AN EXPERIMENT OF MEASURING POSITION AND ATTITUDE OF SPACE DEBRIS BY STEREO-VISION IN ORBITAL OPTICAL CONDITION

Shoya TOMORI(1), **Satomi KAWAMOTO**(2), **Masato HAYASHI**(2), **Yasuhiro KATAYAMA**(2), **Shingo YOSHINAGA**(3), **and Yoshiki MORINO**(4)

(1) *Waseda University, 3-4-1 Okubo Shinjuku-ku, Tokyo, Japan, s-myk@akane.waseda.jp*
(2) *JAXA, 7-44-1 Jindaijihigashicho Chofu-city, Tokyo, Japan, Email: {kawamoto.satomi, hayashi.masato, katayama.yasuhiro}@jaxa.jp*
(3) *Waseda University, 3-4-1 Okubo Shinjuku-ku, Tokyo, Japan, yoshinagarden@asagi.waseda.jp*
(4) *Waseda University, 3-4-1 Okubo Shinjuku-ku, Tokyo, Japan, morino@waseda.jp*

ABSTRACT

The amount of space debris on orbit around the Earth has been increasing due to explosions or collisions in space. If the volume of debris continues to increase, future space development could become more difficult, and thus the situation requires active debris removal (ADR). In the process of removal, a debris removal satellite has to approach the space debris –a non-cooperative target– and, requires essential technology to measure the relative position and attitude between itself and the space debris. We studied stereo-vision three-dimensional (3D) reconstruction and model-based matching for relative position and attitude estimation, because both can be compactly structured and useful for a wide and diverse range. In our stereo-vision system, feature points are extracted from two cameras images, and correspondent points are searched. These points are then reconstructed to 3D and a cylinder model is applied the 3D point cloud. Finally, the relative distance and attitude are estimated based on this applied cylinder model.

In order to confirm that stereo-vision is useful for applying to ADR, we conducted measuring experiments under simulated orbital optical conditions in this report. We also used the stereo-vision system to measure the relative distance between debris and cameras and the relative attitude of debris. In this experiment, we used an optical simulator that can simulate an orbital optical condition, and used 1/30 and 1/100 scale H2A upper-stage models as the targets. This simulator has a three-axis rotation stage for the debris model and a three-axis translation stage for the cameras. It also has a simulated sunlight and a projection apparatus that can dynamically project Earth in the background of the debris model. Using the simulator, we can simulate any orbital optical condition.

First, assuming that the debris removal satellite (DRS) approaches the target debris from about 200 [m] to about 30 [m], we conducted measuring experiments using the 1/100 scale model under the simulated optical condition. In the results of this experiment, the mwasured distance is accurate except some points, but the measured attitude is unstable. Next, assuming that the debris removal satellite (DRS) approaches the terget debris from 70 [m] to 30 [m] and that then maneuvers aound the debris above the PAF side, we conducted measuring experiments using the 1/30 scale model. On the side of the debris facing the cameras, measurment errors in distance are within 10% but measurment errors in attitude are over 30 [deg]. However, the attitude of debris is difficult to measure when the PAF side of debris turns toward the cameras.

As a result of the experiments, we could estimate the distance and attitude of debris, even when made difficult by the PAF side of debris facing the cameras, and thus confirmed that stereo-vision is sufficiently applicable to ADR under certain conditions, except in the cases cited. Therefore, in the difficult case of making certain measurments, measuring accuracy is being improved by changing the stereo-vision system parameters and using another algorithm.

Key words: Active Debris Removal; ADR; Non-cooperative Rendezvous; Stereo-vision; Three-dimentional (3D) Reconstruction.

1. INTRODUCTION

The amount of space debris has been increasing due to explosions or collisions in space. Space debris has had a significant impact relative to the operation of satelites. As shown in Figure 1, in order to maintain space development at the current level, 5-10 objects of large-sized debris must be removed each year[1].

Today, active debris removal technologies are being studied around the world, and some methods where a propulsion system is attached to debris are being considered among those technologies. In the process of removal, a debris removal satellite has to approach the space debris —a non-cooperative target— and requires essential, technology to measure the relative position and attitude between itself and the space debris. A non-cooperative target refers to any object having free movement, but

Proc. 7th European Conference on Space Debris, Darmstadt, Germany, 18–21 April 2017, published by the ESA Space Debris Office
Ed. T. Flohrer & F. Schmitz, (http://spacedebris2017.sdo.esoc.esa.int, June 2017)

lacking any reflectors for rendezvous. Active methods and passive methods are considered to measure the relative distance and attitude in approaching process. Each method has following features:

- Range Finder (Active Methods)
  - It can accurately measure distance.
  - It is unsuitable for a wide and diverse range.
  - It will be large stuctured and expensive.
- Image Measurment (Passive methods)
  - It can be useful for a wide and diverse range.
  - It can be compactly structured and less expenssive.
  - It needs complex algorthm and improvement of measurment accuracy.
  - It can be effected by orbit optical conditions.

In order to carry out space debris removal less expensively, we studied stereo-vision three-dimensional (3D) reconstruction and model-based matching for relative position and attitude estimation. Both can be compactly structured and useful for a wide and diverse range, and also boast of many ground-level achievements, such as a collision avoidance system for cars. However, thre are few example using in space and the process of approaching debris under optical conditions on orbit around the Earth must deal with the following challenges.

- Images look different due to the position of the sun.
- Images look different due to the attitude of debris.
- Images look different due to the distance between the debris removal satelite (DRS) and debris.
- The debris model is probably different from the target debris due to aging degradation.
- Optical conditions, attitude of debris, and distance between the DRS and debris are intricately and continuously changing.

In order to confirm that stereo-vision 3D reconstruction and model-based matching are useful under optical conditions on orbit around the Earth, we report the results of experiments that we conducted in this paper, assuming the DRS approach to debris on orbit. In the experiments, we assumed that the terget debris is the upper-stage of rockets, given the similar shapes, lower degree of secrecy, and simple movements due to their cylindrical shape and that objects exist which do not spin due to interference with a geomagnetic field[5][4].

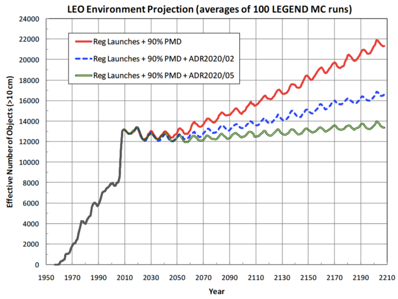


Figure 1: Transition estimation of the number of cataloged space debris in case of ADR[1]

2. OPTICAL SIMULATOR

It is important to obtain images sufficiently similar to those obtained in space. Therefor, we used an "optical simulator" to conduct the experiments. Figure 2 shows a schematic view of the optical simulator.
This optical simulator has following device cofiguration.

- 3-axis Rotation Stage for Debris Model
- 3-axis Translation Stage for Chaser
- 2-axis Rotation Stage for Simuated Sun
- Projection Device of Dynamical Earth Background
- $1/100$ or $1/30$ scale HIIA Upper-Stage Model

Using these devices in an integrated mannar, we can simulate not only the optical conditions on orbit around the Earth but also the sequence of debris removal.

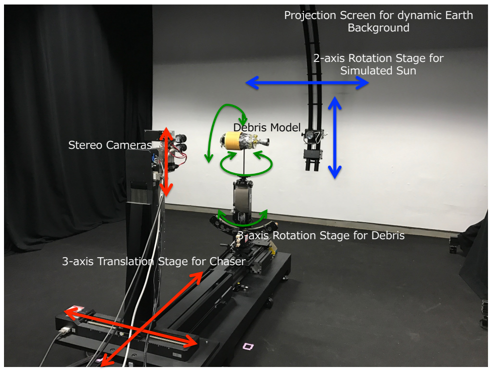


Figure 2: Schematic view of optical simulator

3. EXPERIMENTS METHODS

We conducted two types of experiments. First, we assume that the chaser approaches from 200 [m] to 70 [m].

Figure 3 shows the profile of the middle term approach. Second, we assume that the chaser approaches from 70 [m] to 30 [m], and then maneuvers around the debris above the PAF side. Figure 4 shows the proximate operation profile.

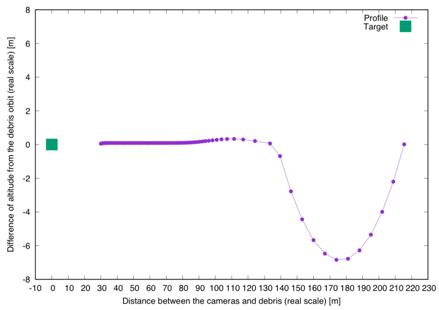


Figure 3: Approaching Profile(Middle Term)

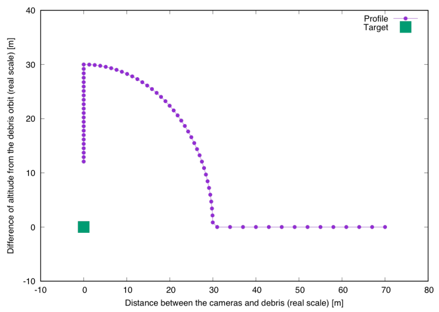


Figure 4: Approaching and Maneuvering Profile(Proximate Operation)

3.1. The axis of coordinate

Figure 5 shows the coordintes of the simulator. An origin of the translation stage for the chaser is the distant position 2000 [mm] from the debris model, but all estimated results are based on the cameras coordinates (fixed on the right camera). The attitudes of debris are defined as each rotaion angle around the x, y, and z axes that represent the angles of pitch, roll, and yaw. In addition, the roll angle starting point is defined in case the nozzle side of the debris faces the cameras, and the yaw angle starting point is defined in case the center axis of the debris is horizontal. In these experiments, the debris featured an approximated cylindrical shape, so we ignored the pitch angle.

3.2. Simulation conditions

We assumed the following simulation conditions:

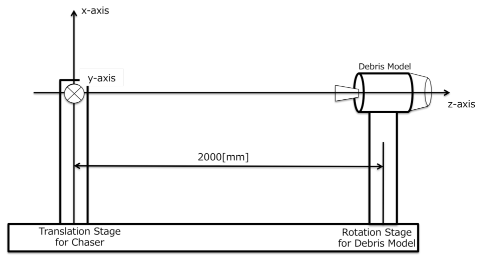


Figure 5: Coordinate of Simulator

- Debris Orbit
  - Sun-synchronous orbit
  - Circular orbit above the Earth 623.04 [km]
  - Oribit inclination 97.86676 [deg]
- Starting points of debris
  - LAT. -0.121 [deg]
  - LONG. 104.792 [deg]
- Starting points of solar direction
  - Solar azimuth 19.367 [deg]
  - Elevation angle 27.749 [deg]
- Rendezvous metheds[3]
  - Over 70 [m] -> V-bar hopping
  - 70 [m]-30 [m] -> Forced motion
- Obtaining images per 30 [sec]

In these experiments, relative distances and attitudes are estimated by the following processes:

1. Obtaining images by two cameras
   Using two synchronized cameras, two images from different position are obtained at the same time.
2. Extracting feature points based on intensity changes
   Compared with the surroundings, the major intensity change points are extracted.
3. Matching of corresponding feature points
   In order to conduct the stereo process, it is necessary to match the corresponding feature points.
4. Stereo image processing
   Using the principle of the stereo method, distances are calculated for each feature point.
5. 3D reconstructing feature points
   Based on calculated distances, all feature points are used to reconstruct a three-dimensional space.
6. Cylinder model fitting to reconstructed feature points
   The cylinder model is optimally fit to all reconstruction feature points.

7. Estimating relative position and attitude based on the center of the cylinder
   The calculated cylinder center is defined as the relative position of space debris and inclination of the cylinder from each axis defined as an attitude of debris.

4. EXPERIMENT 1

We assumed that the chaser approaches the debris from 200 [m] to 30 [m], and then conducted measuring experiments. Images are obtained every 30 [sec], and relative distance and attitude are estimated at the same time. In order to ensure the reproducibility, we repeated measuring experiments ten times.
Figure 6 shows the estimated result of distance. Given the estimation shown in Figure 6, this system is sufficiently accurate to measure the distance between cameras and debris except for a few points, and this graph shows a very similar trend. The maximum error is 12%.
Figure 7 shows the estimated results of the attitude of debris. In this graph, the estimation is unstable and has large errors, and the maximum error is over 80 [deg]. This graph suggests that it is difficult to accurately estimate the attitude of debris from a long distance. And when comparing Figure 6 with Figure 7, we find differences in distance between the profile and estimated value, and differences in the attitudes of debris. Thus, the estimated distance is sufficiently accurate, but the estimation of attitude is generally unstable.

There are two reasons why the estimation of attitudes is unstable. First, the images are out of focus. Second, the numbers of feature points is too low. In these experiments, the focus of the cameras is fixed and at the 30 [m] point of real distance, images are most visually in focus because at this point satellite motions are changed from approaching to poximate operation. In proximate operation, it is necessary to more accurately estimate the attitudes of debris, and ensure that focus is visually in focus. Figure 8(a) shows an image obtained at 200 [m] in real distance; Figure 8(b) shows the image obtaind at 30 [m]. In comparing Figures 8(a) and 8(b), we found that the image obtained at a longer distance is out of focus. The number of feature points also effects the accuracy of estimating the attitudes of debris. As the cylinder model fits to reconstructed feature points in these experiments, it is difficult to fit to the cylinder with fewer feature points. The longer the measuring distance, the smaller the debris model captured as an image. It is difficult to extruct feature points to a small debris model. Moreover, the numbers of feature points are related to the focus of an image, and an images out of focus makes it difficult to extract feature points. Given the small debris model used, the errors in estimating attitudes rarely effect the result of estimating distance. If the focus of the cameras can be changed and each image is visually in focus, we can possibly expect improved accuracy in measureing the attitudes of debris. We consider that camera focus can be changed to a few fixed focuses in proportion to the estimated distaces.

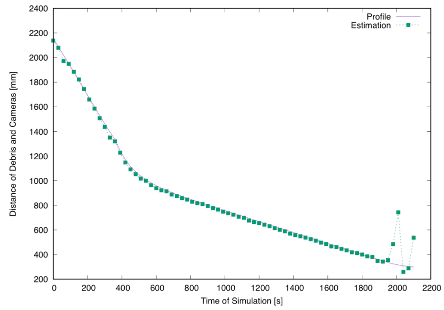


Figure 6: Estimation Results of Distance

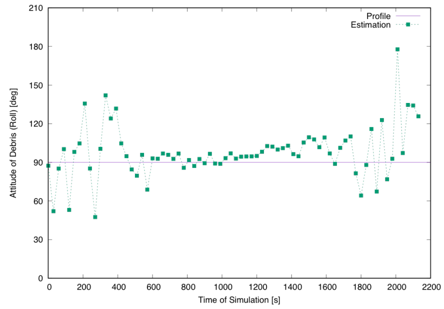


Figure 7: Estimation Results of Attitudes of Debris (Roll)

(a) The Image obtaind from 200 [m] (b) The Image obtained from 30 [m]

Figure 8: The Difference Obtained Images

In order to compare the measuring results with the profile, we plot the measuring results and the approaching pfofile on Figure 9. From Figure 9, the estimated relative positions in an difference of altitude from the debris orbit have errors. The reason of these errors is that, because upper half of debris is lit by sunlight, the feature points extracted from there. Therefore, our system estimates that the center of debris is the center of upper half of debris.

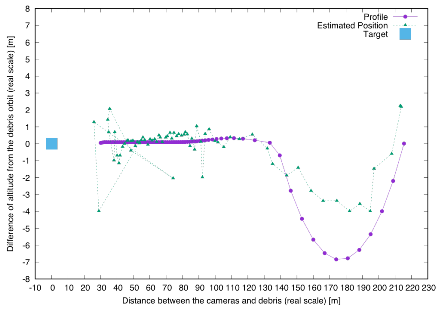


Figure 9: The Estimated Results And The Profile

5. EXPERIMENT 2

We assumed that the chaser approaches the debris from 70 [m] to 30 [m] and maneuvers around the debris above the PAF side, and then we conducted measureing experiments. Images are obtained every 30 [sec], and the relative distance and attitude are estimated at the same time. In order to sure the reproducibility, we repeat the measuring five times.

Figure 10 shows the estimated result of distance. From this graph, the estimation accuracy of distance is sufficient for application to ADR in the approaching process, and the estimated distance is accurate in the first half process of maneuvering sequence, but in the latter half of the sequence, the estimated distance is inaccurate. Errors in estimation are constant lasting more than 1000 [sec] in simulation time. Figure 11 shows the estimated results of the attitudes of debris. In the approaching process, attitude estimations are unstable and the maximum error is 40 [deg]. However, in the proximate operation, the estimation accuracy of attitude is sufficient for application to ADR by 150 [deg] of debris attitude. Over 150 [deg] of debris attittude, it is difficult to estimate the attitude of debris accurately.

Figure 12 shows the estimated result of the relative position of debris. From this graph, most parts exist at the center of this graph, but some parts of the estimated result have x-axis errors. This graph suggests that in the proximate operation, estimating position is difficult, paticularly on the x-axis. Figures 10, 11, and 12 all suggest that only the estimated attitude of debris is unstable in the approaching process, but in the proximate operation, suggest that the accuracy of estimation is closely ralated to both.

From Figures 10 and 11, distance estimation is sufficiently accurate, but estimating attitude is unstable in the approaching process. The reason for this instability differs from that in experiment 1. In experiment 2, there is a sufficient numbers of feature points for estimating. The reason for the attitude estimation error concerns the part extacted from a feature point. If more feature points are extracted from PAF, the side of the cylinder is fit to the side of PAF. Because the side of PAF has an inclination, the estimaed attitude has an error corresponding to the inclination of the PAF. The same can be said for the side of nozzle. However, attitude estimation accuracy is expected to be improved by changing the sensitivity of extracting feature points, as more fearute points will be extracted from the side of debris.

In proximate operation, however, there is another reson for the estimating errors of attitude. As a satellite maneuvers around the PAF side, feature points can be extracted from PAF. Figure 13 shows the cylinder model fitting result. From Figure 13 the feature points extracted from PAF are fitted to the side of the cylinder because the length is lower than another part of the debris. We are considering another algorithm to estimate the attitude of debris above 150 [deg], because in this experiment, the result suggests that cylinder fitting algorithm is applicable to cases whre the side of the debris faces the cameras[2].

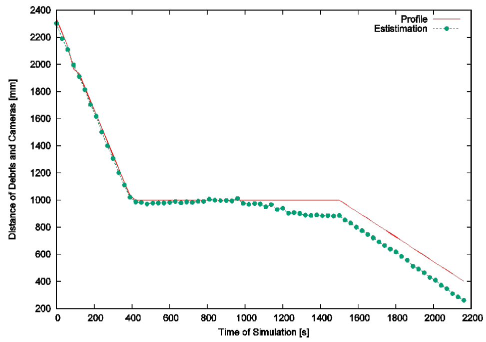


Figure 10: Estimation Results of Distance

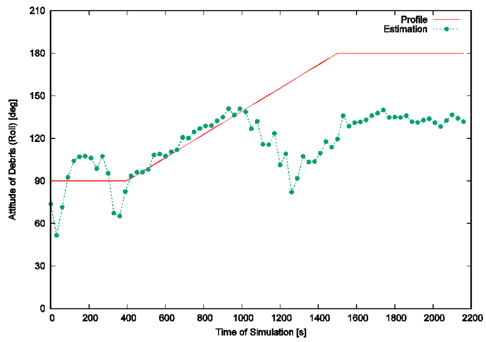


Figure 11: Estimation Results of Attitudes of Debris (Roll)

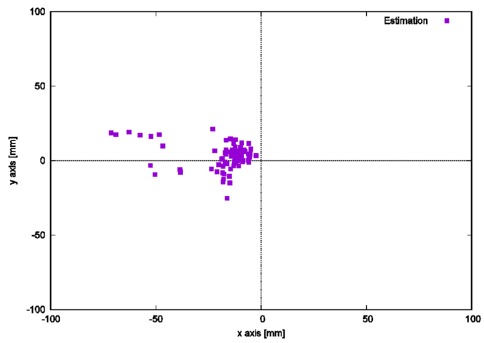
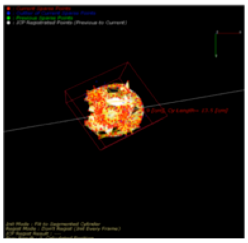
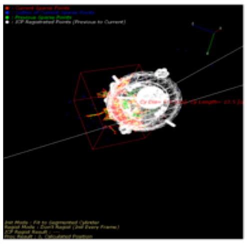


Figure 12: Estimation Results of Attitudes of Debris (Roll)



(a) The Result of Extracted Feature Points (Front View)



(b) The Result of Cylinder Fitting (Side View)

Figure 13: Cylinder Fitting Result

6. CONCLUSIONS

We suggested that stereo-vision three-dimentional reconstruction amd model matching are useful for measuring the distance and attitude of space debris under optical conditions around the Earth in this paper. In middle term approaching, this system is sufficientry accurate measure the distance between the debris and cameras, but the estimations of attitude of debris are unstable and have a large error. In short term approaching, the estimation accuracy of distance is suffient for application to ADR, and the estimated distance is accurate in the first half process of maneuvering sequence, but in the latter half of the sequence, the estimated distance is in accurate. In the approaching process, attitude estimations are unstable. However, in the proximate operation, the estimation accuracy of attitude is sufficient for application to ADR by 150 [deg] of debris attitude. The result in this experiments suggests that cylinder fitting algorithm is applicable to cases whre the side of the debris faces the cameras and it is necessary to apply another algorithm to final proximation operation[2].

REFERENCES

1. J.-C. Liou,(2012). Orbital Debris Modeling. National Aeronautics and Spase Administration,NASA
2. Kouichi Shibasaki, Wataru Oobayashi, Satomi Kawamoto, Junichi Aoyama,(2017). Conceptual Study of Mechanical and Sensing System for Debris Capturing for PAF, 7th Space Debris Workshop, JAXA
3. Naomi Murakami, Toru Yamamoto,(2016). Rendezvous Strategy for the Active Debris Removal Missions, 7th Space Debris Workshop, JAXA
4. Praly, N., Petit, N., et al,(2011). Study on the eddy current damping of the spin dynamics of spatial debris from the Ariane launcher, 4TH European Conference for Aerospace Sciences
5. Satomi Kawamoto,(2012). Overview of Active Debris Removal, Proceedings of the Space Science and Technology Conference