

## Computer Vision in Space: Optical Navigation Technology Development for Hayabusa-2

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Computer vision (CV) is a research field aiming to establish technologies by which information of objects is extracted from their images. Using CV technologies, our research group are developing methods to construct shape model of an asteroid for Hayabusa-2 navigation. We report this activity in this article. In addition, applying CV technologies to space environment has a potential to drive CV itself to a new research direction. We also touch on this observation.

For Hayabusa-2 navigation, we need to know shape of the destination asteroid, but the long distance between the asteroid and the earth prevent us from measuring it from the earth. Therefore we have to measure it after the arrival to the asteroid. Because active measurement methods need too much power, we are developing methods using images taken from the spacecraft.

Our project is mainly run by Dr. Seiji Sugita at Univ. of Tokyo and Dr. Naru Hirata at Aizu Univ., who are researchers in planetary science. However, because shape reconstruction techniques using images have intensively been studied in CV and CG (computer graphics) areas, the project is contributed by Dr. Hiroshi Ishikawa at Waseda Univ. and the author from CV area, and Dr. Shigeo Takahashi at Univ. of Tokyo from CG area.

We have applied a structure from motion technique developed in CV without modifications to the shape reconstruction of asteroids. We have had a minimum result required for Hayabusa-2 navigation, but more precise model is needed to make the navigation more certain and flexible. Therefore, we are combining photometric stereo to it.

Photometric stereo is a shape reconstruction method utilizing reflectance information of objects. However, we cannot directly apply such techniques developed in CV to the asteroid, because the conditions assumed in CV are fairly different from our case. The CV techniques assume that a number of images are taken from the same position, but the spacecraft cannot be controlled in such a way because it requires too much fuel. In addition, the reflectance models are different; Lambertian and Phong, for example, are used in CV, but we need algorithms based upon models such as Hapke and Minnaert, which describe reflectance of planet materials. Therefore, we are developing new algorithms that match the space environment for Hayabusa-2 navigation.

Looking at the origin of CV, it was regraded as a part of artificial intelligence research and has been motivated by artificially realizing functions of visual systems of human beings, or creatures in general. It seems that, from this reason, methods developed in CV tend to be general-purpose, and also that environments on the earth are implicitly assumed. Therefore, algorithms in CV are sometimes not applicable to problems in space science. However, viewing the situation from a different point, it may inspire CV itself to a new research direction by giving clear purposes.

When assuming usage in space, the following peculiarities are observed. The light source is usually only the sun, so it often suffice to consider only parallel light as the illumination. We can develop algorithms fully taking advantage of this simplicity. As mentioned above, reflectance models special to planet are used. If the process is executed in spacecrafts, the amount of computation is very limited, so the view point to develop a minimum algorithm to fulfill the objective becomes important. On the other hand, if images are transferred to the earth, the number of images is limited, but usually no limitation exists in amount of the computation. In such a case, CG-CV loop where a CG model is iteratively modified so that the generated images match to the observed images becomes to have reality. In addition to stated above, computing other information needed for space science than shape, estimating error information (variance), and so on, are important tasks for space science. We believe developing these techniques is an important direction of CV research.

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