

Asteroid shape estimation by Structure-from-Motion

Structure-from-Motion 法による小惑星形状推定手法の検討

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ABSTRACT

We evaluate applicability of shape reconstruction tools on asteroid exploration mission including Hayabusa-2 mission. *Bundler* and *PMVS2* are tested with an asteroid image data set obtained by Hayabusa-1 mission. They are released to public as open source software. *Bundler* can produce a sparse point cloud shape of an object by the Structure-from-Motion technology. *PMVS2* cooperatively works with *Bundler* to make a finer and denser shape model. A shape model reconstructed by these tools satisfies general requirements as an initial shape model used in the early stage of the mission. Especially, rapid processing is an advantage over previous methods. We also evaluate minimum requirements on number of images and observing geometry at the initial mapping observation to produce an initial shape model.




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Introduction

- Asteroid shape model
 - Safe navigation of a spacecraft
 - Scientific analysis
- Hayabusa-2 Shape Reconstruction Study Group
 - working in the Hayabusa-2 science team



Hayabusa-2
http://www.jaxa.jp/projects/sat/hayabus2/index_j.html
(Akihiro Ikeshita)


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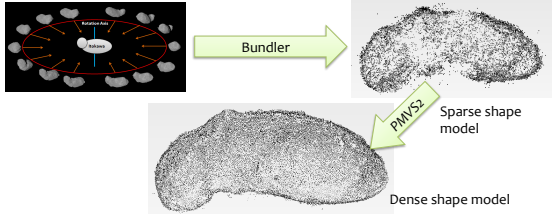
Studied methods

- Structure from Motion (This talk)
 - Robust and stable
 - Open source toolkit is available
- Photometric stereo
 - Developed in the camera team (Univ. of Tokyo)
 - Advanced and ambitious
- Gaskell tool (Stereo-Photoclinometry, SPC)
 - Used in Hayabusa-1 mission and other small body missions
- Complementing each other

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Shape Reconstruction by Bundler and PMVS2



- Open-source software packages
 - Bundler [N. Snavely, 2006]: Structure from Motion
 - PMVS2 [Y. Furukawa, 2012]: Multi-View Stereo

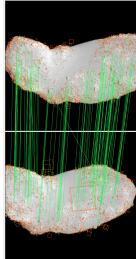
4



Bundler


Procedures and technologies

- Feature point extraction by *SIFT* (Scale-invariant feature transform)
 - 128 element feature vector
- Pairing of feature points based on similarity of SIFT feature vectors over image sets
- Estimation of 3-D coordinates of paired points and camera parameters by *bundle adjustment* technique



Pairing of SIFT feature points

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Objectives

- Confirm a fundamental applicability of Bundler and PMVS2 on space exploration data
 - Do they work well on asteroid images?
 - Model resolution and Accuracy?
- Investigate minimum requirements on observation for shape reconstruction
 - How many images do we need?
 - Restriction on geometry of observation?

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Test Data Set: 169 Itokawa images of Hayabusa-1

- Rotation phase interval : 2 degrees (ave.)

Rotation Axis
Itokawa

Result: Point Density Map

- 0.33 points/m² (ave.) (= 1.7 m mesh)
 - 10 times finer than the Hayabusa-1 initial model
- x2.4 Input Image resolution (0.7 m)
 - Expected image resolution on Hayabusa-2: 2 m
 - Expected model resolution: 5-6 m mesh

Result: Point Density Map

- Polar regions are not reconstructed

Polar regions

- Viewing geometry
 - Edge-on observation
 - Polar regions are always oblique to the camera
- Featureless smooth surface
 - Bundler and PMVS2 cannot find much features to be tracked

Accuracy Evaluation

- Reference Model (tentative ground truth)
 - The finest shape model by Gaskell
- Error: Euclid distance from a reconstructed point to a closest polygon of reference model
- RMS of errors: overall accuracy of the model

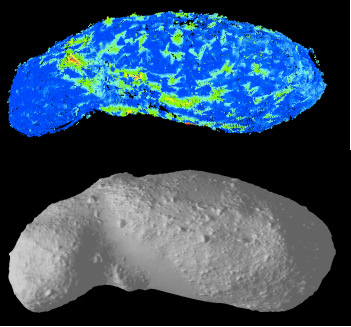
A polygon of Gaskell model A reconstructed point

Error maps

- RMS: 4.3 m (~ x6 of the image resolution)

Error distributions

- No apparent relationship is found between landforms and error distributions
 - Rough terrain
 - Smooth terrain
- Head- and Tail-ends are relatively fair
 - Viewing geometry?



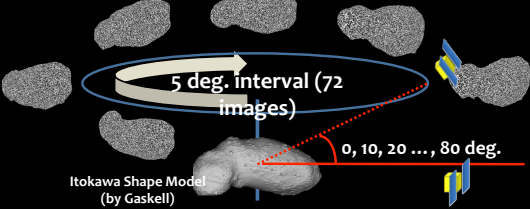
Summary on this section

- Bundler and PMVS2 can give a shape model of asteroids from images with appropriate accuracy and resolution as an initial model
 - Great improvement from the initial model of Hayabusa-1
 - Better accuracy and resolution with very short processing time (within several hours)
- Minimum rotation phase interval: 5-6 deg.
- Detailed models for touch-down site selection and scientific analysis should be reconstructed other methods (e.g. photometric stereo or Gaskell tool)

Experiments on Geometrical Conditions

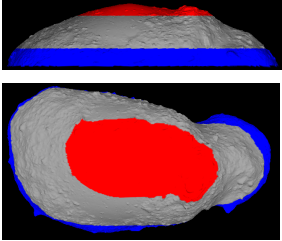
- Viewing geometry
 - Polar regions are not reconstructed from an edge-on (equatorial) data set
- 1999 JU3 rotation state: still ambiguous
 - Consideration on the pole-on case
- No available images of an asteroid with geometry variation (sub-Spacecraft latitude)
 - Synthetic images from the shape model

Synthetic image data sets



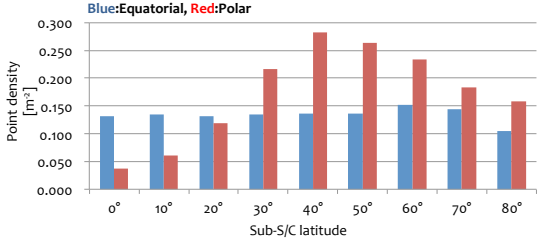
- Varying sub-S/C latitudes
- No light source: random textures

Evaluation



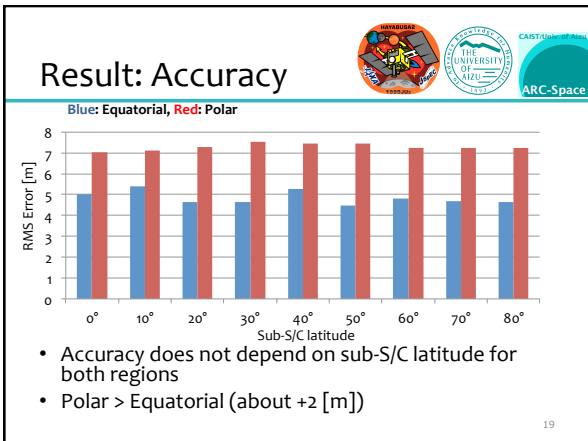
- Evaluate accuracy and mesh density on **Equatorial** (0~15 deg.) and **Polar** (45~ deg.) regions

Result: Point Density



Sub-S/C latitude	Equatorial Point Density [m ⁻²]	Polar Point Density [m ⁻²]
0°	0.13	0.04
10°	0.14	0.06
20°	0.13	0.12
30°	0.14	0.22
40°	0.14	0.28
50°	0.14	0.26
60°	0.15	0.23
70°	0.15	0.18
80°	0.11	0.16

- Constant density for the equatorial region
- Comparable density for the polar region with > 30 deg.

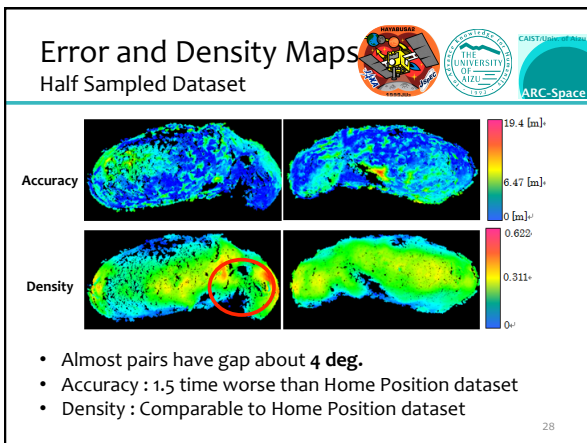
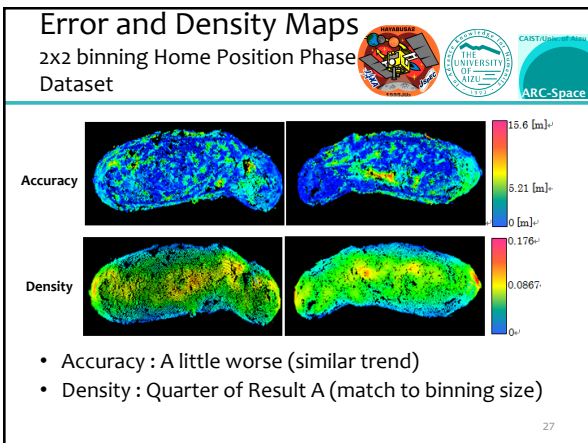
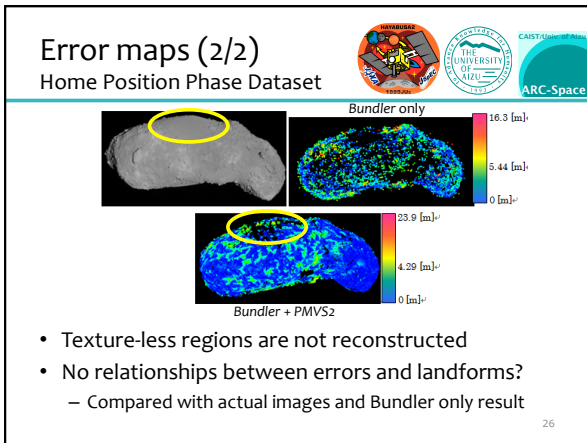


Summary on this section

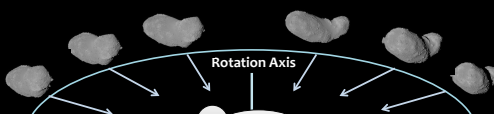
- Bundler and PMVS2 can give a shape model even at high sub-S/C latitude condition
- If the target asteroid has the edge-on condition, a S/C maneuver to 30-40 deg. is enough to cover the polar regions

Conclusions

- Basic applicability of Bundler and PMVS2 to asteroid exploration missions is confirmed
 - Suitable for production of initial models
- Minimum requirements on source data sets are investigated
 - Rotation phase interval (< 5 deg.), model/image resolutions (x2.4), and sub-S/C latitude (>30 deg.)



Results with Actual Images



Dataset	Resolution [m/pixel]	The number of images	Reconstruction
A : Home Position Phase	0.70	169	Succeeded
2x2 binning of A	1.50	169	Succeeded
Half Sampled of A	0.70	85	Succeeded
One-third Sampled of A	0.70	57	Failed
Gate Position Phase	1.50	166	Failed

Failure Case 1

One-third Sampled Dataset

- Reconstruction process failed
- Almost pairs have gap about **6 deg.**
 - Insufficient feature matching (pre-process) among images
 - The limit of image pair gaps is about 5 degrees

Failure Case 2

Gate Position Phase Dataset

- Reconstruction process failed
 - Insufficient feature matching because of large gap (5 or more deg.) between image pairs

Gap Histogram (Gate Position Phase)

Mean:2.16
Variance:2.67
Max:8.16

Gap Histogram (Home Position Phase)

Mean:2.13
Variance:0.42
Max:10.3