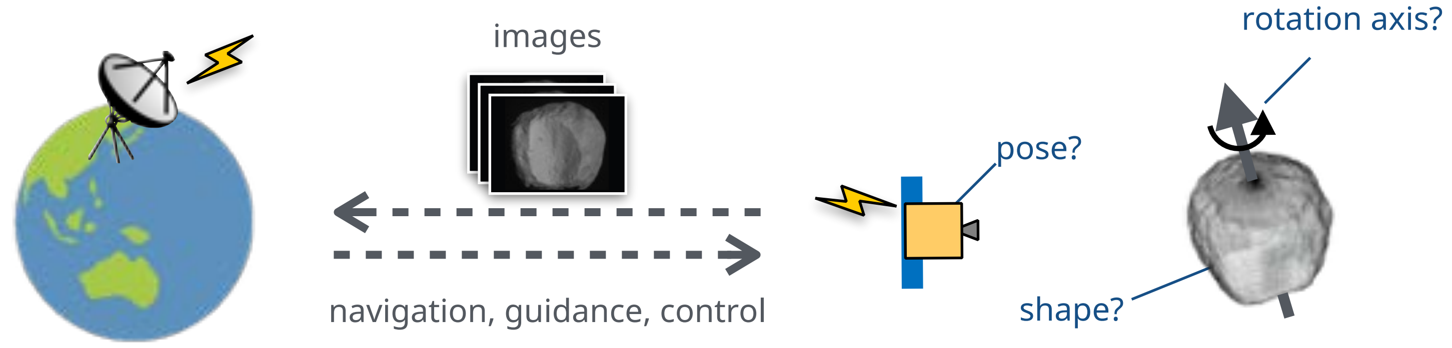
Simultaneous Estimation of Shape and Motion of an Asteroid for Automatic Navigation

N. Takeishi, T. Yairi (Univ. Tokyo), Y. Tsuda, F. Terui, N. Ogawa and Y. Mimasu (JAXA)

Motivation: SLAM with Hayabusa-2

2, 4, 5

- We test **SLAM framework** with asteroid explorer **Hayabusa-2** for asteroid shape estimation using **monocular** images.



- What should be considered?
  - **Asteroid is rotating** (axis is uncertain only w/ ground observation).
  - Spacecraft is also moving slightly at home position (~20km away).
  - Shading is harsh due to lack of scattering light (now out-of-scope).

Previous mission: Hayabusa

3

- Rendezvous procedure of previous explorer Hayabusa needed **a heavy workload** on operators.

Rendezvous procedure [Demura+ 06, Shirakawa+ 06]

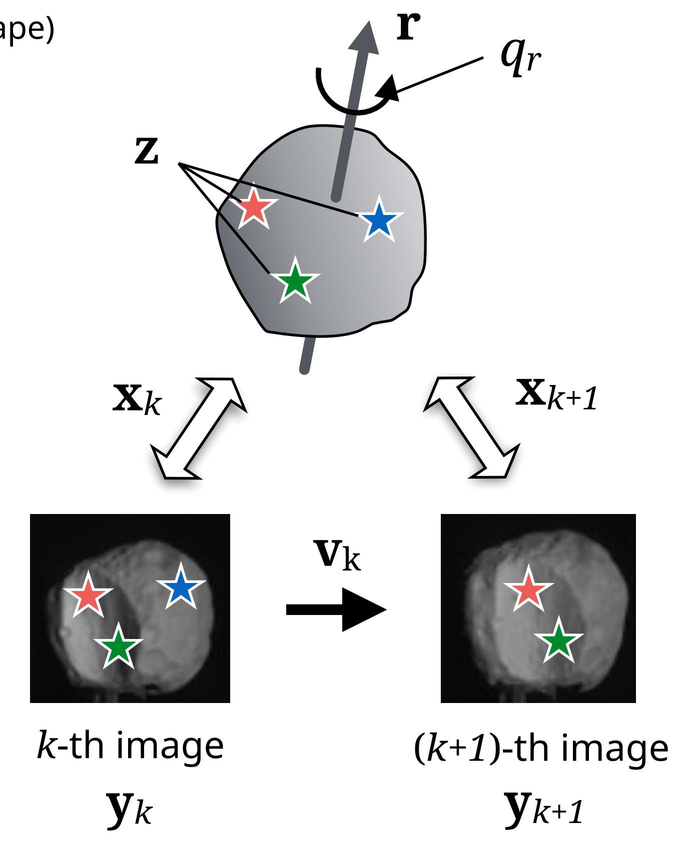
1. Tracking of landmarks (from >200 images)
   - to estimate axis and epipolar geometry.
   - Operators **manually tracked on no sleep!**
2. Shape estimation
   - using limb profile & multi-view stereo,
   - **manually fusing** info. of landmarks, STT, ...
3. Approach (to ~500m)
   - taking an image every 10 minutes,
   - **manually tracking** landmarks w/ GUI.
4. Final descent using target markers

➡ ***Our goal is to automate 1.-3. and give operators enough sleep!***

Problem setting and solution

6, 7

- We have 2D positions of landmarks $\mathbf{y}$ as observation.
- **Three types of unknowns** to be estimated, **rather than two** in a standard SLAM:
  - Landmarks' positions $\mathbf{z}$ (asteroid's shape)
  - Asteroid's rotation axis $\mathbf{r}$
  - Relative poses $\mathbf{x}$



Process model

- rotation q_r, noise q_{vk}
- camera movement $\mathbf{v}_k \sim N(0, \mathrm{Q})$

$$\mathbf{x}_k = f\left(\mathbf{x}_{k-1}, q_r\right) \cdot q_{vk} + \mathbf{v}_k$$

Observation model

- n-th landmark in k-th image
- noise $\mathbf{w}_k \sim N(0, \mathrm{R})$

$$\mathbf{y}_k^{(n)} = h\left(\mathbf{x}_k, \mathbf{z}^{(n)}\right) + \mathbf{w}_k$$

- Expectation conditional maximization (ECM) [Meng&Rubin 93]
  - optimizes parameters conditioned on the others in M-step.

Algorithm of ECM-SLAM

8

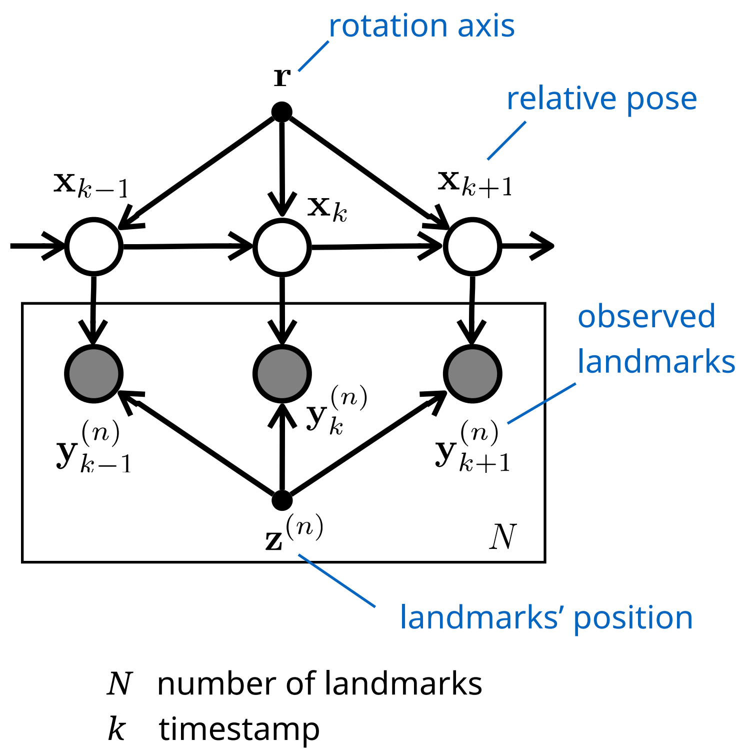
1. Initialization
2. E-step
   - auxiliary particle filtering to estimate $p(\mathbf{x}_k \mid \mathbf{y}_{1:k})$
3. M-step (1)
   - optimize $\mathbf{z}$ conditioned on $\mathbf{r}$

$$\min_{\mathbf{z}^{(n)}} \sum_k \left\|\mathbf{y}_k^{(n)} - h\left(\mathbb{E}[\mathbf{x}_k], \mathbf{z}^{(n)}\right)\right\|_2^2$$

4. M-step (2)
   - optimize $\mathbf{r}$ conditioned on $\mathbf{z}$

$$\min_{\mathbf{r}} \sum_{l=2}^{k} \left\|\mathbb{E}[\mathbf{x}_l] - f\left(\mathbb{E}[\mathbf{x}_{l-1}], q_r\right)\right\|_2^2$$

5. Iterate 2.-4. until convergence



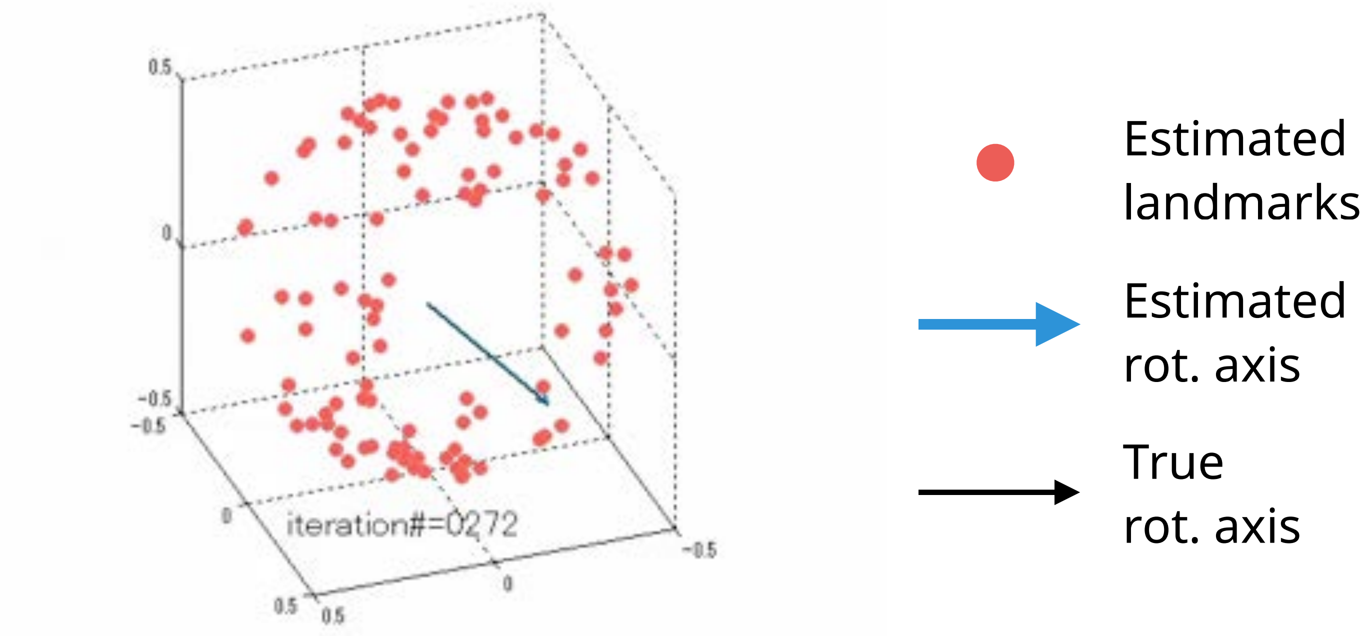
N number of landmarks
k timestamp

Experiments

Synthetic data

9

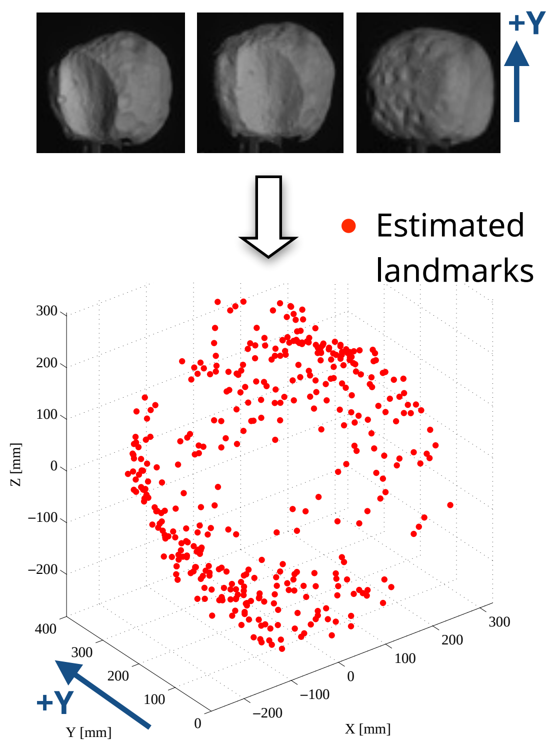
- Landmarks are scattered on **sphere** with **single-axis rotation**.
- We observed landmarks on foreground with **slightly moving camera**.



Asteroid mock-up

10, 11, 12

- Images of mock-up taken under **condition equivalent to Hayabusa-2** at 23.59km from the target asteroid.
- Landmark selection:
  - Extract SIFT keypoints.
  - **Select robust keypoints**.
- Result of shape estimation:
  - RMSE ~ **1.8 cm** (mockup ~ 43 cm)
  - If diameter is 1km, this equals to approx. 40m. (still large for use)



Future work

15

- Modeling asteroid's dynamics
  - This work deals only with the kinematics
- Modeling spacecraft's dynamics
- Integrating dense shape estimation