C06

デブリ除去ミッション用画像航法アルゴリズムの検討

Study on visual based navigation algorithm for active debris removal missions

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近年、デブリの増加が問題となっている。その対策として、デブリ除去衛星を用いたデブリの積極的除去(ADR)が注目されている。デブリへ接近する段階では、非協力ターゲットであるデブリとデブリ除去衛星の相対距離の計測方法に課題があるが、その方法はまだ確立されていない。そこで著者らは、可視光カメラを用いた非協力ターゲットとの相対距離計測方法を検討した。具体的には、相対距離が 1km～30m の場合に、デブリ除去衛星がデブリへ接近するための、比較的計算コストの低い画像航法アルゴリズムを試作した。また、JAXA の光学シミュレータを用いて、相対距離が 1km～30m の接近軌道を模擬し、オンボードで相対航法演算を実施し、計測精度と計算速度を評価した。本発表で結果等を報告する。

In recent years, a growth of space debris is recognized as a significant problem. As a one of the solutions of above problem, Active Debris removal (ADR) using debris removal satellites have been attracted attention. For the phase of approaching debris, there is a problem with the method of measuring the relative distance between debris which is non-cooperative target and the satellite. Therefore, Method for measuring the relative distance with the debris using a visible light camera is studied. First, image based navigation algorithm is prototyped, which is adapted to range from 1 km to 30 m. Then, the algorithm is evaluated using JAXA's optical simulator that simulate approach trajectory and light environment of space. It shows good performance and low calculation cost, result of the execution on single board computer. This paper presents about these results.

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Document number : 18KT021115

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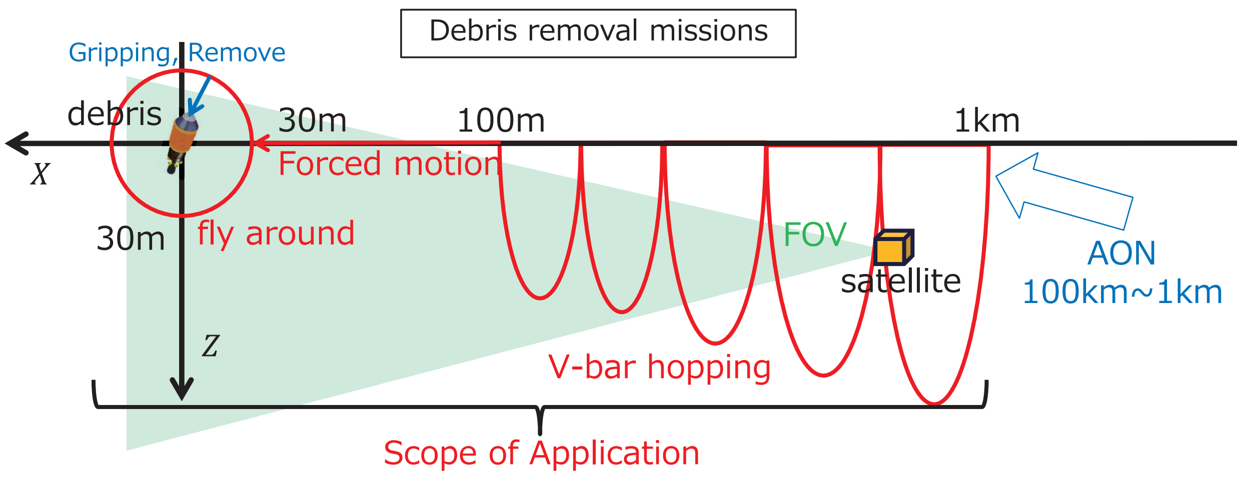
1．Introduction
1．1　Background

【Background】

Active Debris removal (ADR) using debris removal satellites is needed to approach to debris(non-cooperative target), however the method have not been established.

⇒ **JAXA / KHI examined the vision based navigation algorithm targeting the upper stage of a rocket.**



1．Introduction
1．2　Purpose

【Purpose】

- To examine and prototype the vision based navigation algorithm for calculating the relative position with debris.
- To clarify basic performance and issues by ground test.

【Specific content】

- Vision based navigation algorithm with a small calculation load that can be processed on onboard computer (chapter 2)
- Ground evaluation using optical simulator (chapter 3)

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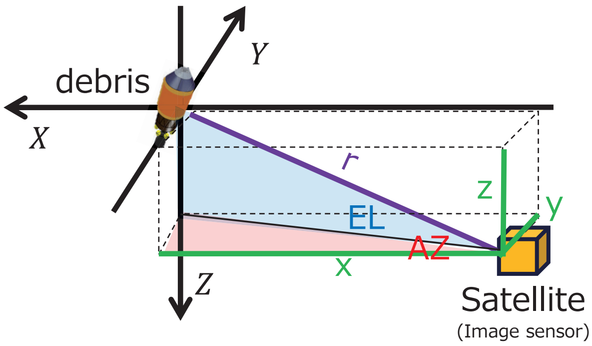
2. Vision based navigation algorithm

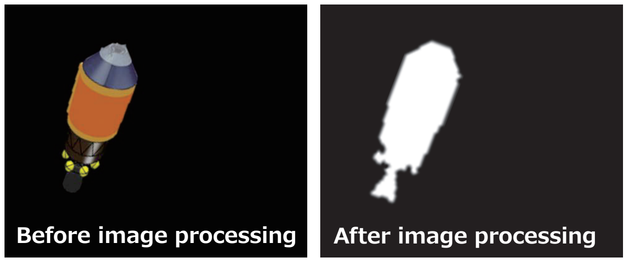
2. 1 Overview

【Overview of vision based navigation algorithm】

Debris removal mission is to approach debris from more than 100km distance, to attach EDT to PAF, and reduce speed. This vision based navigation algorithm is focused 1km to 30m approach trajectory.



coordinate system



Obtained image

In this method, debris is captured using sunlight and albedo with visible light camera. Relative position(r, x, y, z), Azimuth(AZ), Elevation(EL) is obtained by performing image processing on the acquired image.

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2. Vision based navigation algorithm

2. 2 Entire processing flowchart

【Flowchart】

Vision based navigation algorithm entire processing flowchart is shown the following. The red frame part is detailed in Section 2.3.

1. Sunshine/shade judgement
It is able to judge the mission can be conducted or not, and the light projector use or not.

2. Change narrow range / wide range camera
Camera is changed according to the relative distance to debris.

3. Change exposure condition
Exposure time and gain is set properly according to the relative distance to debris.

4. Setting image processing range
In order to accelerate the processing, image processing is performed within a limited range by reflecting the previous calculation result.

5. Lens flare reduction processing
Lens flare caused by over-exposure is reduced (section 2.3.2).

6. Binalization, Erosion-Dilation, and labeling processing.
Each component is labeled after binarization and noise rejection.

7. Feature value extraction processing
The shape of the debris is detected by combined the parts. The short side and the centroid of the debris are detected.

8. Rejection of abnormal values
Abnormal data is rejected.

9. Calculating relative position with debris
Relative position is calculated from the short side / centroid (section 2.3.1).

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2．Vision based navigation algorithm
2．3 Detail of Processing
2．3．1 Relative position measurement

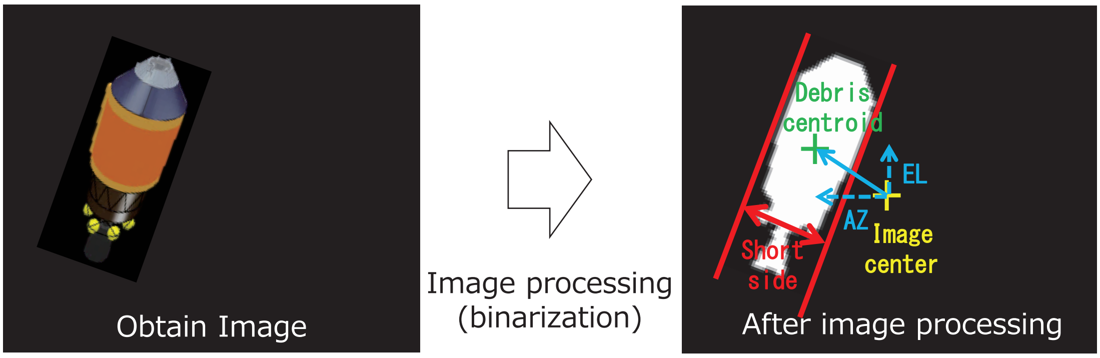
【Measuring the relative position 】

The method of measuring the relative position

- Relative distance is calculated by short side (not affected by posture change).
- Azimuth(AZ) and elevation(EL) is calculated by debris centroid.

$$x[m] = \frac{\text{Debris diameter}[m]}{\text{Short side}[pix] \times \text{IFOV}[rad]}$$

$$\text{AZorEL}[rad] = \frac{\text{Centroid position }[pix]}{\text{Focal length }[pix]}$$



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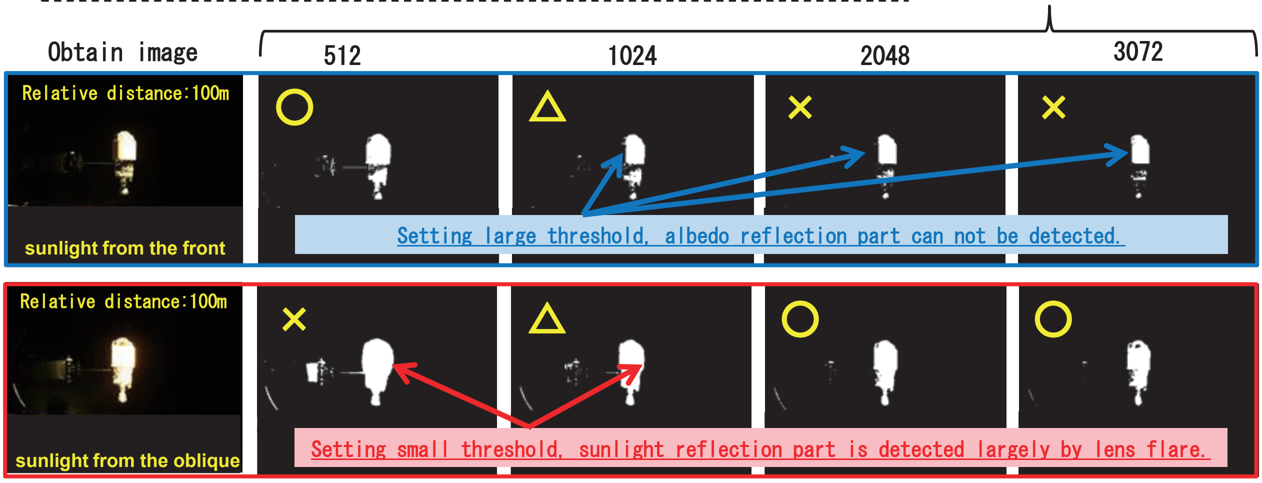
2．Vision based navigation algorithm
2．3 Detail of Processing
2．3．2 Lens flare reduction processing

【Problems of binarization】

In this method, the relative distance is calculated from debris short side, therefore it is necessary to correctly recognize the size of the debris. However, it is difficult to eliminate the influence of lens flare and to capture reflected albedo light with a fixed threshold.

Albedo incident part ⇒ contraction by binarization (shadow)
Sunlight incident pert ⇒ expansion by binarization (bright)

Threshold value
Max gradation : 4096



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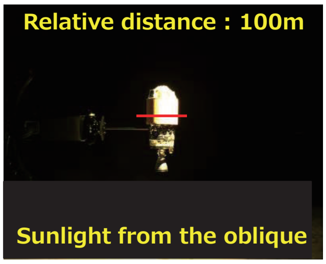
2. Vision based navigation algorithm

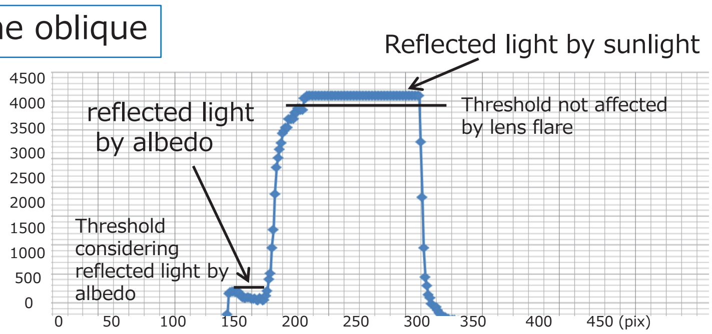
2. 3 Detail of Processing

2. 3. 2 Lens flare reduction processing

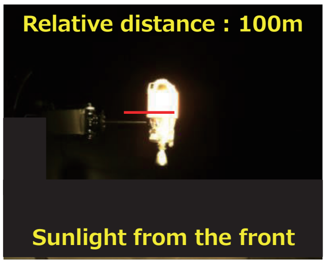
【Luminance of debris】

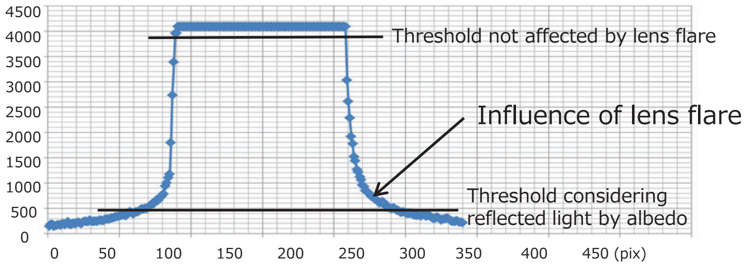
Case of sunlight hits from the oblique





Case of sunlight hits from the front





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2. Vision based navigation algorithm

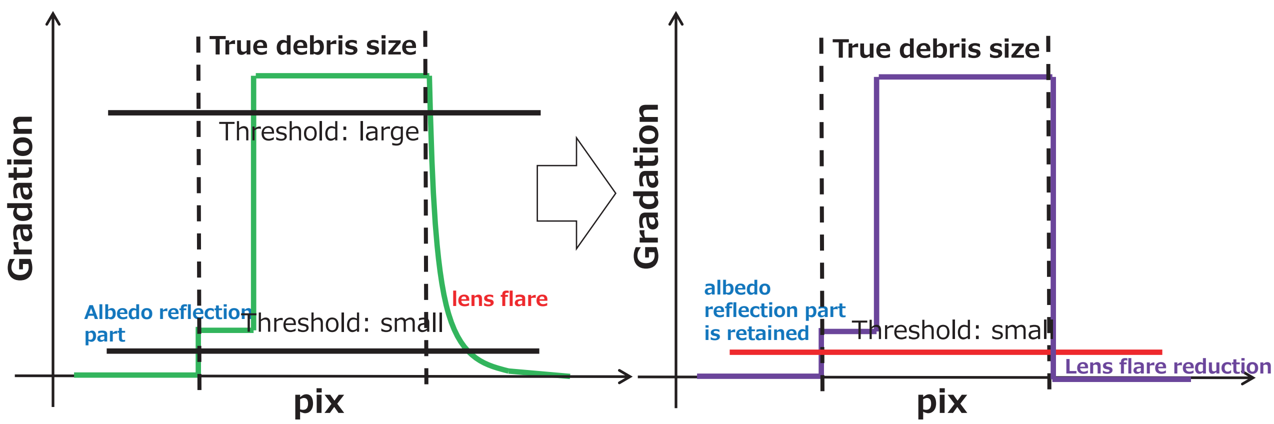
2. 3 Detail of Processing

2. 3. 2 Lens flare reduction processing

【Lens flare reduction filter】

The error can be suppressed, if reducing influence of the lens flare, retaining albedo reflection part and setting small threshold.

⇒Detecting the gradient and applying sharpening processing, it can be reduced the lens flare while retained albedo reflection part (next page).



Only binarization　　　Lens flare processing + binarization

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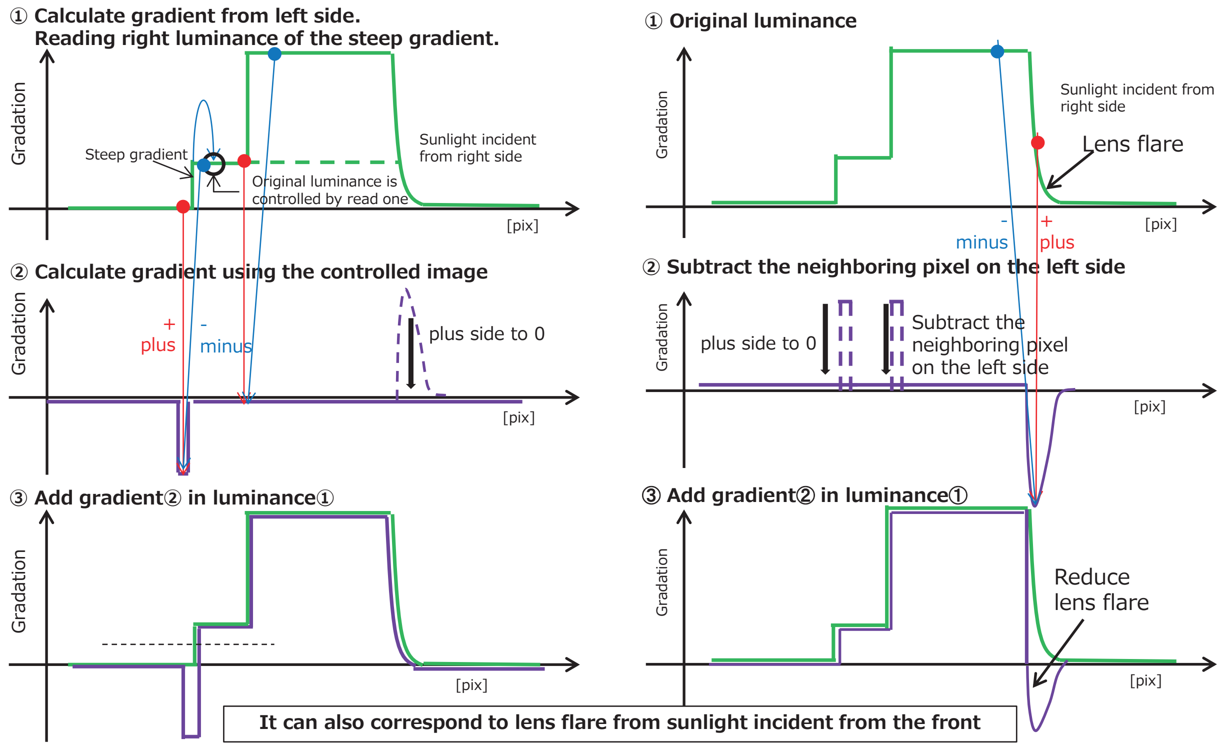
2．Vision based navigation algorithm

2．3　Detail of Processing

2．3．2　Lens flare reduction processing

GREEN : Original luminance
PURPLE : After lens flare reduction processing

Processing from left side | **Processing from right side**



It can also correspond to lens flare from sunlight incident from the front

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2．Vision based navigation algorithm

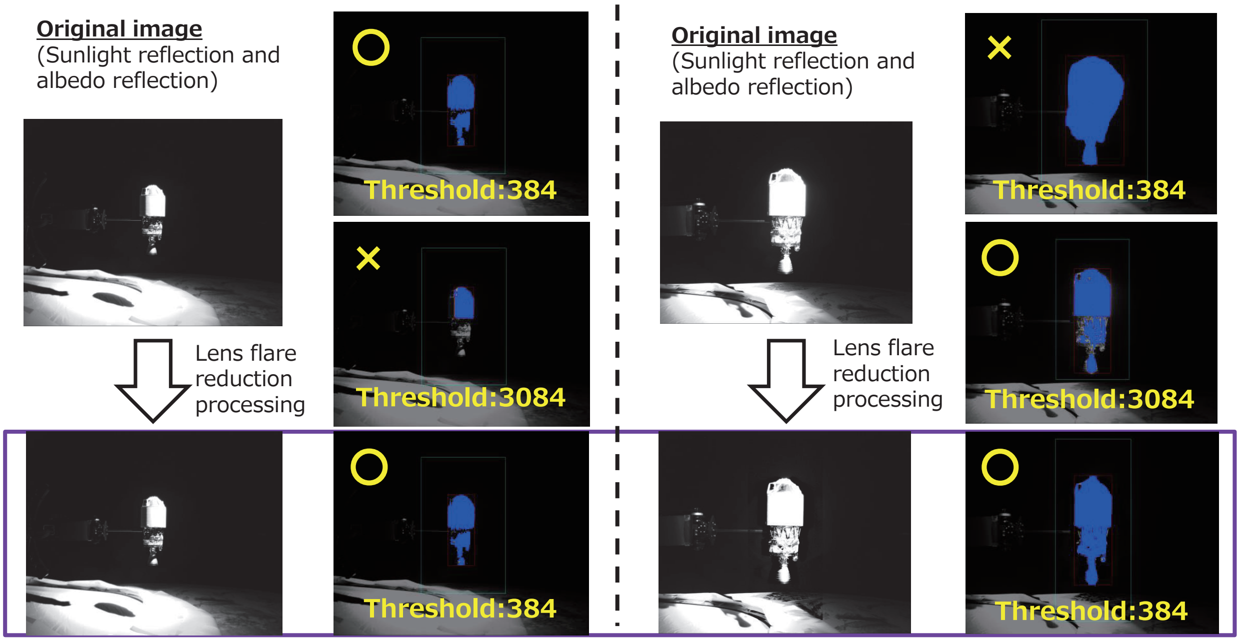
2．3　Detail of Processing

2．3．2　Lens flare reduction processing

【Application result 】

Debris is able to be detected regardless of the light direction (Threshold : small).

Sunlight from the oblique | **Sunlight from the front**



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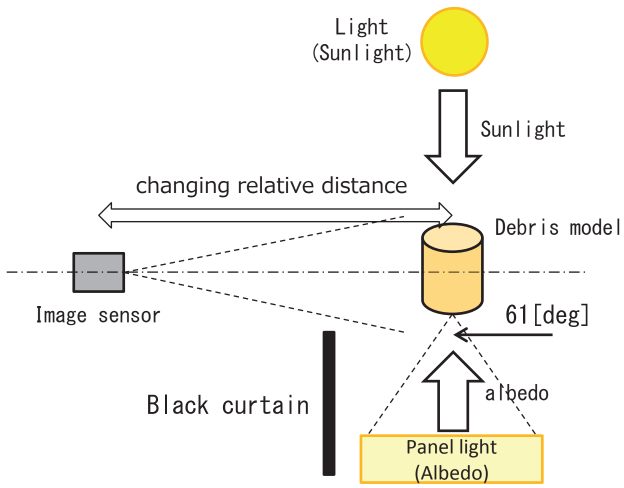
3．Vision based navigation evaluation test
3． 1 Outline

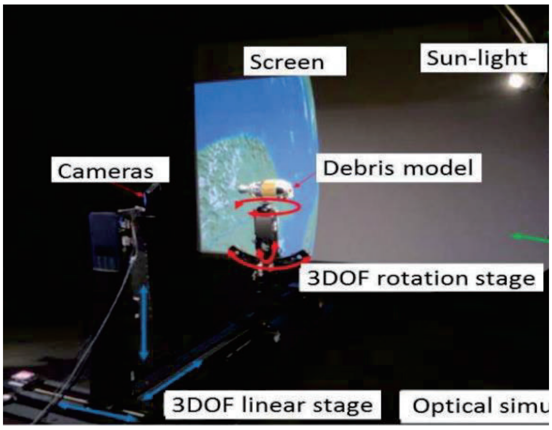
【Outline】

Measurement accuracy is evaluated about 1km~30m approach trajectory by JAXA's optical simulator. The error is evaluated by changing relative distance of image sensor to debris model.

Orbital condition is assumed about orbit altitude is 600km and inclination is 98deg.



Schematic chart



Optical simulator (JAXA) ※1

※1 CURRENT STATUS OF RESEARCH AND DEVELOPMENT ON ACTIVE DEBRIS REMOVAL AT JAXA

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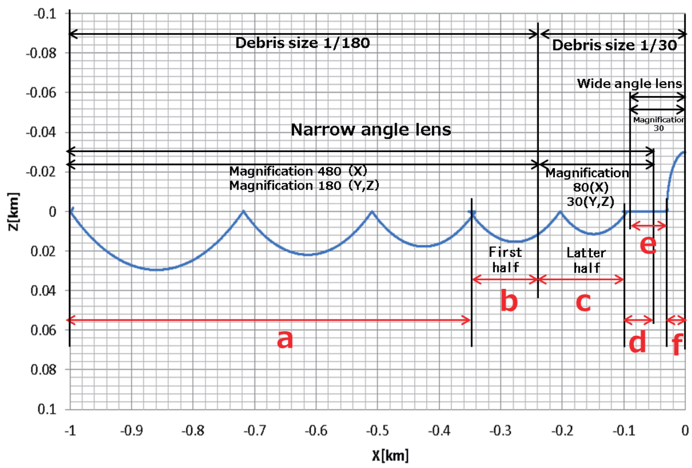
3．Vision based navigation evaluation test
3． 2 Test condition

【Simulation range】

Vision based navigation is evaluated by simulated 1 km-30m approach trajectory using optical simulators.※1



a. **1km~350m** V-bar hopping
b. **350m~240m** V-bar hopping (first half)
c. **240m~100m** V-bar hopping (latter half)
d. **100m~50m** forced motion (Wide angle lens)※2
e. **90m~30m** forced motion (narrow angle lens)※2
f. **30m** circular orbit flyaround※3

※1 Movement of debris on image is simulated by adjusting lens and debris size in proportion to relative distance.
※2 Wide angle / narrow angle switching at 50 m to 90 m
※3 The fly-around is assumed to be operated in the shade using a light projector.

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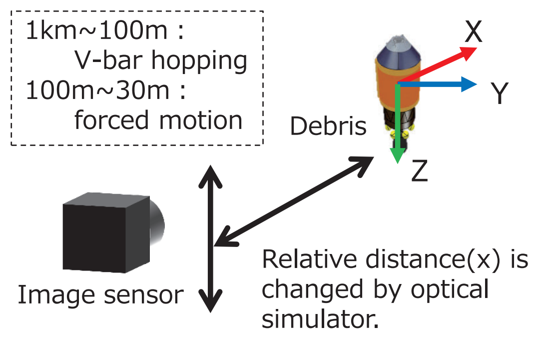
3．Vision based navigation evaluation test
3．2　Condition

【Test case】

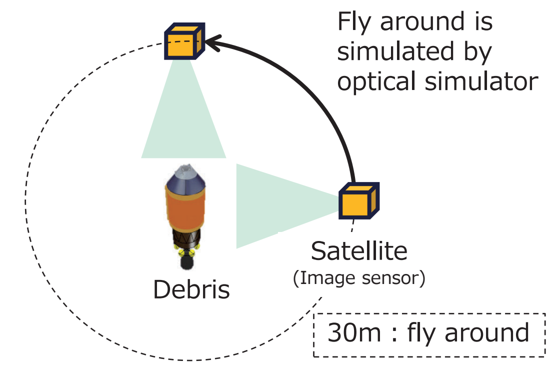
Evaluation test is operated by optical simulator using following conditions.

Case	Local sun time at descending node	Rotation	Albedo	Notes
Nominal	13:30	none	5%	• This case is assumed debris is not rotated, and approached by V-bar hopping or forced motion. • The fly-around is assumed to be operated at night.

【Approach 1km~30m (a~e)】



【fly around (f)】



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3．Vision based navigation evaluation test
3．3　Result

【Evaluation method】

The result is evaluated in the following.

This algorithm is evaluated by bios error and random error using divided data by test case.

【Position error】

bios error[%] : $\frac{\text{True value} - \text{Measure value}}{\text{True value}} \times 100$ (Average)

random error(3σ) [%] : $\frac{\text{True value} - \text{Measure value}}{\text{True value}} \times 100$ (3σ)

【Angular error】

bios error [deg] : $(\text{True value} - \text{Measure value})$ (Average)

random error(3σ) [deg] : $(\text{True value} - \text{Measure value})$ (3σ)

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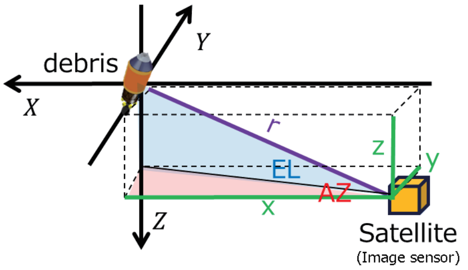
3．Vision based navigation evaluation test
3．3 Result

GREEN：within target range, RED：out of target range
In parentheses of the table, main error factors other than ① are described.
All the random error is greatly affected by ①.

【Result】
- Measurement error about position and angle in nominal case is shown in the following.
- Measurement result is shown next page.

Measurement error about position and angle in nominal case.

Item	Error type	object	Target value	Approach trajectory					Fly around
				a	b	c	d	e	f
Position (Distance)	Bios error [%]	r	5 [%] (error factor)	-6.39 (④)	8.5 (③)	2.59	2.63	0.76	-5.79 (⑤)
	Random error [%]	r	3 [%] (error factor)	12.89 (③④⑥)	8.7 (③)	11.18 (③)	7.92 (③)	7.03 (③)	16.92 (⑤)
Angle	Bios error [deg]	AZ	0.7 [deg] (error factor)	0.19	0.4	0.2	0.33	0.07	0.21
		EL		-0.09	-0.22	0.29	0.61	0.45	0.9 (⑤)
	Random error [deg]	AZ	0.4 [deg] (error factor)	0.12	0.16	0.2	0.21	0.19	0.33
		EL		0.1	0.22	0.43 (②)	0.24	0.15	2.39 (⑤)



【Error factor】
① large range of calculating standard deviation.
② gap of centroid position of pitch direction.
③ albedo reflection part can not be detected
④ sunlight reflection part is detected largely by lens flare
⑤ changing angle of debris
⑥ quantization error
⑦ bokeh, gray processing, focus point.

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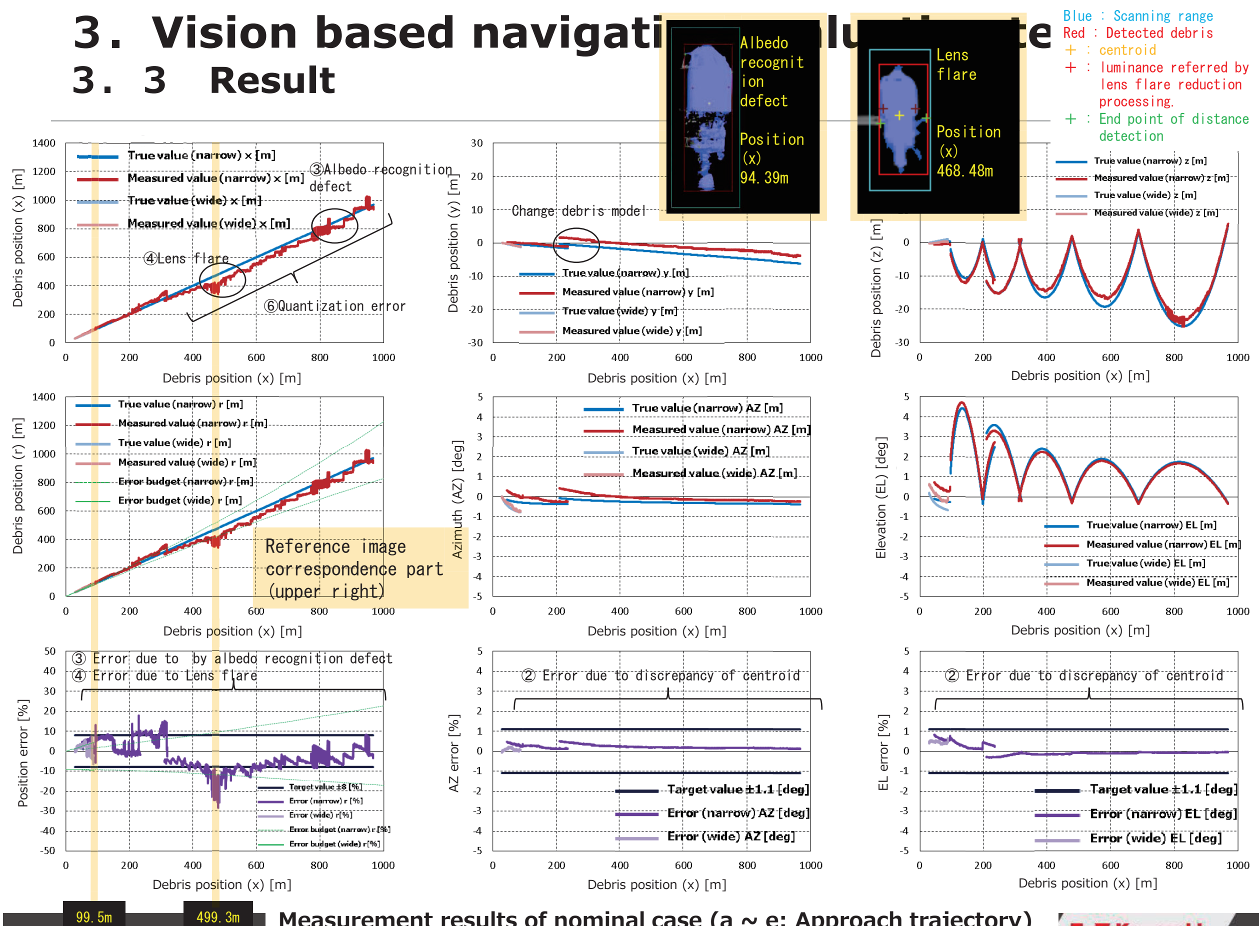
3．Vision based navigati...
3．3 Result



Measurement results of nominal case (a ~ e: Approach trajectory)

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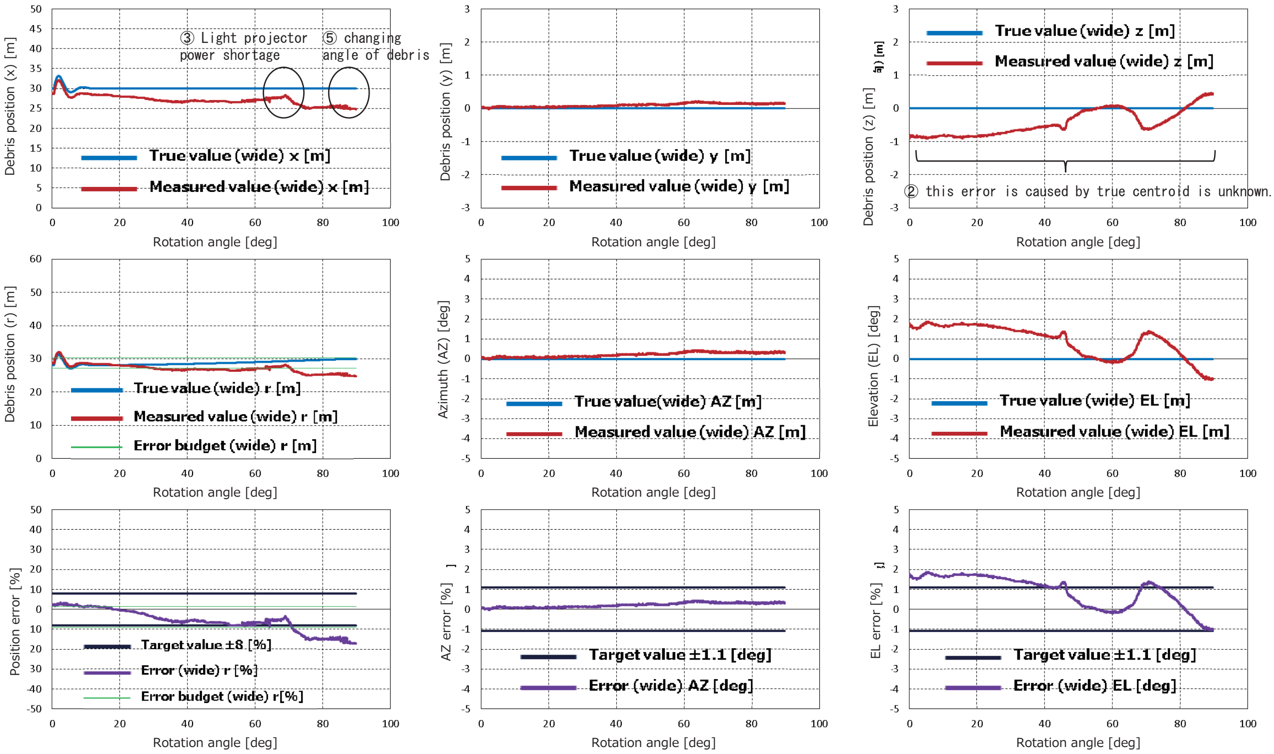
3. Vision based navigation evaluation test
3. 3 Result



Measurement result of nominal case (f: fly around)

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3. Vision based navigation evaluation test
3. 3 Result

【Summary】

- **The error is generally within the target range, except errors due to lens flare (specular reflection).**
- **At the fly around, Good results is obtained in the shade, except the error due to changing angle of debris.**
- **The main factor of the error is depended on the relative distance and sun position.**

【Issue and measures】

- **The error due to lens flare and albedo**

⇒ improving performance of lens flare reduction processing, adjusting parameter, and so on.

- **Quantization error**

⇒ improving performance of camera and so on.

- **The error due to changing angle of debris**

⇒ Taking some margin on the safe side to avoid collisions.

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4. Summary

【Summary】

- The vision based navigation algorithm is prototyped using visible camera as the method of measuring relative position of non-coordination target for JAXA's ADR missions.
- This algorithm is evaluated by JAXA's optical simulator. Concretely, relative position error is evaluated by simulating 1km to 30m approach trajectory and calculating relative position by onboard computer.
- As a result , the error is generally within the target range, except errors due to lens flare (specular reflection).
- Lens flare(especially specular reflection) is dominant error factor. Therefore, it is need that iris is opened as large as possible and exposure time is controlled as small as possible.

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