Dynamics Observation of Space Objects Using Adaptive Optics Simulation and Light Curve Analysis

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ABSTRACT

Defining a state of space objects by optical observation is major theme for many researchers. optical measurements of cosmic object enables us to obtain the information of attitude motion, surface characteristics and shape of the object which cannot be got by telemetry data. Using these information, we can contribute to grasp the health. Various methods exist for optical observation, but photometric observation and imaging observation are considered in this research. In this paper, we discuss the estimation of the attitude motion of a space object in the Geostationary region(GEO) using imaging observation. This analysis is based on simulations considering the performance of the AO system and the telescope and atmospheric fluctuation, and proposes the attitude determination method applying the method using computer vision. In the future, we aim at improving the accuracy of dynamic estimation by combining this method with photometric observation and clarifying the system requirements for actual observation.

1. INTRODUCTION

In recent years, space environmental pollution by space debris is getting worse and risk of collision with space debris is increasing. In Geostationary earth orbit(GEO), there are many communication or meteorological satellites. Therefore, Geosynchronous spacecraft sometimes take the avoidance of collision with space debris in order not to receive serious damage, such as break of solar paddles. To be aware of debris environment or to avoid accidental collisions, space objects both operational spacecraft and debris are tracked with optical measurements. Using optical measurements enable us to check up the operational states of spacecraft and to remove large debris. Nowadays, the health of an operational spacecraft are monitored with telemetry data on the ground, but if the spacecraft is out of order, we cannot obtain correct data from it.

In this laboratory, researches on dynamic observation of cosmic objects using optical observations on objects in GEO, which is based on the simulation of photometric observation such as light curve observation of MMAE and Unscented Kalman filter have been conducted[1]. However, the problem is that the initial value (angle, angular velocity of attitude) given to the Kalman filter cannot be determined and that the system requirements for actual observation cannot be determined. When observing the dynamic state of a cosmic object, it is general practice to combine several methods such as spectroscopic observation, photometric observation, polarization observation or imaging observation because it is difficult to obtain sufficient precision with only one observation. Therefore, in this research aims to combine imaging observation and photometric observation for more accuracy and determination of system requirements. Specifically, we are thinking to estimate the initial state quantity given to the Kalman filter of the photometric observation simulation by performing image observation simulation. In the imaging observation simulation, software named “SOAPY”[2], which simulates atmosphere dissipation, characteristics of the telescope and the performance of the adaptive optics system is used. Conducting this imaging simulation, which Parameterize system performance, It is possible to define the requirements of the system for the requested accuracy. In order to achieve that aim, in this paper, we propose a method to estimate its initial attitude by performing an observation simulation on the space object in the GEO.

2. METHOD

As mentioned above, in this research, we estimate the attitude of the space object in the GEO by imaging observation. This method is under the assumption that the 3D model of the target object has been already known. To briefly explain the method, a dataset composed of images of all attitudes of the target satellite is created, and images of the data set are compared with the target image. Estimation of attitude is performed by finding images of data sets with features close to the target image. The method can be summarized into several procedures as follows.

2.1 Creation of dataset images $I_n(i,j)$ to estimate target satellite attitude

Fig. 1 shows the The target satellite, JCSAT-3. The specifications are shown in the Table. 1 and Table. 2. From this 3D model, data set that is used for the attitude estimation is generated. Actually, image of target satellite is obtained by actual observation, however, in this simulation the image is also generated using the 3D model, because optical system is assumed that need very high performance and it is costs too much. In this simulation, an image of the target satellite is defined as $T(i,j)$. On the other hand, dataset images is defined as $I_n(i,j)$, where n is index of an image. Images $T(i,j)$ and $I_n(i,j)$ are rendered by "Blender", and surface specification is considered. The sun direction and observer direction are expressed in the coordinate system fixed to the space, and the attitudes of $T(i,j)$ and data set $I_n(i,j)$ are expressed with xyz-Euler angle related to the satellite. Both the directions of sun and observer are fixed in the simulation, because it is necessary to estimate the attitude of the target satellite at a certain moment in an observation. Therefore, only 3D model of the target satellite rotates to generate the dataset of its attitudes.

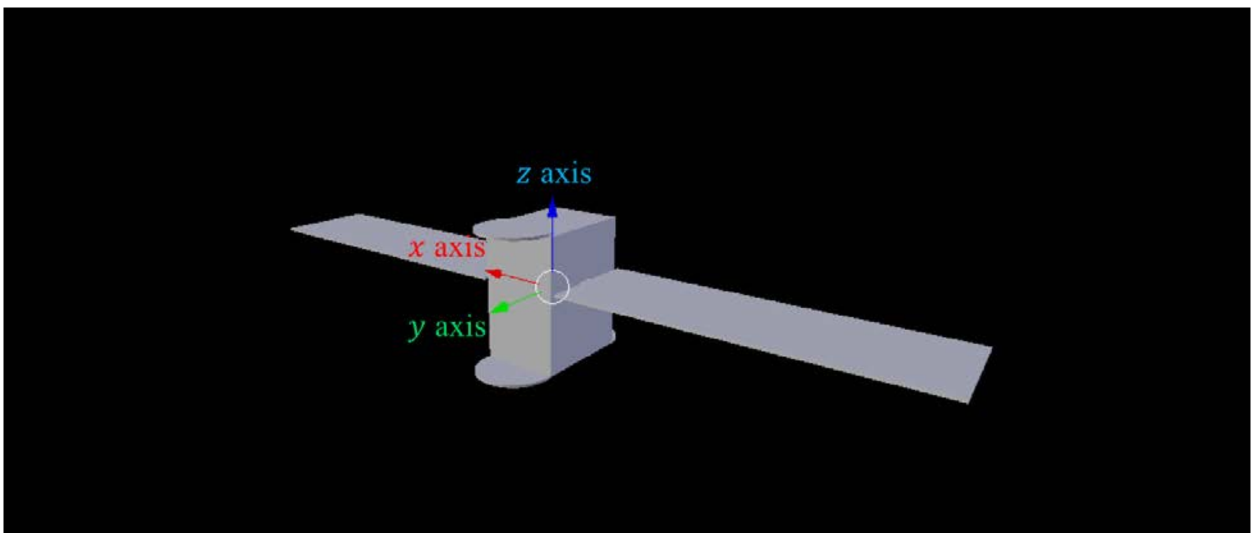

Fig. 1. 3D model of JCSAT-3

Tab. 1. 3D model size and mass properties

Height stowed	4.9m
Width stowed	2.8m × 3.8m
Solar Arrays deployed	26.2m
Antennas deployed	7.5m
Weight	1841kg

Tab. 2 3D model surface properties

	Width stowed	Solar Arrays deployed	Weight
Bus	0.1	0.6	0.3
Paddles	0.76	0.16	0.08
antenna	0.16	0.56	0.28

2.2 Convolution of $T(i,j)$ and $I_n(i,j)$ to create processed images $T'(i,j)$ and $I'_n(i,j)$

In this process, some kind of noises are added in order to simulate the actual observation. By using SOAPY, the performance of the telescope, the characteristics of the adaptive optics, and the effect of the atmospheric disturbance are computed, and the result is outputted into the form of Point Spread Function(PSF). Convoluting the original images$I_n(i,j)$ or $T(i,j)$ with PSF, simulation images $T'(i,j)$ and $I'_n(i,j)$ can be generated. This process can be expressed in the following equation (1),

$$\begin{bmatrix} I'_n(i,j) \\ T'(i,j) \end{bmatrix} = \sum_{i=0}^{M-1} \sum_{j=0}^{N-1} \begin{bmatrix} I_n(i,j) \\ T(i,j) \end{bmatrix} \cdot PSF(i-i', j-j') \qquad (1)$$

where the i and j are index of pixels, and size of image is (M, N). Example of the computation is shown on Fig. 2. When this method is conducted in actual observation, the PSF can be obtained by observing a guide star or laser guide star near the target satellite. In this simulation, observed noise is not added.

original image PSF: Point Spread Function simulated image

Fig. 2. Examples of original image, PSF and simulated image

2.3 Extraction of feature vectors

To estimate estimate attitude of $T'(i,j)$, it is necessary to compare $I'_n(i,j)$ and $T'(i,j)$, and an image in $I'_n(i,j)$ that has similar features to the $T'(i,j)$ is likely to be the solution. In this simulation, values of SAD and ZNCC are chosen for the evaluation criteria to define the feature. SAD represents the the brightness of the image, and ZNCC represents the brightness distribution of images. SAD is expressed by following equation (2)

$$R_{SAD,n} = \frac{\sum_{j=0}^{N-1} \sum_{i=0}^{M-1} (I'_n(i,j) - T'(i,j))}{\sum_{j=0}^{N-1} \sum_{i=0}^{M-1} T'(i,j)} \qquad (2)$$

Where $R_{SAD,n}$ is nondimensionalized with sum of luminance of $T'(i,j)$ to express the proportion difference from $T'(i,j)$. On the other hand, ZNCC is expressed by following equation (3)

$$R_{ZNCC,n} = \frac{\sum_{j=0}^{N-1}\sum_{i=0}^{M-1}(I'_n(i,\ j) - \overline{I'_n})(T'(i,\ j) - \overline{T'})}{\sqrt{\sum_{j=0}^{N-1}\sum_{i=0}^{M-1}(I'_n(i,\ j) - \overline{I'_n})^2 \times \sum_{j=0}^{N-1}\sum_{i=0}^{M-1}(T'(i,\ j) - \overline{T'})^2}} \tag{3}$$

where the bar on the value represent average of the value. $R_{ZNCC,n}$ ranges from 0.0 to 1.0, and it computes $\cos\theta$ between images when the images are considered as a vector. Therefore, the bigger the $\cos\theta$ is, the similar the their luminance distribution are. Using the two characteristics values, characteristics vector $\boldsymbol{f}$ can be defined for each $I'_n(i,j)$ and $T'(i,j)$ as shown in the equation (4).

$$\begin{gathered} \boldsymbol{f}_{I'_n} = (R_{SAD,n}\ , R_{ZNCC,n}) \\ \boldsymbol{f}_{\boldsymbol{T'}} = (0\ , 1) \end{gathered} \tag{4}$$

$\boldsymbol{f}_{\boldsymbol{T'}}$ is always $(0.0\ , 1.0)$, because image of target satellite itself is the evaluation criteria.

2.4 Comparison of feature vector between $\boldsymbol{T'}(\boldsymbol{i},\boldsymbol{j})$ and $\boldsymbol{I'_n}(\boldsymbol{i},\boldsymbol{j})$

Finally, Every vector of $I'_n(i,j)$ is evaluated for similarity with $T'(i,j)$. In this process, the evaluation is performed by the following equation (5).

$$\mathrm{norm}_n = \left\| \boldsymbol{f}_{I'_n} - \boldsymbol{f}_{T'} \right\| \tag{5}$$

Since $\boldsymbol{f}_{\boldsymbol{T'}}$ is always $(0\ , 1)$, equation (5) can be simplified into equation (6).

$$\mathrm{norm}_n = {R_{SAD,n}}^2 + (R_{ZNCC,n} - 1)^2 \tag{6}$$

Since it is considered that the smaller the difference of Characteristic vector between $T'(i,j)$ and $I'_n(i,j)$, the closer the attitude $T'(i,j)$ and $I'_n(i,j)$ is, we can estimate the attitude of the $I'_n(i,j)$ with reference to the difference of the norm_n.

3. SIMULATION CONDITIONS

In this section, configuration of simulation is explained.

- Target Object

As is mentioned above, target object is JCSAT-3 in GEO.

- Direction of sun and observation

Direction of sun and observation are expressed by the vector in the coordinate system fixed in the space. They are shown in tab. 3. Fig. 3 shows the directions on the coordinate.

- SOAPY

SOAPY is used to generate PSF including the effect of atmosphere, telescope and adaptive optics. Configuration of computation is the Canary telescope system, which is used for tutorial of SOAPY. Note that outputted PSF size is changed to 0.15 arcsec to simulate high-resolution image.

- Members of dataset

Images of 46656 attitudes are in dataset, whose each axis is divided in 36 pieces.

Tab. 3. direction of sun and observer

Sun direction	-0.94	0.34	-0.04
Observer direction	0.59	-0.60	0.55

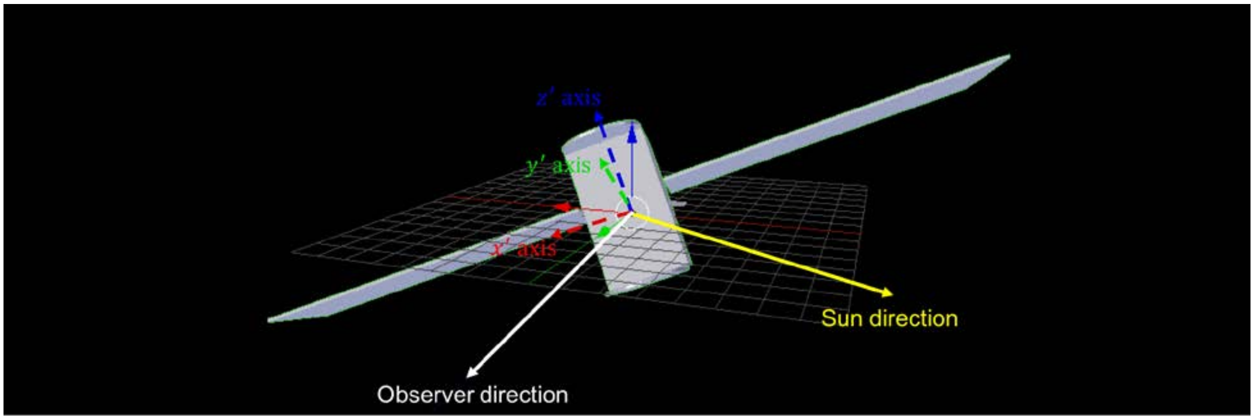

Fig. 3. directions on the coordinate and rotated body-fixed axis

4. RESULTS AND DISCUSSION

In this section, results of attitude estimation simulation will be shown. The results of computing the characteristics vector $\boldsymbol{f}_{\boldsymbol{T'}}$ and $\boldsymbol{f}_{I'_n}$ are shown in the Fig. 4. In Fig. 4, the gray dots are the $\boldsymbol{f}_{I'_n}$, and red dot is $\boldsymbol{f}_{\boldsymbol{T'}}$. The area surrounded the red line contains $\boldsymbol{f}_{I'_n}$ that have characteristics relatively similar to $\boldsymbol{f}_{\boldsymbol{T'}}$, and some $\boldsymbol{f}_{I'_n}$ have the attitude that is correct or near to $\boldsymbol{f}_{\boldsymbol{T'}}$. Next, computing equation (5), nine images that have characteristics most similar to image of target satellites are shown in Fig. 5. At first glance all images $I_n(i,j)$ have a high similarity to $T(i,j)$, however, In case of $n = 45680$ the number of antenna is different; It means $I_{45680}(i,j)$ is pointing in the opposite direction to $T(i,j)$. From this In the case of symmetrical observation objects, it is found that the difficulty of estimation increases, but it can be considered that such results can be avoided, because actual satellites have no exact symmetry.

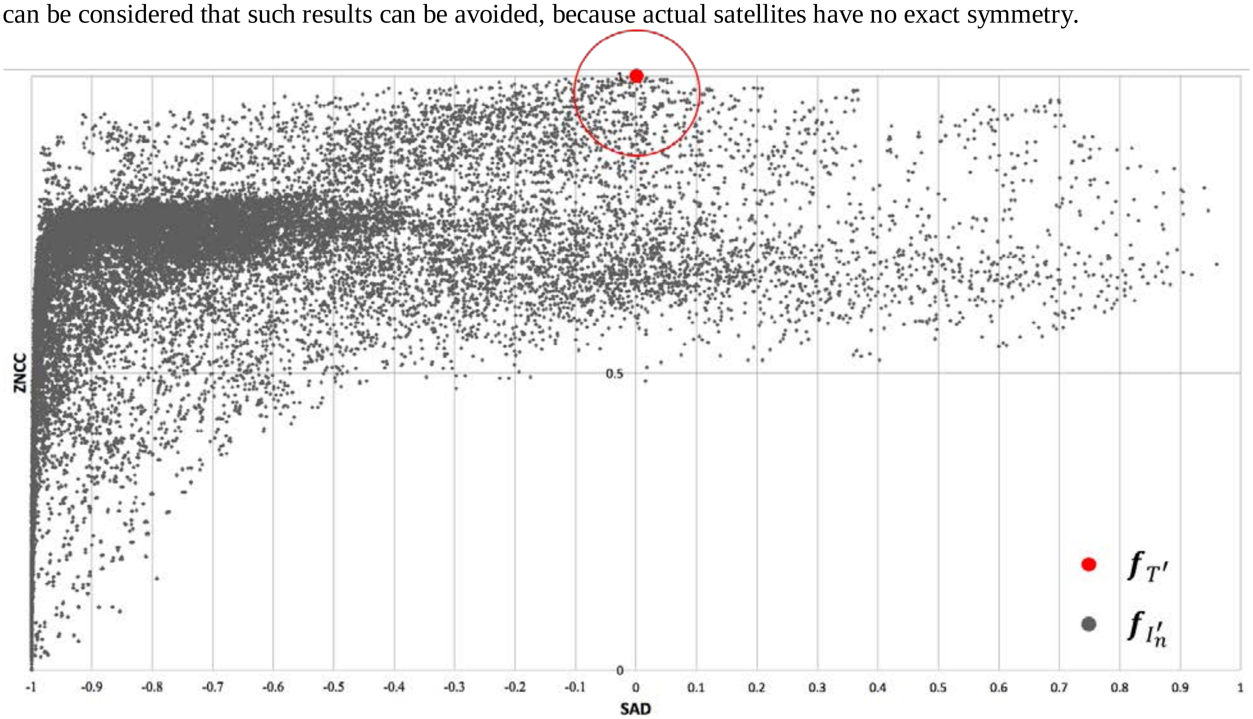

Fig. 4. distribution of all characteristic vectors $\boldsymbol{f}_{I'_n}$ and $\boldsymbol{f}_{\boldsymbol{T'}}$

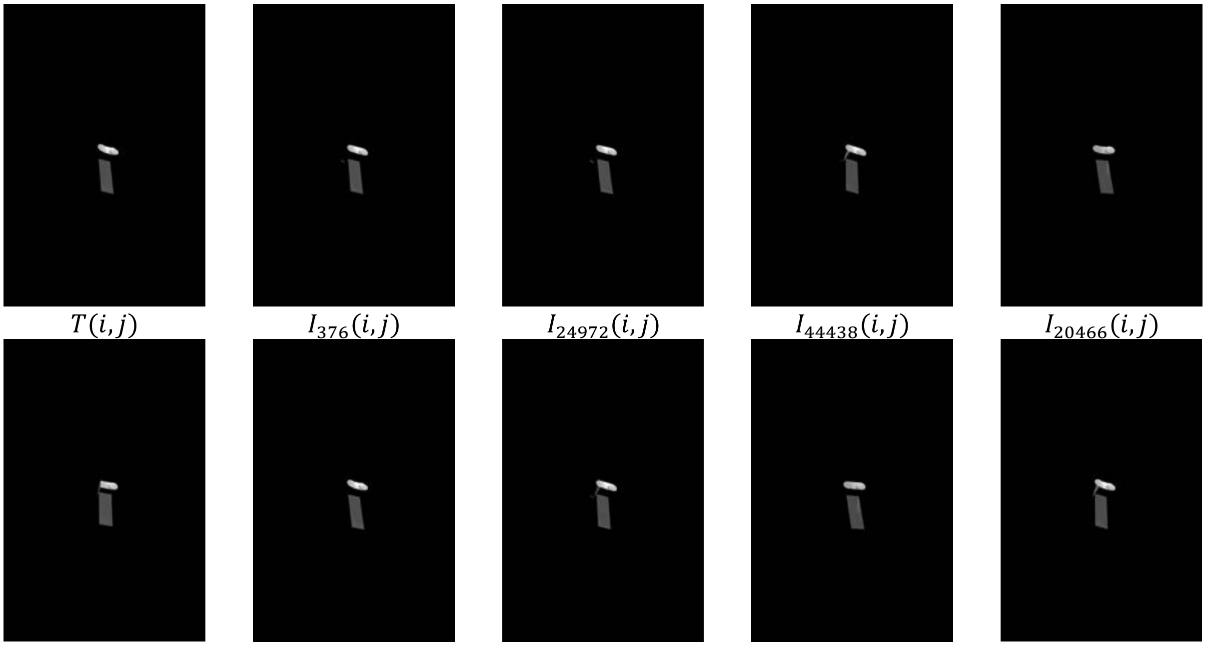

Fig. 5. $\boldsymbol{T(i,j)}$ and $\boldsymbol{I_n(i,j)}$ that has the characteristics most similar to $\boldsymbol{T(i,j)}$ (Bright processed)

5. CONCLUSION

In this paper, the attitude estimation of satellites in GEO using imaging observation simulation is presented. Conclusion is as follows.

- Using SOAPY, effects of atmosphere, telescope system and adaptive optics can be combined for the simulation.
- To estimate attitude of the target by imaging observation, the method extracting characteristics vector from every images and comparing them is proposed
- Results is partial success, however, there are some problems to be solved such as observed noise, symmetry of space object, define system requirements for actual observation and evaluation of estimation error

6. REFERENCES

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2. Andrew Reeves, *Soapy: an adaptive optics simulation written purely in Python for rapid concept development*, Proc. SPIE 9909, Adaptive Optics Systems V, 99097F (2016/07/27); doi: 10.1117/12.2232438;