SIMU-LANDER
Hazard avoidance & advanced GNC for interplanetary descent and soft-landing

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3rd International Workshop on Astrodynamics Tools and Techniques

ESTEC - 04/10/06
Outline

• Simulator presentation
• Models
• Hazard avoidance:
  – Hazard mapping function
  – Piloting function
• Navigation function
• Guidance
• Control function
• Improvement
• Demonstration
Simulator Functionnalities

- Camera or LIDAR or radar (if no HM needs)
- Navigation
- IMU
- Risks maps
- Shadow zones
- Scientific interest
- Local slope
- Hazard Detection (Camera or LIDAR)
- Maps & time fusion
- Simplified guidance
- Re-targeting
- Guidance constraints (propellant, visibility …)
- Control relative velocity

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Simulator Objectives

- Hazard avoidance & GNC platform for interplanetary powered descent soft-landing developed for:
  - Lander mission and vehicle concept studies
  - G, N, C and sensors trade-off and specifications
  - GNC and hazard avoidance algorithms assessments
  - Performance analysis

- Platform dedicated to Mars or Lunar Lander mission studies to design the mission & GNC of a descent & landing system
Simulator Architecture

- Simulink environment
- Modular and generic architecture allowing easy models and flight software improvements, adaptation to any planet
- Data flow transfers by the mean of Simulink buses
- Environment/Dynamics: currently models for lune or mars
Simulator
Flight software architecture

- Several navigation modes: Inertial Only Navigation, Vision, Radar and LIDAR (under development) Based Navigation
- Retargeting (supervisor in the loop) or not
- Algorithms step by step G,N,C validation available
Environment models

- **Planet**: spherical or ellipsoid; Kepler, J2 or J3 gravity model
- **Environment (Mars)**: Atmosphere (EMCDB), Aerodynamics (6 dof) & Wind models
- **Propulsion/Dynamics**: Parametric propelled lander (up to 20 thrusters)
- **MCI**: variable mass, C & I constants, CoG offset
- **Sloshing modes**
- **Monte-carlo mode**
Environment models
Scene generator

- PANGU (V2.6) : Synthetic Scene generator

- Craters
- Boulders
- Dunes
- Ground model
- Shadows
- Illumination
- Ambiant light
- Light Reflection models
Environment models
Scene generator

- **Main assets of Pangu:**
  - Possibility to create a client/server interface with Matlab:
    - Matlab => camera position/attitude
    - Pangu => associated picture
  - Possibility to use MOLA DEM from the NASA to generate the surfaces
  - Possibility to create surfaces of different resolutions

Mars photography

Pangu picture using the MOLA
Sensors models

- IMU: bias and scale factors
- LIDAR: currently model from PANGU
- Camera model

- Blur effect
- Pixellization
- Optical transfert function

IR

Convolution

Image

Add CCD Noise

Noisy image
Sensors models

- Doppler radar:
  - Generic raw data model \((r, r_{dot})\)
  - Detailed error models: misalignments, bias…
  - Operationnal limitations
Hazard avoidance

- Give to the guidance function the location of a landing site considered as safe
- This process is divided into 2 functions
  - Site classification: produce risk maps for different criteria
    - Slopes
    - Shadows
    - Obstacles (e.g. craters, boulders…)
  - Piloting function: map fusion & decision process to determine, given the guidance and mission management constraints, the best safe target for landing
- Objective: to maximise mission success even in difficult terrain
Hazard mapping – Camera Shadows and saturated zones detection

- Passive camera cannot detect obstacles in dark and saturated areas
- The "shadow and saturated zones risk map" can so be simple using thresholds techniques

Image generated by PANGU

Shadow risk map
Hazard mapping – Camera Obstacles detection

- Texture analysis: An obstacle can be feared under space changing response
- Methods:
  - Variance
  - Correlation
  - Derivative of the correlation
- CPU requirements and obstacle size coverage can be improved with Gaussian or Laplace pyramids

Variance

Derivative of the correlation

PANGU image
Hazard mapping – Camera Obstacles detection

- Precisely locate craters and boulders (example with variance method with three window sizes – multi-resolution - on the image):

- With camera:
  - Camera field of view: 70°
  - Image size: 1024x1024 pixels

- Smallest obstacle detected 50cm at a 100m altitude
Hazard mapping – Camera Slope estimation

- **Shape from shading / Carlotto**
  - Typical assumption needs
    - Lambertian reflectance model
    - constant albedo on the surface of the moon
    - sun is the unique light source and is distant
    - sun elevation known

- **3D reconstruction by move without previous simplification assumptions (currently under development):**
  - From image motion between several images
  - “Reconstruction” from 3D points delivered by the camera (NPAL)
Hazard mapping – Camera Slope estimation

Reference slope map

- Altitude map
  - From DEM

- Slope map
  - mean plane computation with the least median squares method
Hazard mapping – LIDAR

- LIDAR based (under development)
  - Regridding ➔ 3D elevation model
  - Mean slope computation
  - Roughness computation
Hazard avoidance Piloting function

- Pre define site
- Original maps

- GNC information
  - Lander to candidate sites state
  - Guidance function for sites accessibility

- Evolution of the site risk
- Available fuel
- Sites/attributes time history

- Decision maker
  - Evidence theory (Dempster-shafer), fuzzy logic...

- Scientific interest & sun visibility

- List of candidate sites

- Texture risk map
- Shadows risk map
- Slopes risk map

Fusion & decision Processes

New landing site

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Navigation function

- Provides to guidance the vehicle relative state with respect to the chosen landing site

- Navigation state:
  - Relative position
  - Relative velocity
  - Attitude quaternion of the vehicle with respect to the local geographic frame
  - IMU defects (biases and drifts)
Navigation function

• Generic filter of navigation:
  – State-of-the art Extended Kalman filter
  – Inertial propagation
  – Update with altitude, velocity or attitude measurements
  – Generic implementation

  ➔ measurements can come from any external sensor:
  • Radar altimeter
  • Doppler radar
  • Camera
  • Imaging radar
  • Lidar
Navigation function Camera

- Sensor information ➔ measure of relative motion
- Vision Based Navigation:
  - Tracking of landmarks through successive images
    - Features points extraction and matching
    - Computation of the homography (camera rotation and translation) – Horn algorithm -
    - Range sensor needed
  - Processing of camera rotation and translation to update the filter
Navigation function
DOPPLER RADAR

- Sensor measurements processings to update the filter
Navigation function
LIDAR

Lidar raw data processing (under development)

- Scanning Lidar provides 3D maps of the form two angles and a range
- Raw measurements are processed to obtain a 3D map onto a regular grid in the local geographic frame
  - Measurement extraction
  - Hazard mapping
- Measurement extraction:
  - Altitude
  - Velocity from two consecutive maps
Velocity extraction:

- Estimate common area $W$ between two consecutive maps $Z_1(x,y)$ and $Z_2(x,y)$
- Translation $(T_x, T_y, T_z)$ between maps obtained by minimizing:

$$
v = \sum_{W} (Z_1(x + T_x, y + T_y) + T_z - Z_2(x, y))^2
$$

Knowledge of translation and delay between two maps

→ Velocity measurement
Guidance and control functions

- **Guidance:**
  - acceleration cmd ⇒ rate of max. available thrust
  - Selection among several techniques:
    - gravity turn / neural networks / feedback trajectory control / bilinear tangent law / predictor-corrector
  - Robust to retargeting

- **Attitude control:**
  - classical PID controller for the 3 axes

- **Thrust monitoring function:**
  - Braking: number of engines to be ignited (0-1-2-3 for each cluster)
  - Y-Z (X) control: deadband zone for ignition of braking (roll) thrusters
Guidance Statistical analysis

- Monte-Carlo analysis based on 100 runs
  - Deviations on propulsion, aerodynamics, initial conditions…
  - Vertical velocity at landing < 2.2 m/s at 3σ (mean = 1.8 m/s)
Demonstration

Video