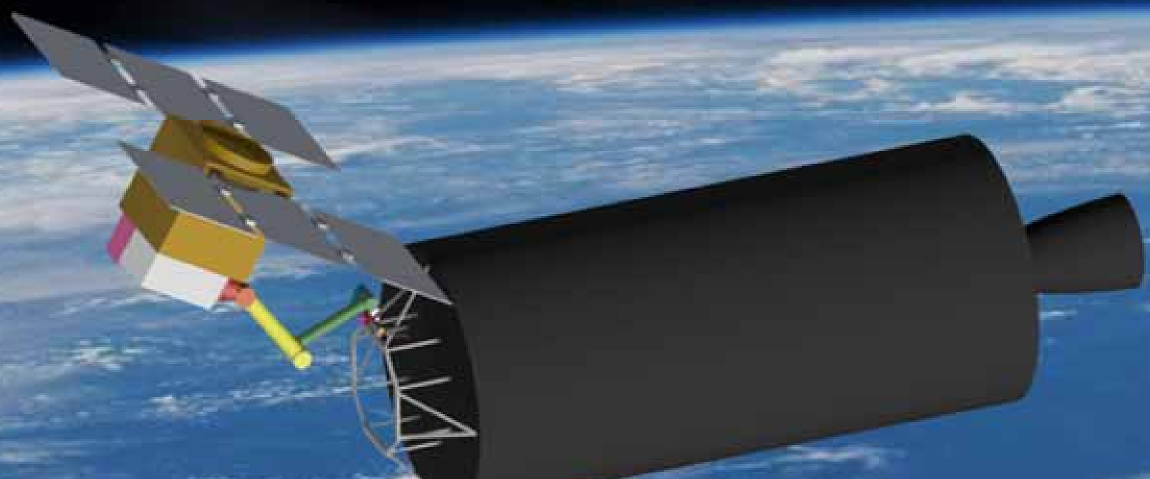
押し付け動作のみでの把持を実現する トラス構造把持エンドエフェクタの研究

An end-effector for gripping truss structures requiring only a pushing motion



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Naoki KAWAGUCHI
Keisuke TAGA
Tokyo Institute of Technology

Astrodynamics Symposium 2022. July 25

Index

- Background and Purpose
- Design Concept & Development
- Performance evaluation
- Conclusion

Background

- The number of spacecraft is increasing

Demand for **On-Orbit Services** is also increasing

Repair and Inspection

Refueling

Space debris removal

- Required technologies for

On-Orbit Services

Approach

Motion estimation

Capturing & Grasping

- Mechanism design
- End Tip Control

etc…

The establishment of technology is essential

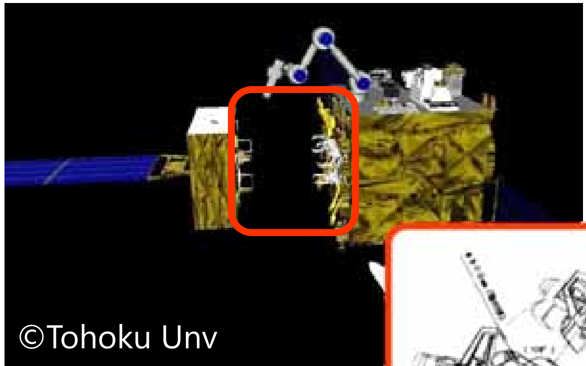
Non-cooperative targets

- Cooperative docking mechanism

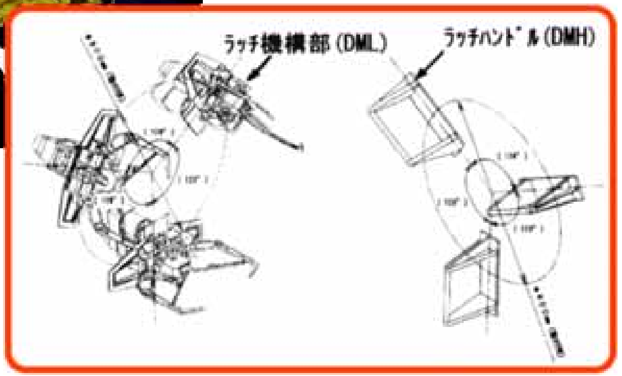
：6-DOF constraint mechanism using paired geometries

Non-Cooperative:

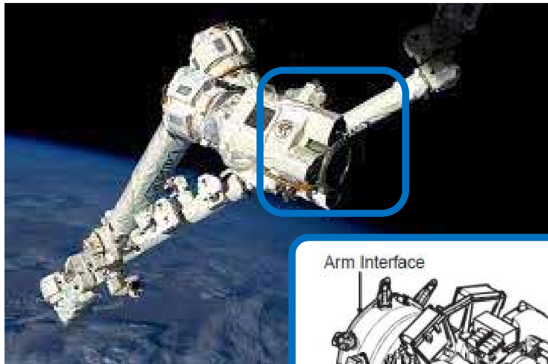
- Losing control
- No target marker
- No cooperative docking mechanisms



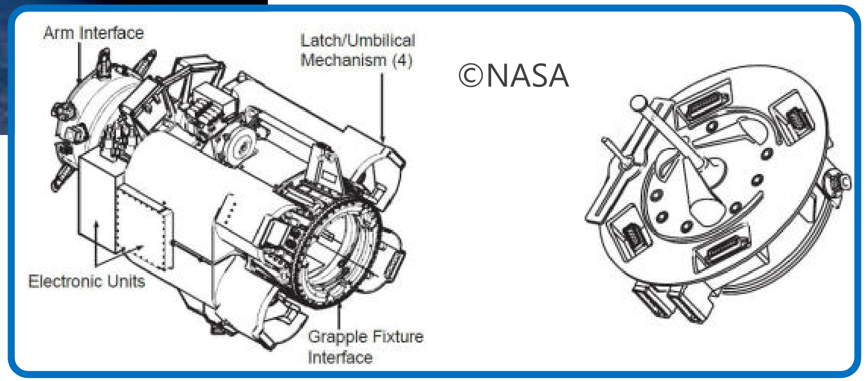
ETS-VII



Docking Mechanism



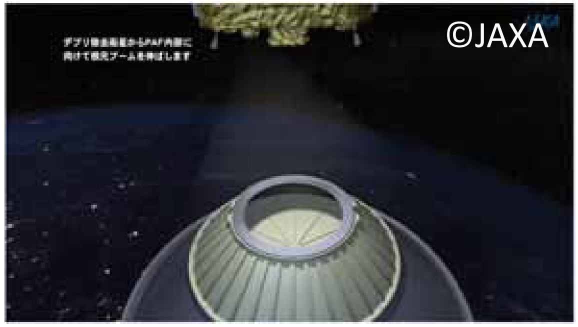
SSRMS



Latching End-Effector　　Grapple Fixture

- Targets of On-orbit services： **Non-cooperative**
  - Debris and existing satellites don’t have **cooperative docking mechanism**

Previous research on non-cooperative mechanisms



JAXA PAF capture concept ©JAXA

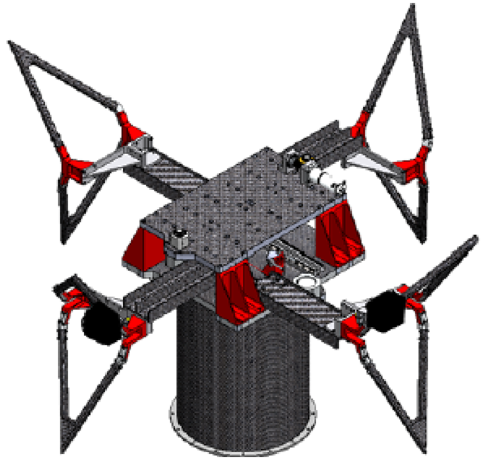


Figure 10. CAD image of HKK

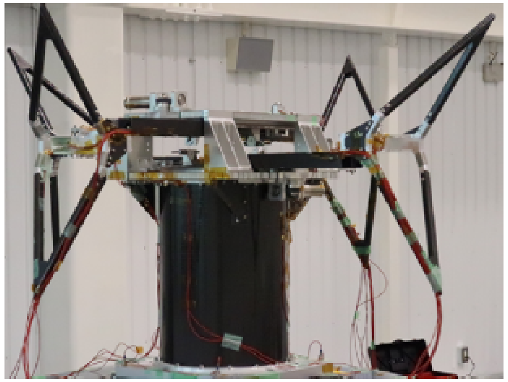
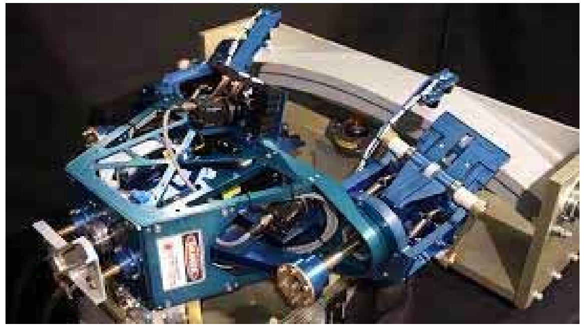


Figure 11. image of developed HKK

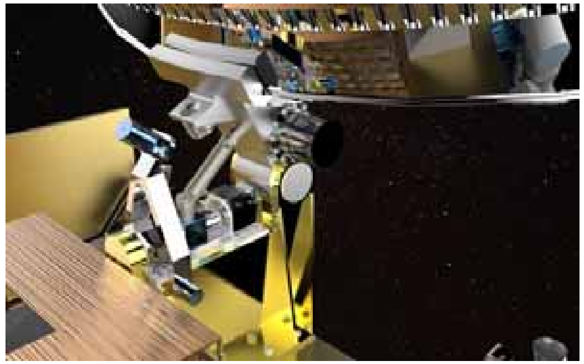
HKK©JAXA

©NASA

Gecko Gripper ©NASA On robot



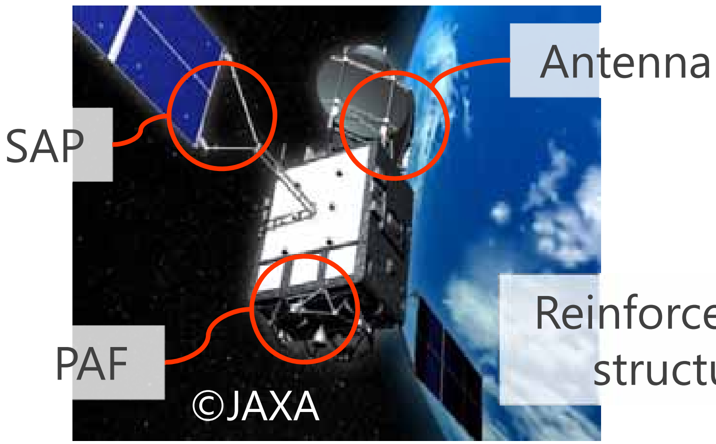
LAR Capture Tool ©MDA

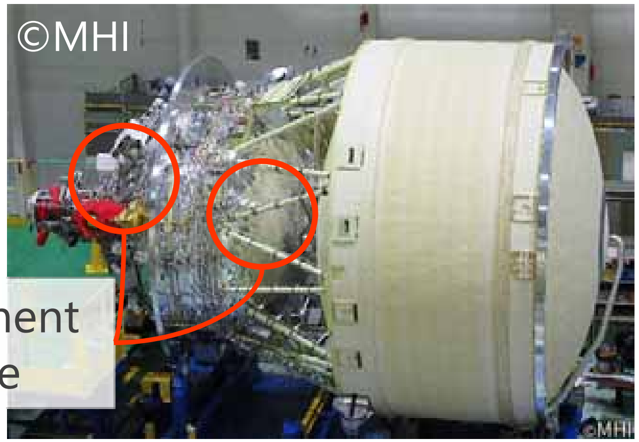


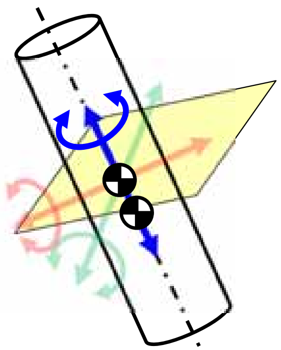
SENER's clamping mechanism ©ESA

Capture targets

- Target parts: Truss structure
  - Trusses are used in various parts of the spacecraft.
  - Geometric constraints of up to 4 DOF for a single cylinder







4-DOF

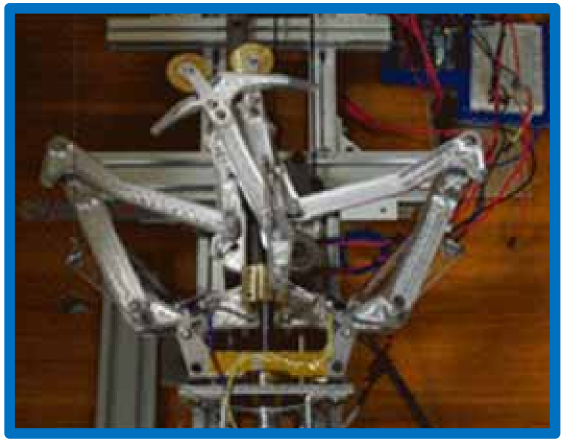
Our research group is developing **“Low Contact Force grasping Hand (LCFH)”** for cylindrical structures.

Low Contact Force Grasping Hand

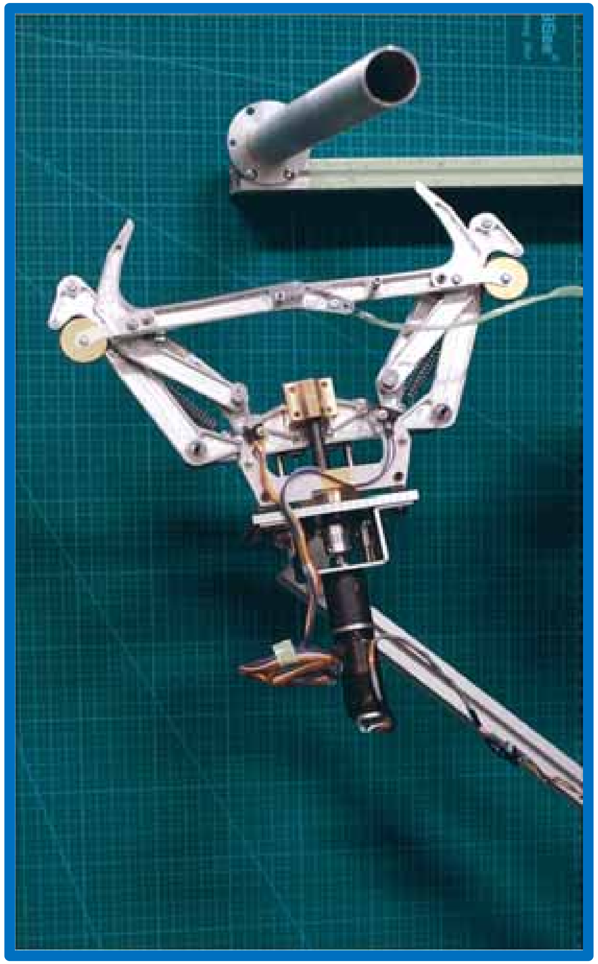
- Features
  - Low contact stiffness and Quick capture

So, Grasping is possible by pushing away against the cylindrical structure

  - Position and attitude errors can be tolerated.
  - Retry motion available
  - Electric actuator-less



Retry motion



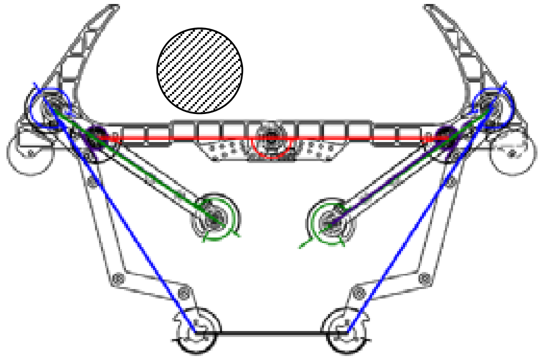
Approach and capture motion (LCFH-1)

Each state of the LCFH's grasping claw unit

Nakanishi Lab

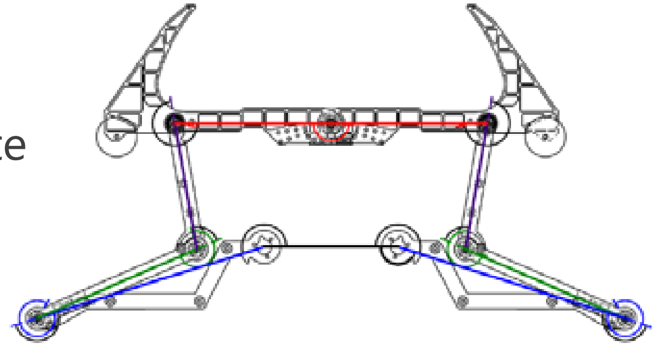
- ## Waiting state

: Before contact with target



- ## Return state

: Return to Waiting state



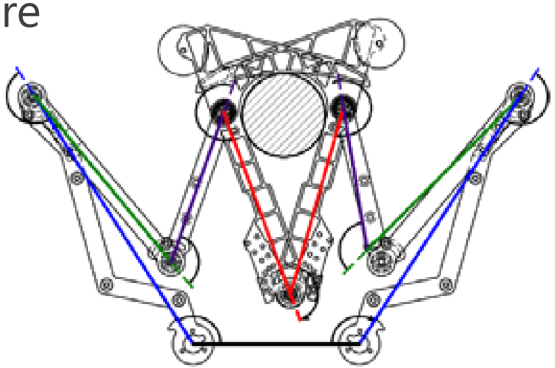
Rotate motor

Contact

Reverse motor

- ## Caging state

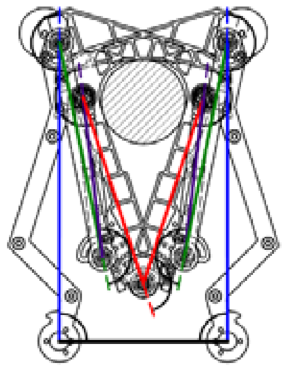
: Geometrical enclosure around a target



Rotate motor

- ## Fixed state

: High gripping by an actuator



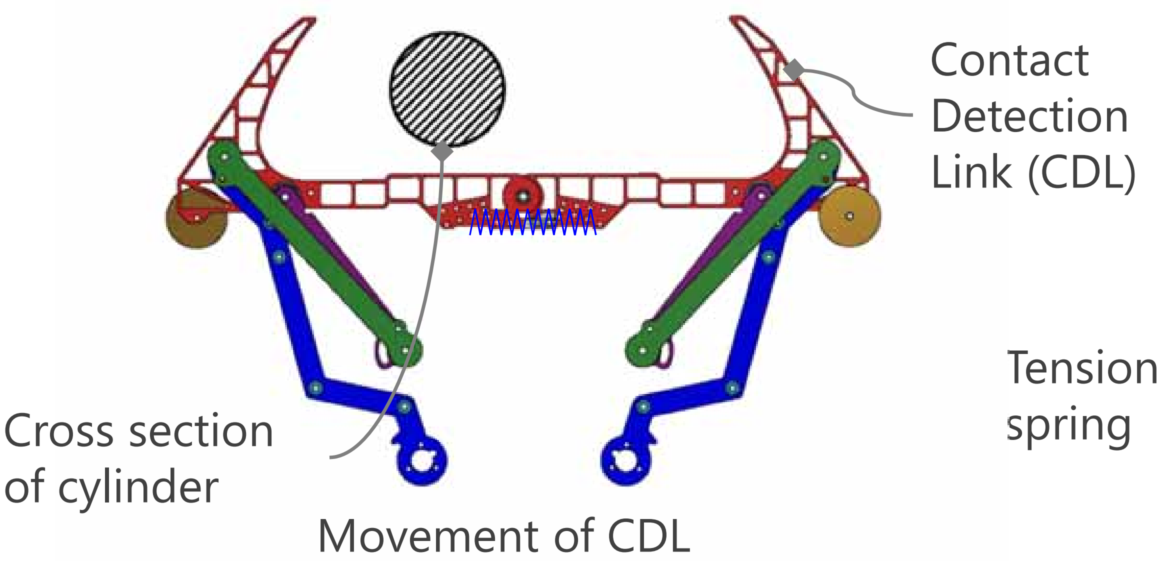
Movement of Grasping claw unit

Nakanishi Lab

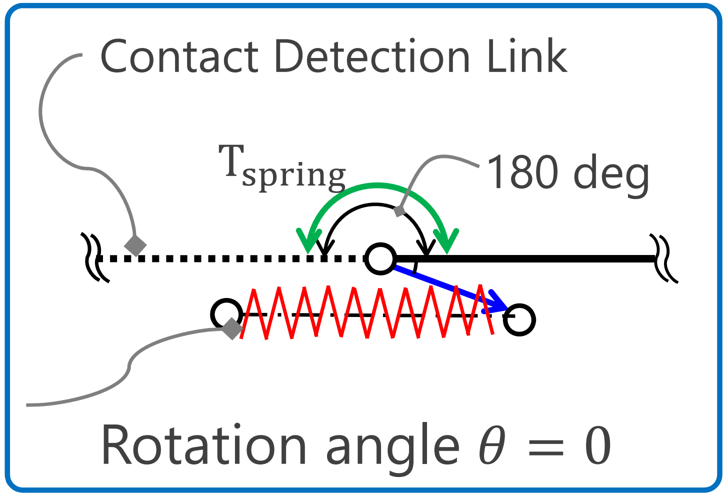
- **Waiting state to Fixed state**

CDL: contact detection link

1. CDL is held in mechanical singularity by the stopper and spring.
2. Cylinder contacts CDLs and displacement occur.
3. Direction of the torque is reversed and the CDLs are closed.
4. Enclosure possible.
5. The motor drives the linkage and become Fixed state.



Movement of CDL



Schematic diagram

Waiting state to Fixed state

CDL: contact detection link

1. CDL is held in mechanical singularity by the stopper and spring.
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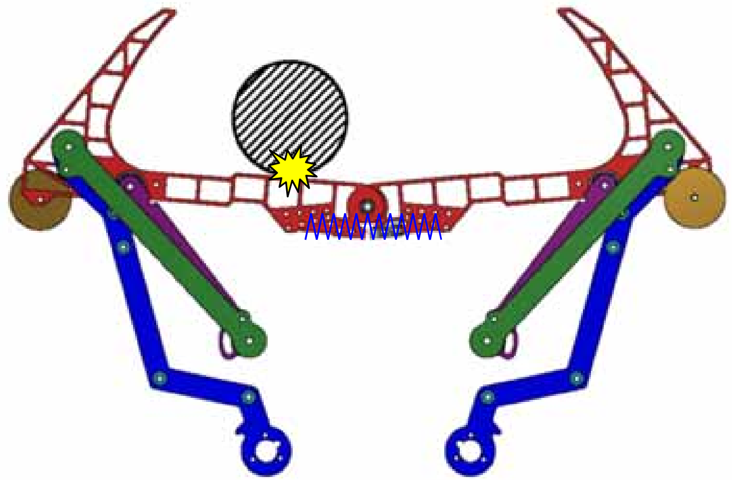
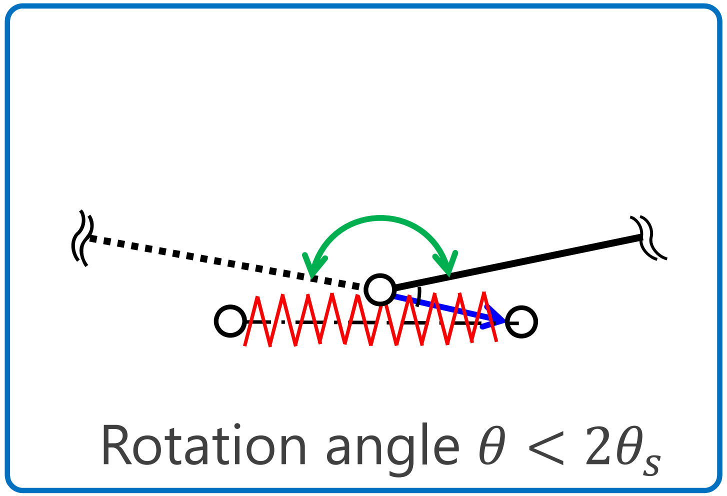


Movement of CDL



Schematic diagram

Movement of Grasping claw unit

Nakanishi Lab

- Waiting state to Fixed state

CDL: contact detection link

1. CDL is held in mechanical singularity by the stopper and spring.
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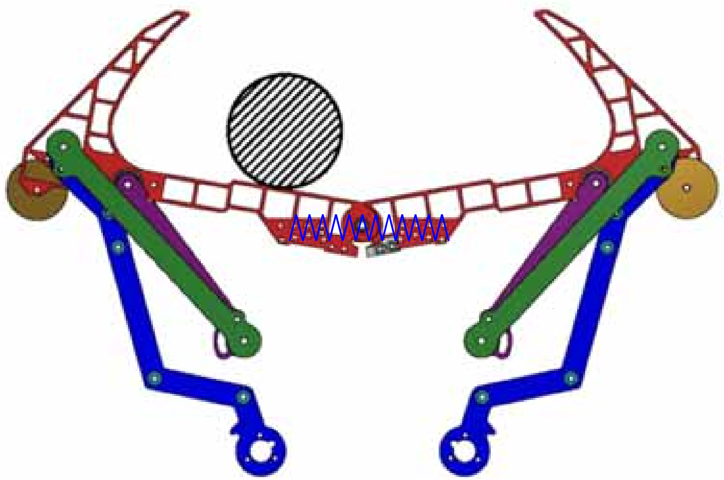
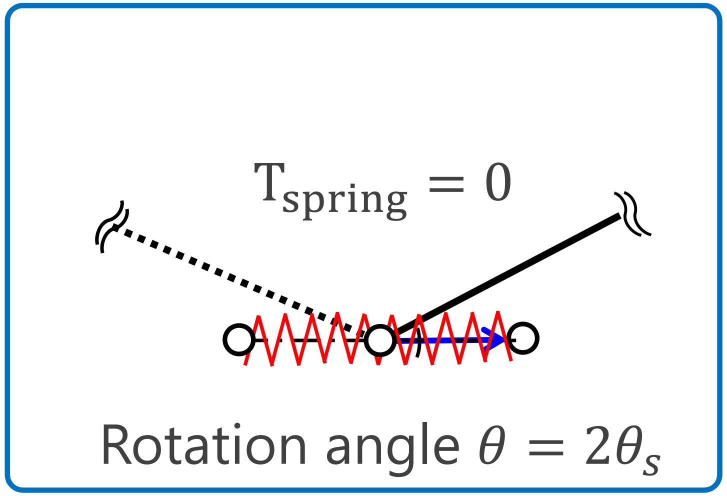


Movement of CDL



Schematic diagram

Movement of Grasping claw unit

Nakanishi Lab

Waiting state to Fixed state

CDL: contact detection link

1. CDL is held in mechanical singularity by the stopper and spring.
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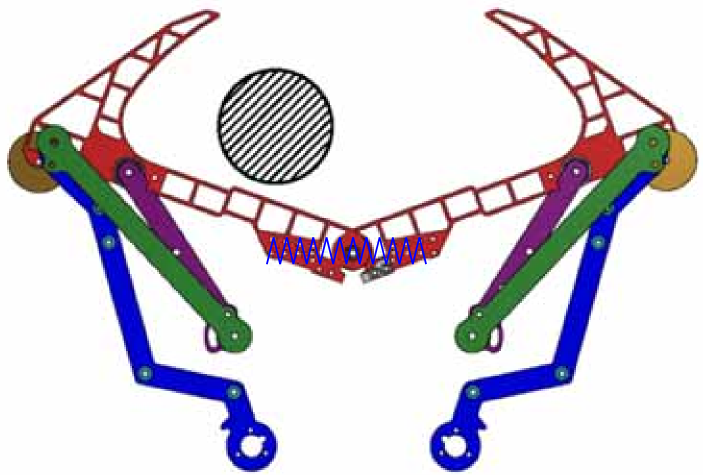
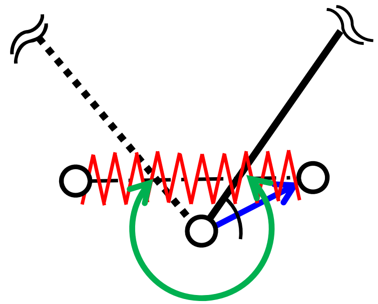


Movement of CDL



Rotation angle $\theta > 2\theta_s$

Schematic diagram

Movement of Grasping claw unit

Nakanishi Lab

● Waiting state to Fixed state

CDL: contact detection link

1. CDL is held in mechanical singularity by the stopper and spring.
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3. Direction of the torque is reversed and the CDLs are closed.
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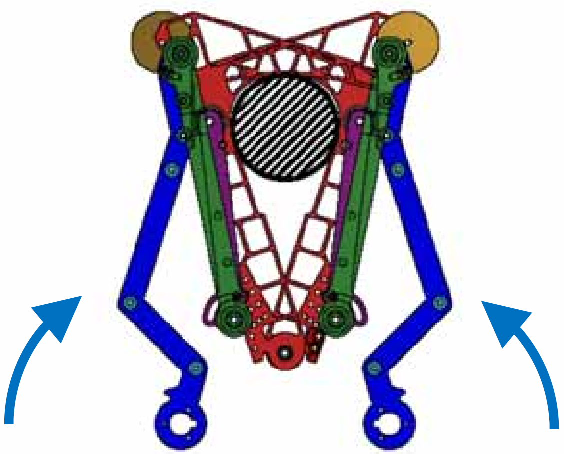


Movement of CDL

Basic Specification

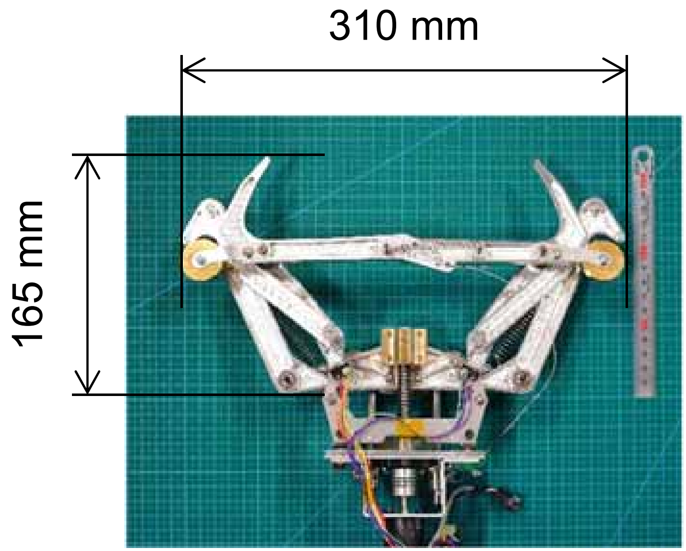
Size (w/o separate mechanism):
310mm x 165mm x 50mm

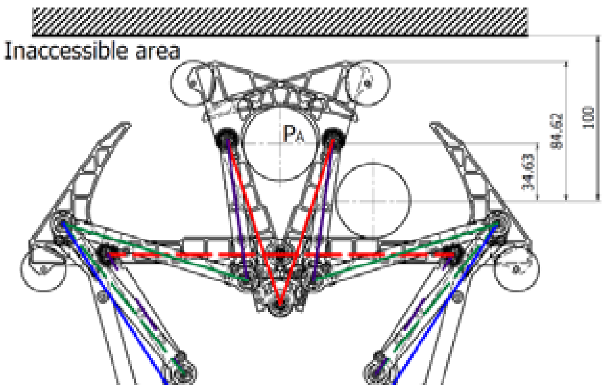
Weight (w/o separate mechanism):
458g

Required clearance to inaccesible area:
100mm

Acceleration capacity (before capture motion):
9.8m/s^2

Load tolerance (after capture):
> 110N



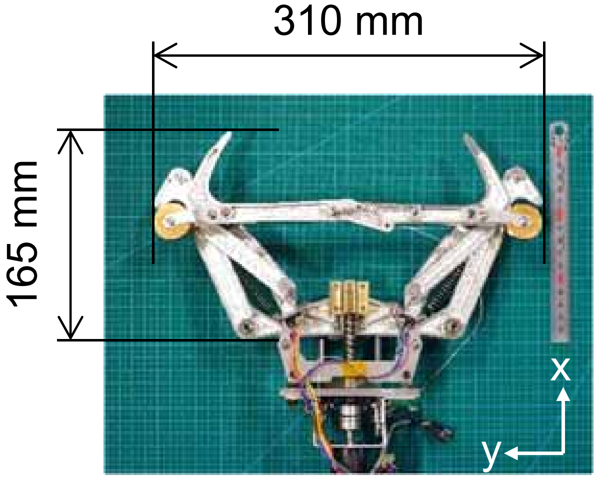


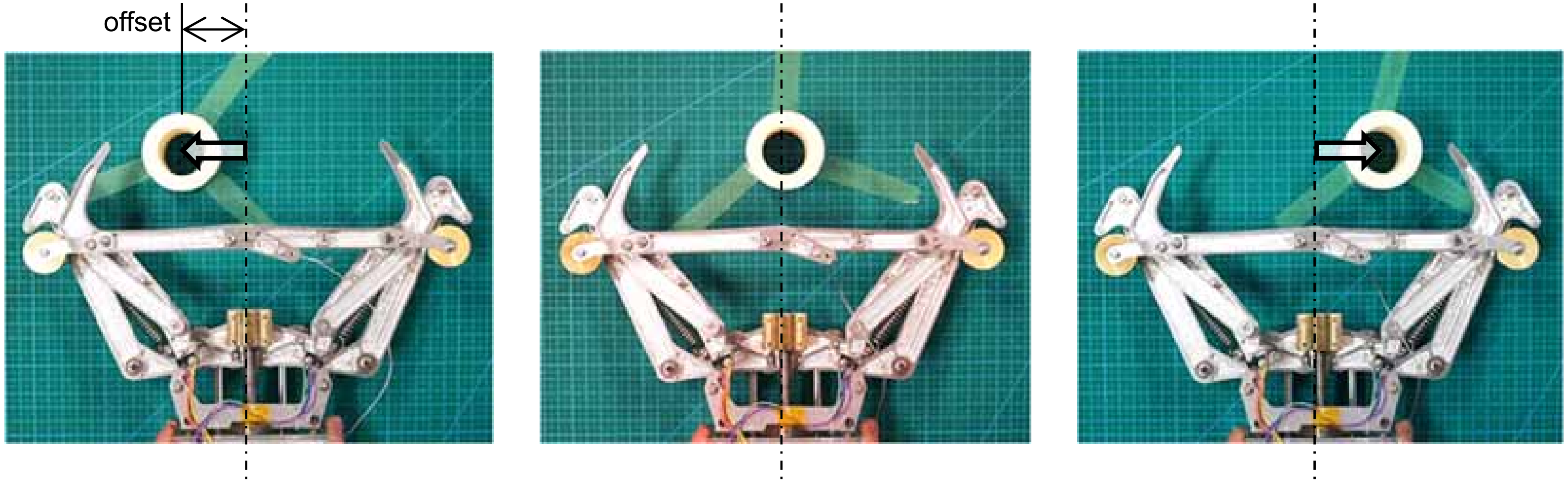
Capture capability

Nakanishi Lab

Misalignment capability

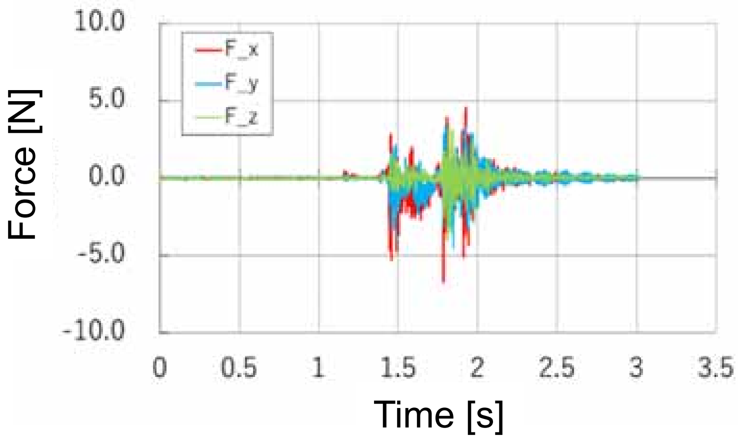
Target diameter: 30〜60mm
Target Offset: ±50mm，±5deg (roll, pitch, yaw)

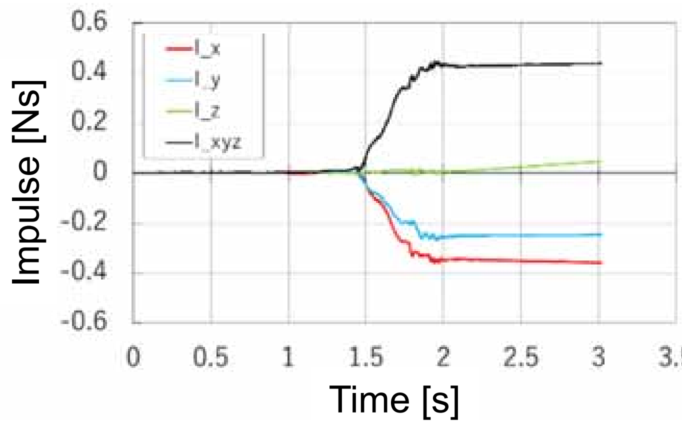




Initial Contact force

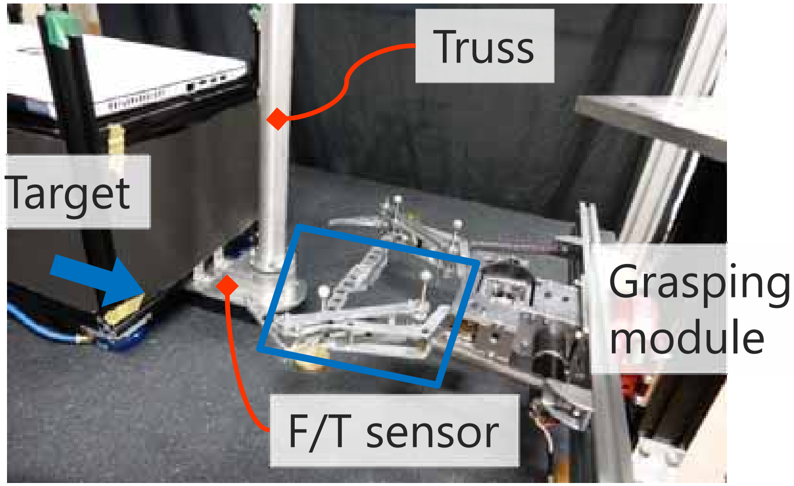
Target diameter: 60mm
Target Offset: S_D 50mm



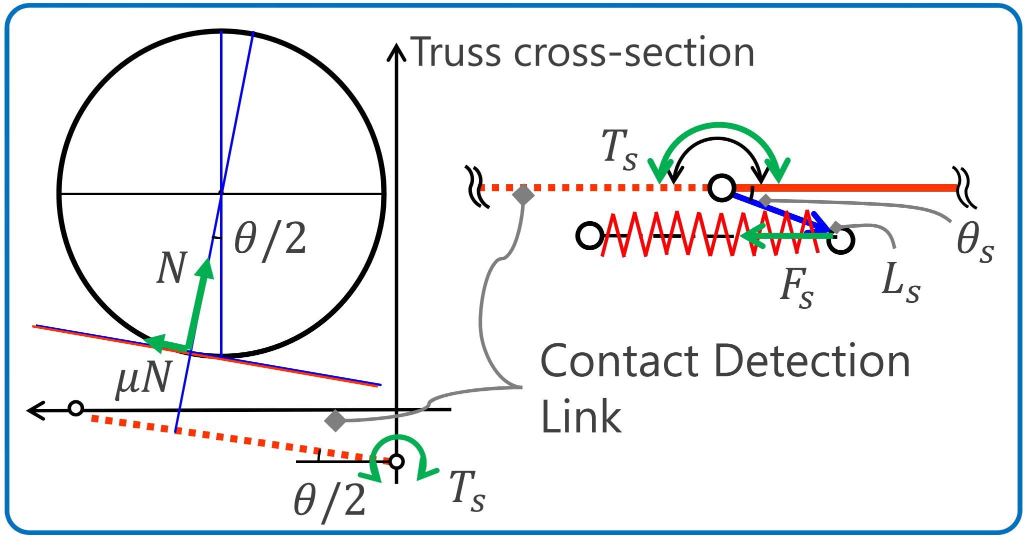


Dynamics collation ①

- Purpose: To evaluate the model of the mechanism by experiment and analysis
- Method:
  - Collision of a target in 2D microgravity
  - Calculate the target motion, joint displacement, and force when push away



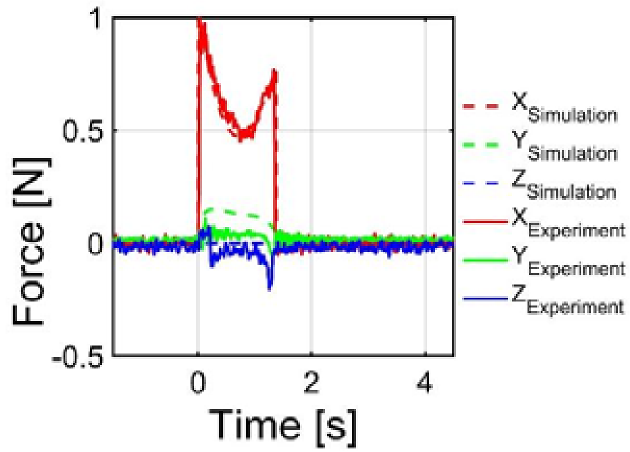
Microgravity experimental setup

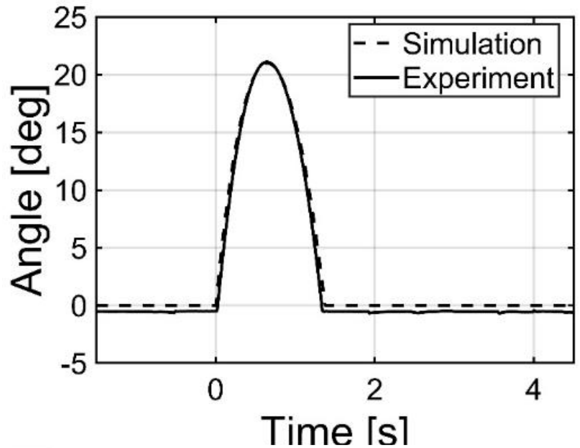


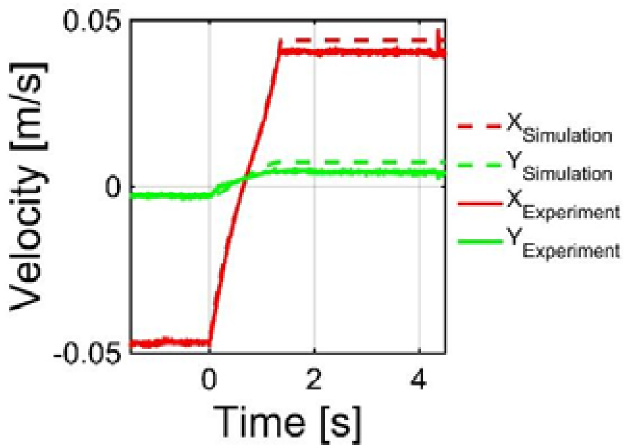
Model in contact with truss

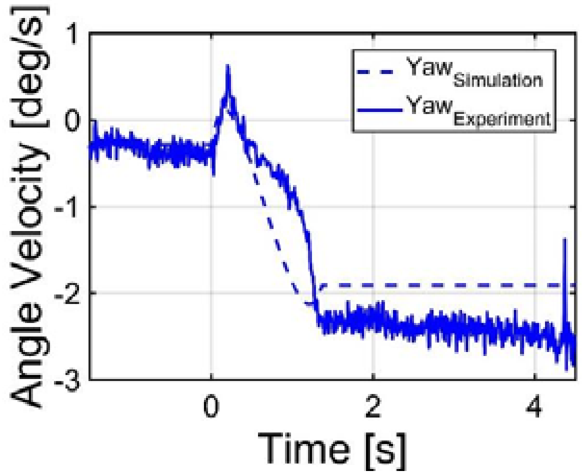
Dynamics collation ②

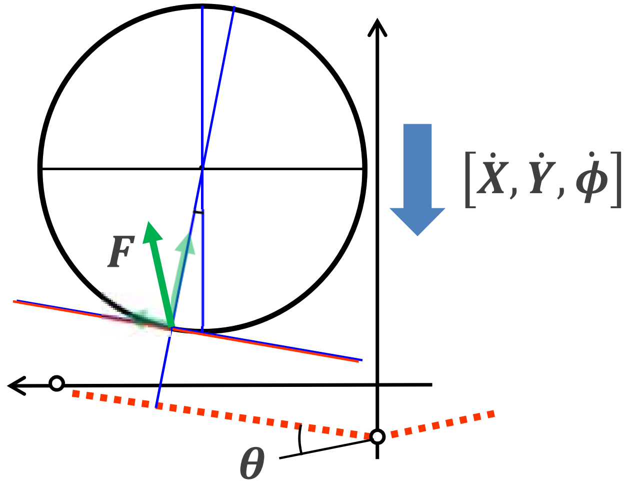
- Result







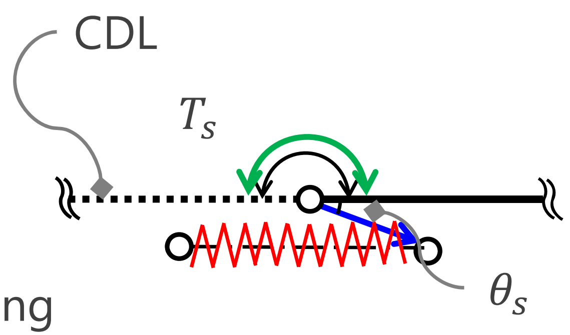




Experiments show that the collision model is valid.

Considerations from Collision experiment

- Purpose: Evaluate the success of the grasping motion with the required work
  - External work is applied that exceeds the elastic energy of the spring



- Elastic energy threshold W_s

$$W_s = \int_0^{2\theta_s} T_s \, d\theta + D$$

θ_s: Mounting angle of tension spring
T_s: Torque by tension spring
D: Dissipated energy

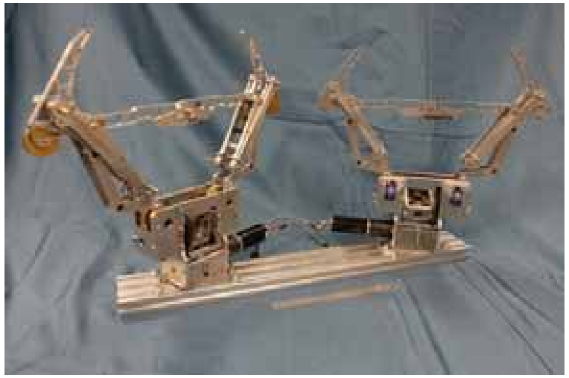
- Relative kinetic energy of EE and target W_k

$$W_k \leq \frac{1}{2} m_t (\boldsymbol{v}_E - \boldsymbol{v}_t)^T (\boldsymbol{v}_E - \boldsymbol{v}_t)$$

$\boldsymbol{v}_E$: EE velocity
$\boldsymbol{v}_t$: Target velocity
m_t: Target mass

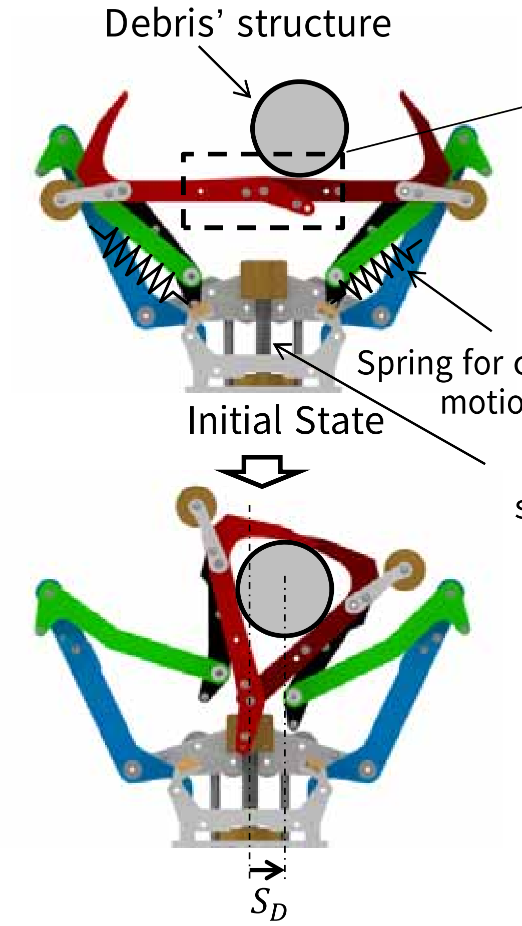
Low Contact Force Grasping Hand

Nakanishi Lab

	LCFH-1	LCFH-2	LCFH-3
Purpose	● Space debris removal (using EDT*) * Electrodynamic tether	● Space debris removal (using thruster)	● Refueling ● Repair etc…
DOF	Geometric 2	Geometric 4+friction 2	Geometric 6
Appearance			

LCFH-1

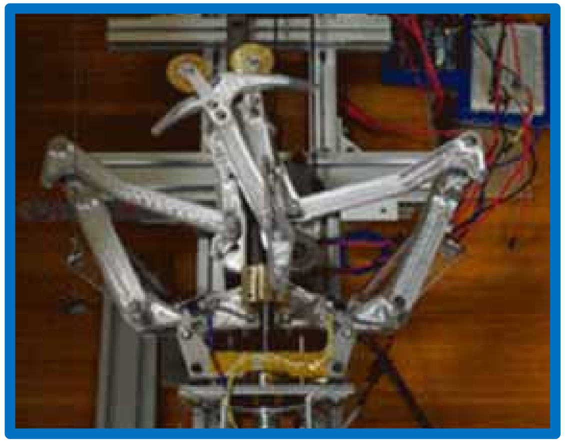
For Space debris removal (using EDT)



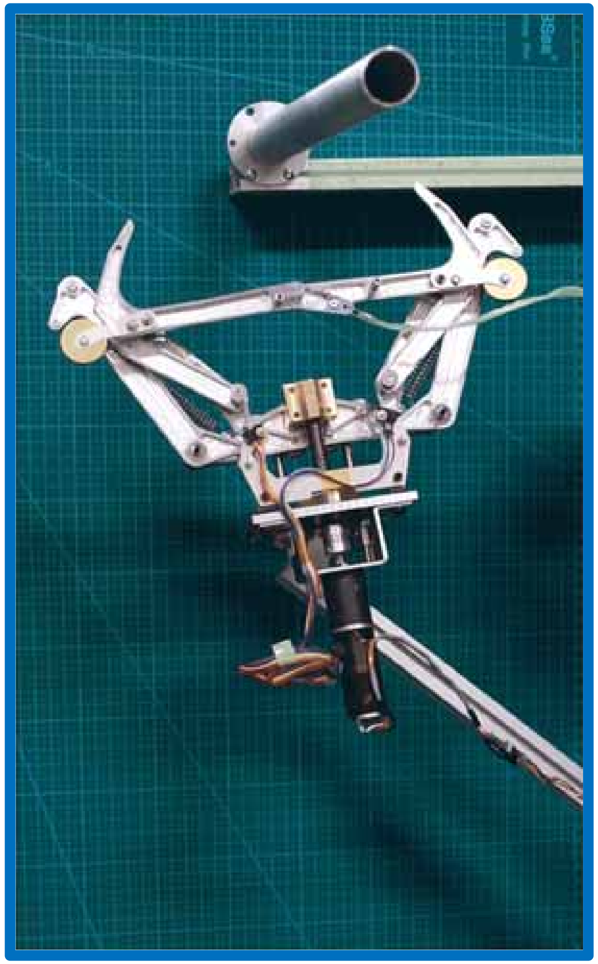
Singularity of the link maintains the gripper state

When the debris contact with this point, the singularity is broken and the capture motion is started by spring.

EDT ©JAXA



Reset motion to initial state



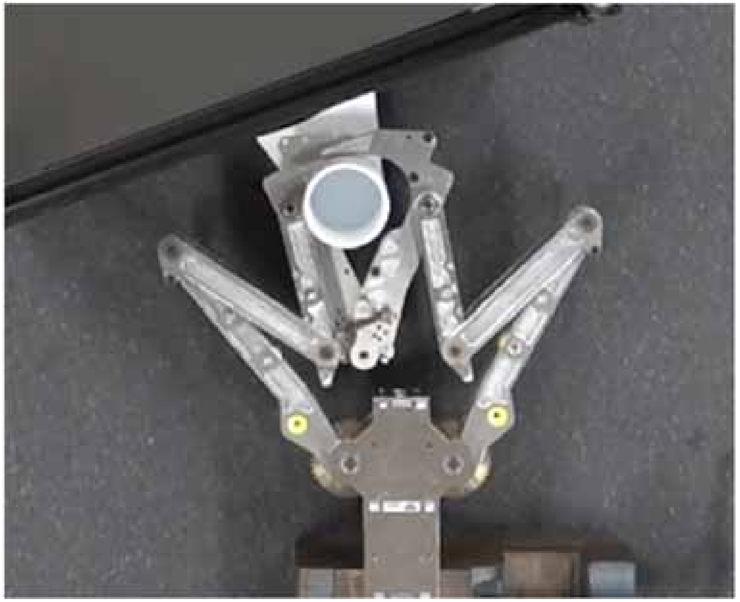
Capture motion

LCFH-2

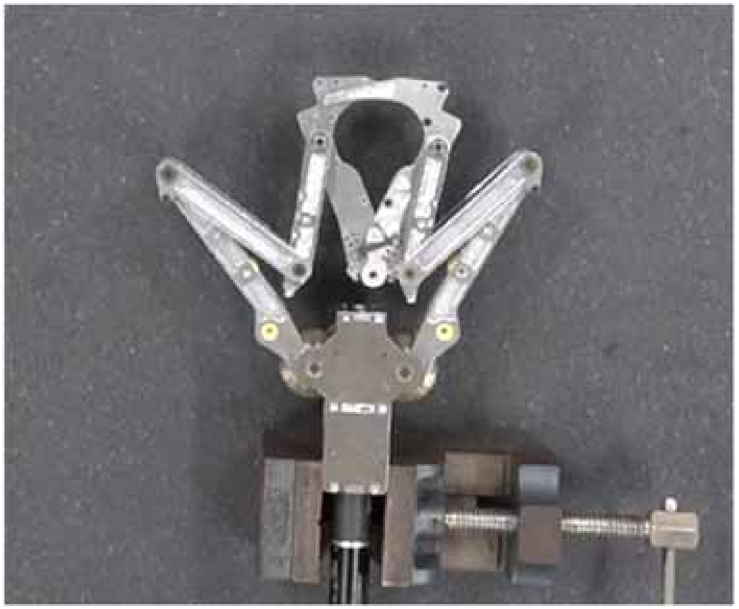
Nakanishi Lab

● For Space debris removal (using thruster)

Contact detection and enclosure



Grasp and tighten

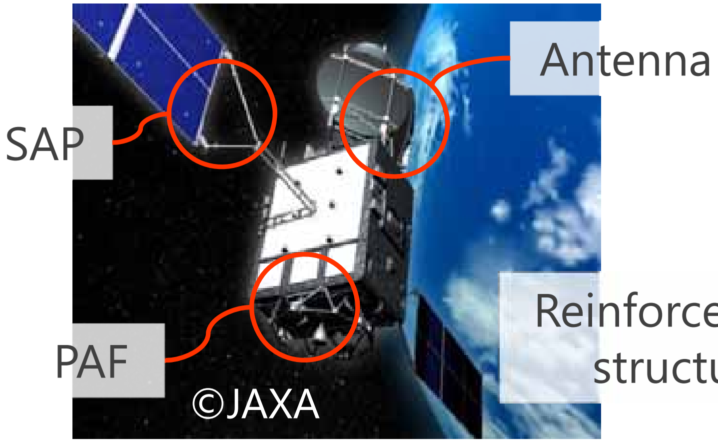


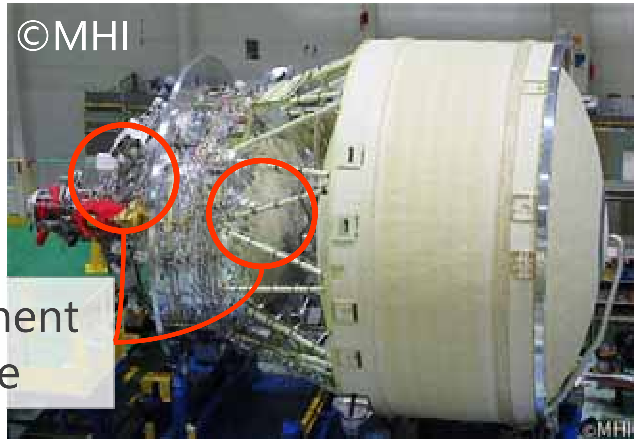
Return to initial state

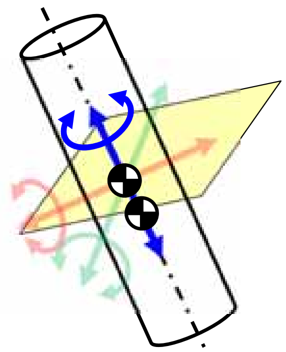
Concept of LCFH-3

Nakanishi Lab

- Target parts: Truss structure
  - Trusses are used in various parts of the spacecraft.
  - Geometric constraints of up to 4 DOF for a single cylinder



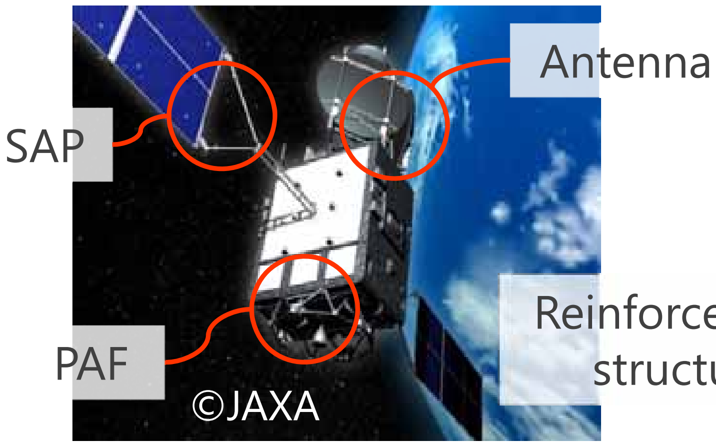


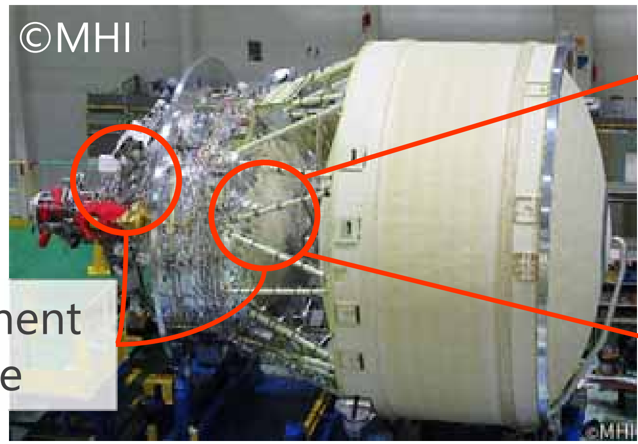


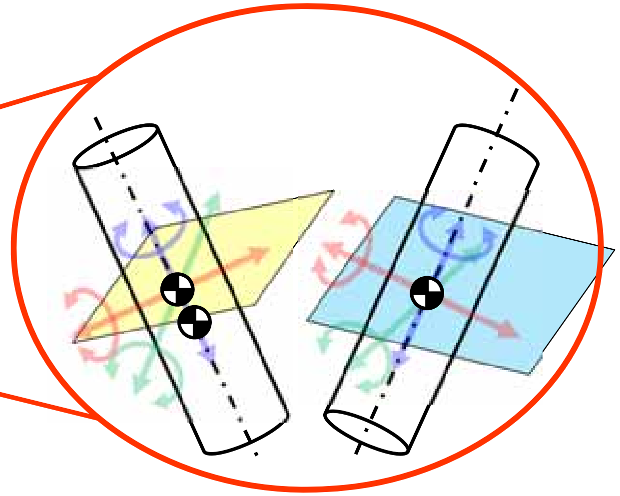
4-DOF

Concept of LCFH-3

- Target parts: Truss structure
  - Trusses are used in various parts of the spacecraft.
  - Geometric constraints of up to 4 DOF for a single cylinder
  - **6-DOF constraint is possible by using a V-shaped intersection**







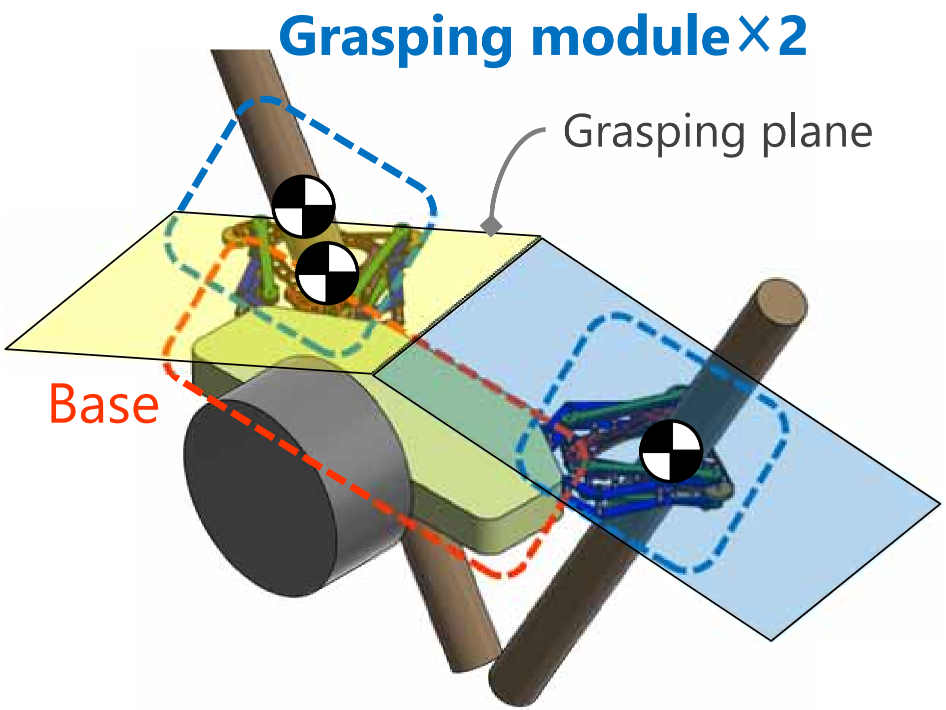
Design a mechanism to capture V-shaped structures using LCFH

6-DOF constraint is possible with 3 or more constraint points

Conceptual study of the grasping system

- Proposed grasping method:

2 cylinders of the truss are fixed by symmetrically placed fingers.



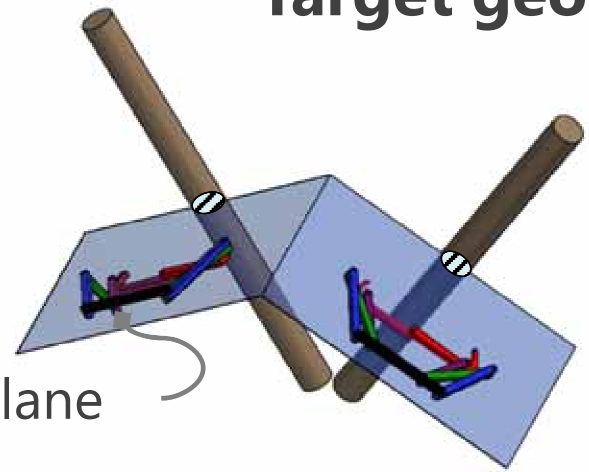
Proposed Grasping Method

it is impossible to use the LCFH as-is for the Grasping module.

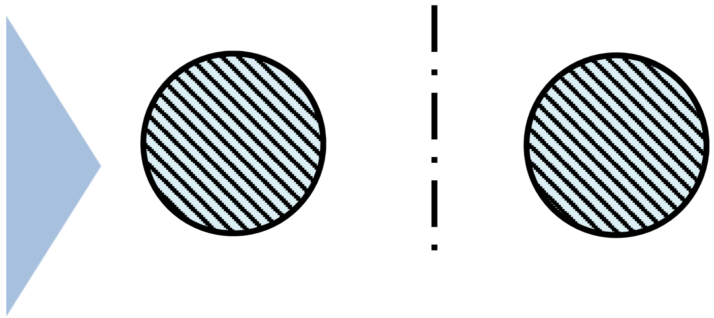
Grasping module Design Problem

- Problem：Position and attitude error results in different Truss cross-section of Grasping plane

Target geometric relationship



Grasping plane



Truss cross-section

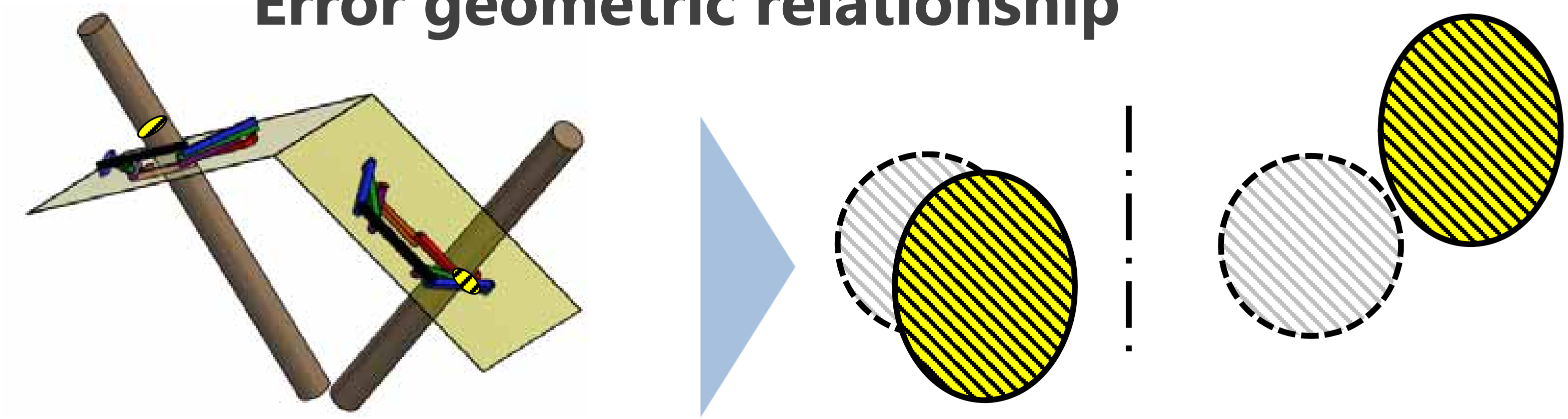
- Fixing motion of LCFH-1,2 causes relative motion to the truss.
- Fixation must be adapted to the **position and shape** of cross section

Underactuated grasping is needed to match the position and shape of the Truss cross-section

Grasping module Design Problem

- **Problem：** Position and attitude error results in different Truss cross-section of Grasping plane

Error geometric relationship



Truss cross-section

  - Fixing motion of LCFH-1,2 causes relative motion to the truss.
  - Fixation must be adapted to the **position and shape** of cross section

Adaptive grasping is needed to match the position and shape of the Truss cross-section

Design requirements for end-effectors

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- Design requirements from robotic satellite systems

Requrement	Design value
Relative position and attitude error tolerance	• Position error: ±10 mm • Attitude error: ±1.0 deg • **Adaptive grasping** required
Continuous gripping and fixation	• when no voltage is applied • **High gripping force** and no back-drivability

Both **Adaptive grasping** and **High ripping force** are required.

Design of Grasping module

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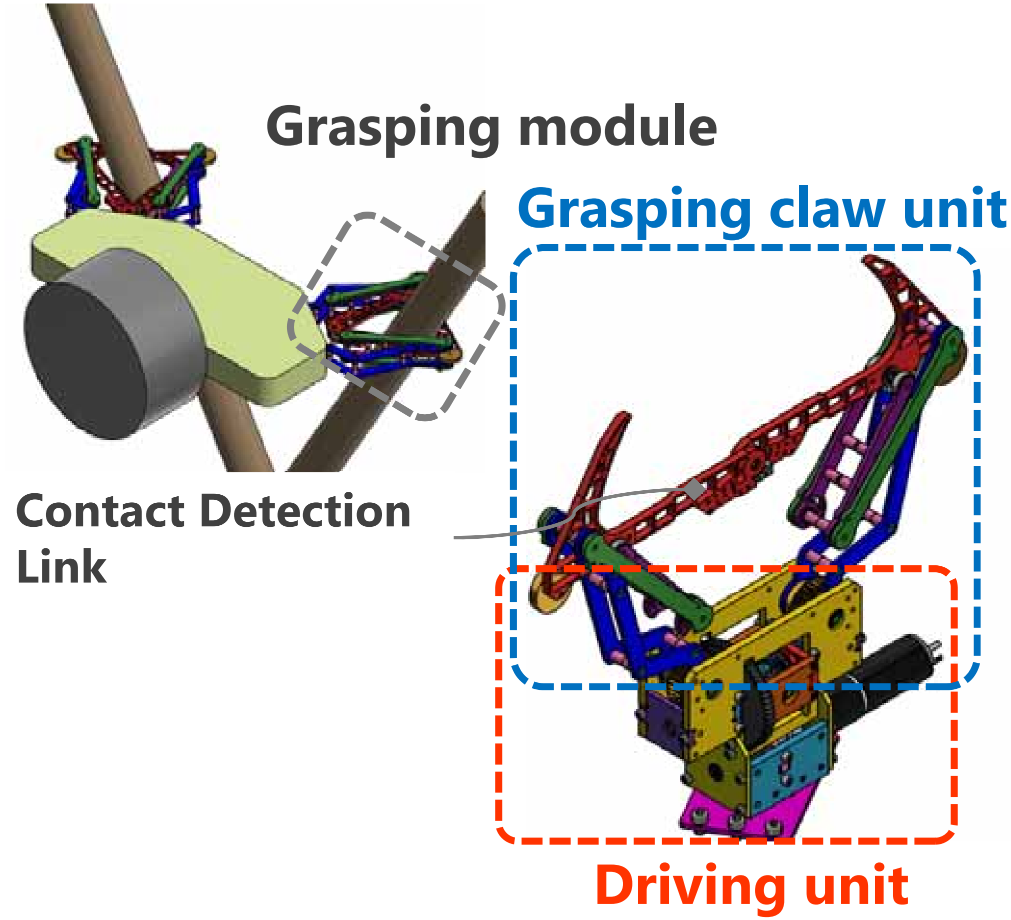
Grasping module consists of **Grasping claw unit** and **Driving unit**



Grasping claw unit

Design based on LCFH

- Low contact stiffness and Quick capture
- Position and attitude errors can be tolerated.
- Retry motion available

Driving unit

Design in a new way

- Adaptive grasping and High gripping force

Driving unit configuration

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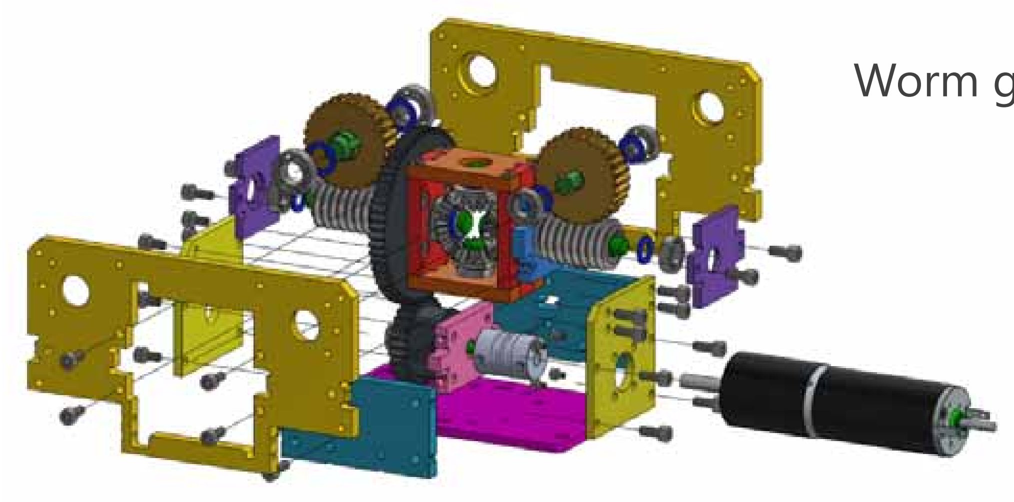
- **Adaptive grasping**

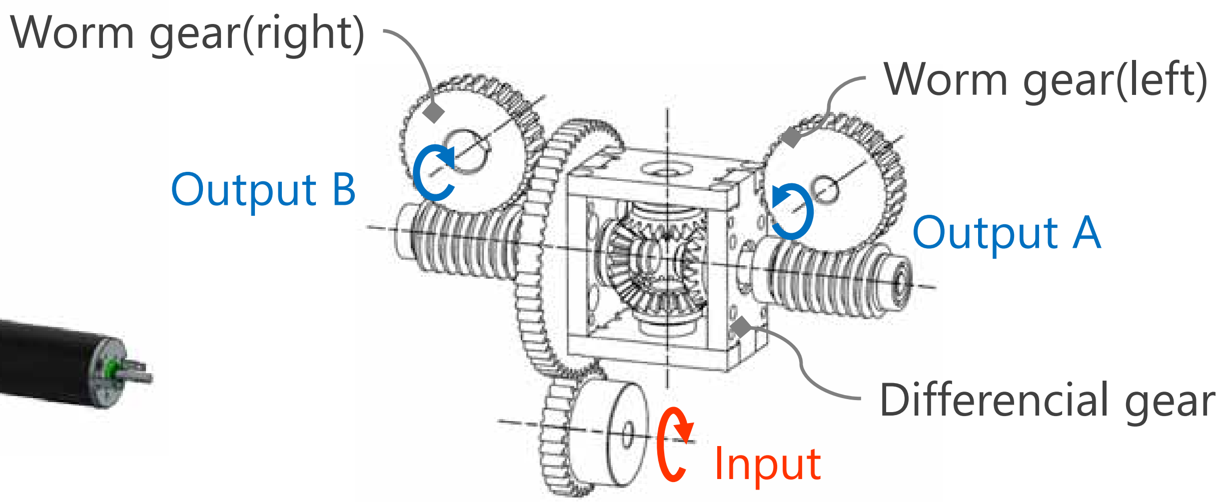
: **Differential gear** makes 1 input into 2 outputs. (underactuated mechanism)

- **High gripping force**

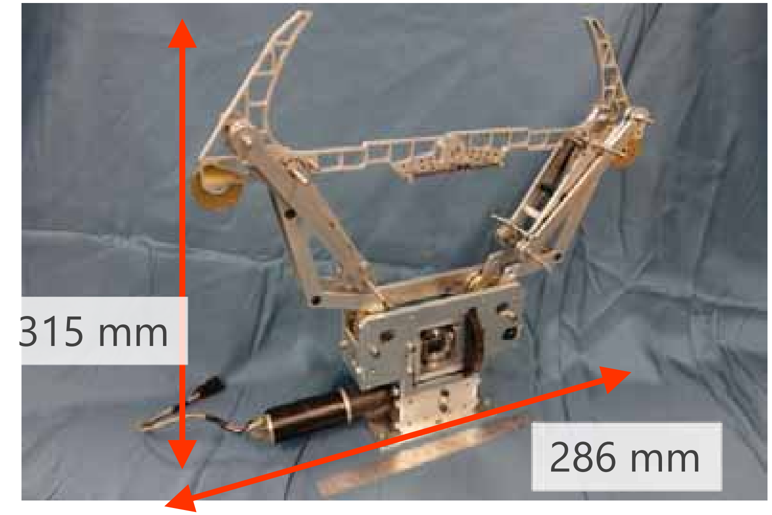
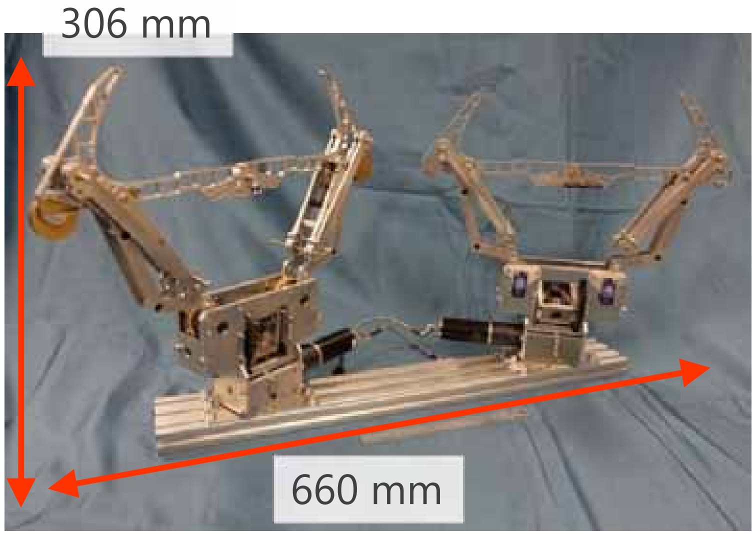
: Utilizes **Self-locking** of **Worm gear**.



Development drawing



Prototype specifications

	Grasping module	Entire system
Appearance		
Weight	1.5 kg	3.6 kg

Movement of Caging to Fixed state

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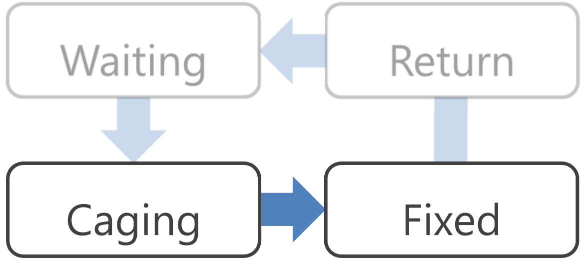
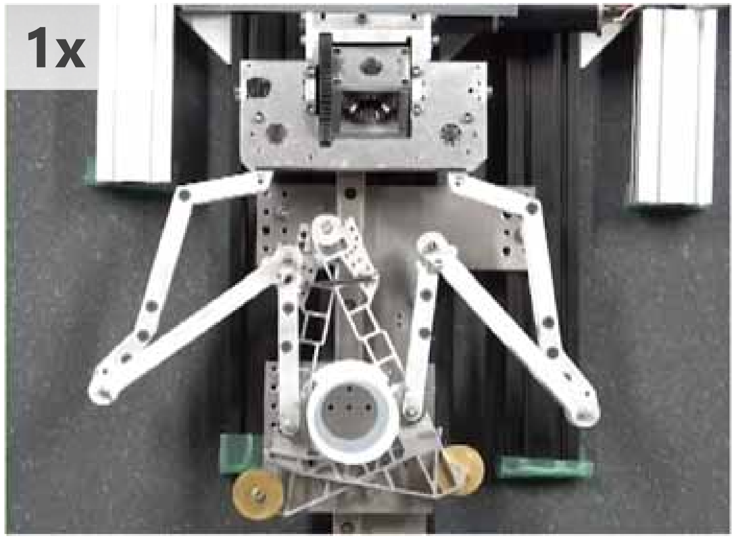
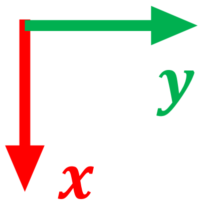
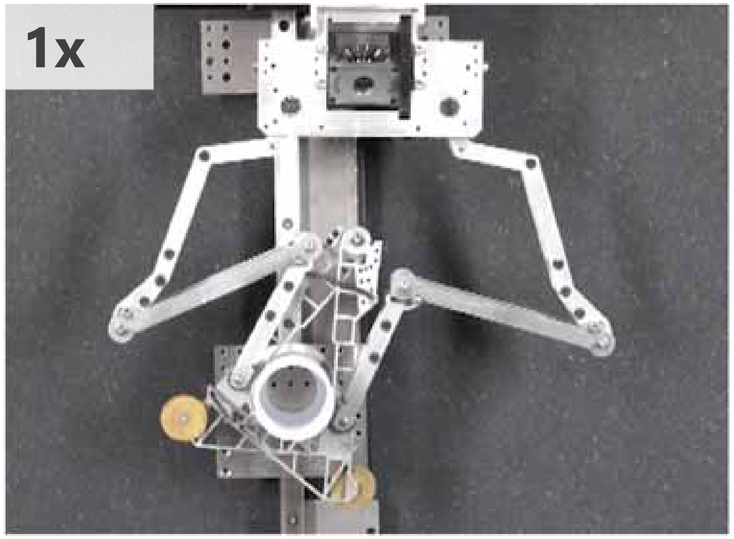
- Method: Grasping the cylinder on the linear guide
- Result:









Y-axis direction offset: 0 mm

Y-axis direction offset: 66 mm

Movement of Fixed to Waiting state

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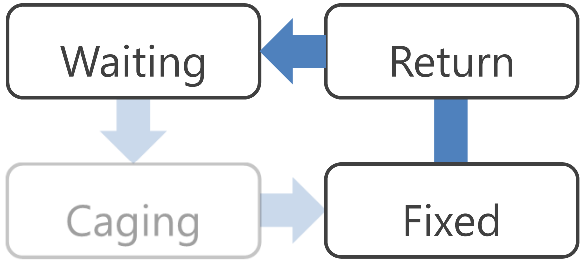
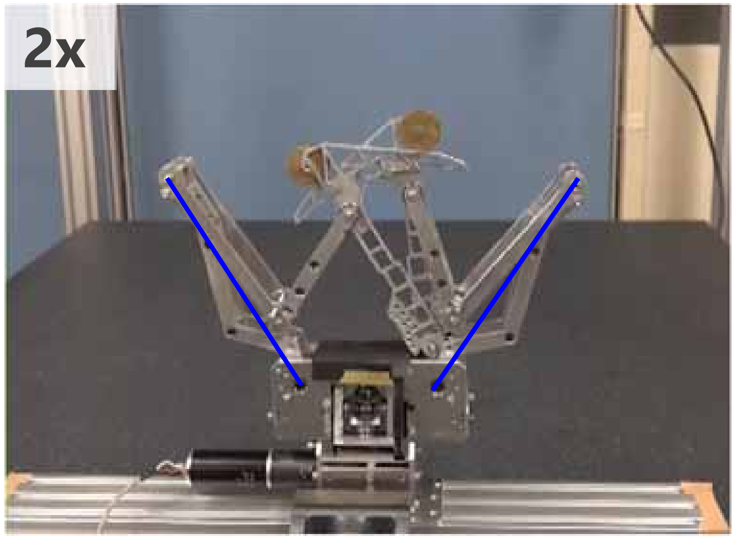
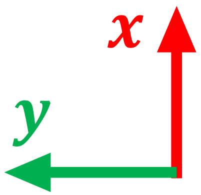
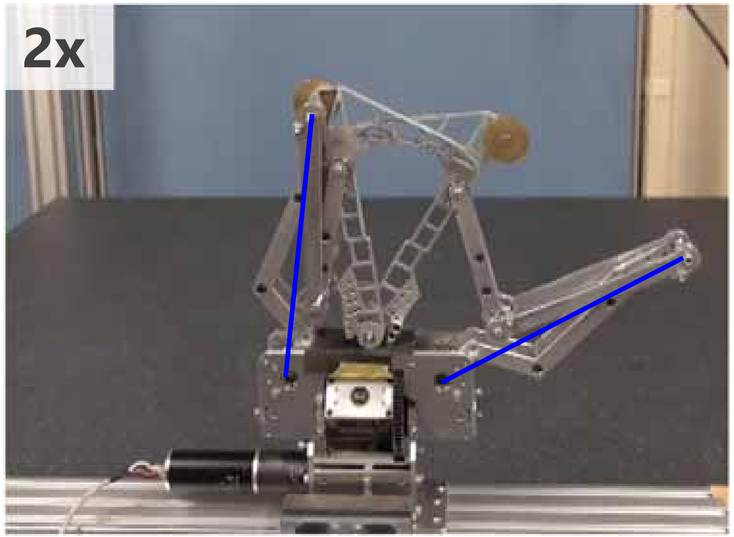
- Method: Under gravity environment
- Result:





Y-axis direction offset: 0 mm



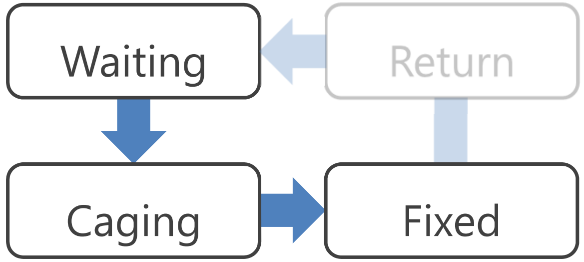


Y-axis direction offset: 66 mm

Movement of Waiting to Fixed state

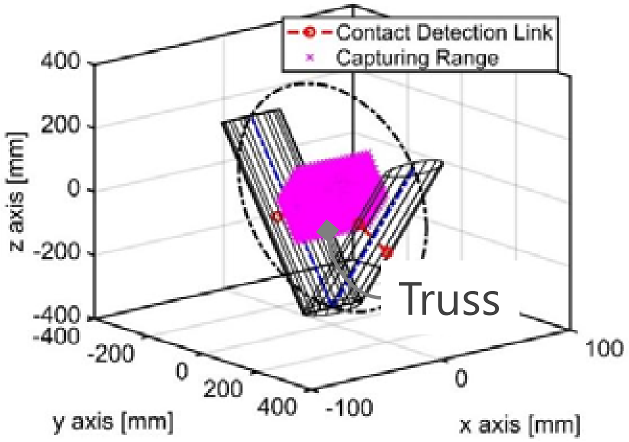
Nakanishi Lab

- Purpose: Concept experiment
- Method: Collision in 2D microgravity
- Result:

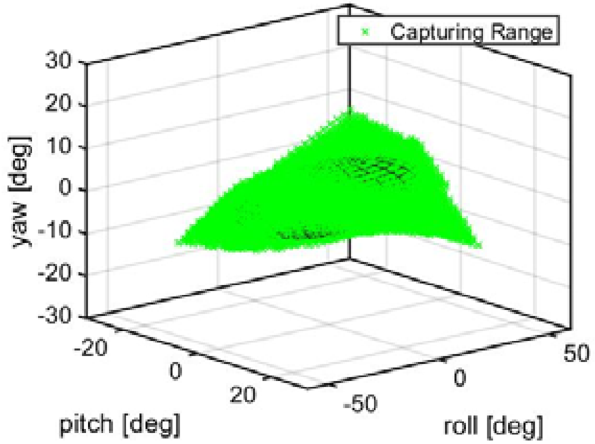


Tolerance region analysis

- Result



Position error area



Attitude error area

Axis	Maximum permissible error	Satellite endpoint accuracy
X [mm]	±27.5	±10
Y [mm]	±51.5	±10
Z [mm]	±89.2	±10
Roll [deg]	±42.5	±1.0
Pitch [deg]	±8.5	±1.0
Yaw [deg]	±8.5	±1.0

Satisfy the setting requirement value

Satellite system study can be performed based on the calculated values

Conclusion

- Proposed method and design requirements for 6-DOF constraint of the truss structure
- Clarified the design method of the grasping mechanism for the truss structure.
- Grasping by pushing away was shown to be possible.