithm work is evolving techniques developed at NASA JPL during the former ALHAT project.[12]

III.D.2. PL&HA Data Fusion for Improving Navigation

SPLICE is supporting fundamental research in navigation algorithms to improve knowledge precision, enhance robustness, and identify promising new methodologies. The modeling of the terrain-relative measurements and the intelligent fusion of those measurements within a Kalman filter is a focal research area.[13,14] Investigations are also underway to determine the sensitivity of navigation knowledge to relative-sensor and terrain (e.g., ellipsoids, DEMs, etc) model fidelity, as well as the effect of sequencing different model fidelities during the EDL timeline.[15] Research efforts are also looking at the theoretical underpinnings of fusing classic Kalman filtering techniques with image-based localization techniques.[16,17]

III.D.3. Dual-Quaternion 6-DOF Intelligent Guidance

Traditional engineering approaches to guidance policy design consider three-degree-of-freedom (3-DOF) translation-only dynamics and neglect physical state and control constraints. Subsequent high-fidelity 6-DOF simulations and analyses then adapt the 3-DOF guidance policies to meet spacecraft pointing requirements and ensure adherence to physical state and control constraints. This process comes at the cost of potentially reducing the trade space for feasible guidance designs, as well as requiring extensive analyst effort to verify that unconstrained 3-DOF designs subsequently satisfy the constrained 6-DOF requirements.

SPLICE is supporting fundamental research into a 6-DOF dual-quaternion guidance (DQG) algorithm for powered descent that intrinsically incorporates 6-DOF coupled (translation and rotation) constraints, state triggered constraints, and other relevant state and control constraints.[18,19] The DQG algorithm makes use of convex optimization methods to solve the constrained 6-DOF guidance problem. The DQG formulation is particularly suitable to convexification of both the dynamics and constraints, which offers computational efficiency and a guaranteed solution (provided problem feasibility). DQG is highly relevant to PL&HA because ConOps phases such as Hazard Detection (Figure 1) have 6-DOF coupled state constraints. During the HD Phase, the HD Lidar must be actively pointed to scan a specific terrain region while the spacecraft itself is translating.

In comparison to traditional approaches, the DQG algorithm framework provides the potential to reduce the analysis time required for guidance policy design because the framework is fully 6-DOF and incorporates relevant PL&HA constraints. Additionally, the 6-DOF formulation and convex optimization-based approach allows automatic, and thus broader, searches of the trade space for valid guidance policies. This same formulation is also conducive to onboard implementations because convex algorithms can be solved in polynomial time and to a prescribed level of accuracy.

IV. Testbeds

Component-level and integrated system-level tests are critical to the PL&HA TRL maturation process. The SPLICE project is conducting numerous component-level tests in lab, ground, and airborne test facilities to evaluate component technology performance. System-level testing is a challenge, however, as the intended operational environment for PL&HA technologies is within a spacecraft GN&C subsystem performing an

EDL trajectory profile. To accomplish integrated system-level tests, SPLICE is leveraging two testbeds, a HWIL simulation and suborbital rockets.

IV.A. HWIL-based Simulations

The SPLICE HWIL simulation testbed (Figure 5) at NASA JSC has been implemented for use in the development, performance testing, and validation of PL&HA subsystems and flight software, as well as for future playback and analysis of field test data. The HWIL testbed provides a low-cost method for system-level development and validation prior to incurring the higher costs of field/flight testing or spaceflight mission infusion. The HWIL testbed incorporates physical avionics, sensor hardware, ground consoles, and a 6-DOF high-fidelity simulation. The simulation is developed using the JSC Trick framework, which integrates 6-DOF dynamic body models, environment models, and sensor and actuator models. The HWIL testbed is being used in the development and performance testing of the DLC EDU architecture, which executes flight software within the NASA cFS framework. The HWIL simulation testbed and the cFS-based flight software together provide the SPLICE project with capabilities that support future DLC migration to the HPSC flight processor, as well as validation of PL&HA technologies in simulated flight-like environments to advance TRL and mitigate risk in future spaceflight applications.

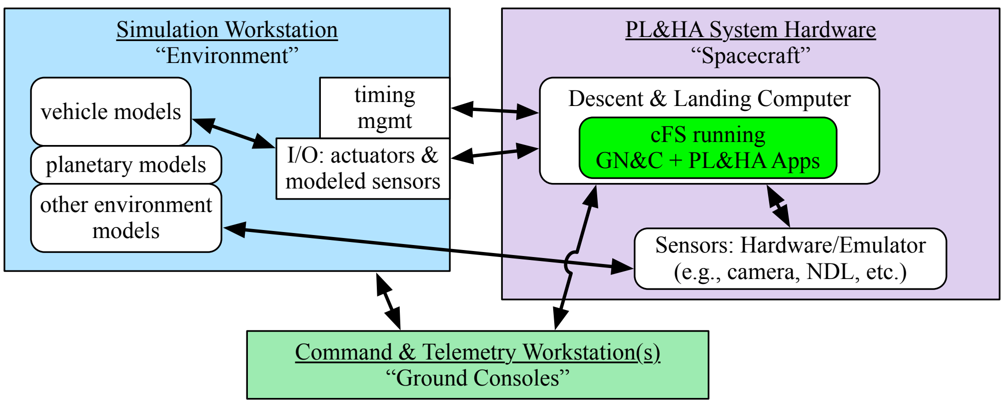

Figure 5. Illustration of the SPLICE hardware-in-the-loop simulation testbed.

IV.B. Suborbital Rockets

Suborbital rockets provide another valuable capability for integrated testing and maturation of EDL and PL&HA technologies. These testbeds provide terrestrial, moderate-cost capabilities to evaluate PL&HA technologies (in open-loop or closed-loop) within a vehicle GN&C subsystem performing dynamically-relevant powered descent and landing. This additional test capability provides further risk reduction and systems-level TRL maturation prior to the PL&HA technologies being infused into a high-cost spaceflight mission.

Multiple suborbital rockets have been leveraged within the NASA PL&HA community during previous projects: the ALHAT project[3] in 2014 tested a prototype NDL and HD system in closed loop onboard the NASA Morpheus vehicle; the JPL ADAPT (Autonomous Descent and Ascent Powered-Flight Testbed) project[20,21] in 2014 tested JPL TRN in open loop onboard a Masten Space Systems (MSS) Xombie vehicle; and, the COBALT project[4,22,23] in 2017 tested the NDL and JPL TRN in open loop onboard a MSS Xodiac vehicle.

SPLICE will make use of suborbital rockets to test and mature PL&HA technologies as opportunities and needs arise. STMD is promoting the maturation of multiple TRN capabilities for lunar infusion. Plans are currently in development between SPLICE and the STMD Flight Opportunities Program to conduct a suborbital flight test in 2019 of a lunar TRN capability being developed at the Charles Stark Draper Laboratory[24] based on prior US Government funded work. Other tests of SPLICE focal technologies and other PL&HA technologies are being considered as risk reduction for potential lunar mission applications.

V. Closing Remarks

The SPLICE project is developing multiple PL&HA technologies that will achieve TRL 5-6 by the end of FY 2020 and be well positioned for infusion into potential near-term robotic missions to the Moon. The SPLICE and HPSC project partnerships on the DLC, HPSC-surrogate processor, and the PL&HA software architectures will aid in the transition of SPLICE software onto the flight HPSC, once available, as well as facilitate additional infusion opportunities for the flight HPSC processor. Additionally, the architecture ConOps studies ongoing between the SPLICE and ESM projects will provide NASA within broad insight into mission infusion opportunities and the paths for future PL&HA technology investments.

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References

[1]Steering Committee for NASA Technology Roadmaps; National Research Council of the National Academies, *NASA Space Technology Roadmaps and Priorities: Restoring NASA's Technological Edge and Paving the Way for a New Era in Space*, The National Academies Press, 2012.

[2]Office of the Chief Technologist, *2015 NASA Technology Roadmaps*, NASA, 2015.

[3]Carson III, J. M., Robertson, E. A., Trawny, N., and Amzajerdian, F., "Flight Testing ALHAT Precision Landing Technologies Integrated Onboard the Morpheus Rocket Vehicle," *Proc. AIAA Space 2015 Conference & Exposition*, AIAA 2015-4417, Pasadena, CA, August 2015.

[4]Carson III, J. M., Restrepo, C. I., Seubert, C. R., Amzajerdian, F., Pierrottet, D. F., Collins, S. M., O'Neal, T., and Stelling, R., "Open-Loop Flight Testing of COBALT Navigation and Sensor Technologies for Precise Soft Landing," *Proc. AIAA Space 2017 Conference & Exposition*, AIAA 2017-5287, Orlando, FL, September 2017.

[5]Doyle, R., Some, R., Powell, W., Mounce, G., Goforth, M., Horan, S., and Lowry, M., "High Performance Spaceflight Computing (HPSC) Next-Generation Space Processor (NGSP): A Joint Investment of NASA and AFRL," *International Symposium on Articial Intelligence, Robotics, and Automation in Space (i-SAIRAS 2014)*, Montreal, Canada, June 2014.

[6]Woffinden, D., Robinson, S., Williams, J., and Putnam, Z., "Linear Covariance Analysis Techniques to Generate Navigation and Sensor Requirements for the Safe and Precise Landing – Integrated Capabilities Evolution (SPLICE) Project," *Proc. AIAA 2019 SciTech/GN&C Conference*, San Diego, CA, January 2019.

[7]Cianciolo, A. D., Striepe, S., Lugo, R., Karlgaard, C., Powell, R. W., Tynis, J., Woffinden, D., Sostaric, R., and Carson, J., "Defining Navigation Requirements for Future Missions," *Proc. AIAA 2019 SciTech/GN&C Conference*, San Diego, CA, January 2019.

[8]Amzajerdian, F., Pierrottet, D., Hines, G., Petway, L., and Barnes, B., "Fiber-based Doppler Lidar Sensor for Vector Velocity and Altitude Measurements," *Frontiers in Optics 2015*, OSA Technical Digest, 2015.

[9]Amzajerdian, F., Hines, G. D., Petway, L. B., Barnes, B. W., and Pierrottet, D. F., "Development and Demonstration of Navigation Doppler Lidar for Future Landing Mission," *Proc. AIAA Space 2016 Conference & Exposition*, Long Beach, CA, September 2016.

[10]Pierrottet, D. F., Hines, G. D., Barnes, B. W., Amzajerdian, F., Petway, L. B., and Carson III, J. M., "Navigation Doppler Lidar Integrated Testing Aboard Autonomous Rocket Powered Vehicles," *Proc. AIAA 2018 SciTech/GN&C Conference*, AIAA 2018-0614, Kissimmee, FL, January 2018.

[11]Villalpando, C., Werner, R., Carson III, J., Khanoyan, G., Stern, R., and Trawny, N., "A Hybrid FPGA/Tilera Compute Element for Autonomous Hazard Detection and Navigation," *Proc. IEEE Aerospace Conference (AEROCONF 2013)*, March 2013.

[12]Ivanov, T., Huertas, A., and Carson, J., "Probabilistic Hazard Detection for Autonomous Safe Landing," *Proc. AIAA Guidance, Navigation, and Control Conference*, August 2013.

[13]Ward, K. C. and DeMars, K. J., "Including Topographical Effects in Slant-Range Modeling," *Proc. AIAA 2018 SciTech/GN&C Conference*, AIAA 2018-1333, Kissimmee, FL, January 2018.

[14]Helmuth, J. C., Ward, K. C., and DeMars, K. J., "Fusion of Multiple Terrain-Based Sensors for Descent-to-Landing Navigation," *Proc. AIAA 2019 SciTech/GN&C Conference*, San Diego, CA, January 2019.

[15]Kratzer, K., Helmuth, J., Ward, K., and DeMars, K., "Impact of Sensor Model Fidelity and Scheduling on Navigation Performance," *Proc. AIAA 2018 SciTech/GN&C Conference*, AIAA 2018-1334, Kissimmee, FL, January 2018.

[16]McCabe, J. S. and DeMars, K. J., "Robust, Terrain-Aided Landing Navigation through Decentralized Fusion and Random Finite Sets," *Proc. AIAA 2018 SciTech/GN&C Conference*, AIAA 2018-1332, Kissimmee, FL, January 2018.

[17]McCabe, J. S. and DeMars, K. J., "Landing Navigation With Terrain Aiding Using Prioritized Features," *Proc. AIAA 2019 SciTech/GN&C Conference*, San Diego, CA, January 2019.

[18]Reynolds, T. P., Szmuk, M., Malyuta, D., Mesbahi, M., Acikmese, B., and Carson, J. M., "A State Triggered Line of Sight Constraint for 6-DoF Powered Descent Guidance," *Proc. AIAA 2019 SciTech/GN&C Conference*, San Diego, CA, January 2019.

[19]Malyuta, D., Reynolds, T. P., Szmuk, M., Mesbahi, M., Acikmese, B., and Carson, J. M., "Discretization Performance and Accuracy Analysis for the Rocket Powered Descent Guidance Problem," *Proc. AIAA 2019 SciTech/GN&C Conference*, San Diego, CA, January 2019.

[20]Trawny, N., Benito, J., Tweddle, B., Bergh, C. F., Khanoyan, G., Vaughan, G. M., Zheng, J. X., Villalpando, C. Y., Cheng, Y., Scharf, D. P., Fisher, C. D., Sulzen, P. M., Montgomery, J. F., Johnson, A. E., Aung, M., Regehr, M. W., Dueri, D., Açikmeşe, B., Masten, D., O'Neal, T., and Nietfeld, S., "Flight testing of terrain-relative navigation and large-divert guidance on a VTVL rocket," *Proc. AIAA SPACE 2015 Conference & Exposition*, August 2015.

[21]Scharf, D., Regehr, M., Dueri, D., Acikmese, B., Vaughan, G., Benito, J., Ansari, H., Aung, M., Johnson, A., Masten, D., Nietfeld, S., Casoliva, J., and Mohan, S., "ADAPT Demonstrations of Onboard Large-Divert Guidance with a VTVL Rocket," *Proc. IEEE Aerospace Conference*, March 2014.

[22]Carson III, J. M., Seubert, C. R., Amzajerdian, F., Bergh, C., Kourchians, A., Restrepo, C. I., Villalpando, C. Y., O'Neal, T., Robertson, E. A., Pierrottet, D. F., Hines, G. D., and Garcia, R., "COBALT: Development of a Platform to Flight Test Lander GN&C Technologies on Suborbital Rockets," *Proc. AIAA 2017 SciTech/GN&C Conference*, AIAA 2017-1496, Grapevine, TX, January 2017.

[23]Restrepo, C. I., Carson, J. M., Amzajerdian, F., Seubert, C. R., Lovelace, R. S., , McCarthy, M. M., Tse, T., Stelling, R., and Collins, S. M., "Open-Loop Performance of COBALT Precision Landing Payload on a Commercial Sub-Orbital Rocket," *Proc. AIAA 2018 SciTech/GN&C Conference*, AIAA 2018-0613, Kissimmee, FL, January 2018.

[24]Steffes, S. R., Monterroza, F., Mario, C., and Benhacine, L., "Optical Terrain Relative Navigation Approaches to Lunar Orbit, Descent and Landing," *Proc. AIAA 2019 SciTech/GN&C Conference*, San Diego, CA, January 2019.