D1

PAF を対象としたデブリ捕獲用把持システムの概念検討
Conceptual Study of Mechanical and Sensing System for Debris Capturing for PAF

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近年急増しているスペースデブリは、人工衛星や宇宙ステーション等に対する脅威となりつつある。デブリの影響を低減するには、これから打ち上げる宇宙機のデブリ発生抑止対策だけでは不十分で、現存するデブリを能動的に軌道から除去する仕組みが必須である。ここではデブリとして数が多いロケットの上段部をターゲットとして、デブリ除去衛星が接近するための画像センサ、及びデブリを捕獲するシステムについて概念検討を行った結果を報告する。

The amount of space debris has been increasing, and that is becoming a threat to the currently operated satellites and ISS. The provision to prevent future spacecraft from being debris is not enough to decrease the risk of debris, an active debris removal(ADR) will be needed. The upper stages of expendable launch vehicle have been remaining in the orbit as space debris, and the number of it is so large. This paper reports the results of conceptual study of mechanical and sensing system for capturing the upper stages of expendable launch vehicle.

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Conceptual Study of Mechanical and Sensing System for Debris Capturing for PAF

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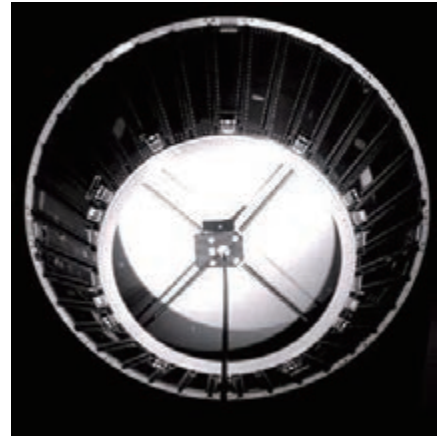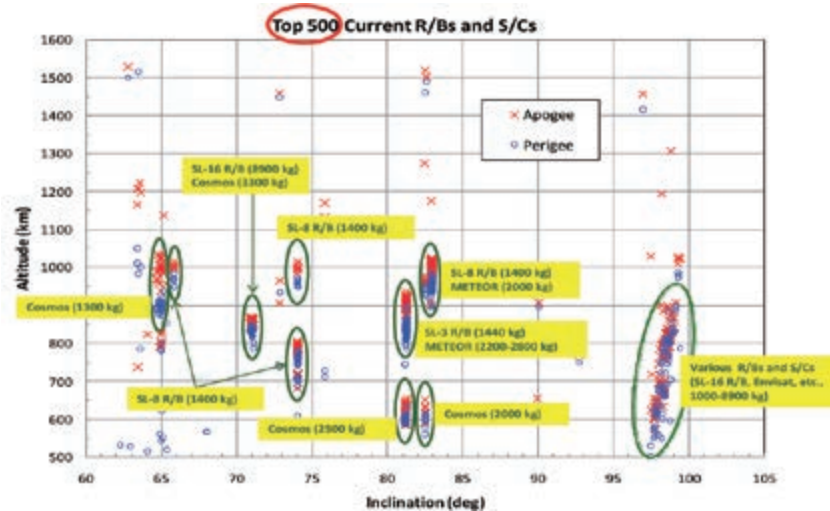

1

Contents

1. Capture target
2. Capture mechanism
3. Image sensing
4. Conclusion

2

1. Capture target

- There are particular crowded orbit.   >1 satellite may be approach to several of debris.

- Debris in sun-synchronous orbit or sun-synchronous sub-recurrent orbit are target.


Ref. J.-C. Liou, An active debris removal parametric study for LEO environment remediation, Advances in Space Research Volume 47, Issue 11, 1 June 2011, pp.1865-1876.

3

1. Capture target

- Upper stage of several of rocket remains in the sun-synchronous orbit.
- Since the upper stage of the rocket have large volume and large mass, it is estimated that the effect due to the collision is large.
- Since a shape is constant for each rocket, it is suitable as an target of recognition and capture.
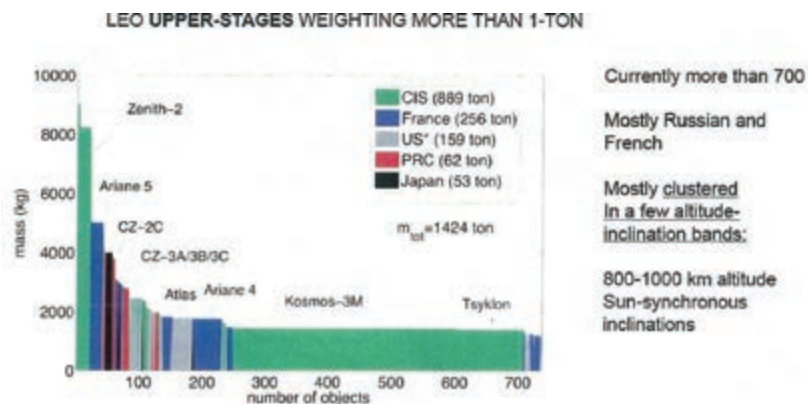
Upper stage of the rocket has been selected as the capture target.

4

1. Capture target

- Many upper stages of rocket have PAF (Payload Attach Fitting).
- The diameter of the satellite attachment are similar size such as 937,1194,1666.
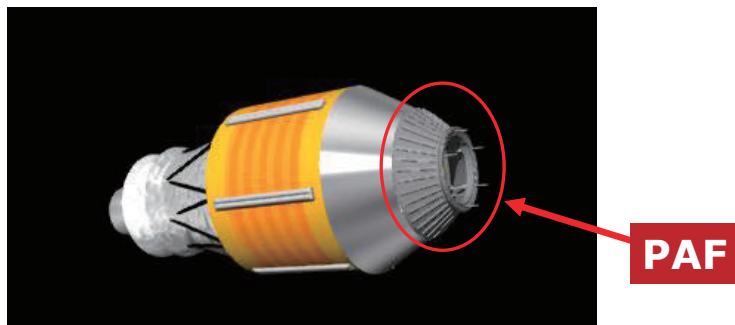
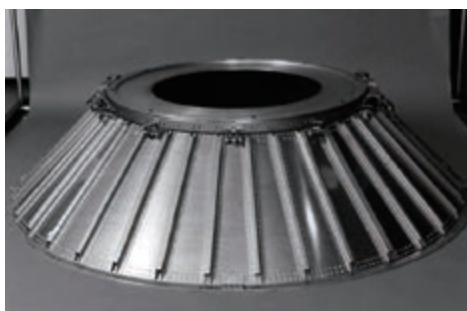
H-2A Rocket 2nd stage image

- PAF is a structure for fixing the satellite, strength and stiffness are secured, shapes are clear.
- PAF is a circular structure. So, it is suitable for image processing at approach.

PAF (Payload Attach Fitting) has been selected as the target, which is applied to a upper-stage of many rocket.

5
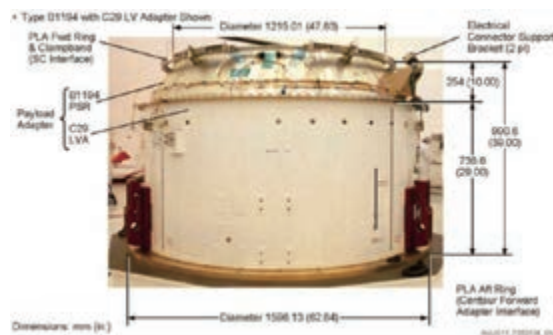
1. Capture target

PAF of various rocket

H-2A rocket PAF1194
(Ref. H-2A rocket users manual)

Ariane rocket PAF1194V5
(Ref. Ariane-5 User's Manual Issue 4 Revision 0)

Atlas rocket Type-B 1194 adapter
(Ref. Atlas V Launch Services User's Guide March 2010)

6

1. Capture target

- When grasping the end face of the PAF as an attachment position of the debris removal device, a plurality of different shapes parts around the ring structure is mounted, the shape of the grasping subject is different depending on the position.
- Since collar portion of the ring structure is narrow, it may not be sufficiently clamped.
- Some push-rods to push satellite are obstacles in the debris rotating state.
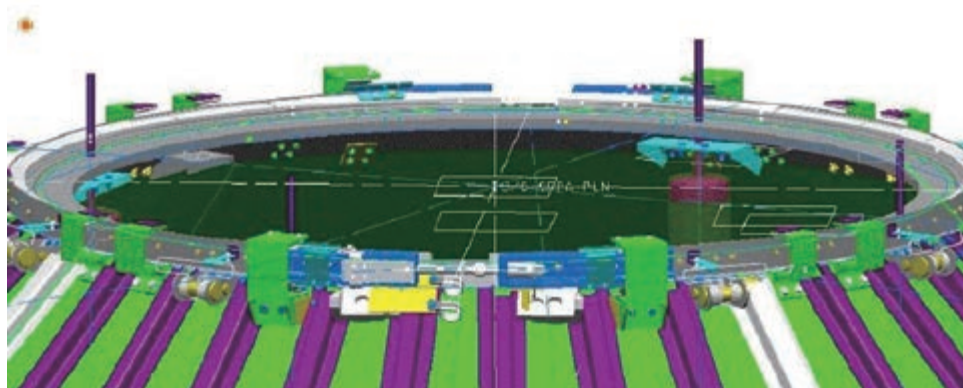
H-2A rocket PAF1194, Detail of satellite interface

**To grip the PAF end surface was estimated to be difficult.**

7

2. Capture mechanism

The upper stage is estimated to be either of the following two states.
- Swinging toward the long axis to the earth by gravity gradient stabilization
- Rotating in orbit

It is necessary to consider the grasp method suitable for each of the two states.
Then, it is necessary to devise a capturing method that can be applied to both states.
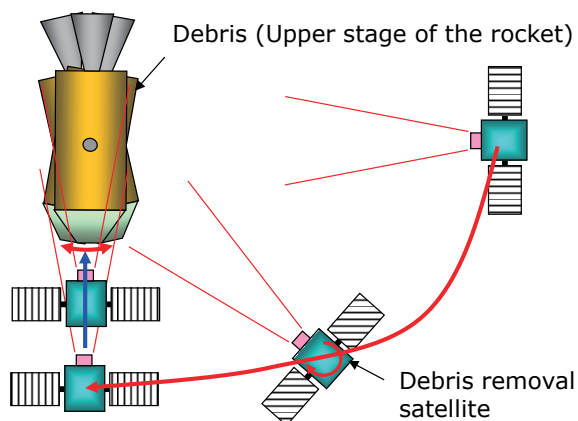
In swing state, approaching after wrapping around the longitudinal direction
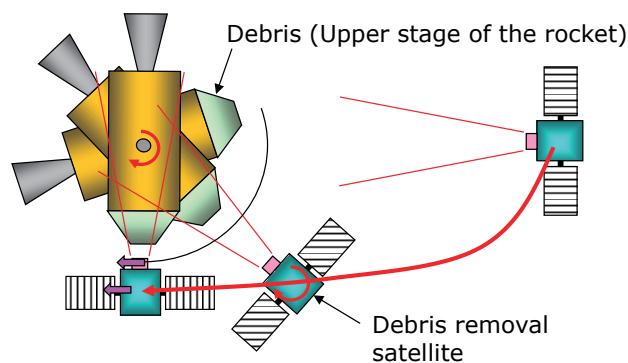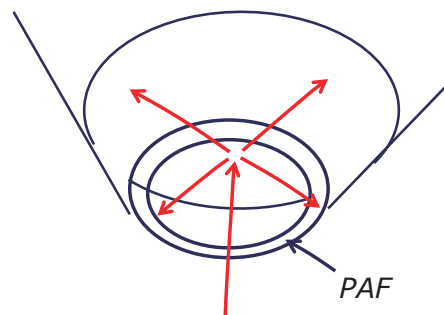
In rotating state, to approach to match the speed of PAF after approaching tangentially

8

2. Capture mechanism

As a method for grasping that are suitable for approaching method, instead of gripping the end faces of the PAF, grasping method by inserting the extendable booms inside the PAF can be considered.

The advantage of this method is as follows.

*   Accuracy of estimating the motion of the PAF, are likely to need to be rough as compared with the case of grasping the end face of the PAF. Because, for inserting the deployment devise into the opening of the PAF having a diameter of about 1m.

*   Since there is no obstacle within the opening, the pattern matching for extracting a location for gripping is not required. Estimation accuracy by image processing may be rough.

*   In order to aim the center of the opening, projections from the end face of such as a push rod is less likely to obstacles.

PAF

9

2. Capture mechanism

*   For inserting the expandable devise to the inside of the PAF
*   For fixing the grasping mechanism to the inside of the PAF

It was considered also to apply the extendable boom for both functions

Prototype of extendable boom

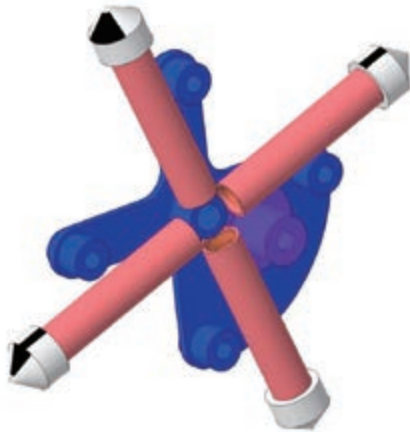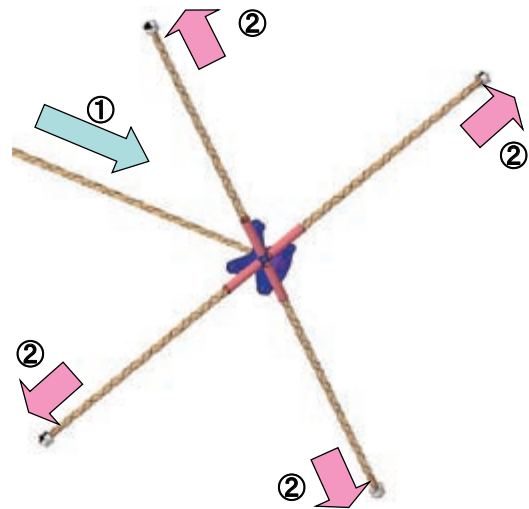Extension (extension speed: about 1m/sec)

Stored

10

2. Capture mechanism

1. By one of the extendable boom, the expandable devise is inserted into the PAF.
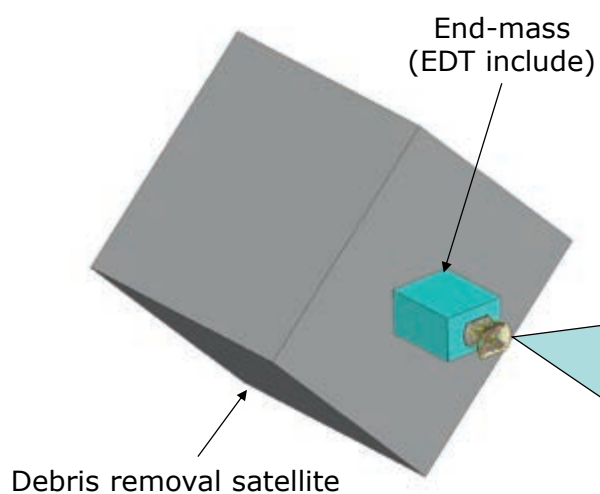2. By four extendable booms extending in the PAF, the grasping mechanism is fixed.

Assembly of four extendable booms
(Stored)
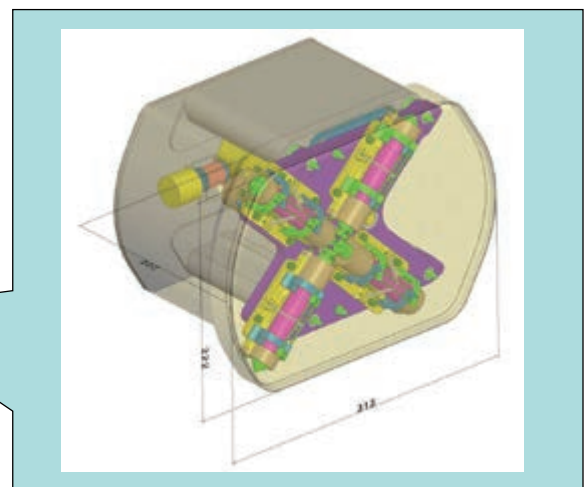
11

2. Capture mechanism

Design examples of the grasping mechanism using extendable boom

End-mass
(EDT include)

Debris removal satellite

Device equipped example
of the satellite structure

Design examples of the grasping mechanism

12

2. Capture mechanism

Grasping sequence

1. By extendable boom, expandable device is inserted into the PAF

2. extendable booms of expandable device are extended in four directions

3. Base of the gripping mechanism is separated, Tether is drawn by Maneuver
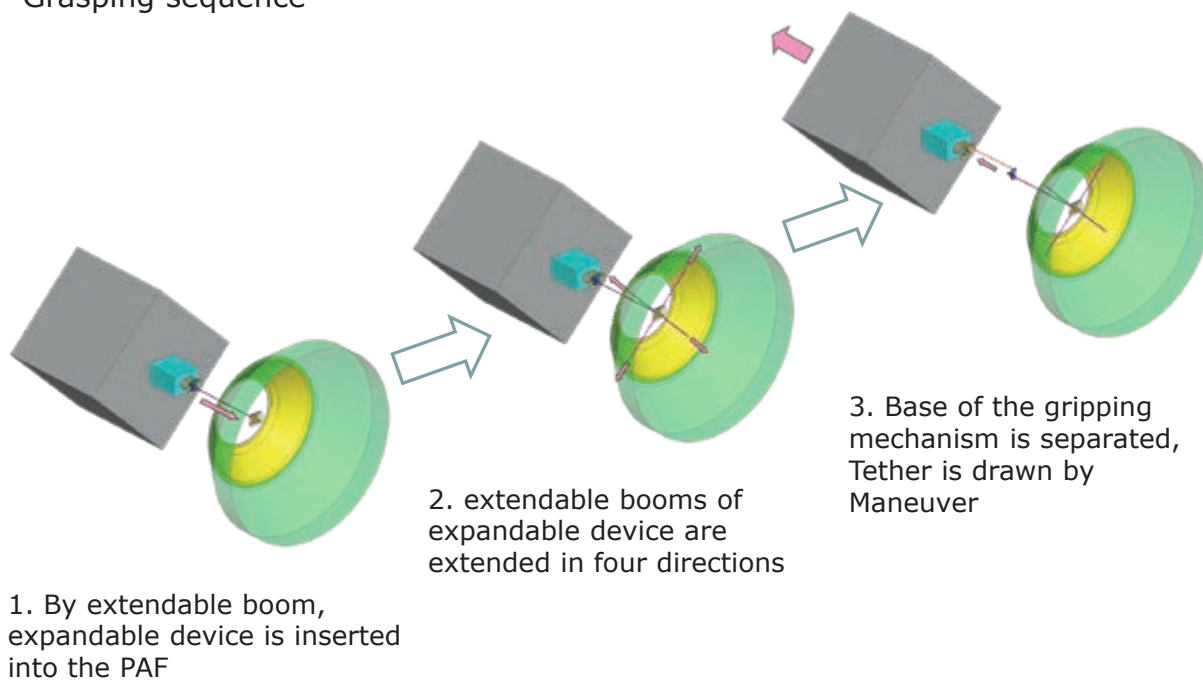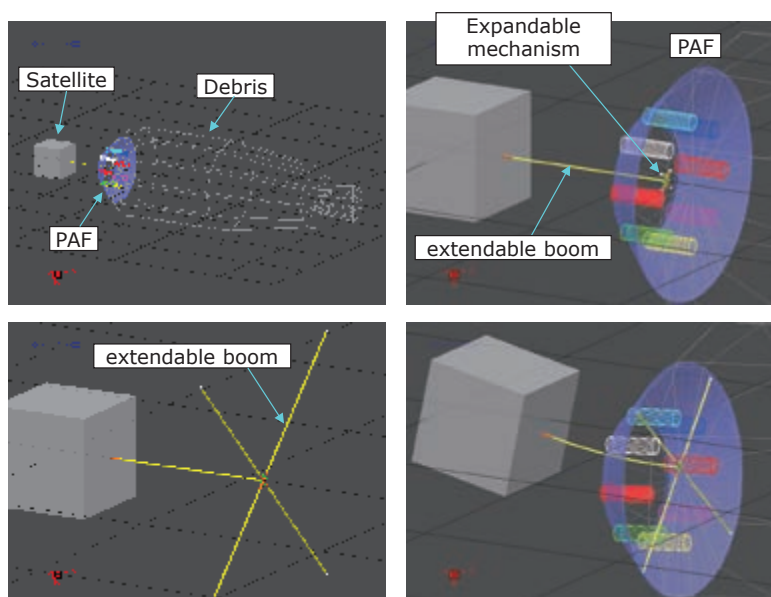
13

2. Capture mechanism
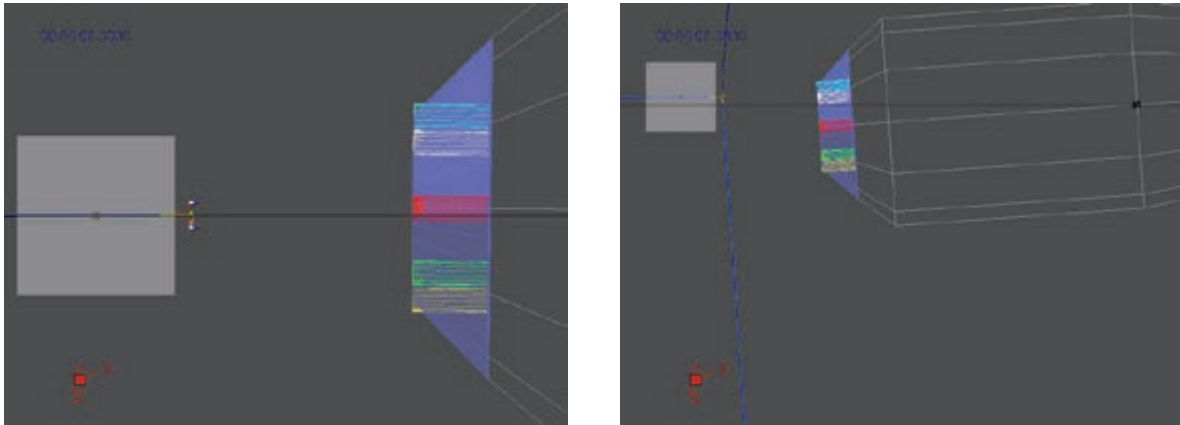
Dynamics analysis of grasping

Analysis model for DADS

14

2. Capture mechanism

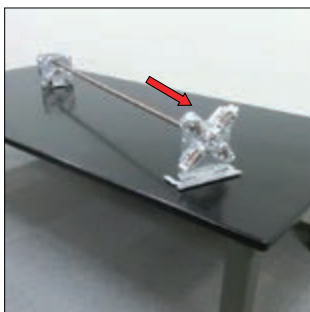Result of dynamics analysis of grasping (example)
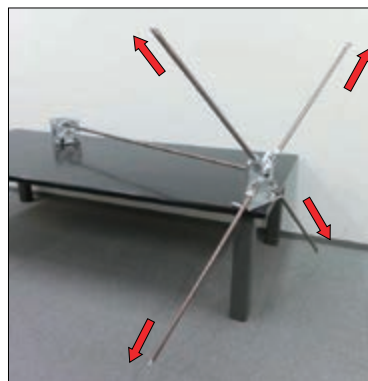

15

2. Capture mechanism

Functional check of the grasping sequence by the functional verification prototype of grasping mechanism

| 1. Stored | 2. By extendable boom, expandable devise is extend | 3. extendable booms of expandable devise are extended in four directions | 4. Base of the grasping device is separated |

16

3. Image sensing

PAF is suitable in the following points as a subject for image recognition.

1. Shape is circular and simple, it is possible to robust recognition with high accuracy.
2. Diameter of PAF is as large as 1m, it is possible to stable visible even from a distance.
3. Material is stable, less possibility of deformation and alteration, it is possible to estimate the reflection characteristics.
4. Internal PAF is void, it is easy to obtain a clear contrast, is suitable for feature extraction.
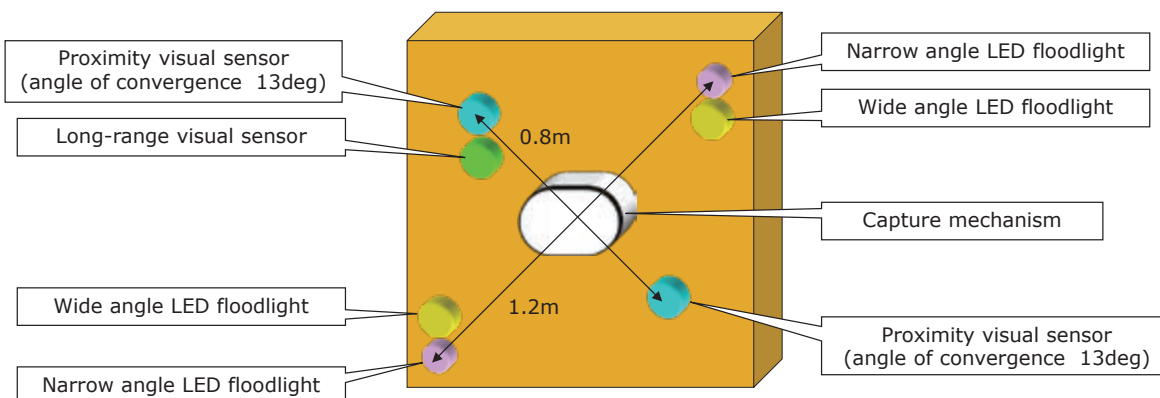

Shape found by image processing
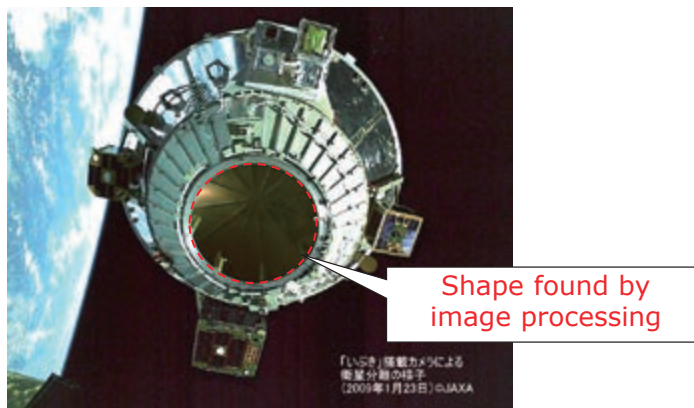
PAF of H-2A 2nd-stage

17

3. Image sensing

Sensor system configuration (optical system)

Proximity visual sensor (PVS)	View angle 53deg / 26deg
Long-range visual sensor (LVS)	View angle 6deg
Wide angle LED floodlight	Irradiation angle 53deg
Narrow angle LED floodlight	Irradiation angle 10deg

Proximity visual sensor
(angle of convergence 13deg)

Long-range visual sensor

Wide angle LED floodlight

Narrow angle LED floodlight

Narrow angle LED floodlight

Wide angle LED floodlight

Capture mechanism

Proximity visual sensor
(angle of convergence 13deg)

0.8m

1.2m

18

3. Image sensing

Measurement sequence

1. Long-range: -120m
- LVS + sunlight, Earth albedo
- Continuous imaging, compression, transmission to the ground
- motion is analyzed on the ground, distance and velocity is calculated.

2. Transition to short-range : 120-30m
- LVS + sunlight, Earth albedo
- Continuous imaging, compression, transmission to the ground
- motion is analyzed on the ground, distance and velocity is calculated.

5. Grasping: 1.5m
- automatic control
- PVS(Wide mode)＋Wide angle light
- Check of expand criteria
- Check of the grasped condition

4. Proximity-range: 8 - 1.5m
- automatic control
- PVS(Wide mode)＋Wide angle light
- Ellipse of PAF is recognized, the relative position and attitude is calculated

3. Short-range: 30 - 8m
- automatic control
- PVS(Zoom mode)＋Narrow angle light
- Ellipse of PAF is recognized, the relative position is calculated

19

3. Image sensing

Long range(- 30m)
Imaging by LVS(Long-range visual sensor)
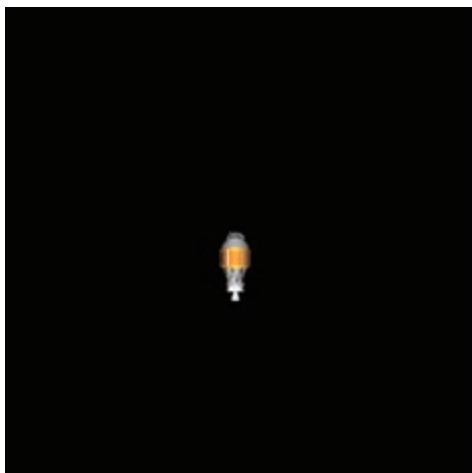ground control

Short range (30m - 1.5m)
Imaging by PVS(Proximity visual sensor)
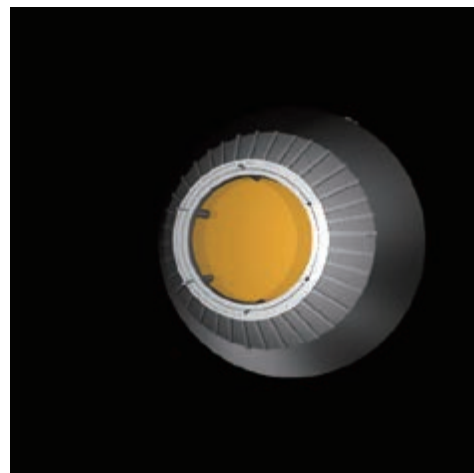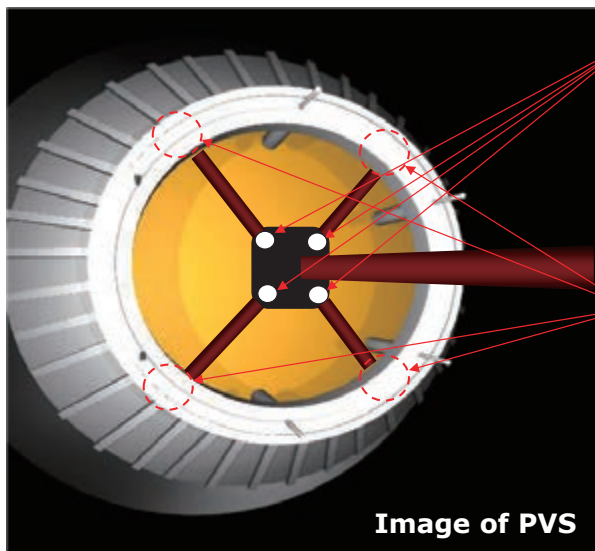Onboard processing

Image sample (300m)

Image sample (4m)

20

3. Image sensing

Image recognition method for Grasping

1. Depth is calculated from the spacing of the markers are measured. The expandable device behind the flange that has entered is verified.

2. From the image, it is detected that the tip of the extendable booms are not in front of the flange.

Image of PVS

For grasping mechanism is a cooperative target, assignment for measurements such as reliability and accuracy are little.

21

3. Image sensing

Study by CG

Create a 3D-CG model H2A second stage, generates a CG image by the rendering to examine the applicability of image processing techniques
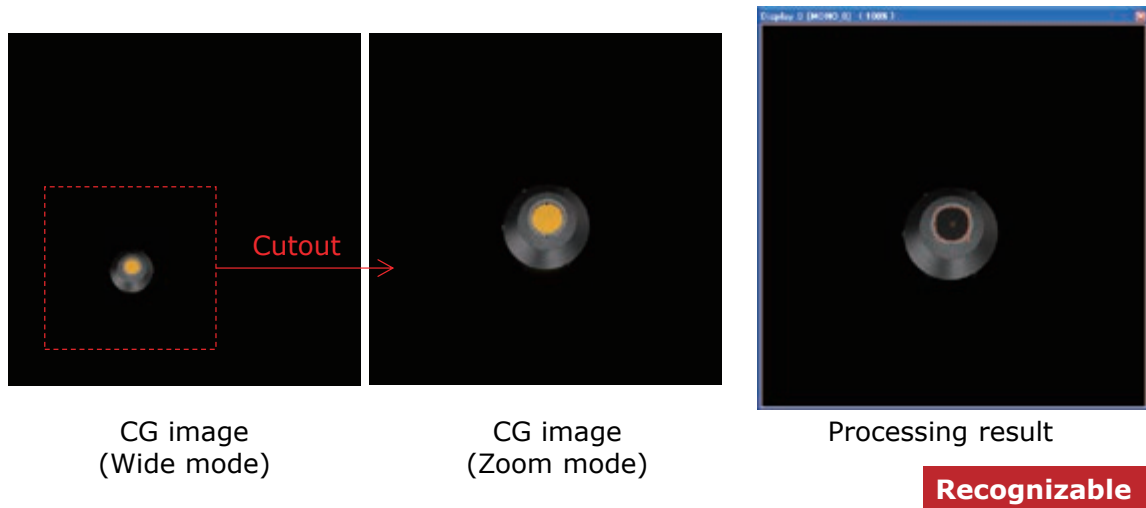

H2-A second stage rendering image

22

3. Image sensing

Examples of study results by CG
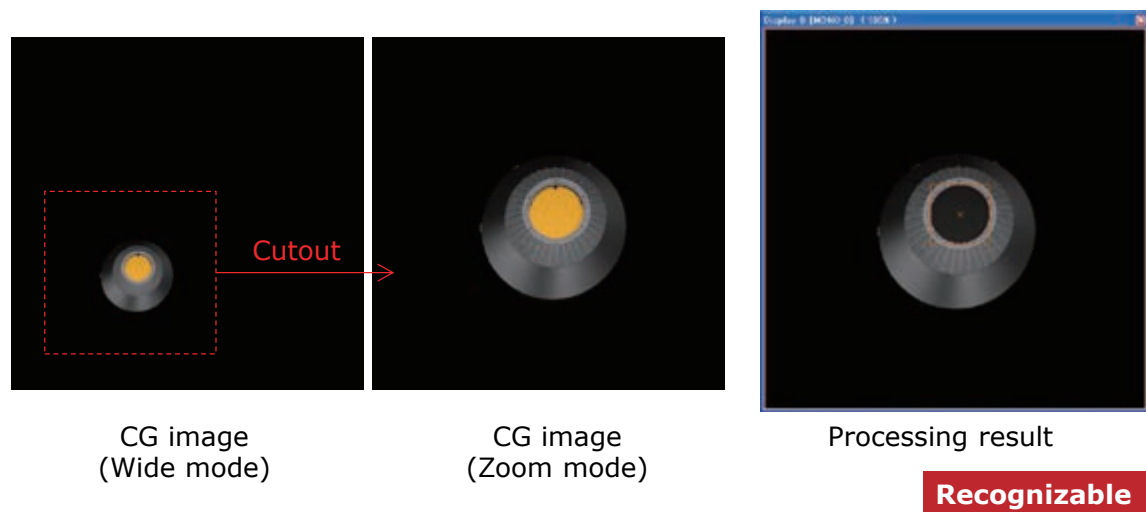
Conditions: Distance 30m, Relative attitude 10 °

| CG image (Wide mode) | Cutout → | CG image (Zoom mode) | Processing result |

CG image
(Wide mode)

CG image
(Zoom mode)

Processing result

Recognizable

23

3. Image sensing

Examples of study results by CG

Conditions: Distance 16m, Relative attitude 10 °

CG image
(Wide mode)

CG image
(Zoom mode)

Processing result

Recognizable

24

3. Image sensing

Examples of study results by CG

Conditions:　Distance 8m, Relative attitude 10 °

CG image
(Wide mode)

CG image
(Zoom mode)

Processing result
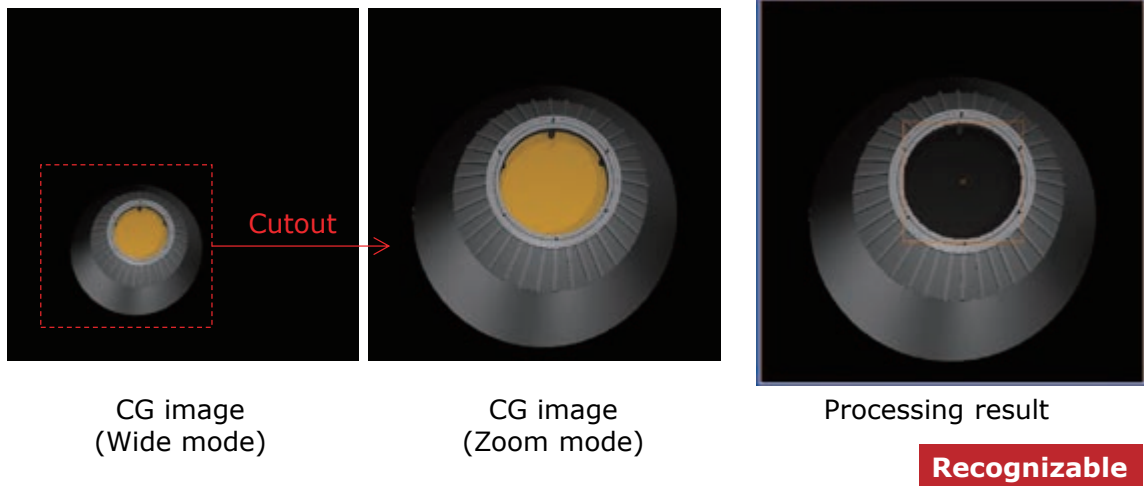
Recognizable

25

3. Image sensing

Examples of study results by CG

Conditions:　Distance 4m, Relative attitude 10 °

CG image
(Wide mode)

Processing result
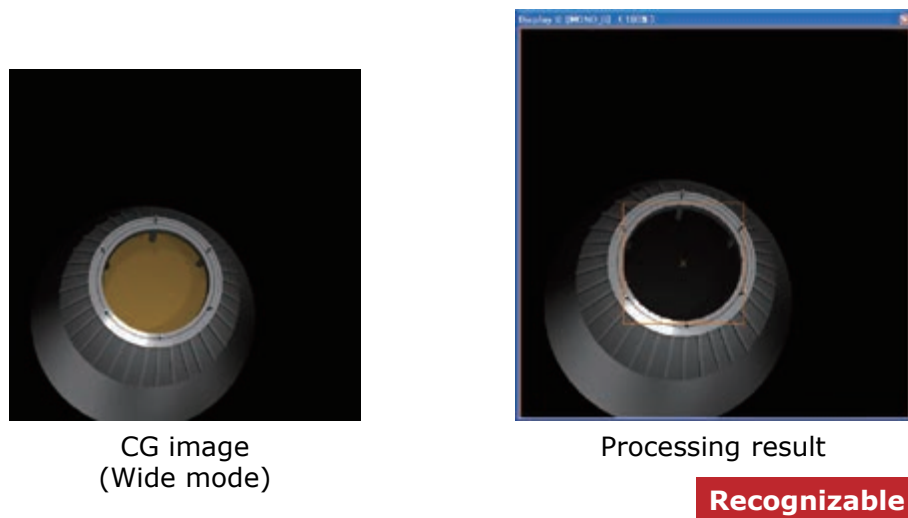
Recognizable
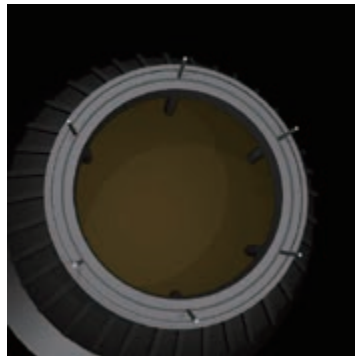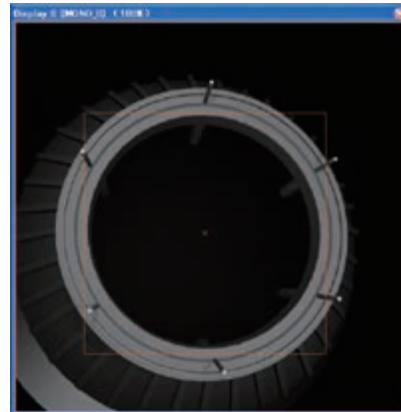
26

3. Image sensing

Examples of study results by CG

      Conditions: Distance 2m, Relative attitude 0 °

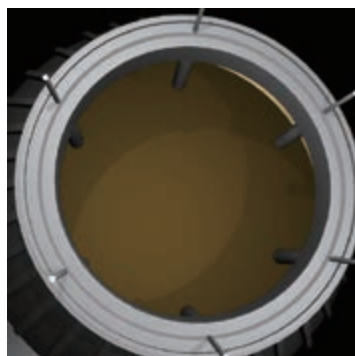CG image
(Wide mode)

Processing result
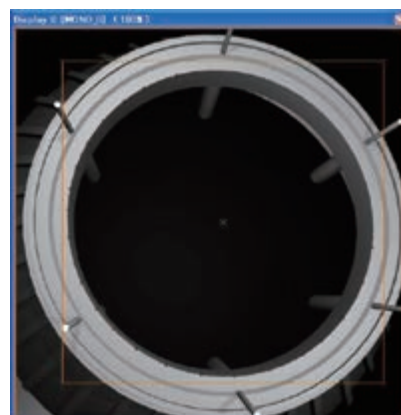
Recognizable

27

3. Image sensing

Examples of study results by CG

      Conditions: Distance 1.5m, Relative attitude 0 °

CG image
(Wide mode)

Processing result

Recognizable

28

3. Image sensing

Image acquisition of PAF

For the trial image processing algorithms, images of PAF were acquired.

- In a dark room to the indoor, the real PAF as the imaging target, in the light of the LED projector, and images were acquired with two cameras.

- This test was executed in the distance range of 16m ~ 1.5m.

- These distances correspond to the short range area.
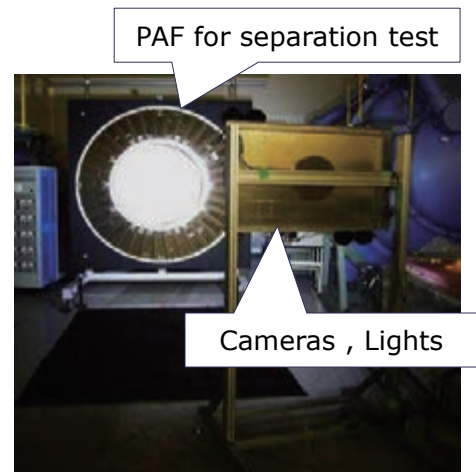
PAF for separation test
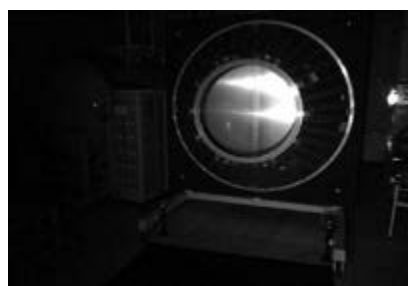
Cameras , Lights

Test situation

29

3. Image sensing

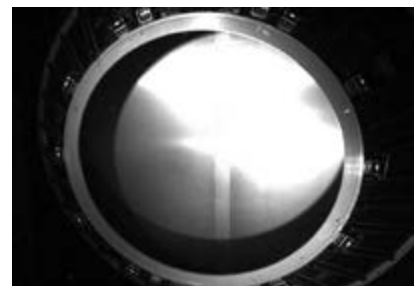Examples of examination results

Distance 16m, Relative attitude 10 °

Distance 8m, Relative attitude 10 °

Distance 4m, Relative attitude 10 °

Distance 1.5m, Relative attitude 0 °

30

4. Conclusion

1. Capture target
   Upper stage of the rocket has been selected as the target. PAF has been selected as a target of the grasp and image processing.

2. Capture mechanism
   Method for capturing debris by gripping the PAF was examined. As a simple and reliable method, a device using an extendable boom was invented.
   Dynamics of the grasping has been analyzed. Feasibility of the grasping methods have been confirmed.
   In addition, a prototype for the functional verification has been made. Technical Issues are being extracted for function and performance.

3. Image sensing
   Imaging target is selected according to the length range. The configuration of Camera and lighting for image processing has been selected.
   The image processing algorithm using the CG was confirmed, it was confirmed that there is enough image processing.
   Additionally, image acquisition examination for real PAF was performed.
   Investigation and trial for image processing algorithm has been developed.

31