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自己位置推定と自律制御を用いた軌道上微小デブリ衝突痕観測ロボットの開発

Development of In-situ Observation Robot for Micro Space Debris Impact Marks Using Localization and Autonomous Control

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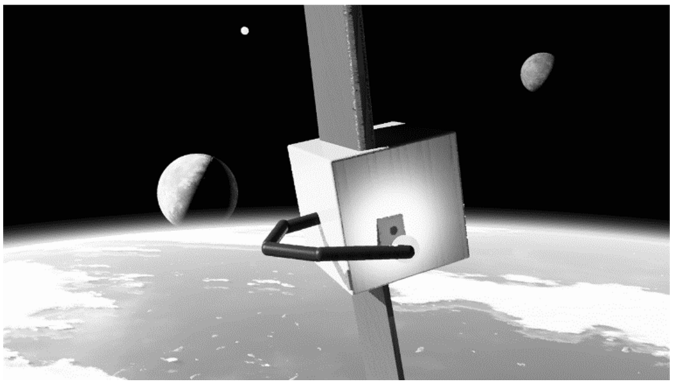
軌道上における微小デブリの存在密度情報にはデータギャップが存在する。回収した宇宙機による解析や観測が比較的困難である SSO や静止軌道において特に顕著である。我々はこれらの軌道上にある宇宙機の観測機器の１つとして、デブリ衝突痕観測システム ODIM を開発している。ODIM は搭載した宇宙機の外観のデブリ衝突痕を自律的に観測することが可能であり、その情報を集約することで微小デブリの存在密度情報の取得を目的としたシステムである。ODIM の観測部は深度カメラと外力を加えても形状維持が可能な構造材料 Morphable Beam(MB)にて構成されている。課題点として、MB 制御はアップリンクによる手動の操作に依存している点が挙げられる。これは MB の柔軟性によって曲げの精度が十分ではないこと、非ホロノミック系であることにより先端位置制御が容易ではことに起因している。本研究ではこれを解決するため､新たな MB を搭載した統合システム MBD-4 と MB の自律制御システムの開発と評価を行った。宇宙機全体の形状データをもとに３次元的に地図情報を作成し、深層学習によって画像処理と自己位置推定技術により，MB 先端位置を割り出すというものである。これにより、ODIM 単体でデブリ衝突痕観測の完全な自動化が見込める。

There is a data gap in the information on the spatial density of micro debris in orbit. This is particularly noticeable in SSO and GEO, where analysis and inspection by recovered spacecraft are relatively difficult. We are developing a debris impact masks observation system, ODIM, as one of the observation instruments for spacecraft in these orbits, which can autonomously observe debris impact marks on the exterior of the onboard spacecraft and obtain information on the existence spatial density of micro debris. The ODIM consists of a depth camera and a morphable beam (MB), a structural material that can maintain its shape even when subjected to external forces. One of the challenges is that the MB control relies on manual operation via uplink. This is because the bending accuracy is not sufficient due to the MB's flexibility, and because it is a nonholonomic system, it is not easy to control the tip position. In this research, in order to solve this problem, we developed and evaluated an integrated system MBD-4 equipped with a new MB and an autonomous control system for the MB. The system creates a three-dimensional map based on the geometry data of the entire spacecraft and determines the current position of the MB tip using image processing on deep learning and localization. This system is expected to fully automate debris impact marks observation with ODIM alone.



Akita University

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Model of micro debris

Table1 Debris estimates by size and their characteristics

		Large debris ～100mm	Small debris 100 mm ～ 10 mm	Micro debris 10 mm ～ 1 mm
Size				
Estimated number	USSSTRATCOM[1)]	20,000	500,000～700,000	100 million
	ESA[2)]	36,500	1 million	130 million～
Means of observation		Optical and radar observations from the ground		None
Hazards by collisions[3)]		Catastrophic	Structural damage	Partial loss of mission capacity
Approach		Removal Collision avoidance maneuver	None	Protective design of spacecraft

The 1st Problem
Spacecraft risk assessment is difficult due to the lack of established micro debris models.

1) The Cabinet Office Space Development Strategy Promotion Secretariat, Recent changes in space debris, available from < https://www8.cao.go.jp/space/taskforce/debris/dai3/siryou1.pdf >(in Japanese).
2) The European Space Agency, Space debris by the numbers, available from < https://www.esa.int/Space_Safety/Space_Debris/Space_debris_by_the_numbers>. 3) UN. Committee on the Peaceful Uses of Outer Space. Scientific and Technical Subcommittee, Technical Report on Space Debris, 1996.

1 Introduction

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How to observe micro debris

1. Observation from the ground (Optical / radar)
2. Inspection of retrieved spacecraft
   Space Shuttle / Hubble Space Telescope
3. In-situ detector
   LDEF / The space debris monitor[4)]
   Pros : No need for calibration
   Cons : A limit to the area that can be installed on a spacecraft.

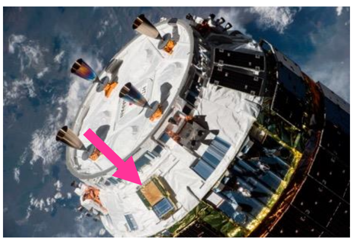

Fig.5 The space debris monitor on HTV[4)]

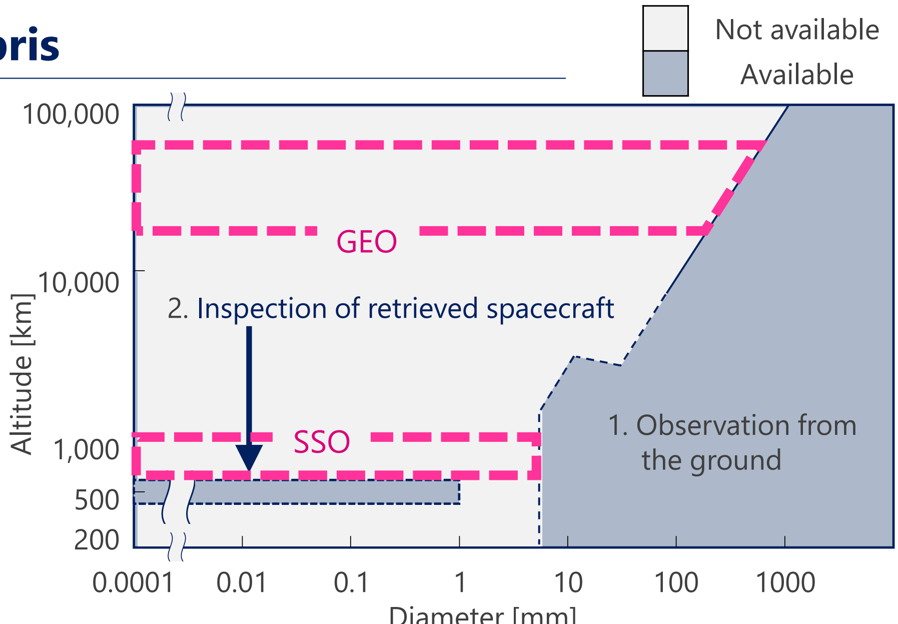

Fig.6 Availability map of information of orbital debris[5) 6)]

The 2nd Problem
A new in-situ observation method is needed to supplement the flux of micro debris

4) Noriko Matsuzaki, Haruhisa Matsumoto, Daiki Nakanishi, Aiko Nagamatsu, Koki Kamiya, Development of JAXA Space Debris Monitor BBM, The 9th Space Debris Workshop, 2021.
5) Yukihito Kitazawa, Kazuo Uematsu, Micro debris Impact Testing and Measurement Technologies, Ishikawajima-Harima Technical Journal, 35-2, 1995, pp. 143-149. 6) J.-C. Liou, Risk from Orbital Debris, RAS Specialist Discussion Meeting on Space Dust and Debris in the Vicinity of the Earth, 2018.

1 Introduction

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Observation of micro debris impact marks

Small size・High speed ▶ Difficult to observe directly

Debris impact marks size is up to 10 times larger than debris[7)]

Debris impact marks as in-situ observation target

Size, direction of impact, and time of impact can be estimated

Develop a robot to observe the surface of spacecraft

Mounted on numerous spacecraft

Improve accuracy of micro debris flux information

Enables risk assessment of spacecraft

The entire spacecraft can be viewed as if it is a large micro debris sensor

7) Drolshagen, G. : Hypervelocity Impact Effects on Spacecraft, Proc. Meteoroids 2001 Conf., pp. 533–541, 2001

2 Overview of Observation Robot

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Estimated flux in SSO

ORDEM

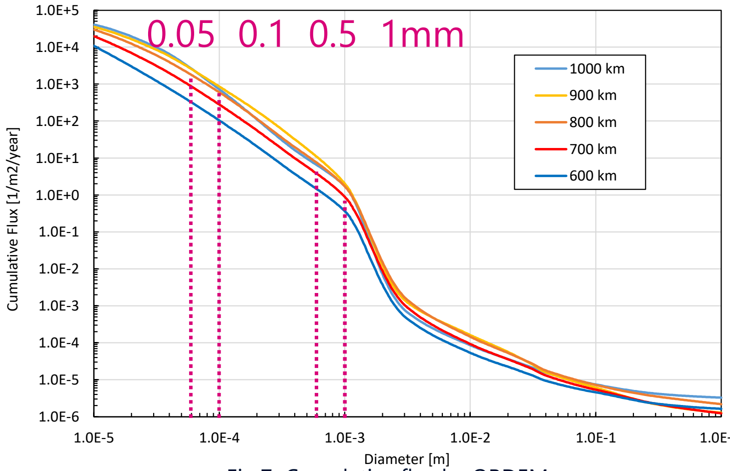


Fig.7 Cumulative flux by ORDEM

MASTER

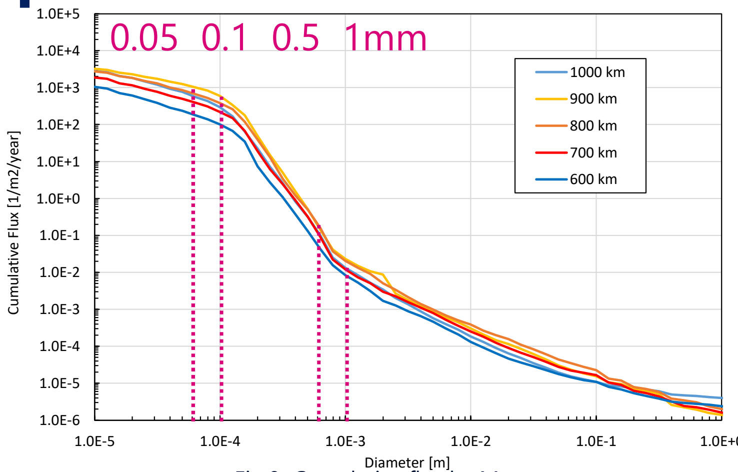


Fig.8 Cumulative flux by Master

Take 4 points as representative points in the zone where the ORDEM and MASTER environmental models diverge significantly and estimate the number of collisions with the spacecraft.

2 Overview of Observation Robot

Number of collisions with spacecraft

$$N_c = F \times A \times T \times N_S$$

N_c: *Number of collisions with spacecraft*
F : *Cumulative Flux* $[1/m^2/year]$
A : *Projected area of spacecraft* $[m^2]$
T : *Time* $[year]$
N_s: *Number of spacecraft*

Fig.9 Overview of GCOM-C ©JAXA

- Installed on 2-ton class satellite as piggy-back payload
  e.g.) GCOM-C SSO 800km
  - Approximate total projected area of the spacecraft A = $16\ m^2$
- Aim for a standard deviation of about 10%, which is superior to ORDEM and MASTER as environmental models.
  - N_c is the target of 100 or more

- $T \times N_S$
  - 0.05 mm ORDEM・MASTER: Shorter than 1 month × 1 spacecraft ▶ LDEF / SDM
  - 0.1 mm ORDEM・MASTER: Shorter than 1 month × 1 spacecraft ▶ LDEF / SDM
  - 0.5 mm ORDEM :1 year × 3 spacecrafts | MASTER :1 year × 14 spacecrafts. ▶ Targets of our research
  - 1 mm ORDEM :1 year × 4 spacecrafts | MASTER :1 year × 256 spacecrafts ▶ Optical / radar

Targets for in-situ observation : 0.5mm ~ 1mm ▶ Selection of Camera

2 Overview of Observation Robot

ODIM : In-situ Observation Robot for Micro Space Debris Impact Marks

Objective
- Micro debris flux information acquired to reduce spacecraft risk
- Proposal for a new robot for in-orbit observation of micro debris impact marks

Design requirements
- Observation target: micro debris in SSO with a particle size of 0.5mm~1.0mm
- Observable range covers the entire surface area of the satellite
- Installed on satellites as piggy-back payload to reduce observation costs
- Compact, lightweight, and power-efficient
  for easy installation on many satellites
- On-board processing
  that minimizes communication
  and does not interfere with the satellite's mission
- Low cost by utilizing consumer components

Table2 Specifications

Size (D×W×H)(Excluding flexible beams)	300 × 355 × 430 mm
Weight	3.69 kg
Power consumption	30 W

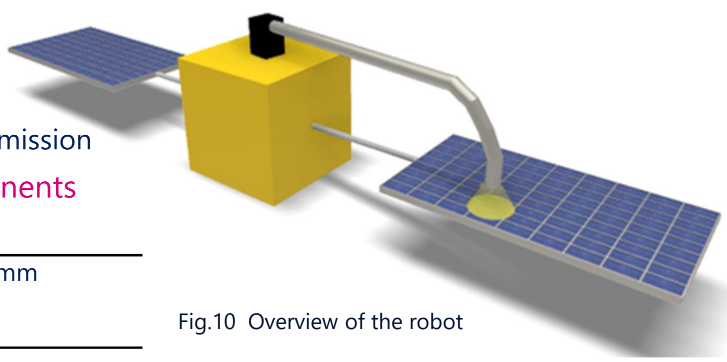
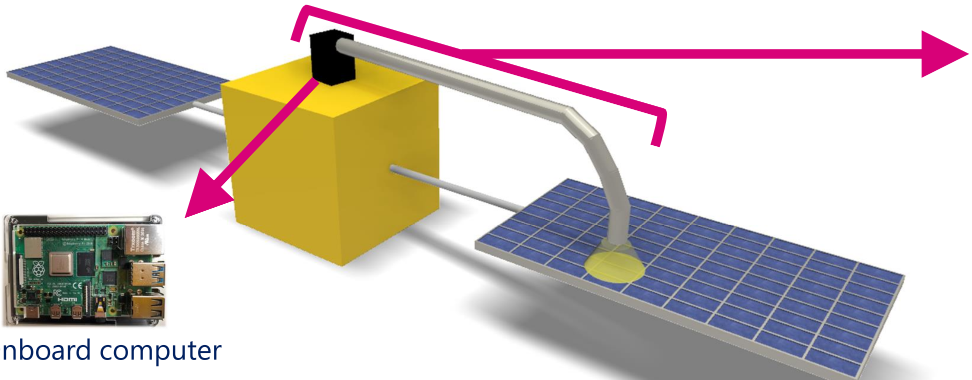


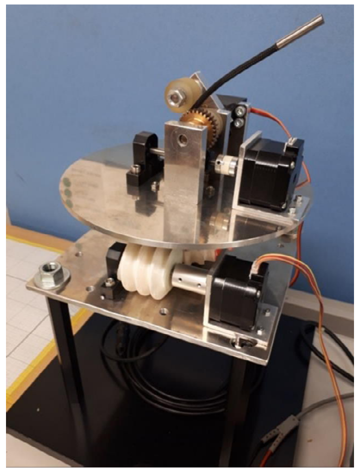
Fig.10 Overview of the robot

2 Overview of Observation Robot

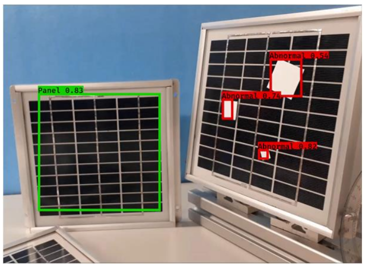


Onboard computer

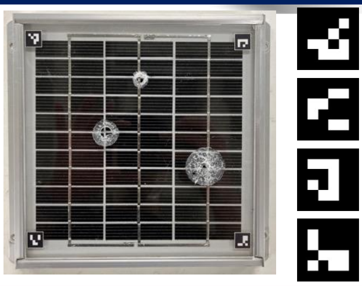
MBD **Morphable Beam Device**



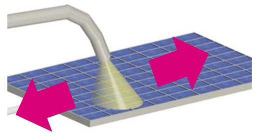
SCAN-2 **Autonomous Observation**



Observation Database



Localization



Autonomous control is possible by linking four subsystems

3 Autonomous Observation using Deep Learning

SCAN-2 : Autonomous Observation System

Objective

- Automatic identification of debris impact marks or not for efficient observation

Overview

- We adopted and improved an object detection algorithm YOLOv5 that can simultaneously process object location and classification
- Supervised learning
- Processing is possible with a single board computer
- On-board processing minimizes communication with the ground

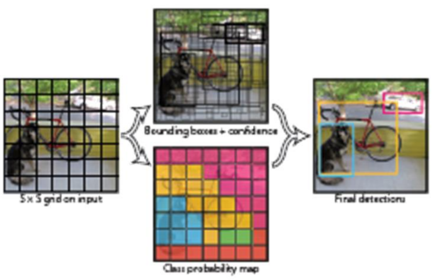


Fig.11 Process flow in YOLO[8]

8) Redmon, J., and Farhadi, A., YOLOv3, An Incremental Improvement, arXiv:1804.02767, 2018.

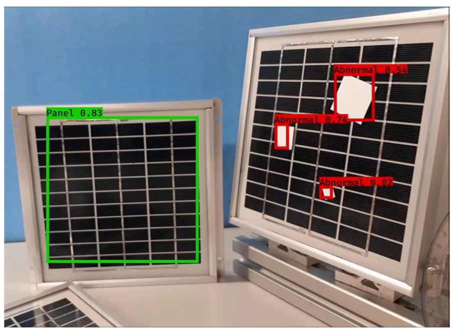


Fig.12 Object detection by SCAN-2

3 Autonomous Observation using Deep Learning 11

Unique training data

- Targeting solar arrays, which occupy most of the surface area of satellites
- Insufficient images of solar array damage in space
  - Collected 100 images of damaged solar array on the ground via the web
  - Use data obtained from the spacecraft as new training data to further improve accuracy
- Annotated and trained on each image
  - Implemented in SCAN-2

Fig.13 Some of training data

Normal solar arrays
Damaged solar arrays

Fig.14 Annotation

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Evaluation experiment of SCAN-2

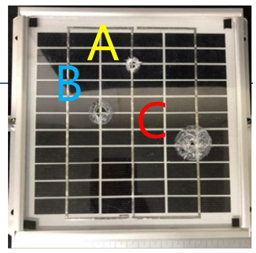

Fig.15 Solar array simulating impact marks

Objective

- Performance evaluation of SCAN-2 (Compared with the previous system SCAN)
- Evaluate under what conditions debris impact marks can be detected

Overview

- Set up an imaging environment that reproduces space
- Prepare a normal solar array and a solar array simulating impact marks

① Measuring confidence score (Varying distances and angles) ▶ Recognition rate

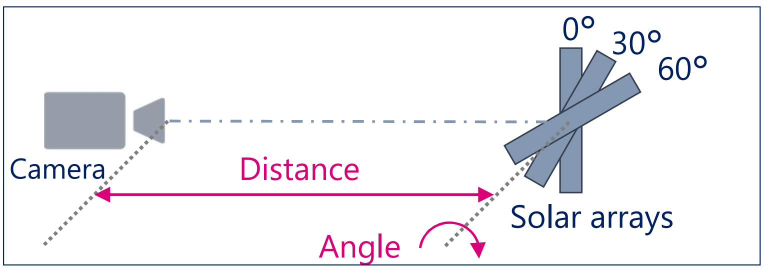

Fig.16 Schematic diagram of the experiment

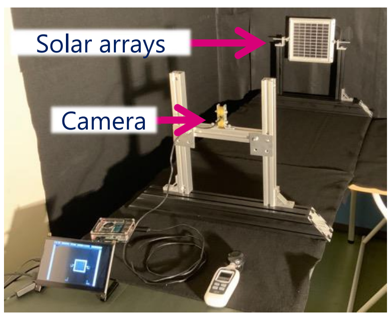

Fig.17 Experimental environment

② Measuring FPS and processing time ▶ Processing speed

Evaluation experiment of SCAN-2

- SCAN-2 and SCAN detected solar arrays and impact marks within 500mm and 30°
- No significant difference in recognition rate
- SCAN-2 outperformed SCAN in both FPS and Processing time

Table4 FPS and processing time

	SCAN	SCAN-2
FPS	0.29	0.64
Processing time[s]	19.0	3.0

SCAN-2 can speed up processing while maintaining accuracy.
SCAN-2 is capable of near real-time observation.

Overview of Coordinate estimation

- For continuous observation of debris impact marks without omissions
- Flexible beam has a high degree of freedom
  - ▶ It is difficult to maintain the distance and angle to the observation target

High-precision coordinate estimation on spacecraft is required

- To reduce cost, coordinate estimation is performed by optical observation without using sensors ▶ Using target markers

Coordinate estimation with an accuracy of a few percent of relative error in any viewing direction

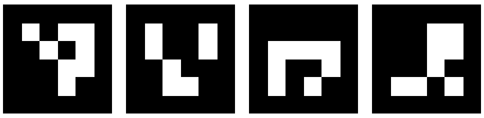

Fig.18 ArUco marker[9)]

Database Example

Table 5 Debris impact marks individual database

Items	Example
ID	1
Time and Date	2022_11_02_071108
Observation No.	1,2,3
Part	Left solar array
Coordinate	[54,67]
Diameter [mm]	5.3

Table 6 Observation database

Items	Example
Start date and time	2022_11_08_070237
End date and time	2022_11_08_080056
How many times	1
Sum of Impact Marks	15

Two databases enable autonomous observation

9) S. Garrido-Jurado, R. Muñoz-Salinas, F.J. Madrid-Cuevas, M.J. Marín-Jiménez : Automatic generation and detection of highly reliable fiducial markers under occlusion, Pattern Recognition, Volume 47, Issue 6, June 2014, pp. 2280-2292, 2014.

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MBD[9)] : Morphable Beam Device

- Morphable Beam is a name for a flexible beam
- The beam can be
  easily reshaped and maintains its shape
  even when the external force is removed
  after reshaping

- MBD-3 is our device that performs
  Three-dimensional control of beam
  - Beam extension
  - Bending
  - Rotation
- Camera mounted on the tip of the beam


Fig.19 Morphable Beam

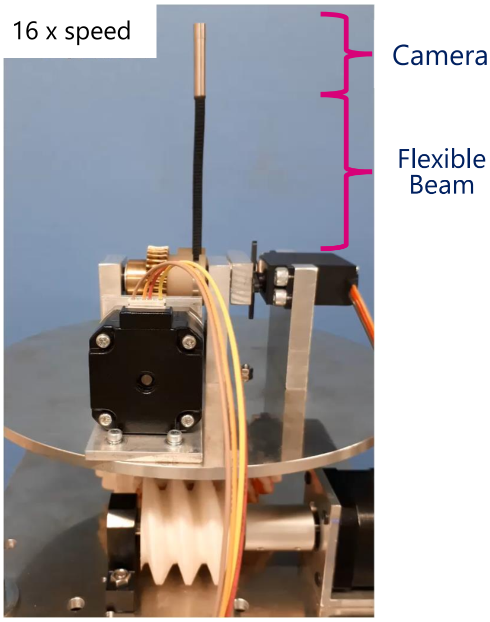

Fig.20 MBD-3 in operation

9) Thomas Iljic, Saburo Matunaga, Yohei Tanaka, MORPHABLE BEAM DEVICE AND ITS VISUAL POSITIONING SYSTEM, IFAC Proceedings Volumes, ,Volume 40, Issue 7, 2007, Pages 871-876

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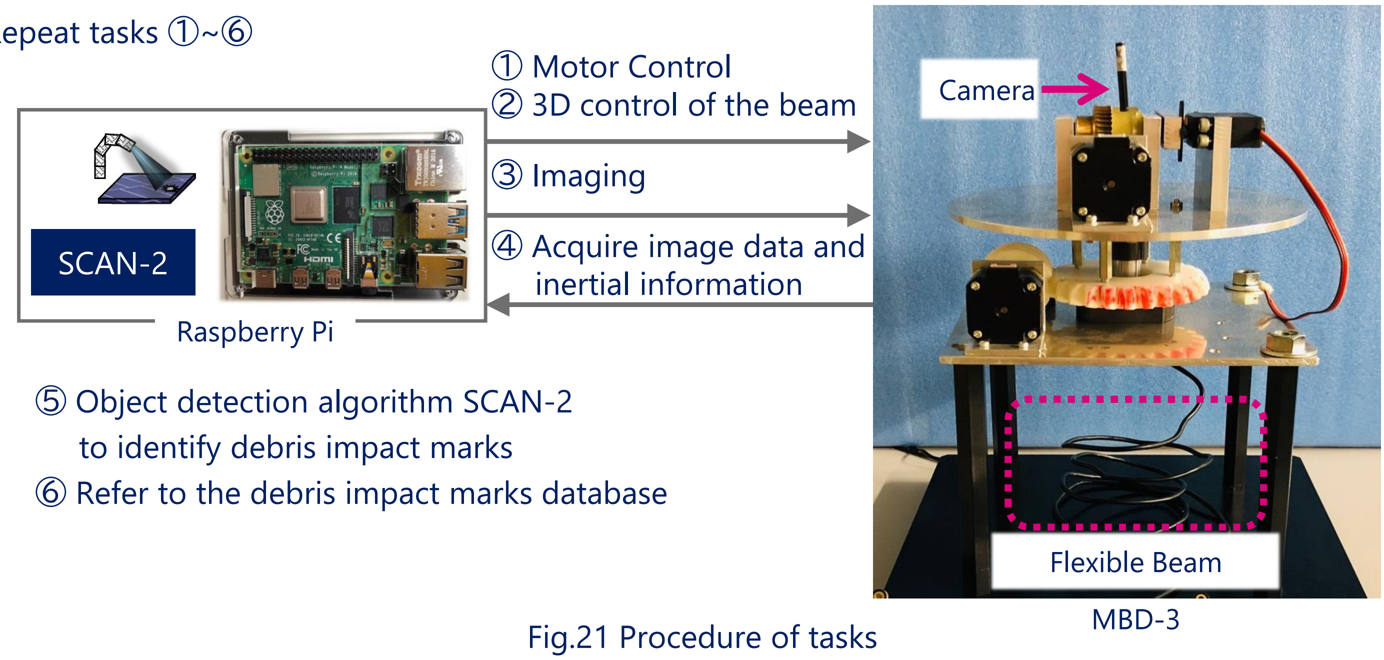
Configuration of MBD-3 and SCAN-2

Repeat tasks ①~⑥



⑤ Object detection algorithm SCAN-2
to identify debris impact marks
⑥ Refer to the debris impact marks database

Fig.21 Procedure of tasks

4 MBD and Localization for Autonomous Control

How to control of the beam

Problem

- The beam control relies on manual operation via uplink
  - The bending accuracy is not sufficient due to its flexibility
  - A nonholonomic system
  - Not easy to control the tip position
- The subject of imaging is a spacecraft ▸ Looks like a selfie.

Solution

- Localization
  - Estimates the position of the camera section at the tip of the beam relative to a spacecraft
  - Examples of use in autonomous car
- Routing
- RGB-Depth Camera

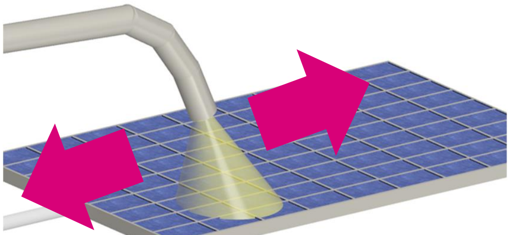


Fig.22 Localization

5 Conclusion and Future Prospects

Conclusion

- Targets for in-situ observation : 0.5mm ~ 1mm
- Proposed a new robot for in-orbit observation of micro debris impact marks
- Design and evaluation experiments of various subsystems
- To automate detection, we developed SCAN-2, which applies object detection
- SCAN-2 succeeded in autonomously observing solar arrays and impact marks
- SCAN-2 is capable of near real-time observation
- A coordinate estimation system and database were built.
  - Possible application to continuous observation of debris with no omissions

Future Prospects

- Develop MBD-4（Improved MBD-3 with RGB-Depth camera)
- Complete developing localization system
  - 3D control of flexible beams linked to observation
    - Full automation of the entire system

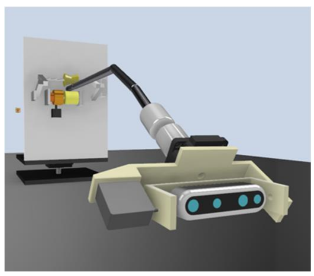


Fig.23 MBD-4
with RGB-Depth camera