**ASTEROID SHAPE RECONSTRUCTION BY OPEN-SOURCE STRUCTURE FROM MOSION TOOLS.**
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**Introduction:** Shape reconstruction of an asteroid from space mission data is important both for scientific needs and for operational needs. The shape model of the target asteroid of the mission is one of the fundamental scientific data, and it is also used to decide the descent course and the landing location of the spacecraft. Although the shapes of distant asteroids are estimated by light curve inversion or radar observation, image data taken by the space probes are used to reconstruct more detailed shape models during the missions.

Here we report results on application of open source shape reconstruction tools to an asteroid image data set. In the previous asteroid missions, in-house developed tools or proprietary tools are mainly used for asteroid shape reconstruction or production of digital terrain models. These tools can cover many aspects of the missions, but they cost the community to develop and maintain them. The research field of computer visions has lot of assets on shape reconstruction tools, and some of them are open to public. They are robust and stable because they are tested in their research field for a long time. We intend to introduce them to the planetary exploration community. Our aim in this paper is to evaluate applicability of the open-source shape reconstruction tools to the exploration mission data. Our efforts are a part of Hayabusa-2 project, a Japanese second asteroid exploration mission.

**Tools:** We test *Bundler* [1] and *PMVS2* [2] in our study. These two tools cooperatively work to reconstruct an object shape from images.

*Bundler* is an open source implementation of a stereo shape reconstruction method called Structure from Motion (SfM). SfM is a method to be able to estimate a shape of the target object from multiple images (e.g. multiple exposures of a moving camera). It also can estimate camera parameters including position and pointing of the cameras for every input image. This means that SfM can estimate both the asteroid shape and spacecraft locations and attitudes in our case. *Bundler* works as follows:

1. Extracting characteristic feature points from the input images by SIFT (Scale Invariant Feature Transform) algorithm [3].
2. Searching corresponding feature point pairs over the input dataset by using SIFT feature descriptor.
3. Estimating 3D positions of the paired feature points and camera parameters by bundle adjustment algorithm [4].

*PMVS2* gives a more dense shape model, since *Bundler* only estimates 3D locations of a limited number of feature points. It is also an implementation of another stereo shape reconstruction (Multi-View Stereo; MVS). It can estimate a dense point cloud representing the object shape from input images and their camera parameters estimated by *Bundler*.

**Test Data:** A global image data set of the asteroid Itokawa taken by AMICA on board the Hayabusa spacecraft [5] is employed to our test data set. It consists 169 images of the asteroid with 0.7 m/pixel resolution. Since the Hayabusa was mainly stayed on the Itokawa's equatorial plane, all images are the edge-on configuration (the sub-spacecraft latitude is ~ 0 deg.) covering full rotation phases of the asteroid with ~ 3 deg. interval. All images in the set were taken within two days (30 Sep. – 1 Oct. 2005), and solar phase angles are almost constant (~ 10 deg.).

We also prepare synthetic image sets that are produced from an existing high-resolution shape model of Itokawa [6] with different viewing geometries from the AMICA observation data set. Because the spin configuration of the target asteroid of the Hayabusa-2 mission 1999 JU3 is still uncertain, we evaluate robustness of *Bundler* and *PMVS2* to varying viewing geometries with these synthetic data sets.

**Results:** Fig. 1 shows a shape model of Itokawa reconstructed from the AMICA image set by *Bundler* and *PMVS2.* The model is a point-cloud format that consists of a swarm of points with normal vector representing the surface of the asteroid. The model has 100,740 points, but the points are not equally distributed over the whole surface. Point density distribution maps in Fig. 2 shows the model has dense points in the equatorial region where represents the sub-spacecraft point. The highest point density is ~ 0.6 $m^{-2}$, and the average density is ~ 0.3 $m^{-2}$, corresponding the mesh resolution of ~ 1.3 m and ~ 1.7 m, respectively. Point densities are low in the polar regions, because viewing angle of these regions are high. Additional experiments using the synthetic image data set demonstrate that an image set with the sub-spacecraft latitude of ~ 30 deg. can sufficiently cover blanks in the polar regions. Another experiment on a synthetic image data set with the sub-spacecraft latitude of 75 – 80 deg. indicate that we can reconstruct the shape of an asteroid that has a spin configuration near the pole-on situation.

Accuracy assessment is carried out by employing an existing high-resolution shape model of Itokawa [6] as a reference, which is considered as the most fine and accurate model ever. Error of our model is defined as a Euclid distance from a point of the model to the closest polygon of the reference model. Fig. 3 shows error distribution maps the model shown in Fig. 1 and 2. The maximum error is over 50 m, but more than 70% of the points have errors less than 1 m. The root mean square of all errors is 4.3 m. The error distribution has no correlation with surface features on the asteroid including boulders, craters or smooth terrains.

**Conclusion:** We successfully demonstrate that *Bundler* and *PMVS2* can be applicable to the asteroid exploration data. An important advantage of these tools compared to previous ones is its short processing time. With our test data, the main process is finished within several hours. Although they require pre- and post-processes, the total analysis time will be drastically shorten. This advantage will be effective in quick evaluation of observation data and decision making during the mission operations. However, circumspect decision on landing locations of the spacecraft requires more detailed and local elevation model. Such fine model will be obtained by other technique. Multi view stereo with high-resolution images, shape-from-shading, or photometric stereo are possible methods.

**References:** [1] Snavely N. et al. (2006) *ACM SIGGRAPH Papers*, 835-846. [2] Furukawa Y. and Ponce J. (2010) *IEEE Transactions on Pattern Analysis and Machine Intelligence*, *32*, 1362-1376. [3] Lowe D. G. (1999) *Proceedings of the International Conference on Computer Vision 2*, 1150–1157. [4] Triggs B., et al. (1999) *ICCV '99*, 298–372. [5] Saito J. et al. (2006) *Science, 312*, 1341-1344. [6] Gaskell R. et al. (2008) MAPS *43*, 1049-1061.

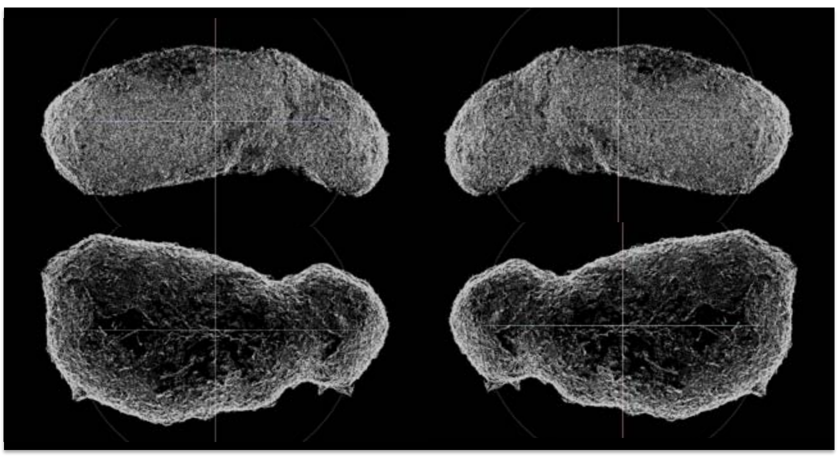

**Fig. 1. Point-cloud shape model of the Asteroid Itokawa reconstructed from 169 AMICA/Hayabusa images by Bundler and PMVS2.**

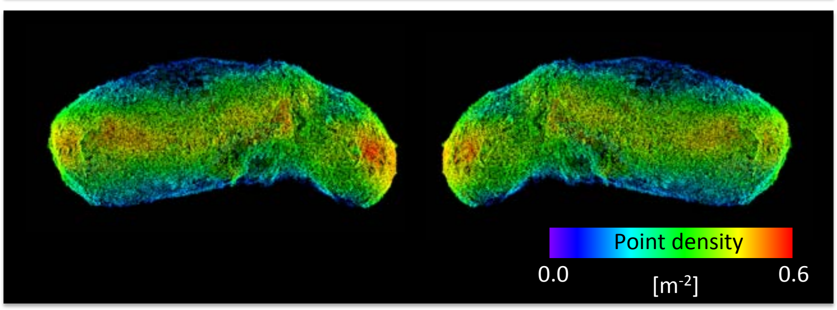


**Fig. 2. Point density (resolution) map of the reconstructed model.**

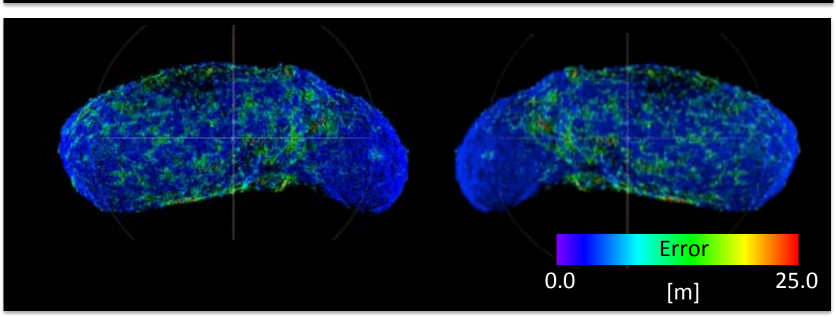


**Fig. 3. Error map of the reconstructed model.**