ESA Workshop on GNC for Small Body Missions

Autonomous GNC Systems Applied to Interplanetary Missions: the NEO Descent and Landing Case

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INNOVATING SOLUTIONS

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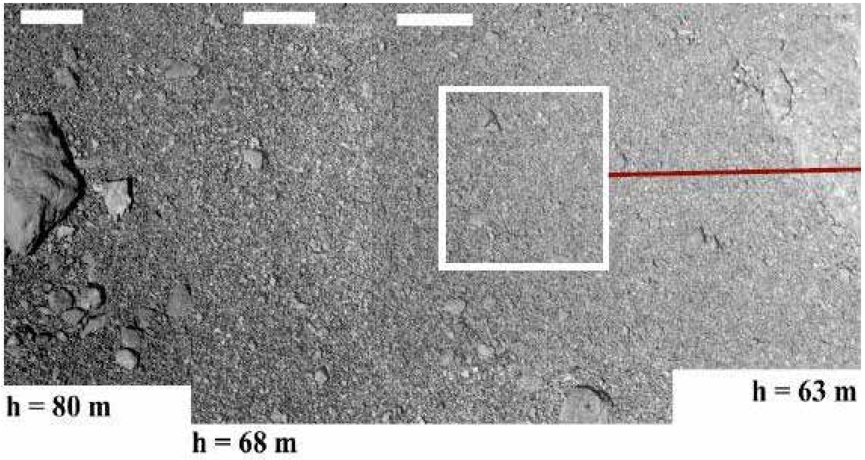


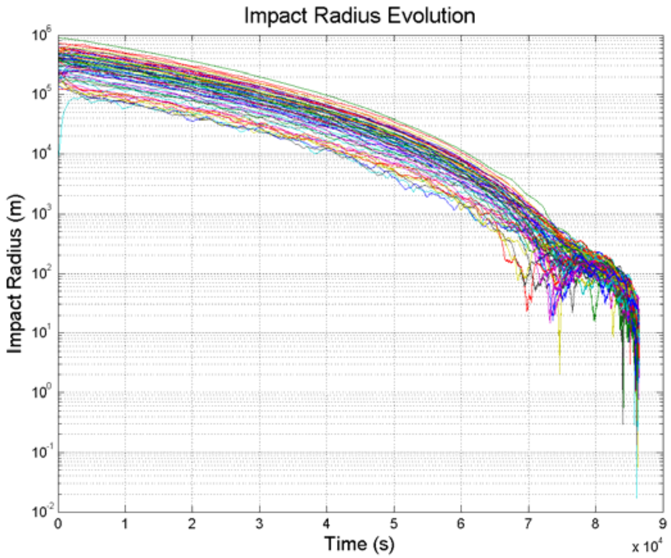
Asteroid Itokawa observed from Hayabusa during close-up #1 (credits JAXA)

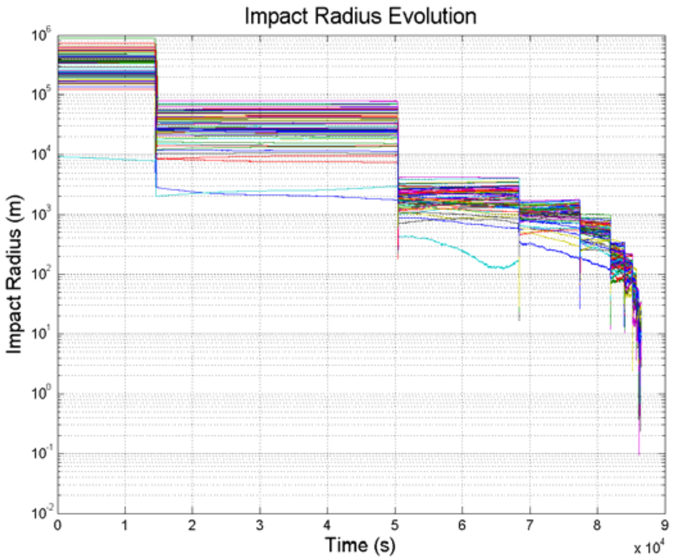
Landing region image taken by NEAR-Shoemaker before landing on 433 Eros (credits NASA)

Autonomous GNC Background - CLEON

Terminal GNC For NEO Impactor

- Mission characteristics
  - – Low-cost (mass, quality)
  - – Small (faint) target
  - – Hypervelocity (10 km/s)
- Sensors: STR + IMU + NAVCAM
- IP: Stacking + Thresholding + Centroiding
- Navigation filters
  - – Digital fading memory
  - – Batch-sequential least squares
  - – Kalman-Schmidt
- G&C strategies
  - – Predictive-Impulsive (10 N)
  - – Proportional Navigation (0.15 N)
  - – Mixed predictive-proportional (1 N)

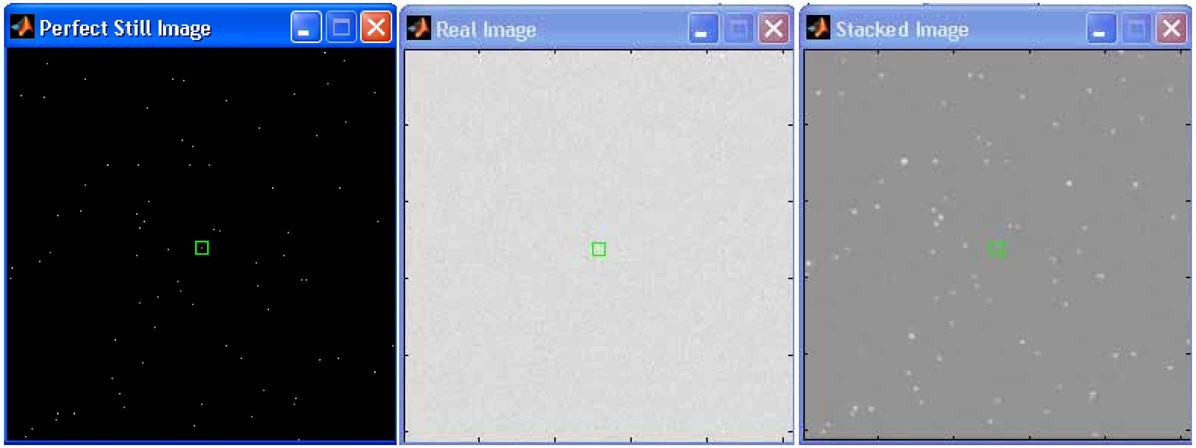


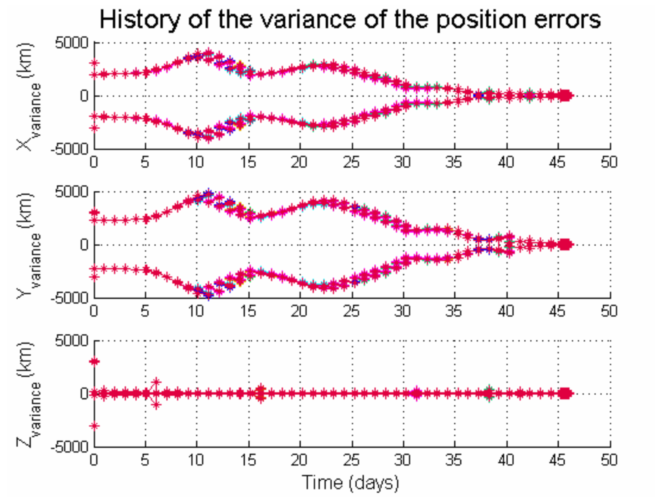


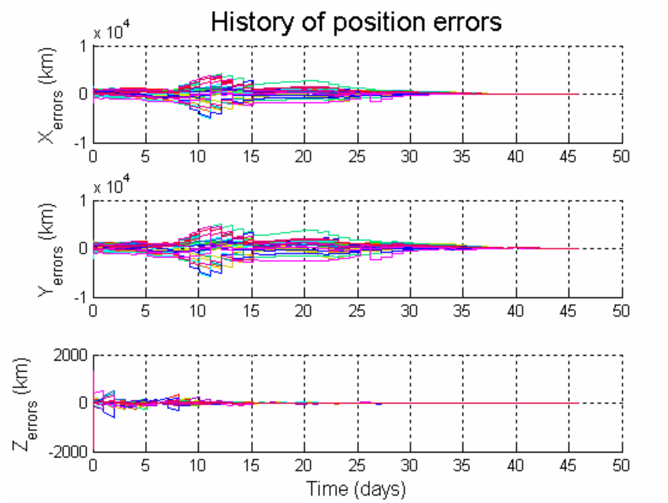
Autonomous GNC Background - CHILON

GNC For NEO Rendezvous (Approach)

  - Low-cost, small target
- Image Processing
  - Target detection & identification
  - Auto-tracking
- Navigation filters
  - Unscented Kalman
  - Kinematic filter (guidance coupling)
- G&C: way-points tracking strategy
  - Differential guidance (impulsive)
  - Optimal control (low-thrust)



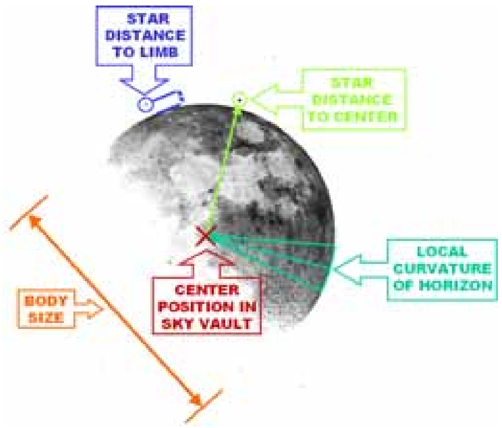


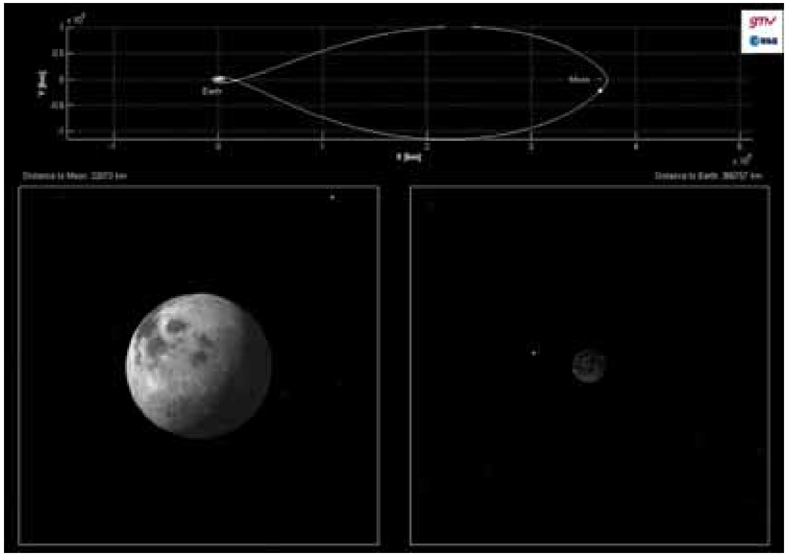


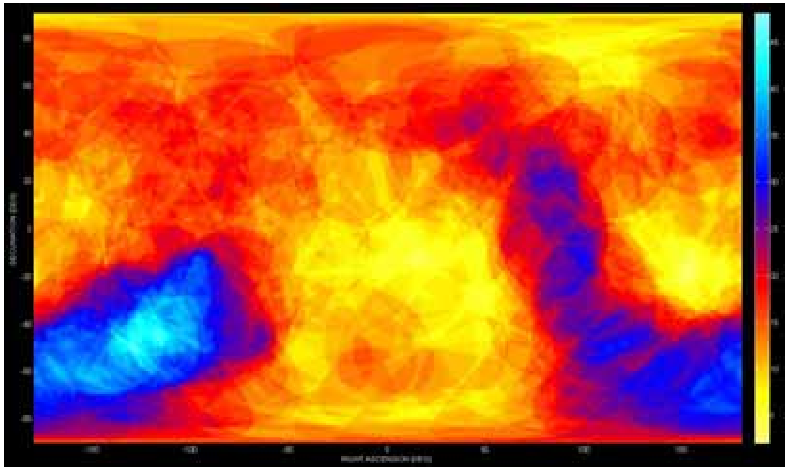
Auto. GNC Background – Lunar Missions (1/2)

Autonomous Navigation for Human Missions (emergency system)

- All phases from LEO to re-entry
  - Sensor sizing (camera-only)
- Different types of optical meas.
  - Earth & Moon directions, ang. size
  - Star to limb, star occultation
  - Image matching
- TRL-4/5 (HIL tests in optical lab.)





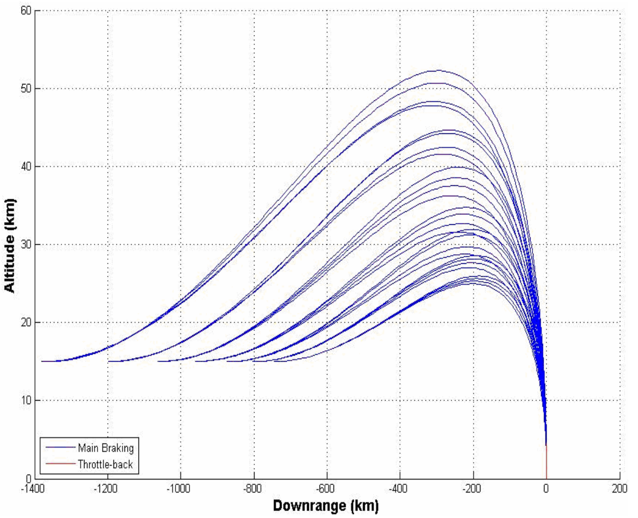


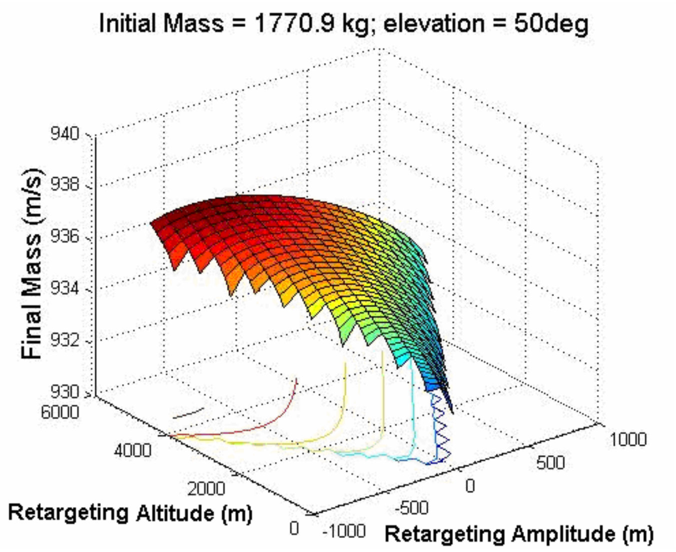
Number of stars brighter than 3.5 magnitudes in a 27.67º-radius circle centred in the direction (between 1 and 48 stars, 16.5 stars in average)

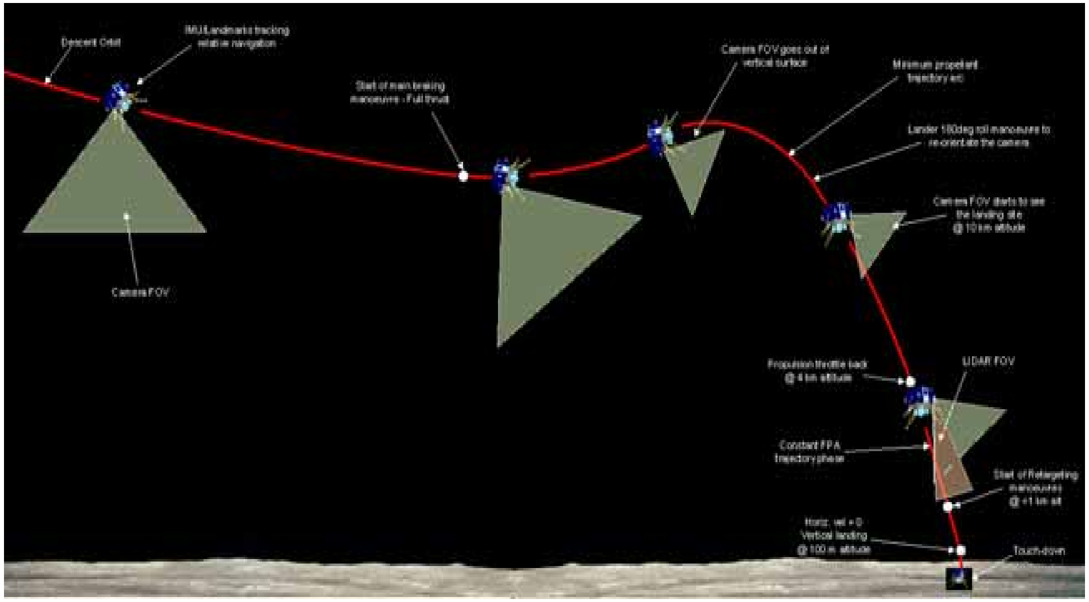
Auto. GNC Background – Lunar Missions (2 / 2)

Auto. GNC for D&L in Robotic Missions

- Precise, soft landing
- Guidance: look-up tables
  - Optimal trajectory ground-computed
  - Retargetting capability (hazard avoidance)
  - Constraints: navigation + ACS
- Feed-forward control (finite-horizon)



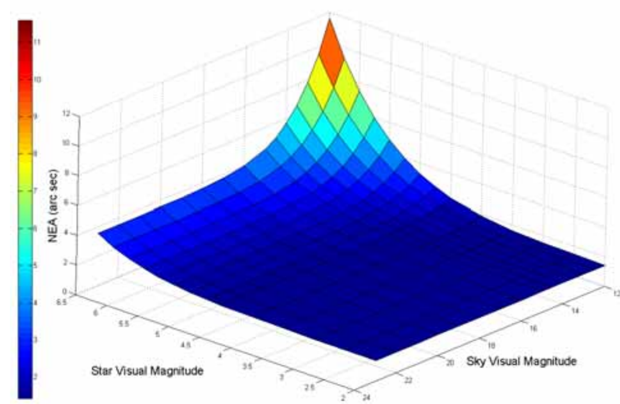


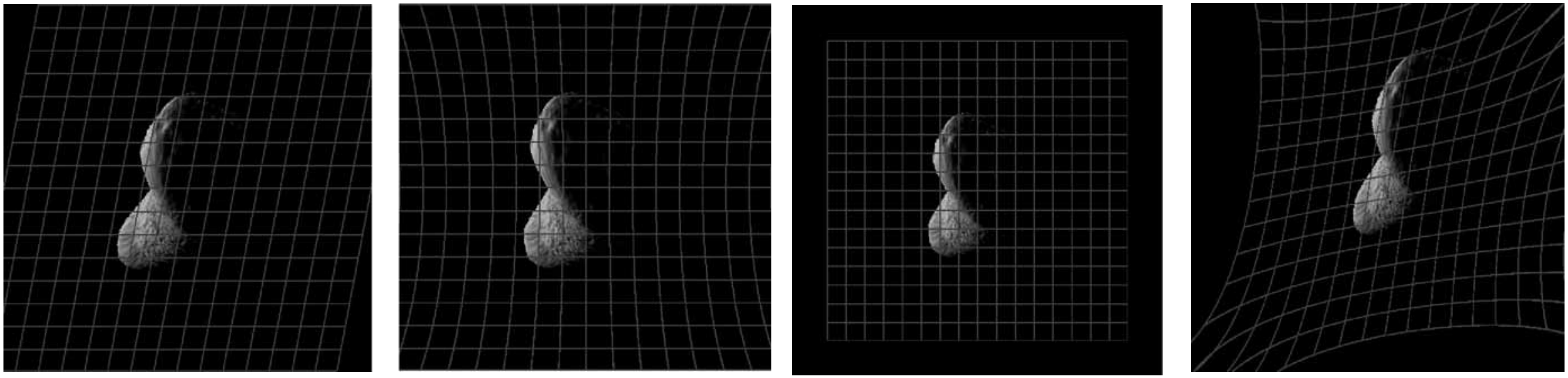


Auto. GNC Background – Validation (1/2)

Monte Carlo analysis with hybrid, multi-rate, high-fidelity simulator

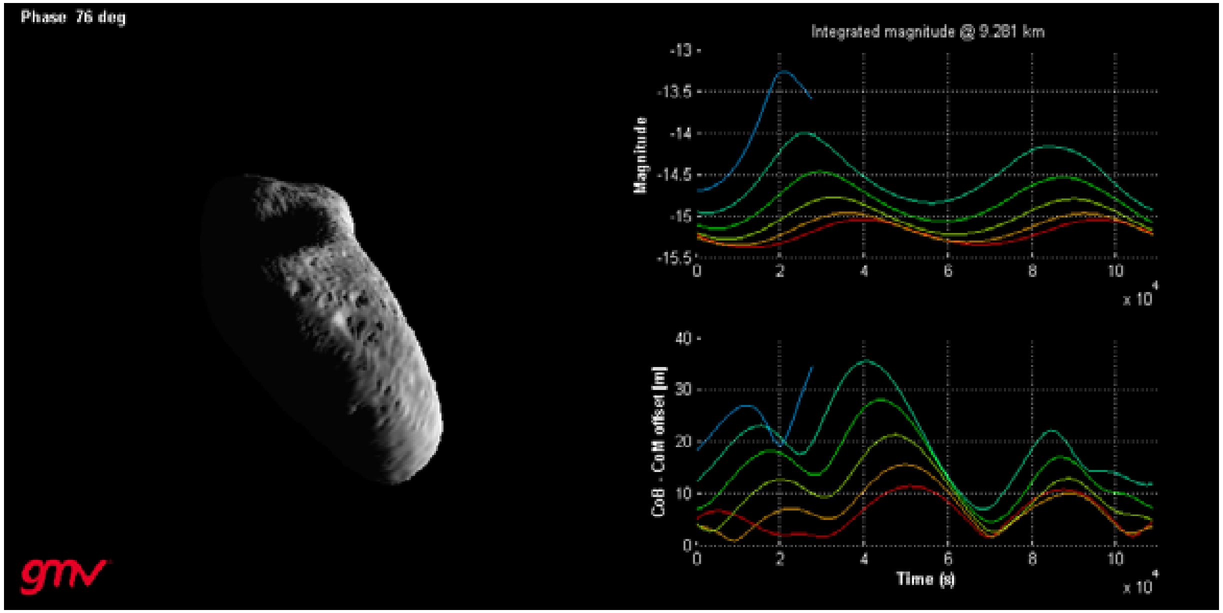
- STR: Tycho-2 catalogue
  - – FOV visibility
  - – Orbital aberration, NEA, CCD distortion
  - – Attitude estimation: q-method
- Realistic asteroid perfect still image
  - – Any shape defined by tiles
  - – Lambertian surfaces
  - – Illumination: self-shadowing

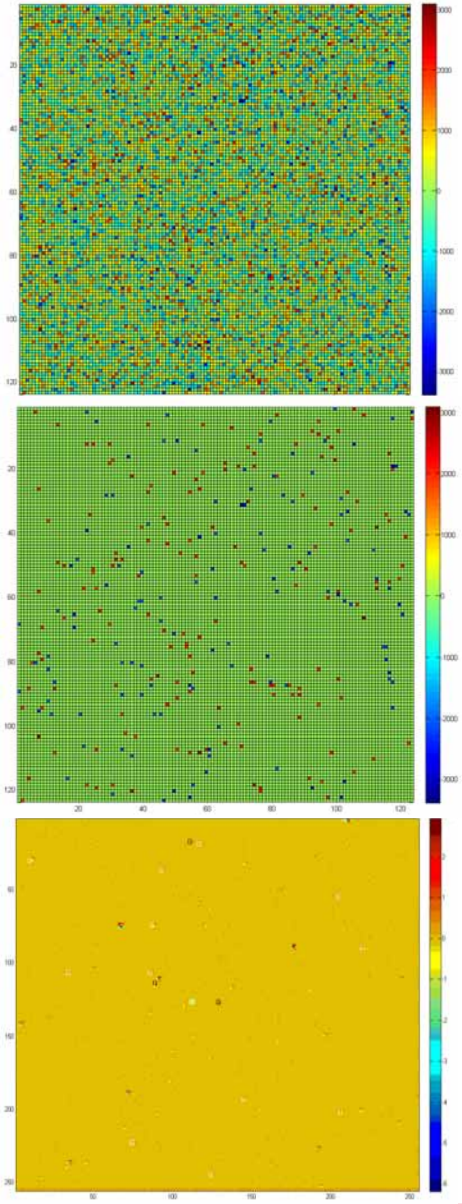




Auto. GNC Background – Validation (2/2)

- Composite perfect still image
  - Real stars (Tycho-2) + occultation
- Real NAVCAM image (bitmap)
  - Optics distortion
  - Motion and optics blur
  - Detector physical characteristics
  - Electronics (read-out, dark current ...)

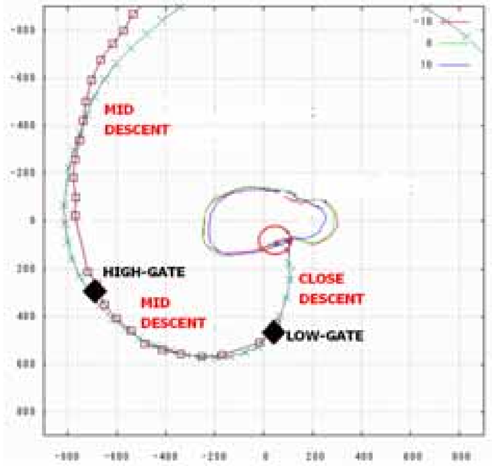




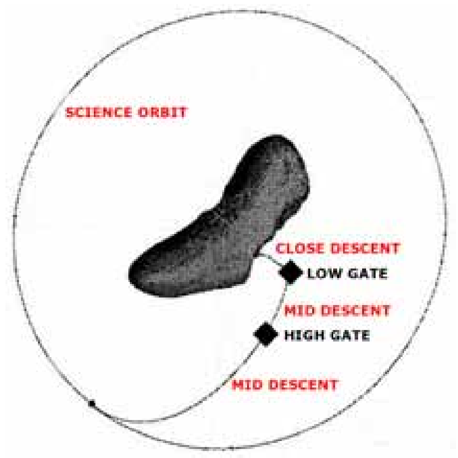
Problem Statement

Design GNC system for terminal descent of a sample return mission to a small NEO

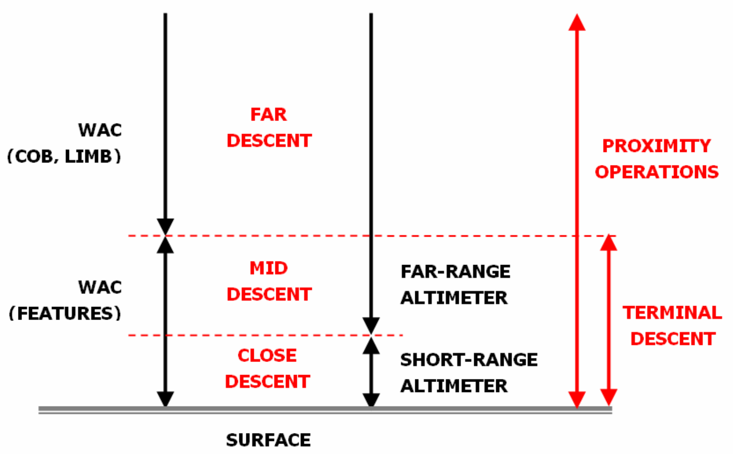
- Terminal descent: approach the surface for sampling (or rehearsal) from a science orbit or gate
  - Close-descent: from low-gate to touch-down or sampling-hovering
    - Low-gate: short-range altimeter start working
      - Surface-relative attitude measurement capability
  - Mid-descent: from characterization orbit/gate to low-gate
    - High-gate: landing site visible



Definitions in Hayabusa D&L trajectory



Definitions in NEAR D&L trajectory



GNC Architecture

- **GNC main design drivers**
  - Different targets: sizes, orbits, shapes, surface features, gravity fields ⇒ combination of different strategies for different sub-phases
  - Communications delay (~O(10) min) ⇒ autonomous GNC (close descent at least)
  - Uncertain asteroid parameters ⇒ robust GNC
  - Typical constraints: mass, power, size, TRL

- **Sensor suite**
  - Close descent
    - WAC (known landmarks) + multiple radar altimeter (surface attitude)
  - Mid descent
    - WAC (known landmarks) + laser altimeter

- **Thrusters**
  - Impulsive maneuvers: 20 N
  - Continuous thrust: 2 N

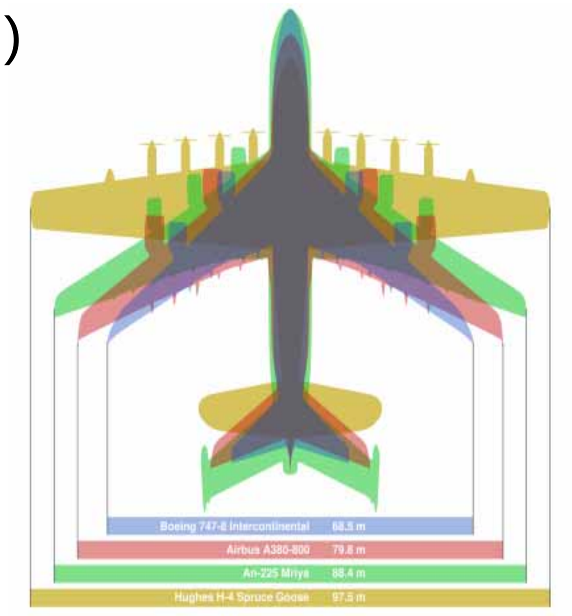
GNC Strategies

Close descent

- Autonomous navigation & control
  - No hazard avoidance (rehearsal before final sampling)
- Two analyzed GNC strategies
  - Continuous thrust @ 2 N
  - Impulsive maneuvers @ 20 N
- Descent profile (example)
  - Start in low-gate @ 100 m above landing site (radial direction)
    - 60-s hovering (navigation convergence)
  - Descent along vertical (radial) at 0.26 m/s
    - Hovering @ 45 m (radial) during 15 s
  - Descent along vertical (radial) at 0.2 m/s
    - Hovering @ 15 m (radial) during 15 s
  - Descent to final hovering: 3 m on local normal to surface (90 s)
    - Hovering @ 3 m (local normal) during 120 s

Scenarios & Simulator

- Considered targets characteristics (**1999 JU3**)
  - Diameter range: 280 – 1080 m (**720 m**)
  - Rotation period: 2.5 – 120 h (**2.5 h**)
  - Mass: 0.58e11 - 9.89e11 kg (**2.15e11 kg**)
- Any sampling location
  - **Equatorial @ 180 m radius**



- Equipment global performance simulation
  - WAC
    - IP accuracy + landmark position error + visibility
  - Altimeter
    - Manufacturer accuracy + pointing accuracy + surface roughness
  - Thrusters
    - Misalignment + thrust magnitude
- Real world dynamics and surface uncertainties

Guidance Algorithms

Impulsive maneuvers

- Differential corrective ΔV
  - Start @ initial hold point (best navigation state estimate)
  - End @ final nominal hold point (2-burns) or landing site (1-burn)
- Analytical closed-form solution of the dynamics
  - Linear expansion of gravity field
  - Constant asteroid rotation velocity
- Accuracy depends on:
  - Navigation accuracy (intermediate TCM)
  - Knowledge of dynamics parameters: gravity field, asteroid rotation
  - Thruster execution errors
  - Thrust/weight ratio
- Trajectory Corrective Maneuvers at predefined times
  - Increase robustness
    - Large uncertainties or higher order terms in the gravity field
  - Simpler and lower ΔV than increase number of hold points

Navigation Algorithm

Unscented Kalman Filter

- Time update
  - Numerical propagation: Runge-Kutta 4th order (fixed stepsize)
    - Gravity parameter, asteroid rotational velocity, SRP, control
- Measurements update
  - Sequential update
  - Measurements check (bad measurements rejected)
  - Observations: range + LOS to known landmarks (pre-selected)
    - Measurements vector changes (dimension)
- No artificial noise
  - Considered parameters: landmarks and landing site position, normal to surface, acceleration bias
    - Augmented state vector changes (dimension)
  - Process noise: control error if thrusting, gravity uncertainty if ballistic
- Accuracy depends on:
  - Measurements accuracy (IP performances)
  - Knowledge of asteroid characteristics and landmarks position
  - Hypotheses error

Control Algorithms (1/2)

Continuous-Thrust Maneuvers

- Optimal thrust profile computed on-ground
  - Thrust acceleration magnitude & direction + thrusting duration
- Optimal feed-forward control
  - LTI system (same assumption as impulsive maneuvers)
  - Zero-order-hold approach
  - Finite horizon: receding or fixed (next hovering-point)
  - Minimum control vector variation wrt nominal optimal thrust profile
  - Analytical closed-form solution of optimal control
  - Constraints (thruster saturation) included
- Accuracy depends on:
  - Navigation accuracy
  - Knowledge of dynamics parameters: gravity field, asteroid rotation
  - Thruster execution errors

Control Algorithms (2/2)

Impulsive Maneuvers

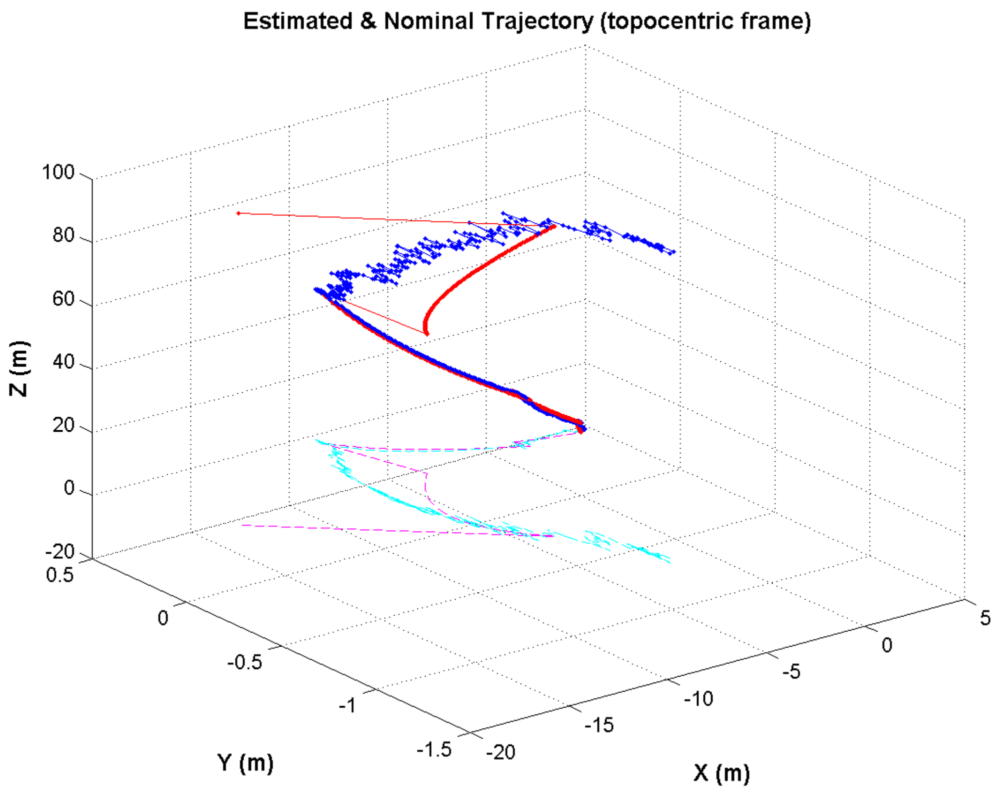
- Thruster time (fixed descent duration)
- Accuracy depends on:
  - Navigation & guidance accuracy
  - Thruster calibration & execution errors

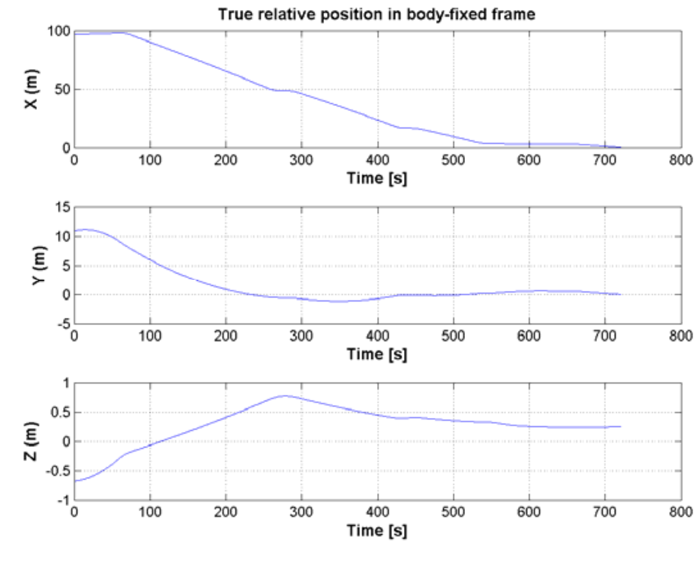
Hovering

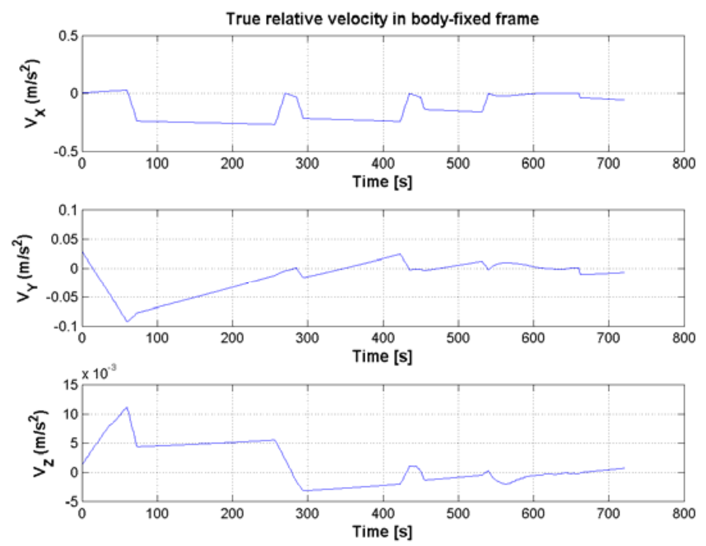
- Optimal feedback control
  - LTI system
  - LQR design
    - Last hovering: tight state control (touch-down hovering)
    - Previous hovering: low propellant expenditure (N & G purposes)
- Non-linear effects considered
  - Thruster saturation
  - Thruster MIB

Performances Assessment

- Trajectory
  - Touch-down velocity: 6 cm/s

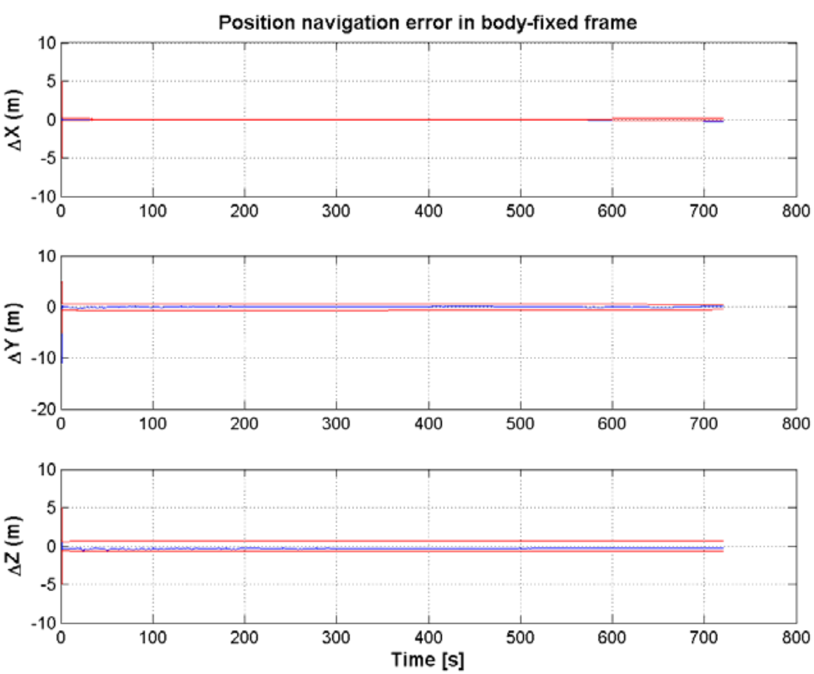


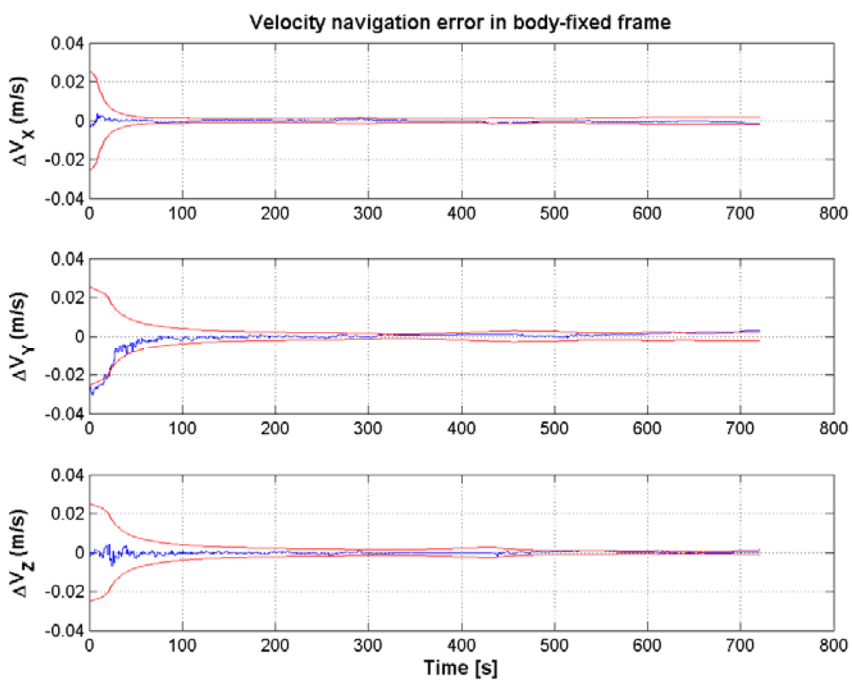




Performances Assessment

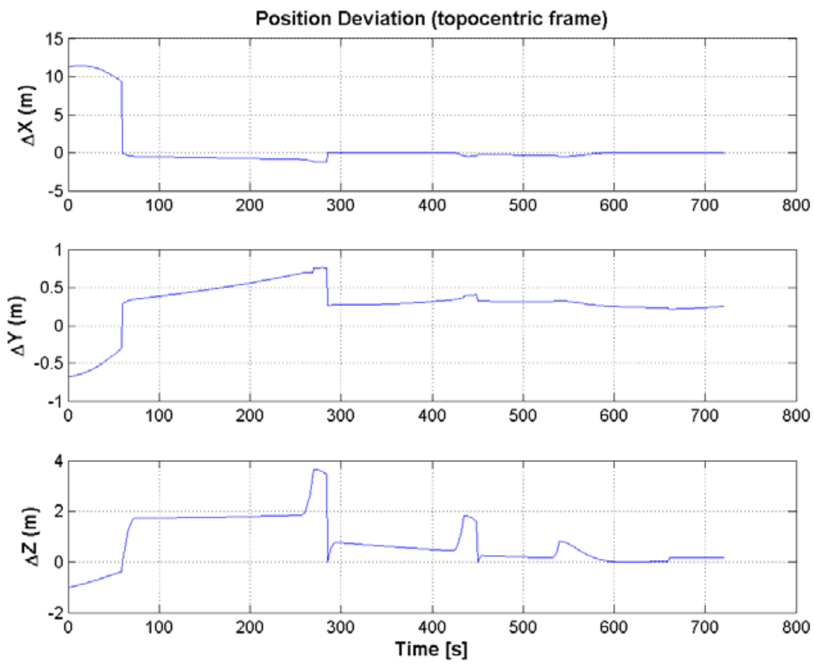
- Navigation
  - Good convergence properties
  - Error providing good landing accuracy: ~1 m & ~5 mm/s

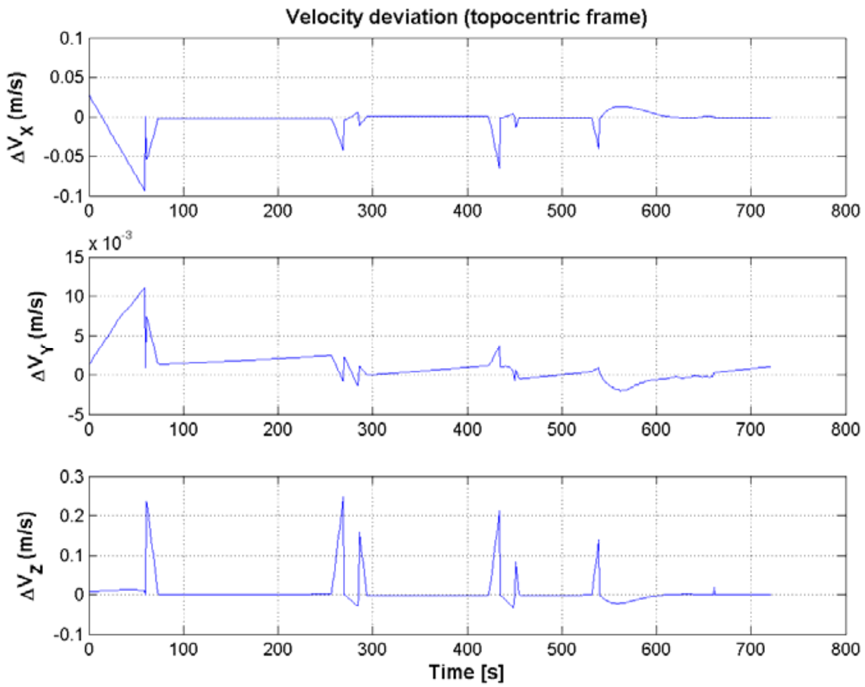




Performances Assessment

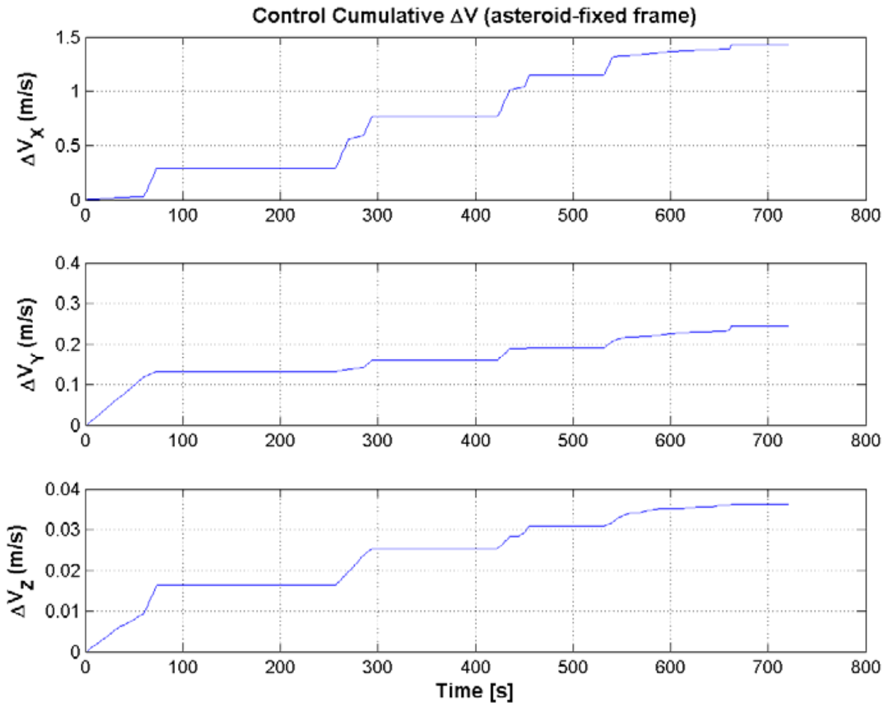
- Guidance
  - Deviation from nominal (guidance) trajectory mainly due to initial velocity errors and gravity expansion errors
  - Acceptable deviations without TCM (few meters at 2nd hovering point)

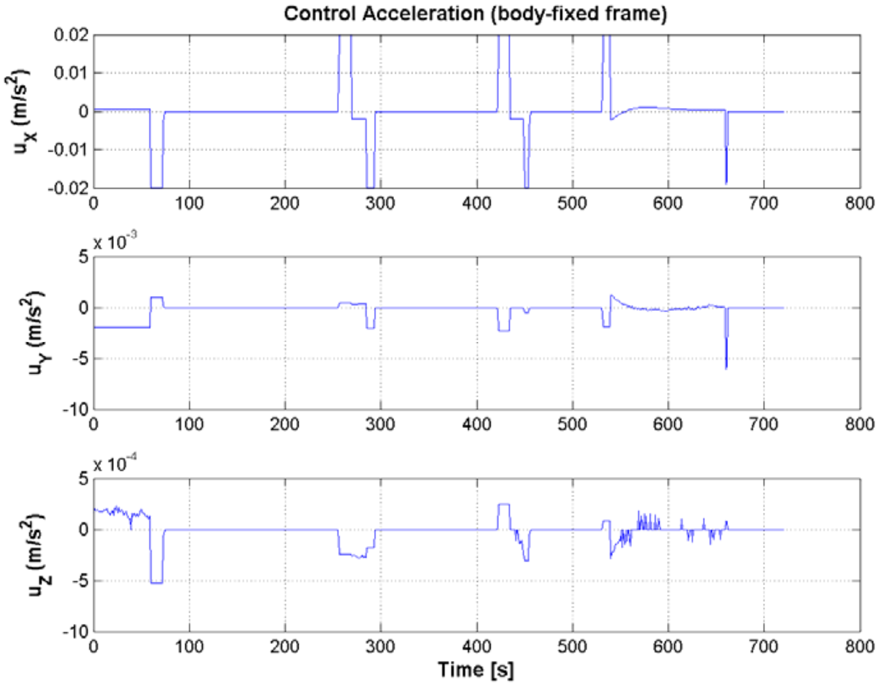




Performances Assessment

- Propellant budget
  - Total delta-V ~1.5 m/s
  - No saturation during hovering





Conclusions

Promising results of autonomous GNC in global performances simulator

- Navigation accuracy enough for precise, soft landing
  - Hypotheses TBC by scientists
  - Low number of known landmarks to be tracked
- Guidance performances acceptable without TCM
  - Further investigation of gravity models effect
  - Way-point tracking capability
- Hovering points loose control reduces propellant expenditure
  - Last hovering control accuracy driven by navigation accuracy
- Delta-V budget in line with previous expectations ~1 m/s
  - Significant reduction possible

Guidance (includes MVM) and Navigation implemented as EMF

- Integration into high-fidelity simulator
- Compilable code

Thank you

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