Vision-Based Autonomous Characterization and Navigation for Asteroids

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CONTEXT

Asteroid probing mission characterization phase :

- Incremental improvement of granularity of models, work-intensive modeling done on ground
- Precedes close navigation phase

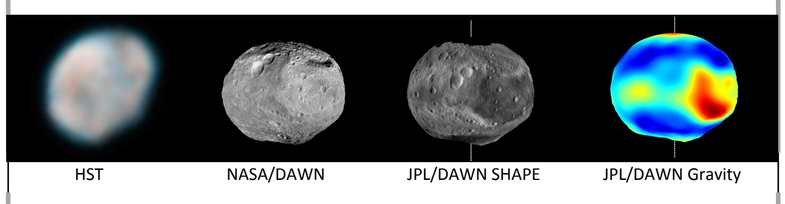


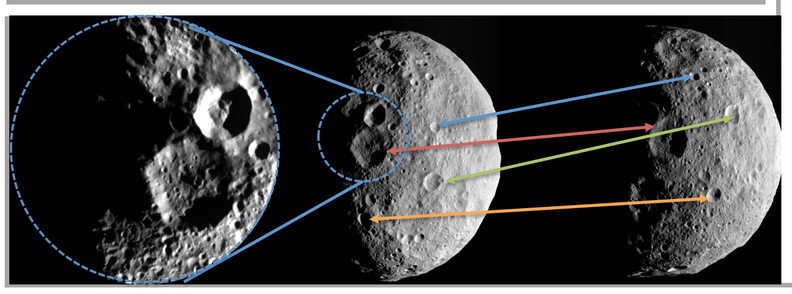
Figure 1 : Increasing detail of asteroid model

Limited pre-mission information on shape and dynamics from Earth, though available at close range. Large distances vastly limit readiness of data and real-time proxy operation of probe by TC/TM, requires sparsely available deep-space communications. Exponentially growing on-board computing power : Higher level of autonomy for probe.

PROJECT GOAL

Develop an autonomous, vision-based system capable of navigating and characterizing the target body at earliest phases of mission.

- Fully embeddable
- Minimal ground segment intervention
- Exploiting images from monocular camera stream
- Probe pose estimation with regards to target asteroid
- Simultaneous estimation of asteroid dynamics and shape



PROJECT CHALLENGES

- Adapt well known robotics-inspired methods to asteroid probing mission
- Ensure invariance of detected features on unknown asteroid surface with regards to scale, camera viewpoint and brightness.
- Ensure robustness of feature tracking with regards to occlusions, local prominence shadows and various noise sources.
- Overcome lack of depth information due to absence of range measurement.
- Ensure fitness of measurements by rejection of outliers.
- Ensure convergence of estimator by retrieval of sensible initial states and associated uncertainties.
- Design towards an embedded real-time operability.

Figure 2 : Variability of asteroid surface features, difficulty of matching (Ceres North Pole Region NASA/DAWN)

SYSTEM DESIGN & IMPLEMENTATION

ACQUISITION SCHEME

Framework
The proposed system can operate within a framework inspired from past and current asteroid probing missions. Taking NASA/Dawn as a prime example, a characterization step at 10,000 km altitude for a body radius of 450 km. This is driven by the typical field of view of navigation cameras, which is narrow to enable it to be used for further scientific purposes.

Detection
The acquired image array is searched for salient features, i.e. changes in brightness gradients. Feature extraction by image processing through Speeded-Up Robust Features (SURF) algorithm. For each keypoint, it produces a unique descriptor vector which is scale- and rotation-invariant, allowing for repeatability and robustness of matching of the same salient feature from different viewpoints.

Illumination
Feature detection based on brightness gradients, pointing towards partially or fully illuminated region of the surface crucial at this step. Given the weakness of the gravitational field, maneuvers can be carried out at very low ΔVs, guaranteeing uninterrupted access to a minimally visible area of the surface.

Adaptability
Tunable detection parameters adjust to mission specifics, target environment and surface characteristics e.g. grain and crater size, distribution, regolith optical properties.

Matching
Based on similarities between landmarks and image keypoints, by minimization of distance between corresponding descriptors.

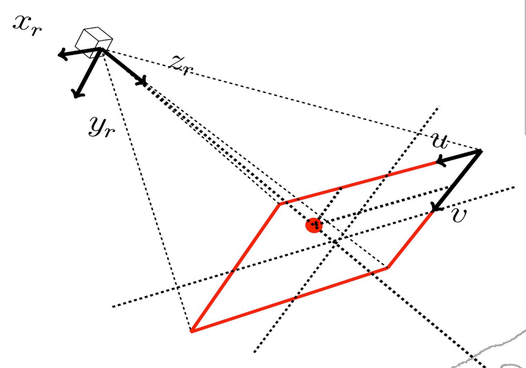


Image acquisition with typical navigation camera:

- Visible band Monochromic
- 5° FOV 1024x1024 array

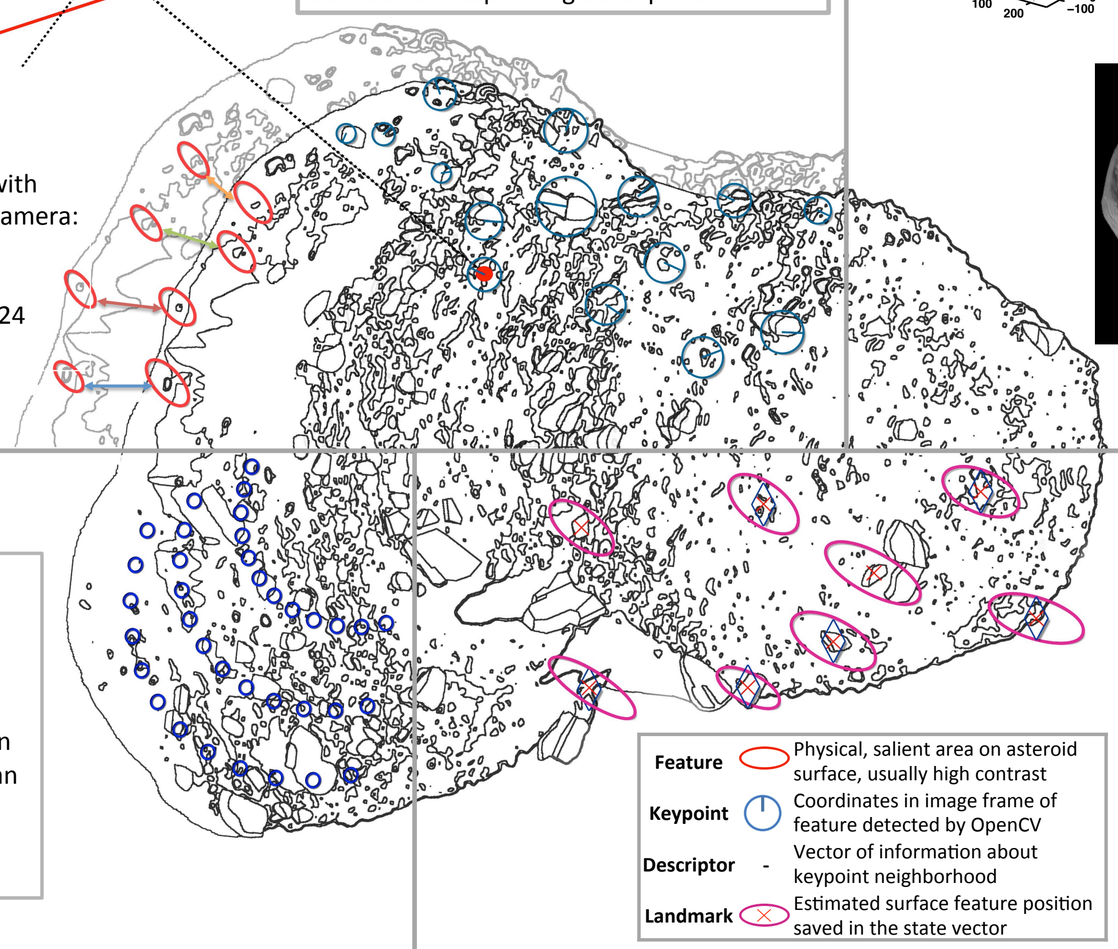


Figure 3 : The Target Asteroid Under Its Various System Phase Perspectives (Example Itokawa JAXA/Hayabusa)

RESULTS

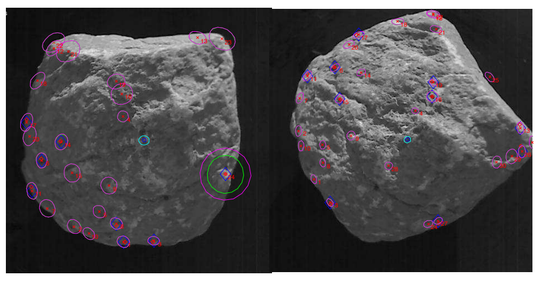


Figure 8 : Successful 2D Coplanar Test Case, Actual Testbench Camera

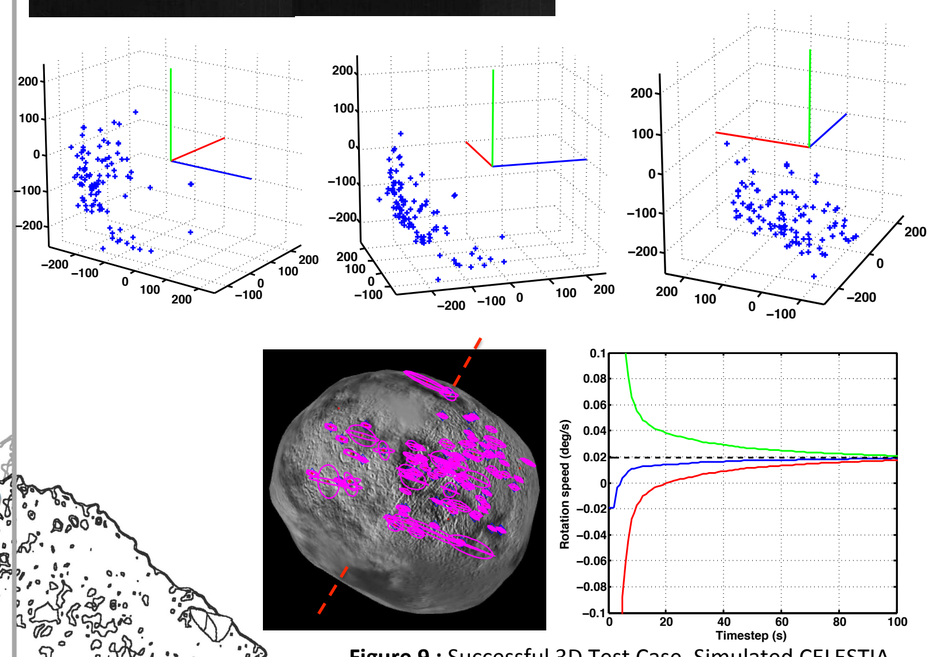
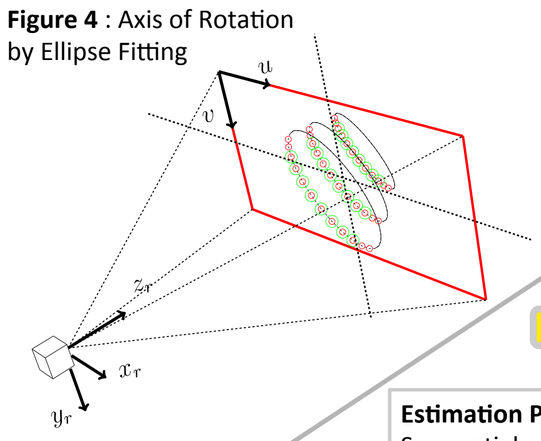


Figure 9 : Successful 3D Test Case, Simulated CELESTIA Images : 3D Point Cloud (top), Cameraview (bottom-left), Convergence of Rotation Speed (bottom-right)

PRIORI DETERMINATION

Primary Rotation Axis
Initial state close enough to global minimum crucial for ensuring convergence of navigation filter. Most sensitive to asteroid parameters, i.e. rotation axis. Extraction of primary rotation axis through fitting of multiple ellipses over a determined number of acquired image frames. Stems from assumption of circular motion in 3D space of feature on a rigid body surface, which projects as an ellipse onto camera frame. Method requires a chase phase, with negligible movement with regards to the asteroid, ensuring elliptical tracks of individual features in the camera frame.

Figure 4 : Axis of Rotation by Ellipse Fitting



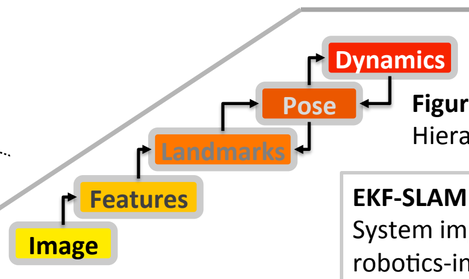


Figure 5 : Information Hierarchy

Implemented with OpenCV/C++ in Matlab/SImulink

Estimation Paradigm
Sequential nature of filter is adapted to on-line real-time execution. Crossing between Structure from Motion (SfM), to reconstruct asteroid shape, and landmark tracking navigation filter, for probe localization.

EKF-SLAM
System implements robotics-inspired Extended Kalman Filter – Simultaneous Localization and Mapping method, which allows simultaneous convergence on probe and target states. Based on minimization of state vector covariances.

Assumptions

- Rigid body rotation around CG + Diagonal inertial matrix
- No external perturbations
- Constant rotation speed and constant rotation axis orientation
- Modeled probe orbit
- Earth-relative spacecraft position measurement + absolute orientation from SST

Robust Tracking
Uses predicted state for Individual Compatibility Test (ICT), reducing matching search space. 1-Point RANSAC used to discard outlier measurement based on fitness with regards to model, increasing robustness to non-gaussian occurrences.

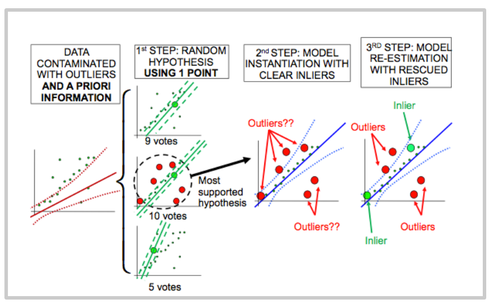


Figure 6 : RANSAC Scheme

ESTIMATION ENGINE

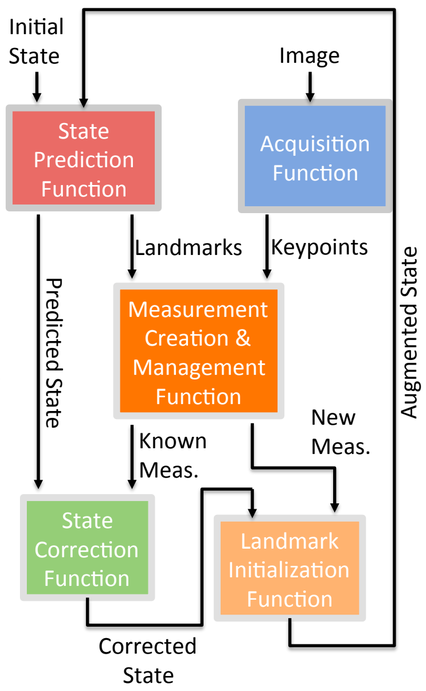


Figure 7 : System Functions

Landmark Initialization
Chosen from pool of detected keypoints with strongest response. Inverse depth parameterization (IDP) of landmarks, ensures gaussanity of error distribution for depth estimation.

ACKNOWLEDGEMENTS

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REFERENCES

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CONCLUSIONS

The developed navigation and characterization system, a vision-based monocular EKF-SLAM, is well-suited for an embedded and autonomous operation during the first phases of asteroid probing missions. This system satisfies the eventual embeddability objective on some fronts: First, EKF-SLAM's well-established, numerous and thoroughly studied applications in environment-aware robotics. Second, its relatively low complexity and sequential nature, as opposed to classical structure from motion by a posteriori minimization over multiple viewpoints. In terms of steps towards greater autonomy, the addition of a priori determination phase further reduces the traditionally extensive involvement of the ground segment for system initialization. This in-situ pattern recognition method overcomes limitations of an estimator initial state derived from Earth-based measurements, e.g. lightcurves, HST. As visible-band monocular cameras are widespread in interplanetary probing missions, the main obstacle towards an actual implementation is current and future limitations in available onboard computing power.