MOON 2020-2030

A new era of human and robotic exploration

BB7: VISUAL NAVIGATION, HAZARD DETECTION AND AVOIDANCE

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ESA/ESTEC Noordwijk
14 December 2015

European Space Agency

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DEFINITIONS AND REQUIREMENTS

NAVIGATION DEFINTION

- NAVIGATION is the process to find the present and future position and orbit of a spacecraft using a series of measurements
  - Step 1: MEASURING
    - Obtaining state vectors (x, y, z, Vx, Vy, Vz,...) at timely intervals
  - Step 2: DETERMINING
    - Reconstructing the orbit and attitude based on a set of state vectors
  - Step 3: PREDICTING
    - Forecasting the imminent future state vector

CCSDS P1J standard

NAVIGATION REQUIREMENTS

Mission Arc	Requirements (3σ)
Interplanetary cruise	500/10000 km (Asteroid / Planet Encounter) 500-1000 km for low-thrust DS maneuver
Interplanetary approach	3 km up to encounter (asteroid) 30 km up to – 3 hrs (gravity assist)
Far rendezvous	100 Km distance error knowledge 1 deg accuracy azimuth and elevation
Intermediate rendezvous	10 Km distance error knowledge 0.1 deg accuracy azimuth and elevation
Close rendezvous	10 m distance error knowledge 0.01 deg accuracy azimuth and elevation
Descent	Velocity < Mach 2 (parachute opening) TAEM gate better than 2000 m wide
Landing and touch down	Velocity < 1 m/s (soft Landing) Precision landing better than 200 m

CURRENT NAVIGATION PERFORMANCES

Mission Arc	Current performances	Means
Interplanetary cruise	10000 km (Asteroid / Planet Encounter) with NPAL camera	
Interplanetary approach	30 km (gravity assist) with NPAL camera	
Far rendezvous	300 m distance error knowledge at 20 Km with LABEN ATV GPS receiver (corporative rendezvous)	
Intermediate rendezvous	1 m distance error knowledge at 1000 m with JENA Laser Range Finder (corporative rendezvous)	
Close rendezvous	0.2 m distance error knowledge at 50 m 0.01 deg accuracy azimuth and elevation with JENA Laser Range Finder (corporative rendezvous)	
Descent	Velocity < Mach 2 (parachute opening) TAEM gate better than 2000 m wide	
Landing and touch down	Velocity < 5 m/s (hard Landing) Precision landing of 50 Km with ExoMars RDA sensor	

HAZARD AVOIDANCE MANOEUVRES

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RETARGETING FUNCTION FOR HAZARD AVOIDANCE

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MOON LANDING SITES EXAMPLES

Amundsen site

Russian reference site

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BUILDING BLOCK 7
COMPONENTS AND ELEMENTS

BB7 Composition and Sub-blocks

- Visual navigation, hazard detection and avoidance Building Block BB7 composed of sub-blocks:
  - 1.- Sensors
  - 2.- Image Recognition and Processing for Navigation
  - 3.- Data fusion
  - 4.- Advanced Guidance and Control algorithms
  - 5.- High Performance Computing
  - 6.- Multi-disciplinary Optimization
  - 7.- Verification and Validation

Sensors

- Vision-based cameras
- LIDAR
  - flash, scan
- Multi-spectral cameras
  - IR and UV
- Altimeters
  - laser, radar

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SENSOR EXAMPLES

- NPAL Navigation for Planetary Approach and Landing camera + image processing board + navigation filter
- PILOT navigation camera (more of this in the next presentation)
- ABPA radar and laser altimeters
- JOP scanning LIDAR
- CAMIR InfraRed camera
- ERB HyperSpectral camera

IMAGE RECOGNITION AND PROCESSING FOR NAVIGATION

- European FEIC (Feature Extraction and Image Correlation)
- Optical Flow Correlators
- Beyond the Kalman Filter estimators
  - deterministic, stochastic

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EXAMPLES OF MAGE RECOGNITION AND PROCESSING FOR NAVIGATION

- Relative Navigation vs Absolute Navigation
- UNI Dundee FEIC (Feature Extraction and Image Correlation): feature detection and feature extraction
- UNI Dresden Optical Flow Correlator
- GMV Beyond the Kalman Filter estimators:
  - Deterministic estimation: Kalman-like estimation, Wiener estimator (WE), Particle filter estimators (PF), Method of moments (MoM), Minimum-variance unbiased estimator (MVUE)
  - Stochastic estimation: Maximum likelihood estimators (ML), Bayes estimator (BE), Minimum mean squared error estimator (MMSE), Maximum a posteriori estimation (MPE), Markov chain Monte Carlo (MCMC

Refined Detected Craters

DATA FUSION

- Hybrid Navigators:
  - Loosely coupled
    - STR and INS
    - INS and CAM
    - INS and LIDAR
    - LIDAR and CAM
  - Tightly coupled
    - GPS and INS

EXAMPLES OF DATA FUSION FOR LANDING

- Use of Several sensors to obtain the best possible state vector
- Surface-relative navigation and Absolute navigation (known landmarks)
- Navigation: (few-meter accuracy): switch from absolute to relative; Additional sensors for surface-relative attitude estimation
- Modular Vision-Based Navigation System design composed of building blocks
  - Image Acquisition System: optics, detector, acquisition, pre-processing
  - Image Processing Board (IPB): implements both HW and SW IP functions through mix of DSP and FPGA (ASIC in a flight implementation)
  - Inertial Measurement Unit (mission-dependent): required by navigation for rolling shutter compensation and aiding
  - Star tracker

ADVANCED GUIDANCE AND CONTROL ALGORITHMS

- Optimal guidance profiles for descent and landing
- Re-targeting functions
- On-Board Real-Time Trajectory Optimisation
- Advanced Robust Multi-variable Control

EXAMPLES OF ADVANCED GUIDANCE AND CONTROL ALGORITHMS

- Optimal guidance for descent and landing
- Advanced multivariable robust control for high accuracy re-targeting functions
- EAGLE Model-based simulator design framework for the development of guidance, navigation and control (GNC) systems and related embedded software for planetary Entry, Descent and Landing systems throughout the development phases of the space system engineering life-cycle (SSEL)
- Automatic generation of production code (C code) is TargetLink® from dSPACE
- The real-time development/simulation environment is based on a dSPACE modular simulator and ASTA LEON spacecraft avionics development platform from Aeroflex that is used for the validation of the embedded flight software
- Simulates and analyses Entry, Descent and Landing systems on planetary bodies with or without atmosphere

HIGH PERFORMANCE COMPUTING

- Multiple Cores CPUs
- European FPGA and DSP
- High performance data buses
- Electronic Data Sheets
- Many-cores Real-Time Operating Systems
- Time and Space Partitioning

EXAMPLES OF HIGH PERFORMANCE COMPUTING

- European elements for high performing data handling architectures:
  - FPGA and DPS
  - Multi-core computers with fault tolerance features
- Real-time Software performance for high computing architectures

MULTI-DISCIPLINARY OPTIMIZATION

- Optimization of trajectories, propulsion, and staging all at once
- Optimization of placement of sensors and actuators
- Co-design of Structures and Control

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EXAMPLES OF MULTI-DISCIPLINARY OPTIMIZATION

- Optimization at once of trajectories, structures, propulsion for Moon landers
- MDO for Moon ascent vehicles: single stage vehicle with all-at-once design optimization
- Co-design of control and structures
- Optimization of sensor placements across mission arcs, mission types, and mission requirements

VERIFICATION AND VALIDATION

- Simulators and Emulators
- SIL=>PIL=>HIL testing sequences
- Ground test benches for optical, infrared and LIDAR V+V
- All-at-once verification and validation facilities
- In-Orbit Demonstrators

EXAMPLES OF VERIFICATION AND VALIDATION

- PANGU Surface modeller: realistic surfaces (MLI, OSR, solar cells…)
- GNC Ground Testing Facilities
  - DLR TRON For Descent and Landing
  - DLR EPOS For Rendezvous and Docking
- PLGTF Ground demonstrator
- MORPHEUS Ground demonstrator
- SPARTAN Ground Demonstrator
- LIRIS In-Orbit Demonstration opportunities

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FUTURE DEVELOPMENTS AND NEEDS

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- Need: Improvement of the current sensor systems
- Need: Improvement of the current estimation function of the navigation chain
- Need: Sensing using different wavelengths (others than visual spectrum cameras)
- Need: Fast, accurate, and robust image processing
- Need: data fusion coming from different sensors, and hybrid navigation
- Need: High performance computing architectures

THANK YOU

European Space Agency