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Dynamic Visual Simultaneous Localization and Mapping for Asteroid Exploration

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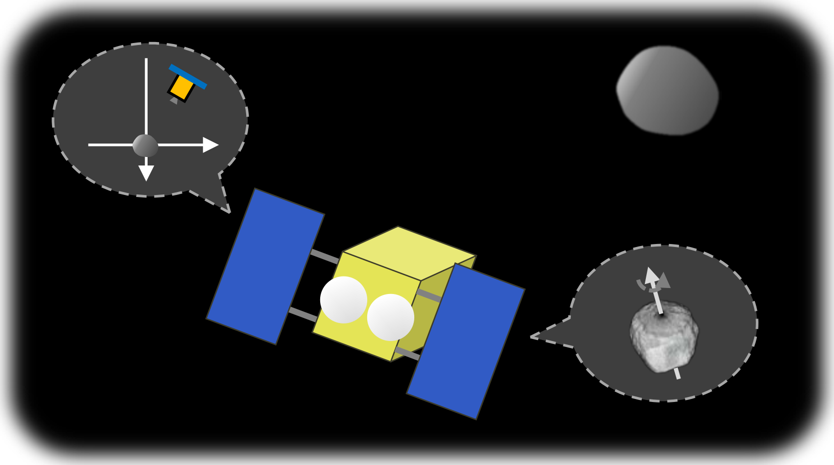
*This is a part of joint work with JAXA Hayabusa-2 team.

Background (1/3)

Navigation and mapping in asteroid exploration

- Two mutually dependent problems:
  - Navigation of spacecraft (relative to asteroid)
  - Mapping of global geometry of asteroid

- Solution from arrival near asteroid to initial descending phase



Background (2/3)

Review on procedures in Hayabusa’s mission

- Mapping
  - ➢ using limb profile
  - ➢ using multi-view stereo
  - ➢ using photometric stereo
  - ➢ and (manually) merging them ☹

- Navigation
  - ➢ manual setting and tracking of landmarks using GUI tool
  - ➢ very hard work ☹

→ These can be integrated and automated as simultaneous localization and mapping (SLAM) problem!

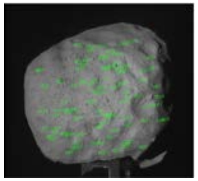
Background (3/3)

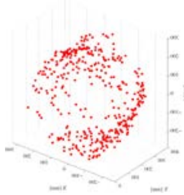
Review on simultaneous localization and mapping (SLAM)

- SLAM = estimation problem of:
  - location of robot (localization)
  - map of environment (mapping)

- Similar problem termed
  structure from motion (SFM) in CV

- SLAM/SFM application in space mission
  - many on moon/planet rovers
  - above asteroid
    - ✓ [Cocaud&Kubota, ’10, ‘12]
    - ✓ [Takeishi+, ’15] etc.
    - ✓ no comprehensive framework yet ☹



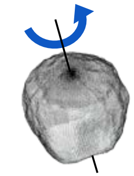


[Takeishi+, ‘15]

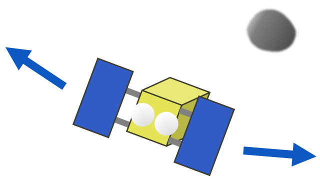
Problem formulation

Main challenges of SLAM for asteroid exploration

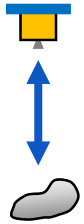
- Asteroid rotates following rigid body dynamics
  - ➢ we want to estimate its parameters explicitly



- Spacecraft also moves
  - ➢ staying around home position, or
  - ➢ traveling by thrusters



- Range finders do not work in high altitude (~20km)
  - ➢ No LRF, no stereo camera ☹



Contribution of this work

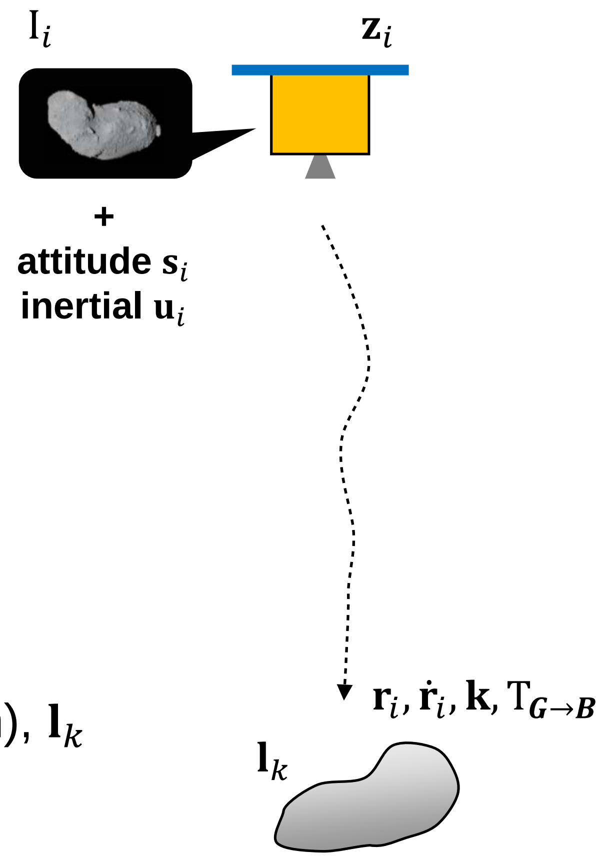
full formulation and implementation of SLAM solution dedicated to asteroid explorer in descending phase

Problem formulation of Asteroid SLAM (1/2)

Input and output of algorithm

Available observation (input)

- measurements of attitude sensor, $\mathbf{s}_i$
- measurements of inertial sensor, $\mathbf{u}_i$
- monocular images, I_i



Unknown quantities (output)

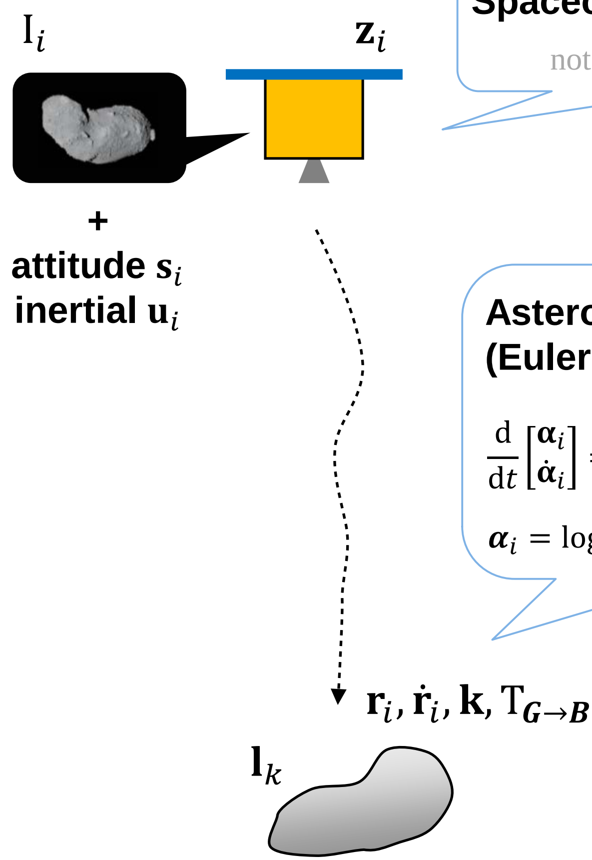
- asteroid's attitude and ang.velo., $\mathbf{r}_i, \dot{\mathbf{r}}_i$
  inertia moment, $\mathbf{k}$
  principal axis and centroid, $\mathrm{T}_{G\to B}$
  shape (set of landmarks' position), $\mathbf{l}_k$
- spacecraft's position and attitude, $\mathbf{z}_i$

Problem formulation of Asteroid SLAM (2/2)

Models on asteroid, camera, attitude sensor and inertial sensor

Calibrated camera model

$$\mathbf{y}_{i,j} = \left(\mathrm{K} \circ \mathbf{z}_i^{-1} \circ \mathbf{r}_i \circ \mathrm{T}_{\boldsymbol{G}\to\boldsymbol{B}}\right)\mathbf{l}_{c_{i,j}} + \mathbf{e}_{\mathrm{landmark}}$$



Spacecraft's dynamis model

not specified, but possibly set

Asteroid's dynamics model (Euler's equation)

$$\frac{\mathrm{d}}{\mathrm{d}t}\begin{bmatrix}\boldsymbol{\alpha}_i \\ \dot{\boldsymbol{\alpha}}_i\end{bmatrix} = \begin{bmatrix}\frac{1}{2}(\gamma_i\dot{\boldsymbol{\alpha}}_i + \dot{\boldsymbol{\alpha}}_i \times \boldsymbol{\alpha}_i - \eta_i\boldsymbol{\alpha}_i) \\ \mathrm{J}^{-1}(-\dot{\boldsymbol{\alpha}}_i \times \mathrm{J}\dot{\boldsymbol{\alpha}}_i + \mathrm{W}_2)\end{bmatrix},$$

$$\boldsymbol{\alpha}_i = \log(\boldsymbol{r}_i)$$

Calibrated attitude sensor model

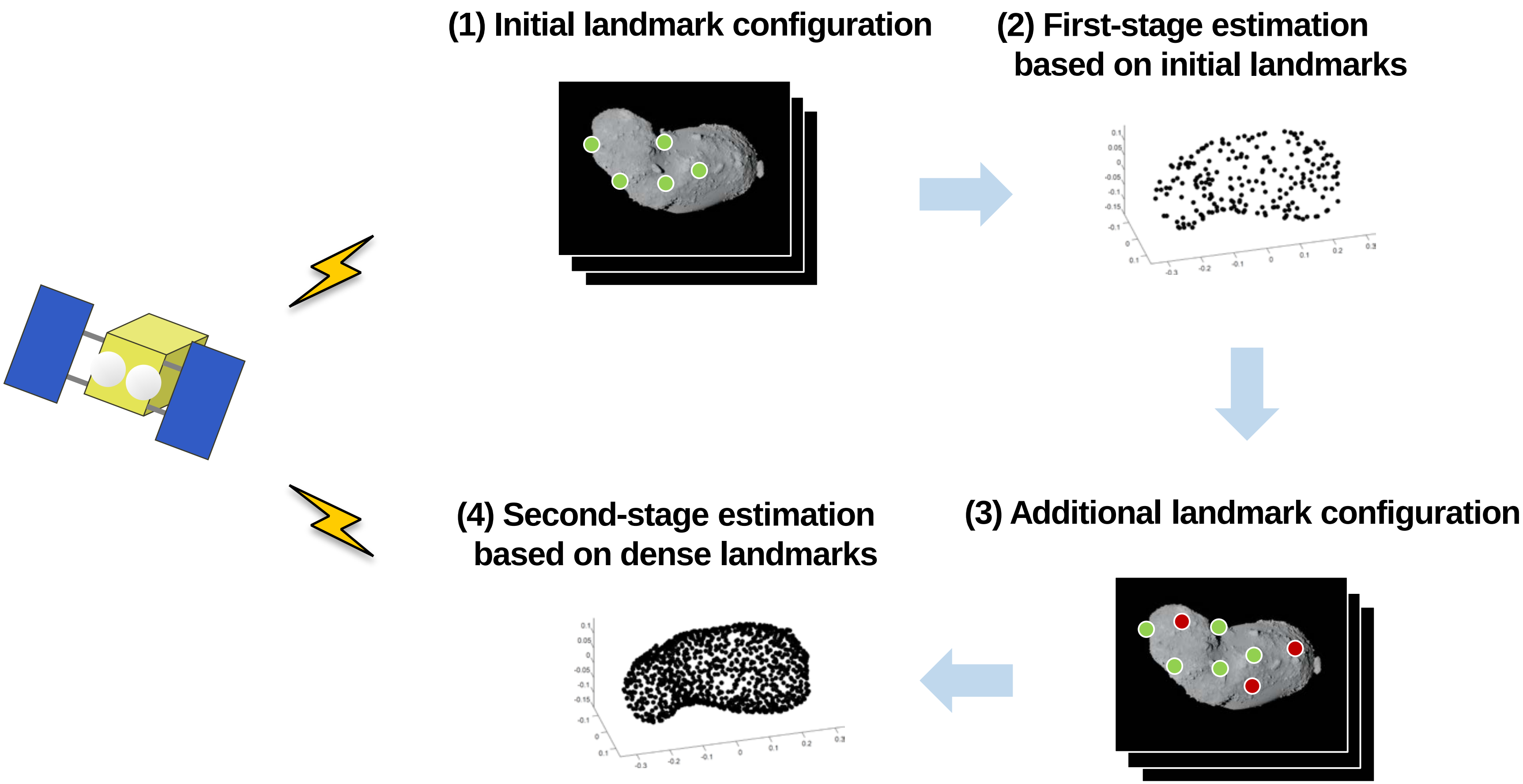
$$\mathbf{u}_i = \mathbf{z}_i \cdot (\mathbf{z}_{i-1})^{-1} \cdot \exp(\mathbf{e}_{\mathrm{inertia}})$$

Calibrated inertial sensor model

$$\mathbf{s}_{\mathrm{i}} = \mathrm{R}(\mathbf{z}_{\mathrm{i}}) \cdot \exp(\mathbf{e}_{\mathrm{sensor}})$$

Proposed method

Overview of proposed method



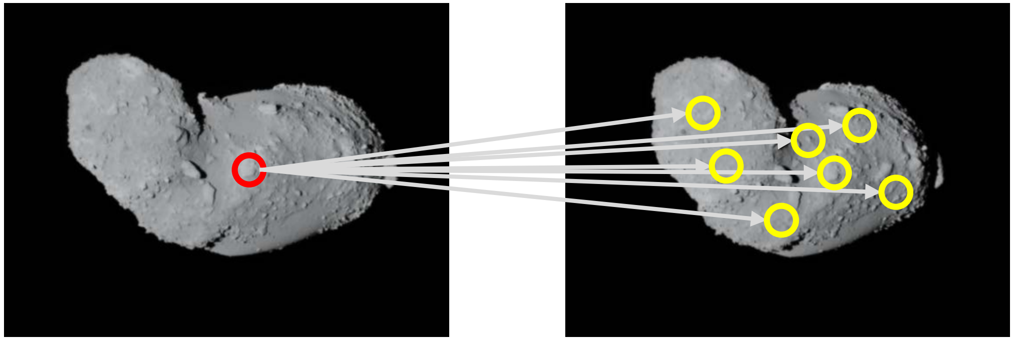
(1) Initial landmark configuration

Configure visual landmarks only with local image descriptors

1. Extract features points using SIFT [Lowe 04]

2. Search match for **all feature points in adjacent image** as candidate, resulting in low recall ☹
   - ➢ because no estimation of geometry is obtained at first

3. Eliminate errors strictly, resulting in even lower recall ☹
   - ➢ removing infrequent matches
   - ➢ removing inconsistent matches by RANSAC



(2) Estimation of unknown quantities: initialization

Incremental optimization of unknown quantities

- Iteration:
  1. initialize quantities on new frame (image)
  2. add initialized quantities to optimization procedure
  3. solution update

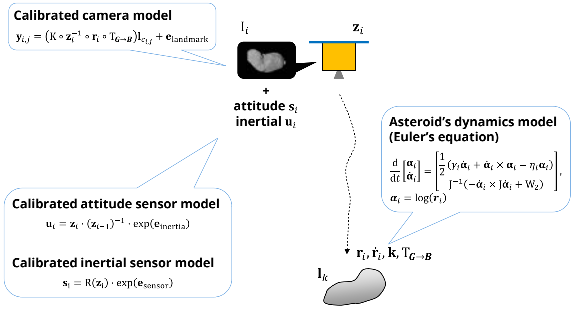
- Robust initialization is not easy because of monocular images
  1. initialize spacecraft's pose by attitude and inertial sensors
  2. initialize asteroid's attitude by five-point method, PnP solver or numerical integration
     - ✓ method is to be empirically chosen
  3. initialize new landmarks' position by triangulation
     - ✓ centralize depth for first pair of images

(2) Estimation of unknown quantities: update

Incremental optimization of unknown quantities

- Iteration:
    1. initialize quantities on new frame (image)
    2. add initialized quantities to optimization procedure
    3. solution update

- Solver: incremental smoothing and mapping [Kaess+, '08]
    - ➢ given model $f(u, o) = 0$ on unknown and observed quantities, incrementally minimize Mahalanobis distance $|f(u, o)|^2_{\mu,\Sigma}$



(3) Additional landmark configuration

Configure new landmarks with geometric information

- "Reuse" disposed feature points in initial landmark configuration
  - searching match for **feature points only in anticipated region** as candidate
  - with first-stage estimation of relative position/attitude

- Further improvement: store visual features and use them to compensate viewpoint changes

Image1

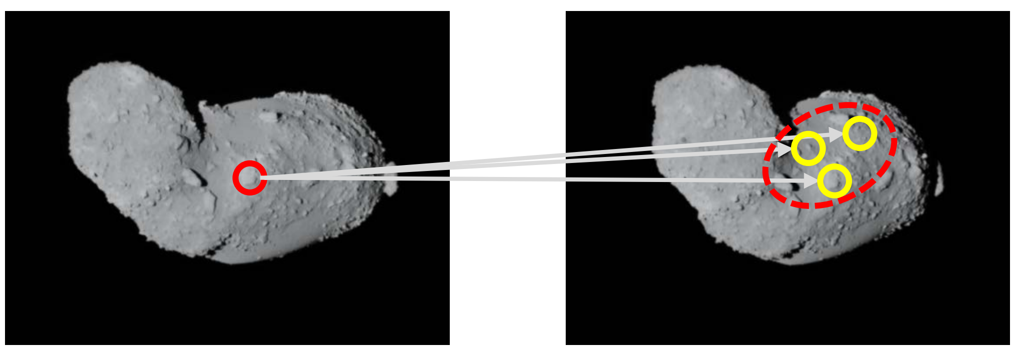
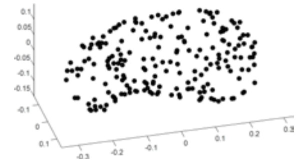


Image2

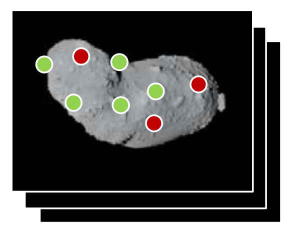
Proposed method: overview (again)

(1) Initial landmark configuration

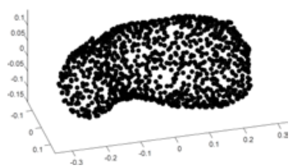
(2) First-stage estimation based on initial landmarks



(3) Additional landmark configuration



(4) Second-stage estimation based on dense landmarks

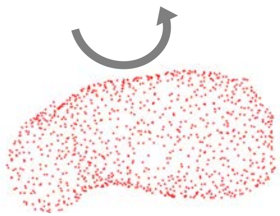


Ordinary procedure of SLAM, but with dedicated models for asteroid explorer and careful initialization procedure for robustness.

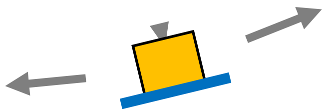
Experiment

Preliminary experiment: setup

- Asteroid (Itokawa) model with 1,000 vertices
  - rotating by 0.088 [rad/img]



- 72 images with randomly-moving camera
  - random walk: mean=0, std=10 [m/img], 0.01[rad/img]
  - occlusion on backside of asteroid
  - random missing of observation

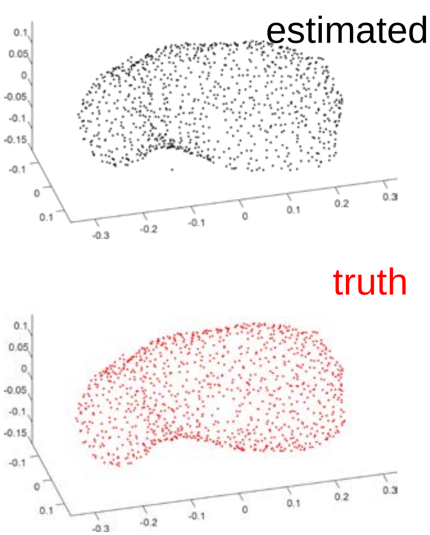


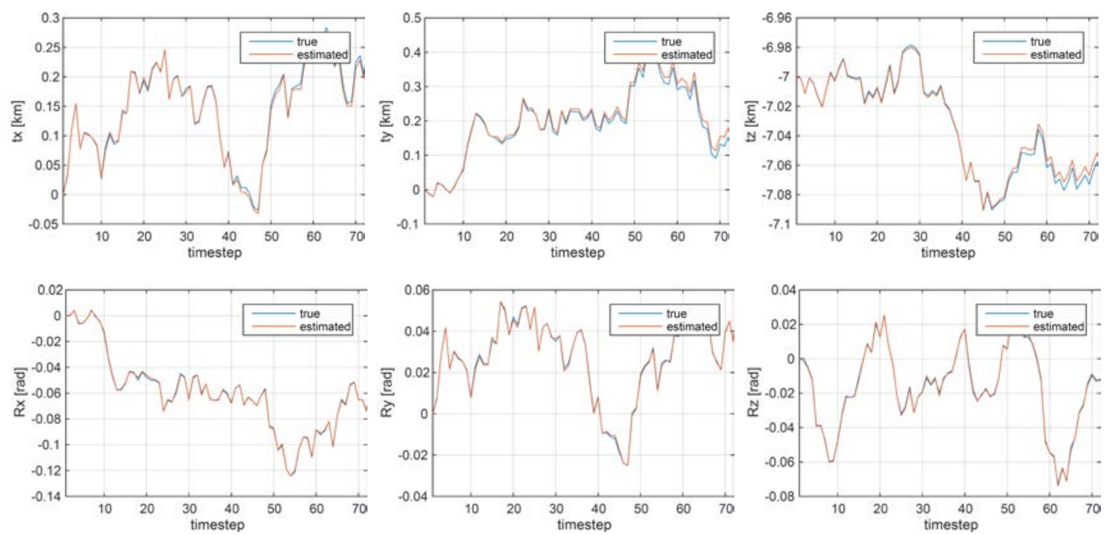
- Measurement noises:
  - camera → mean=0, std=0.1[px]
  - attitude sensor → mean=0, std=0.01[rad]
  - inertial sensor → mean=0, std=10[m], 0.01[rad]

Preliminary experiment: result

- RMS error of estimated shape: 1.46m (Itokawa>500m) (left)
- Position/attitude of spacecraft is successfully estimated (right)

(Preliminary results, and more experiments are necessary)



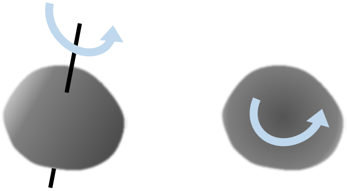


Experiment plan

- With images of asteroid mockup
  - ➢ accurate landmark configuration is possible [Takeishi+, '15]

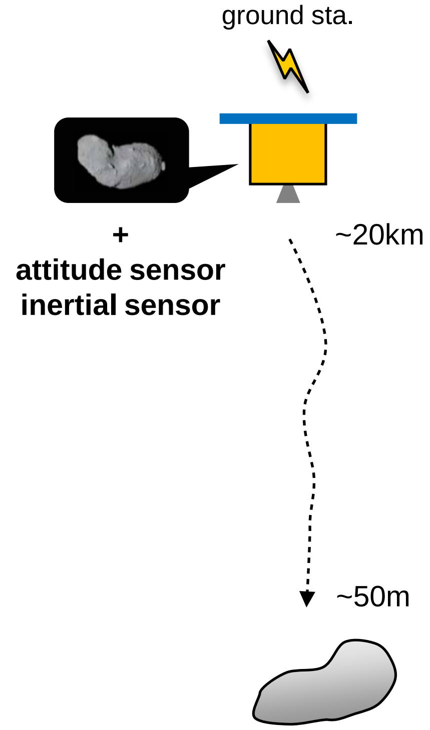
- With images of rotating object taken on ground
  - ➢ incorporating gravity into the model is straightforward

- With synthetic graphics
  - ➢ to investigate effect of lean of rotation axis



Summary: Asteroid SLAM

- First full formulation of SLAM problem for descending phase of asteroid exploration
  - ➢ Outputs
    - ✓ asteroid's attitude and angular velocity
      inertia moment
      principal axis and centroid
      shape
    - ✓ spacecraft's position and attitude
  - ➢ Inputs
    - ✓ measurements of attitude sensor
    - ✓ measurements of inertial sensor
    - ✓ images



- Need more experiments!

*Estimation framework

Incremental optimization of unknown quantities

- Optimization of unknown quantities given observation under dynamics & sensor models
  - ➢ model: $f(u, o) = 0$
  - ➢ minimize Mahalanobis distance $|f(u, o)|^2_{\mu,\Sigma}$

- Incremental optimization
  - ➢ initialize quantities on new frame
  - ➢ add initialized quantities to optimization procedure
  - ➢ update by iSAM [Kaess+ '08]