Development and Testing of Precision Landing GN&C Technologies

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Charts herein include content provided by multiple NASA centers and supporting institutions.
The Motivation for PL&HA Technology

- Enable landing at locations that pose significant risk to vehicle touchdown or payload deployment (including near pre-positioned surface assets)

- Technology has been deemed critical in NASA and NRC Space Technology Roadmaps and architecture studies for future robotic and human missions
  - Required for future human landings on Mars
  - Enabler for robotic exploration of new destinations
What is the NASA PL&HA domain?

- NASA development, testing and infusion of GN&C technologies for controlled, precise and safe landing
- Investments have come through multiple HQ Directorates (STMD, SMD, HEO) and have included multi-center collaboration in past & present projects:
  - ALHAT (Autonomous precision Landing and Hazard Avoidance Technology)
  - LVS (Lander Vision System)
  - COBALT (CoOperative Blending of Autonomous Landing Technologies)
  - Lander Technologies (LT)
  - ILS (Intelligent Landing System)
  - SPLICE (Safe & Precise Landing – Integrated Capabilities Evolution)
- Domain includes technologies for sensors, algorithms, avionics, software & techniques for missions (robotic or human) having various Concepts of Operation (ConOps) and various terrain illuminations (light/shadow/dark)
Goal
• Develop multi-mission technologies that become part of the standard suite of GN&C capabilities
• Develop technologies for robotic missions that also feed forward into future human missions

Approach
• Develop and maintain a PL&HA knowledge base that captures robotic and human mission needs
• Prioritize technologies that promote multiple robotic missions and align to human mission needs
• Form a cross-directorate strategy and leverage multi-center/multi-project partnerships

Agency PL&HA Projects
- ALHAT
- ALHAT / Morpheus
- LVS
- ILS
- COBALT
- SPLICE
- Lander Tech + CATALYST

Infusion Mission Opportunities
- CLPS Public-Private Lunar
- Mars Sample Return
- Discovery
- Europa Lander
- New Frontiers 5
- Human (Lunar -> Mars)
- follow-on PL&HA project

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Progression of GN&C Landing System Capabilities
Controlled – Precise – Safe

GN&C Subsystem

- **Controlled Landing**
  - IMU, Altimeter, Velocimeter, Touch down sensor

- **Precise Landing**
  - Add: Terrain Relative Navigation (TRN)

- **Safe Landing**
  - Add: Hazard Detection & Avoidance (HDA)

**Controlled Landing**

- Minimize vertical descent rate and lateral velocity to ensure a soft (or controlled) touchdown
- No knowledge of global position – “blind” landing

**Precise landing – Terrain Relative Navigation (TRN)**

- Global navigation through onboard matching of real-time terrain sensing data with \( a \ priori \) reconnaissance data
- Enables efficient maneuvering to minimize landing error and avoid large hazards identified in \( a \ priori \) analyses

**Safe Landing – Hazard Detection & Avoidance (HDA)**

- Real-time terrain sensing to identify sites safe from lander-sized hazards that are undetectable in \( a \ priori \) data
- Enables a hazard avoidance maneuver to the identified safe site
- Can be leveraged for subsequent Hazard Relative Navigation (HRN) – similar to TRN
Portfolio of Current **PL&HA** Technologies

**Controlled (Soft) Landing**

*Velocity and/or Range Sensing*

- **Navigation Doppler Lidar (NDL)**
  - TRL 5+ (6 in FY19)
  - Line-of-site velocity of 200 m/s (±1.7-cm/sec, 1σ)
  - Line-of-site range of 4+ km (±2.2m, 1σ)
  - dev & test in ALHAT/Morpheus, COBALT, & SPLICE

- **Long-range Laser Altimeter (LAlt)**
  - TRL 4
  - Range in vacuum, 50+ km (5 cm, 1σ)
  - dev & tested in ALHAT/Morpheus

- **Optical Velocimetry** (many in development)
  - TRL 3+
  - Estimates from image-based feature tracking and optical flow

**Precise Landing**

*Terrain Relative Navigation (TRN)*

- **Passive-Optical/Camera-Based**
  - (requires illuminated terrain: applicable to most missions)
  - JPL Lander Vision System (LVS): camera + IMU +
    dedicated computing **to be TRL 9 with Mars2020**
  - TRN solutions also available from APL, Draper &
    elsewhere in dev for multiple mission concepts
  - JPL Intelligent Lander System (ILS)
    - TRL 5+ (6 in FY19)
    - JPL Intelligent Lander System (ILS)
      - TRL 4
      - in dev for Europa Lander concept

- **Active/Lidar-based**
  - TRL 3-4
  - (dark/shadowed or illuminated terrain)
  - dev & tested in ALHAT

**Safe Landing**

*Hazard Detection (HD) and Hazard Relative Nav (HRN)*

- **Hazard Detection System (HDS)**
  - TRL 4
  - Flash lidar + gimbal + dedicated IMU + dedicated computing
  - Range, 1 km (±8cm, 1σ)
  - Generates 100mX100m map & safe landing sites within 10-12 sec
  - dev & tested in ALHAT/Morpheus

- **Hazard Detection Lidar (HDL)**
  - in dev & test within SPLICE
  - TRL 3 (5 in FY2020)
  - Scan array lidar + FPGA. Provides long-range altimetry and
    rapid medium- & short-range high-resolution terrain maps

- **JPL Intelligent Lander System (ILS)**
  - in dev for Europa Lander concept

**PL&HA Computing**

*Descent & Landing Computer (DLC)*

- HPSC (High Performance Spaceflight Computing) multicore A53 (extendable) +
  FPGAs (extendable) + PL&HA sensor interfaces
  - TRL 3 (5 in FY2020)
  - in dev & test within SPLICE

- STMD

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GN&C for Landing: Status Quo Vs. PL&HA

Mission landing needs and risk posture define which PL&HA capabilities to use

Status Quo
(Blind Soft Landing)

PL&HA
(Precise & Safe Soft Landing)

Initial Entry
mission-dependent deceleration method

Powered Descent

Terminal Descent

Landing Ellipse

Radar Velocimeter

IMU

Altimeter

Initial Entry

Intelligent Powered Descent

Hazard Detection
(Find Safe Site)

Local Divert

Terminal Descent

TRN
Terrain Relative Navigation

HD
Hazard Detection

HRN
Hazard Relative Navigation

TRN: global position knowledge
Minimizes landing ellipse & avoids large hazards seen in reconnaissance maps

HD & HRN: local terrain knowledge
avoid small hazards & minimize local landing error

Velocimetry & Ranging: precise soft landing
Significantly improves navigation precision

Advanced GN&C Algorithms
enables the precise state knowledge and intelligent maneuver logic

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Extensive NASA Portfolio of PL&HA Technology Development & Testing

MER-DIMES: 2001-2004
TRN Precursor

ALHAT 2011 HD Truck Tests at LaRC range

ALHAT 2011 NDL Gantry Tests at LaRC

ALHAT FT3: July 2009, TRN flights over Nevada Test Site

Sounding Rockets: 2005-2010, TRN Flights

Landmarks in Map

Landmarks in Descent Images

LVS Heli Test: Feb/Mar 2014 in Death Valley

Mars analog terrain

Lunar analog terrain (100m X 100m)

ALHATFT5: Dec 2012, NDL+HD flights at KSC SLF

LVS/Xombie Test: Dec 2014 in Mojave, CA

ALHAT/Morpheus: 2014, HD+NDL flights at KSC

COBALT/Xodiac PL&HA Test 2017+ in Mojave, CA
Overview of NASA SPLICE Project (FY2018-FY2020)

- Multi-Directorate, Multi-Center PL&HA project
  - Centers: JSC, LaRC, GSFC, AFRC, MSFC, JPL (in planning for FY19-20), KSC (FY19-20)
  - Directorates: STMD-GCD, HEOMD-AES, STMD-FO, SMD-PSD
    - STMD-GCD: oversight and support for all SPLICE elements
    - HEOMD-AES: support for NDL element and synergy with cFS-based flight software development
    - STMD-FO: support for suborbital flight test element (COBALT portion)
    - SMD-PSD: support for NDL path-to-flight components

- Project Components (Elements)
  - NDL: Implement an **NDL (Navigation Doppler Lidar) Engineering Test Unit (ETU) & Achieve TRL6** in FY2019
  - ConOps: Develop a **multi-mission PL&HA requirements matrix** for relevant robotic science & human exploration destinations (to drive PL&HA infusion & investment)
  - Avionics: Develop an **HPSC-surrogate DLC (Descent & Landing Computer) to TRL 5** for future COBALT tests and spaceflight infusion missions
  - HD: Design, develop, and test a **multi-mission HDL (Hazard Detection Lidar) to TRL 5** with relevance to future robotic & human missions
  - HWIL Sim/SW: Evolve **HWIL sim/test capabilities and PL&HA flight software** to foster PL&HA infusion into NASA & US commercial missions
  - Field Test: conduct NDL environmental tests, validate NDL & HDL performance on airborne vehicles, and lead **closed-loop COBALT flight tests** on the Xodiac suborbital rocket
Closing Remarks

• The NASA PL&HA domain includes a diverse suite of GN&C technologies for precise and safe landing
• Many of these PL&HA technologies are approaching readiness for infusion into near-term robotic science missions
• PL&HA capabilities enable new mission concepts by enlarging the trade space of feasible landing sites for surface exploration
• Development of PL&HA technologies for robotic missions also benefits future human missions
Backup
• Six flights: three open-loop & three closed-loop
• Tested safe and precise landing technologies
  - NDL (Gen-2), HDS (Gen-1), Laser Altimeter
  - TRN was not a part of the Morpheus tests
• Successfully demonstrated integration and flight testing of ALHAT capabilities and techniques
• Performed one flight test in darkness

Approx. 450 m slant range
30 degree glideslope

Launch from “flame trench” pad

Land in 100m x 100 m hazard field

ALHAT Landing Site Selection
2017 COBALT Flights on Masten Xodiac

- COBALT: CoOperative Blending of Autonomous Landing Technologies
- Platform to mature TRL and reduce risk for spaceflight infusion of GN&C PL&HA technologies
- Multi-center collaboration: JSC, Langley, JPL
- Multi-directorate partnership: STMD & HEOMD

**Nav modes:**

- TRN
- NDL
- IMU

**Altitude:**

- 500 m: Apogee
- 465 m
- 300 m
- 250 m
- ~100 m
- ~5 m
- 20 m: Masten Auto-land

**Divert:**

- Laterally at max 25 m/s velocity
- Achieve > 25 m/s downward descent

**Pre launch:** Initialize pose

**ADAPT Altitude:**

- 20 m

**Morpheus Altitude:**

- 60 m

**TRN measurements:**

- Commence (and end)

**NDL measurements:**

- Commence

**IMU only**