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デブリ除去における画像計測と運動推定の検討

Vision-based Measurement and Motion Estimation for Space Debris Removal

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デブリ衛星の除去には、対象物に自律的に接近し、軌道から除去するための機構を取付けるアプローチが有効である。この接近、及び作業において、非協力であるデブリ対象の形状や位置姿勢、運動を推定する計測システムが必須となる。デブリ除去衛星に搭載したカメラによって得られた画像を用いる画像計測が、搭載性やコスト面で有効な計測手段と考えられており、遠方からのデブリ対象への接近から、除去機構の取付け作業までのほとんど全てのフェーズにおいて重要な役割を果たす。本発表では、デブリ除去のための画像計測と運動推定について、各運用フェーズでの役割や検討中の方式についての報告を行う。

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Outline of Space Debris Removal

- The amount of space debris has been increasing over the years and has become a potential problem for space development.
- The prevention of new debris is required in order to continue space activities in the earth orbit.

- In particular, an operation to remove debris from orbit would be effective in curbing the amount of debris.
- Deorbiting a large-scale satellite would be effective in preventing the spread of many smaller pieces of debris from its breakage.
- Presently, the second stage of a launch vehicle, such as the HII-A, is considered an appropriate target for removal.

- The importance of space-debris removal is internationally recognized, and this activity is expected to become industrialized.

Contents of this presentation

- The second stage of the launch rocket is set as a target for removal from earth orbit.
- For deorbiting the target from orbit, a device that can shift its own orbit is attached on the target body.
- A measurement/perception system is required to accomplish this operation through remote and autonomous control.

- The progress of our image-based measurement and motion estimation systems is reported in this presentation.

(Topics of this presentation)

- Image-based measurement and motion estimation for debris removal
- Operational phases of debris removal
- Facilities for and difficulties in image-based measurement and motion estimation systems

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Specific ways to remove debris

- Fixing a device for changing orbit to a debris body
  - By using the Lorentz force caused by the earth's magnetic field and the current of electricity through an Electro Dynamic Tether (EDT) that is stretched over a long distance from the device.
  - Or by using the propulsive force generated by thrusters.

When the removal device is attached to the object's body, we need to make a removal satellite

- approach and rendezvous with the target debris satellite, and
- attach a removal device or grapple the target.

These operations require remote and/or autonomous technology based on robotics.

Conceptual drawing of space debris removal operation by dragging EDT.

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Sensor/perception technology for approach to and capture of debris satellite

In this presentation, an upper rocket, i.e., HII-A, is proposed as a debris target; it is large enough to be approximately observed in its orbit or have its motion observed from a ground telescope.

In addition, its design parameters and materials are preliminarily known.

With all these factors, we can place a removal satellite closer to the debris target by using GPS navigation.

In the final approach and capture phase, more precise perception is required as follows.

- Determination of orientation to the target
- Measurement of distance to the target
- Relative attitude and position between the target and the removal satellite
- Reconstruction of the target (if the design parameters are not available)
- Motion estimation of the target
- Sensing to assist robotic operations

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Comparison measurement/perception system: Image-based sensor and Active optical ranging sensor

The measurement/perception system is composed of an optical camera and/or a range sensor. A quick comparison of their characteristics is presented below.

Range Sensor: LIDAR (LIght Detection And Ranging), LRF (Laser Range Finder)
Advantage in precise measurement of distance or shape
Necessary in long/wide range, downsizing of power, dimensions, and weight

Image-based Sensor: Stereo vision, image-based measurement algorithm
Advantage in (potentially) long/wide range, compact resources
Necessary in speed, resolution, limitation of lighting; more research and development is required

We believe that the image-based measurement system is promising for future applications. Therefore, in this study, we focus on the application of image-based sensing for approaching and capturing the debris.

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Image-based 3D measurement and motion estimation

By analyzing 2D images obtained from the removal satellite, we can create a 3D information, consisting of pose and position estimation of the debris and motion estimation that reflects the nutation/tumbling of the debris.

In this case, the debris is supposed to be the second stage of a launch rocket, such as HII-A; therefore, we already know its designed CAD value. (Fortunately, we already know the debris' dimensions, weight, and materials.)

The 3D information estimated by image analysis will differ according to the projected size (pixels) of the target on images, i.e., the distance from an observer to an object. Therefore, several types of perception algorithms are required during the debris removal operation.

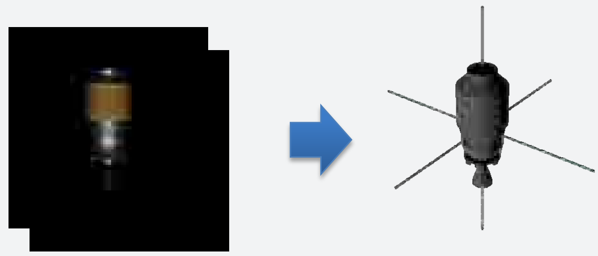

Image-based 3D perception and motion estimation

Image-based 3D perception and motion estimation

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Phasing image-based perception for removing debris

Image-based perceptions (measurement and motion estimation) have different functions according to the distance to the target. (Distances below are T.B.D. values)

Approach Phase: finding a target from long-distance and coarse perception

Finding a target and determining its orientation	~dozens of kilometers
Coarse range finding of distance to the target and its shape	~10 kilometers

Observation Phase: precisely measuring shape and motion and turning around to the target

Precise reconstruction of the target and motion estimation	~50 meters

Removal operation Phase: attaching a removal device to the target

Visual support for the robotic operation	a few meters ~ 50 meters
Checking behavior of target with the device	~30 meters

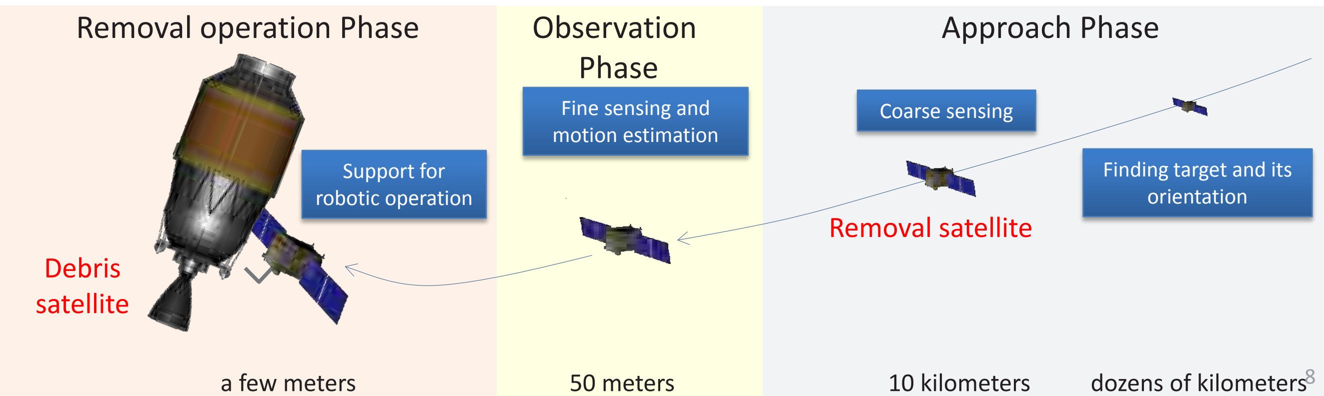

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Image-based perceptions on each phase

Approach Phase

- Finding target and determining its orientation

  From dozens of kilometers to the target, the target, which is projected as being one or a few pixels in size in a telescopic camera, is detected for estimating its orientation from the viewpoint of the removal satellite.

- Course range finding to the target and its shape

  Within about 10 kilometers, the target is projected to 10 pixels more on the image.

  Using a small projected target, the distance to the target and its shape are approximately estimated.

Observation Phase

- Precise 3D reconstruction of the target and motion estimation

  At around 50 meters from the target, its shape and the distance from the viewpoint are precisely measured through image-based perception, i.e., stereo-vision.

  The target motion, such as nutation/tumbling, is estimated by using sequential images.

  For the final approach in the next phase, all perception information of the target should be estimated in this phase.

Removal operation Phase

- Image-based perception for robotic operations

  Until contacting with the target, visual perception or target tracking is continually executed for a robotic operation, i.e., attaching a removal device on the body of debris.

  After attaching the device, the performance of the device is monitored in the middle distance.

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(Note) Debris satellite CG model: HII-A second rocket

In this part of the presentation, we describe how each image-based perception is synthesized using images through computer graphics. The information includes the debris satellite CG model, HII-A second rocket, and camera properties of the removal satellite.

- Cameras on the removal satellite:
  - A camera with a telescopic lens, FOV 6 [°]], for long-range observation
  - Two cameras with a standard lens, FOV 20 [°], for stereo camera sets
  - Image-size: 1000 x 1000 [pixels]
- A debris satellite/target satellite and an upper (second) rocket of the HII-A

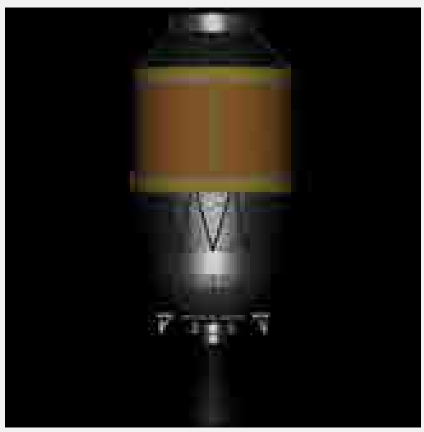
Dimensions of the debris target:
total height 10 [meters]
diameter of body 4 [meters]

Synthesized images from 100 [meters] distance

with standard lens, FOV 20 [°]

projection size of the target 117x273 [pixels]

with telescopic lens, FOV 6 [°]



projection size of the target 391x984 [pixels]

Light source; right behind the sun and under the earth's albedo

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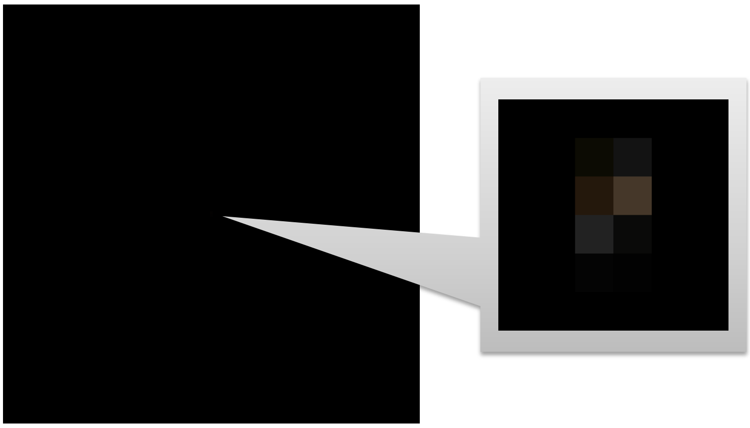
Finding target and determining its direction

- From a very long distance, for example, of the order of dozens of kilometers, the target projected on the image, with a size of one or a few pixels, is detected from an image obtained by a telescopic camera, and the direction from a viewer to the found target is concurrently estimated with the target positions.



Synthesized images from 10,000 [meters] distance with telescopic lens, FOV 6 [°]
Image size 1000x1000 [pixels]

Projection size of the target: 3x2 [pixels]

With a high-resolution camera with a telescopic camera, if the lighting environment is good, the target image can be projected on the image plane with one or a few pixels. As the approximate target position is known from orbital information and GPS navigation, it is relatively easy to find it and distinguish it from stars.

The direction of the target from the observer can be derived from the target position on the image.

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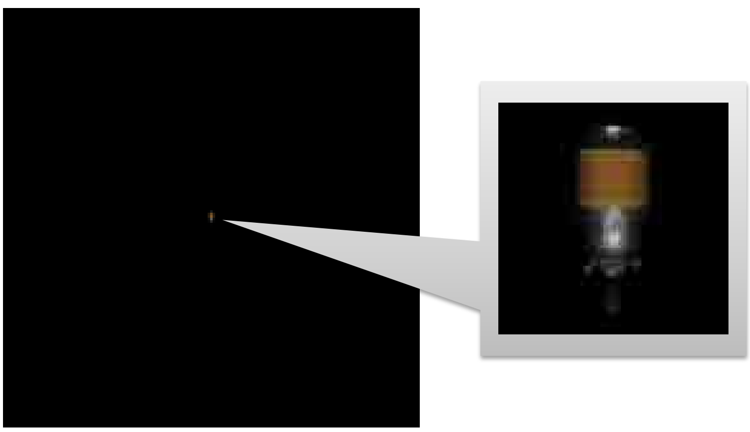
Course range finding with a telescopic image

- An approximate distance between the viewpoint to the target is estimated from the projection size of the target and its design parameters.



Synthesized images from 3,000 [meters] distance with telescopic lens, FOV 6 [°]
Image size 1000x1000 [pixels]

Projection size of the target: 14x34 [pixels]

From 10 kilometers to the target, the projection size of the target will increase by more than 10 pixels.

The estimation accuracy depends on the lighting condition, i.e., the positions of the sun and the earth (albedo).

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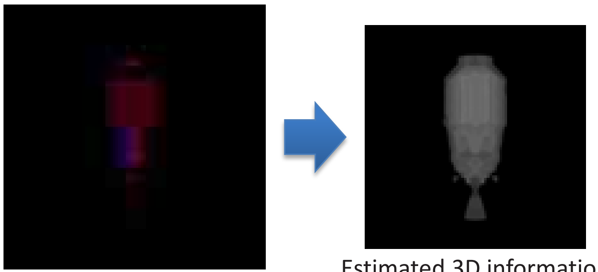
Precise 3D reconstruction with stereoscopic images at close range

- At close range, i.e., within 50 meters, a precise image-based perception, i.e., stereo-vision and/or SFM (Structure from Motion), can be obtained through images of sufficient resolution.

  (With design information of the target, this perception is not so important.)

Synthesized stereo images from 50 [meters] distance with FOV 20 [°] lens, base line distance 0.5 [meters]
Each projection size of the target: 233x591 [pixels]



Overlapped stereo images
left: red, right: blue

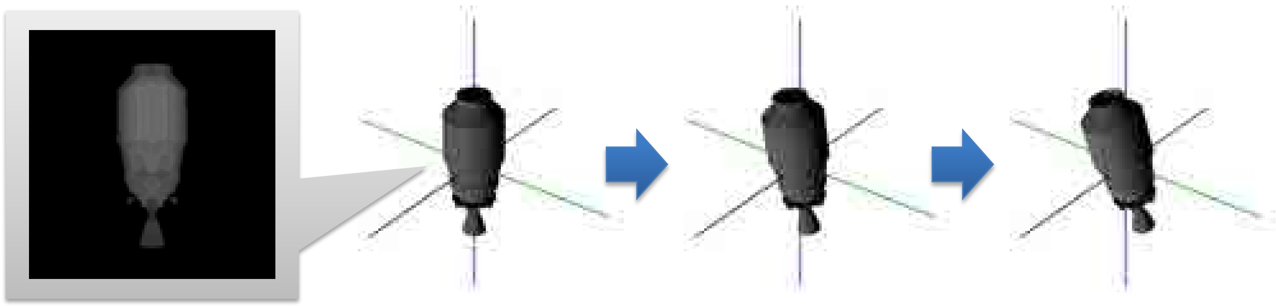
Estimated 3D information
disparity map

By using two camera set at a baseline distance of 0.5 meters, the stereo images obtained indicate the viewing disparity of the target; therefore, the target 3D information can be estimated by stereo matching.
This perception result is an estimate of the shape variation from the known design parameters of the target.

Moreover, from the design parameters, the target’s 3D information can be estimated by the SFM estimation method.

Motion estimation at close range

- It is important to estimate the target’s motion in order to capture it. At close range, i.e., within 50 meters, by using the 3D information that is obtained through stereo-vision and/or a design parameter, motion information of the target can be precisely estimated.



i.e., model fitting motion estimation

Estimated target motion, nutation/tumbling along one’s own orbit.

By sequentially fitting a reconstructed target shape to the designed model, the target motion including nutation/tumbling can be estimated.
The debris motion and the removal satellite motion are included in one motion estimation; therefore, decomposition of the object from the viewer is required.

Properties of image-based perception for debris removal

Facilities of image-based perception:

- Design parameters and detailed shapes of the debris target are known, in which case the second rocket could be a debris target.
- If the target is sufficiently large, its motion is supposed to be simple and slow. The motion can be approximately estimated by an observation from the earth.
- By GPS navigation, a removal satellite can get close to the target.

-> This reduces the difficulties in image-based perception.

Basic difficulties in image-based perception:

- The only light sources are the sun and the albedo from the earth, but their location changes from hour to hour. The time required to circle the earth is about 90 minutes.
- Motion decomposition between the target and the observer
- Wide sensing range: from 10 kilometer (or of the order of dozens of kilometers) to 0 meter
- Limitation of resources on a spacecraft, i.e., camera, CPU, memory, etc.
- Unavailability of actual sample images

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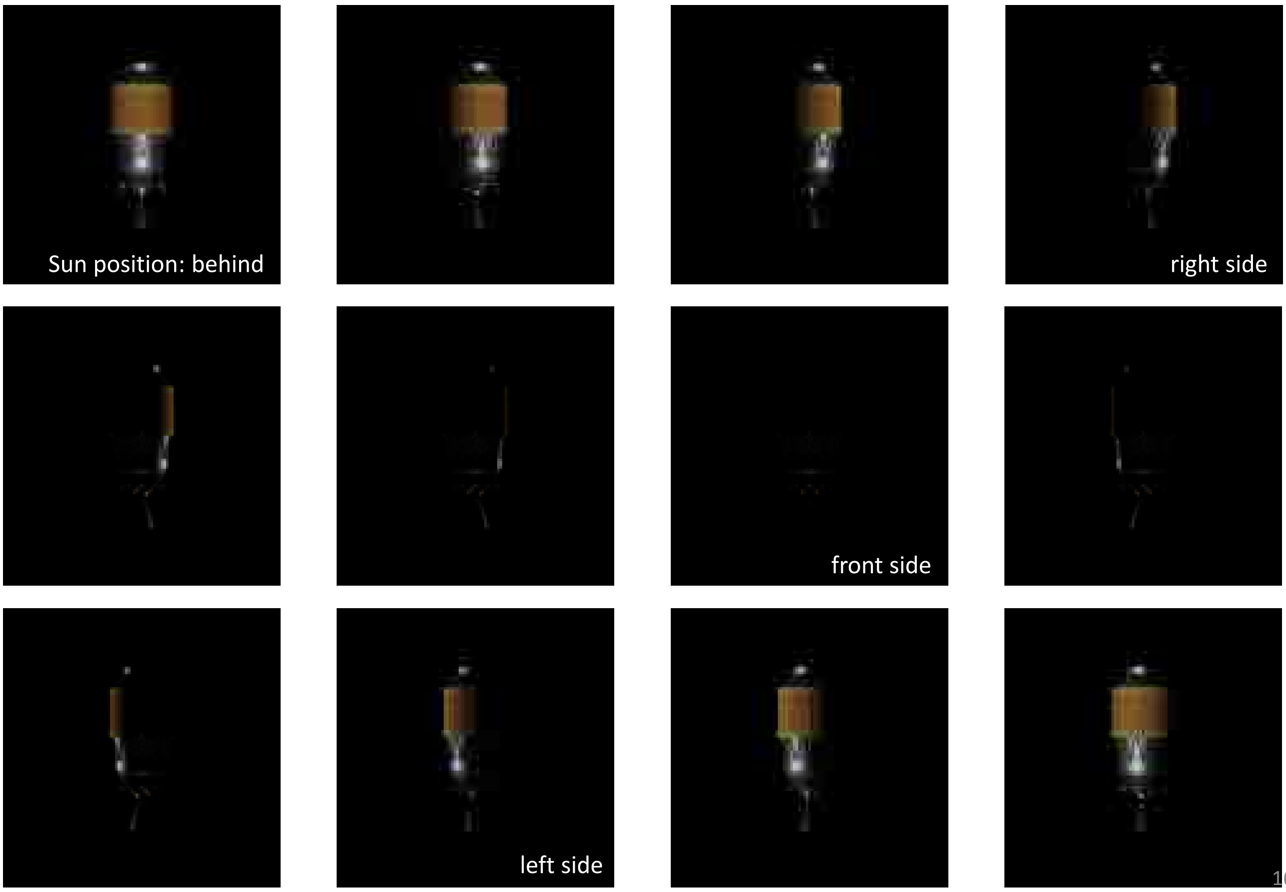
(Reference) Synthesized images from different positions of the sun



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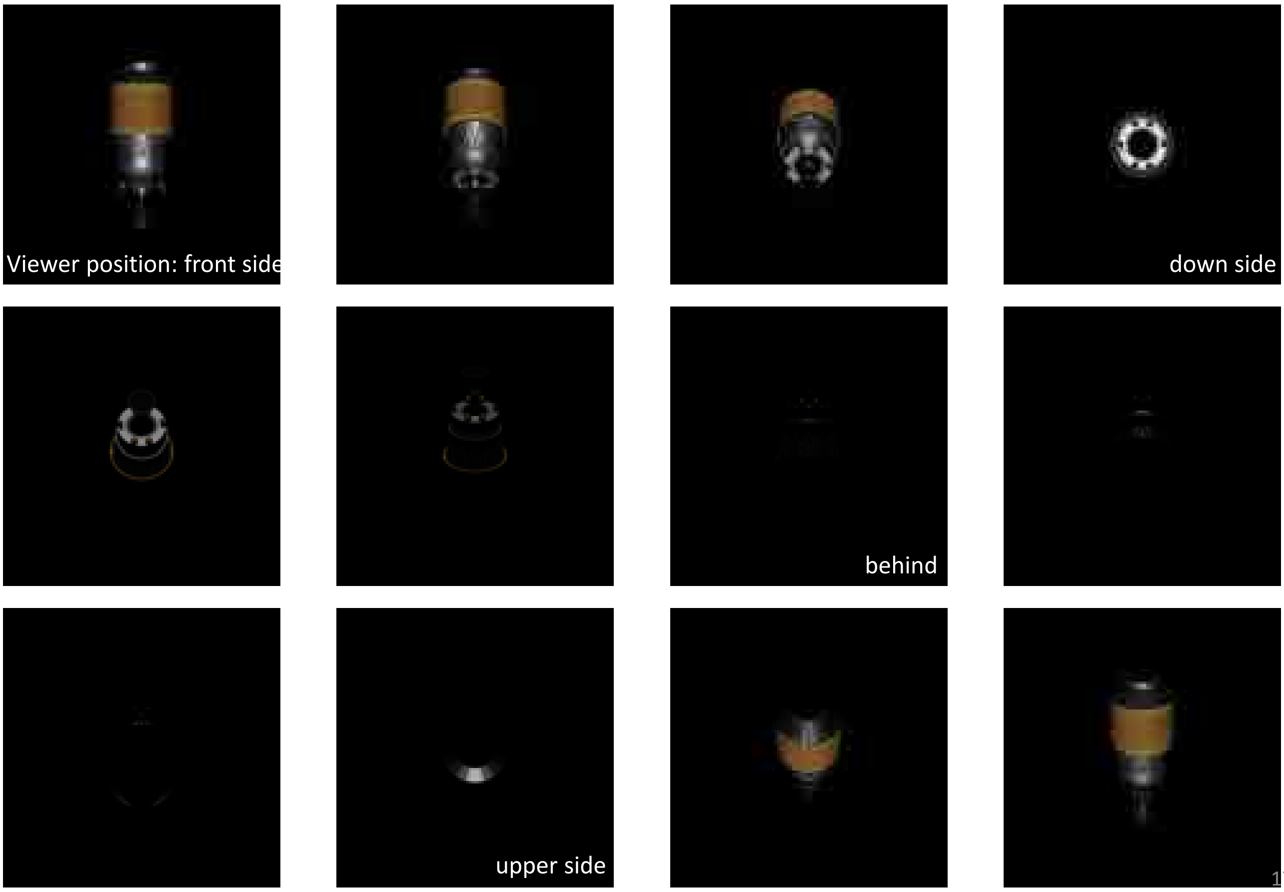
(Reference) Synthesized images from different viewing positions



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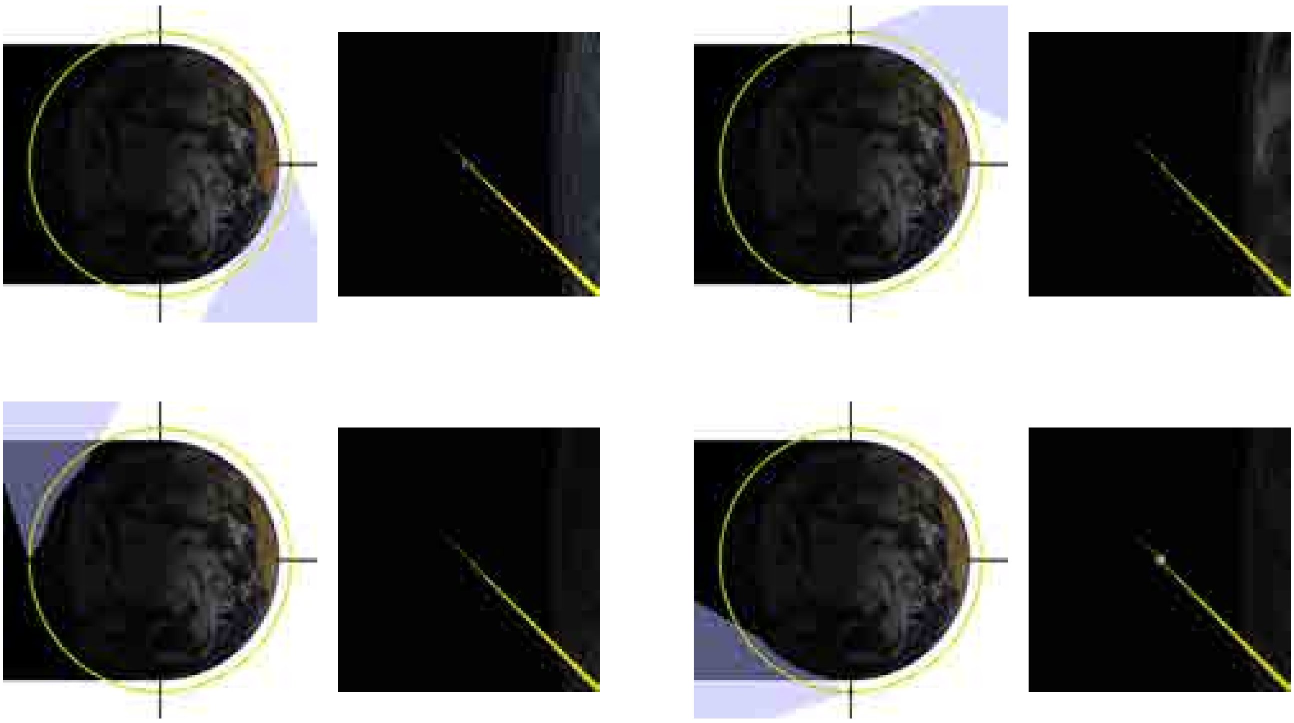
(Reference) Lightning changes in position of the observer rotation on its orbit



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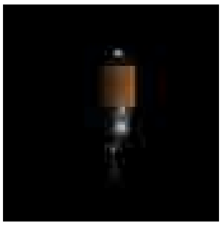
Our activities in image-based perception for debris removal

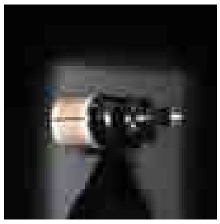
Usually, the research and development of image-based perception requires much experimental evaluation of the proposed methods with the actual images. In the debris removal operation, it is not easy to obtain the actual images of the debris in an earth orbit; therefore, we have to use other means to obtain more realistic images. The following are our activities in this regard.

- Synthesis of images through computer graphics
  - for the performance of the proposed algorithm, tests in many cases
- A miniature scaled model of the debris
  - for actual tests of the cameras, lens, and real material, i.e., refraction on MLI (multi-layer insulation)
- Images of the (actual) HII-A upper rocket in a facility
  - for actual scale tests of the camera, lens, and actual surface materials
- Actual similar images obtained from the ISS, HTV, and HII-A
  - for actual lighting environments

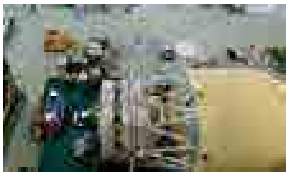
- Through a demonstration experiment on the orbit, actual images are obtained
  - this is a perfect experiment and a unique opportunity.



CG image



Miniature model



Actual satellite (HII-A)

Similar image on the scape (GOSAT)

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Conclusions

- Attaching a removal device to an upper rocket is effective in reducing new space debris in the earth orbit.
- This operation needs remote controlled and/or autonomic robotics technology, and 3D perception plays the most important role.

- This presentation provides an outline of the phases involved in the debris-removal operation in terms of image-based perception, and it describes our activities in this regard.

- In the debris removal operation, we believe that an important and key technology is 3D reconstruction and motion estimation using images obtained by the removal satellite.
- We continue to focus our research and development on image-based perception for debris removal.

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