C13

ADR 作業の為の非協力的ターゲット捕獲・把持機構の検討

A Study of Target Capture Device for Active Debris Removal

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能動的スペースデブリ除去（ADR）作業において，ターゲットの把持および，スラスタや EDT，デオービット膜といったデオービットデバイスの取付は重要なキーテクノロジーの一つである．これまでに確立されている軌道上サービス技術は全て，専用の被把持機構を備え，姿勢が安定化している「協力的」な作業ターゲットを前提している．一方 ADR の対象は「非協力的」なターゲットとなるため，これに対応できる捕獲・把持をできるだけ簡易な機構・制御で実現することが必要である．筆者らは，衛星やロケット上段の構造を利用する・または全体を包み込むことにより把持をした後，直ちにサービス衛星から切り離されることによりデオービットデバイス固定機構としても機能するデブリ把持機構について検討を進めている．本発表では，これまでの取り組みおよび最新の成果について報告する．

In order to realize the active debris removal (ADR), capturing debris and attaching a debris removal device (ex. micro thruster, EDT, and deorbit membrane) to debris is a key technology. Any space robot hands in existence cannot capture debris because they require their dedicated fixtures on the capture target. It is essential to establish a simple grasping system for the uncooperative target without such fixtures. The authors study such a grasping system that can grasp the original structure on debris or grasp its whole body. The system can also become a fixing mechanism for debris deorbit devices after separating from the service satellite (robot). In this presentation, the overview of our gripping systems and the latest issues are introduced.

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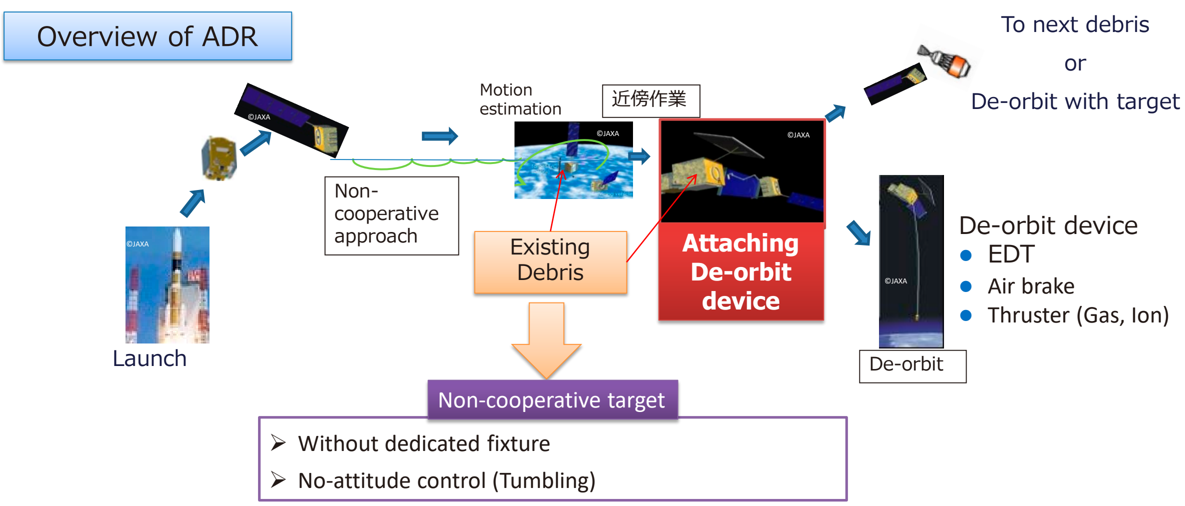
Space Debris WS (2020.Feb.26)

目次

- Background
- Research of capture mechanism for non-cooperative target
  - Debris wrapping system using bi-stable convex spring
  - Twining mechanism that mimics a plant
  - Low contact force truss gripper
- Summary

Background

ADR（Active debris removal）

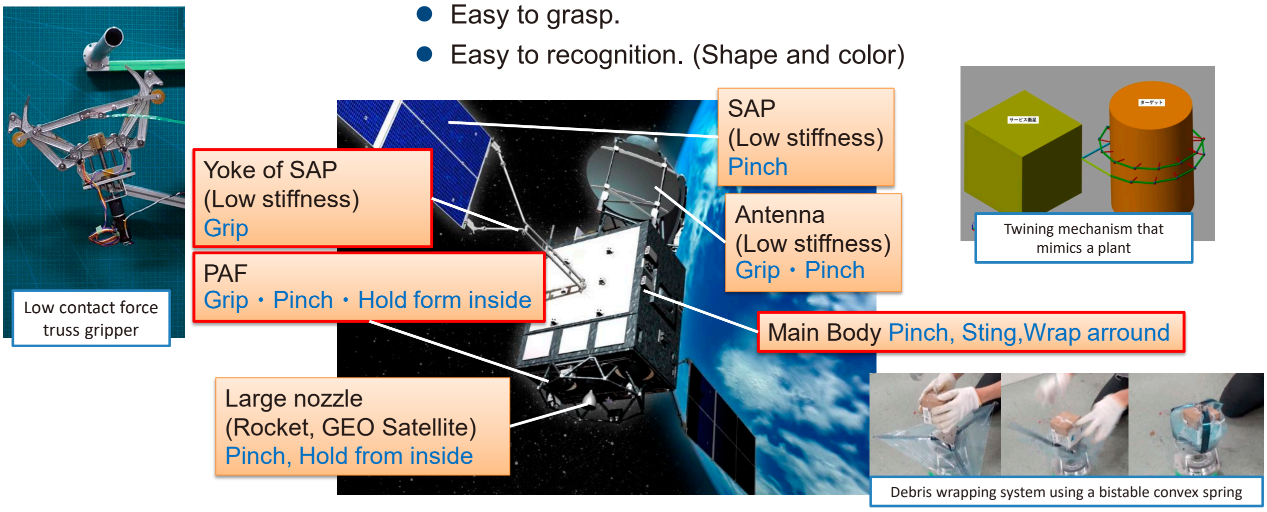


Purpose：
Establishment of a mechanism that enables secure grasping and fixing without causing destruction or ejection by contact force.

Candidate of alternative grapple-fixture on non-cooperative target

"Where" and "How" do we capture on debris?

- Easy to access.
- High stiffness enough to be applied force.
- Easy to grasp.
- Easy to recognition. (Shape and color)



Debris wrapping system using bi-stable convex spring

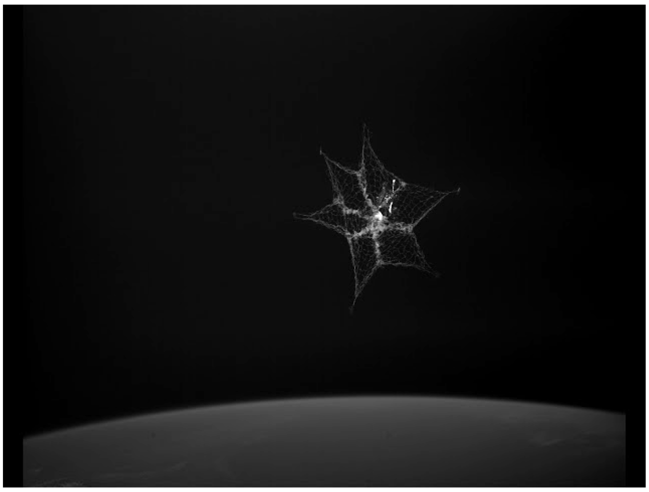
Debris wrapping system using bi-stable convex spring

Wrapping whole body of a target

Ex.) Casting net

Advantege:
No need for gripping I/F, independent of shape

Disadvantage:
Uncertainty in shape maintenance and control

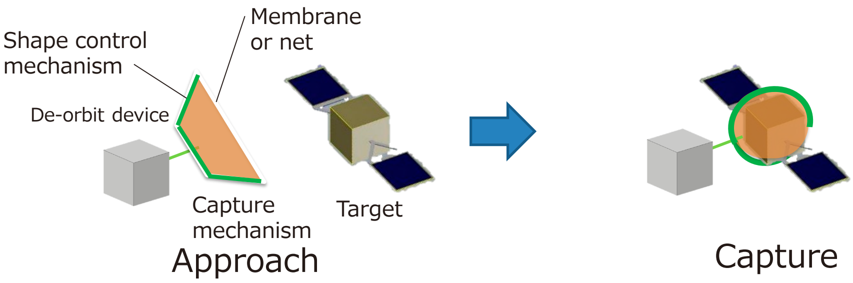

Net casting at RemoveDEBRIS mission ©SSTL

Debris wrapping system using bi-stable convex spring

Wrapping whole body of a target

Concept of the gripper

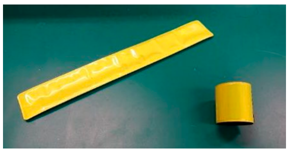
A mechanism that
- holds the shape until contact with the target maintains the grasping state.
- until the deorbit after the completion of grasping.

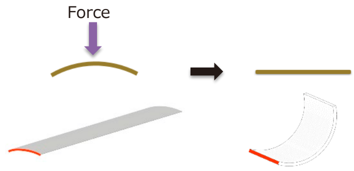


- A structural material that can maintain both the unfolded and grasped shapes is used as a support material for the net and membrane to control the operation of the capture mechanism.

Bi-stable convex spring

- It is commercially available as a wristband.
- As the gutter-shaped cross section is deformed, it transitions between a straight state and a coiled state.
- The coiling force emerges from the point where the force to flatten the cross section is added.

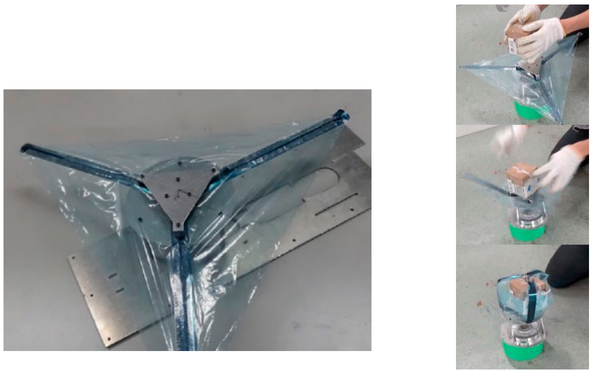




Cross-sectional change of convex spring before and after deformation

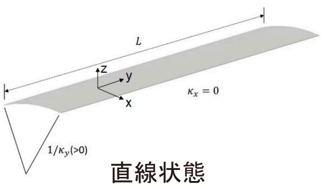
Advantages of Convex Spring

- Maintaining its shape
- Automatic contact detection
- Maintaining wrapping force

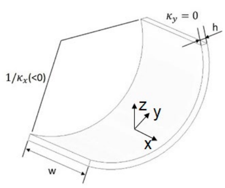


A prototype capture mechanism combined with a membrane.
The gripper is activated when the target contacts the center of the gripper.

Dynamics modeling



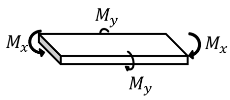
直線状態



巻き付き状態

From bending theory of thin plate,

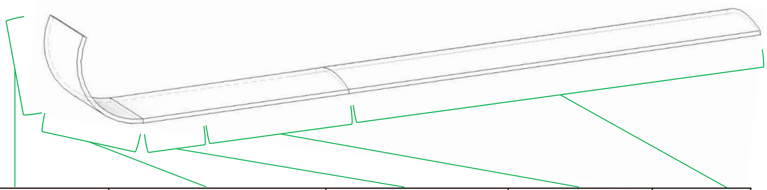
$$\begin{bmatrix}\mathbf{N}\\ \mathbf{M}\end{bmatrix} = \begin{bmatrix}\mathbf{A} & \mathbf{0}\\ \mathbf{0} & \mathbf{D}\end{bmatrix}\begin{bmatrix}\boldsymbol{\varepsilon}\\ \Delta\boldsymbol{\kappa}\end{bmatrix}$$



$$\mathbf{M} = \begin{bmatrix}M_x\\ M_y\end{bmatrix} = \mathbf{D}\Delta\boldsymbol{\kappa} = \frac{Eh^3}{12(1-\nu^2)}\begin{bmatrix}1 & \nu\\ \nu & 1\end{bmatrix}\begin{bmatrix}\Delta\kappa_x\\ \Delta\kappa_y\end{bmatrix}$$

$\mathbf{A}$	Axial rigidity matrix
$\mathbf{D}$	Bending stiffness matrix
$\mathbf{N}$	Stress
$\mathbf{M}$	Bending moment
ν	Poisson's ratio
κ_{x_0}	Curvature in coiled state (no load)

$\boldsymbol{\varepsilon}$	Strain
$\Delta\boldsymbol{\kappa}$	Increment of curvature
E	Young's modulus
h	Board thickness
w	Width of spring
κ_{y_0}	Cross-sectional curvature in straight state

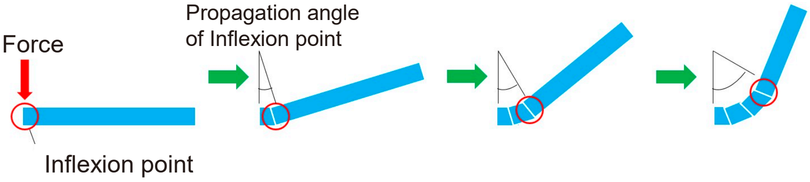


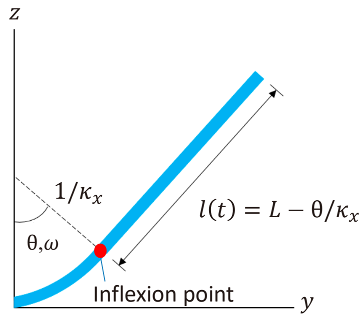
State / Bending moment	Coil stable	Coil transition	Flat	Convex transition	Convex stable
M_x	$D\nu\kappa_{y_0}$	$D\left(\Delta\kappa_x + \nu\kappa_{y_0}\right)$	$D\left(\kappa_{x_0} + \nu\kappa_{y_0}\right)$	0	0

The Coiling torque τ is given as $\tau = wM_x$

Dynamics modeling

Propagation of coiling torque ⇒ Coiling motion of spring





Equation of rotational motion around an inflection point

$$I\frac{d^2\theta}{dt^2} = \tau_0 \quad \begin{cases} \tau_0 = \dfrac{Ewh^3}{12(1-\nu^2)}(\kappa_{x_0}+\nu\kappa_{y_0}) \\ I \cong \dfrac{1}{3}\rho wh\left(L-\dfrac{\theta}{\kappa_{x_0}}\right)^3 \end{cases}$$

The propagation distance along the spring $l(t)$ is:

$$l(t) = \frac{\theta}{\kappa_{x_0}} = L - \sqrt{L^2 - \frac{\beta L}{\kappa_{x_0}}t^2} \quad (\mathbf{0} \le \boldsymbol{l}_{(t)} \le \boldsymbol{L})$$

$$\beta = \frac{Eh^2(\kappa_{x_0}+\nu\kappa_{y_0})}{4(1-\nu^2)\rho L^3}$$

E	Young's modulus
ρ	Density
w	Width
h	Thickness
L	Length

κ	Curvature
ν	Poisson's ratio
I	Inertia moment around inflexion point
τ_0	Coiling torque

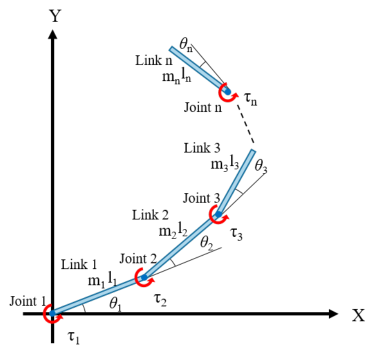
Modeling of convex spring

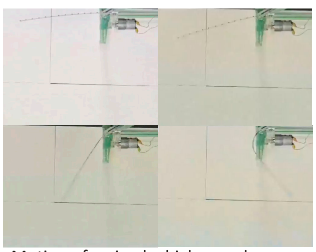
In case that the spring contacts with a target,
the model become complicated.

⇒ Approximation with multi link model

Equation of motion $[\mathbf{I}_{(\theta)}][\ddot{\theta}] + [\mathbf{I}_{V(\theta)}][\dot{\theta}^2] + [c][\dot{\theta}] = [\tau]$

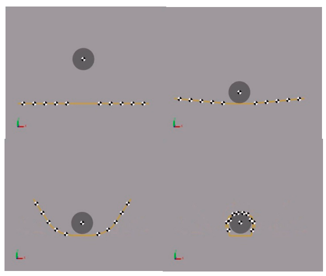
- from Specification of spring
- from Coiling torque model
- from Torque Propagation model





Motion of spring by high speed camera

Simulation result



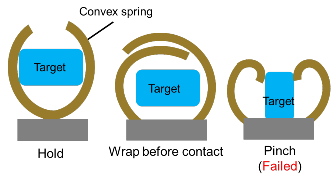
Numerical simulation of target capture

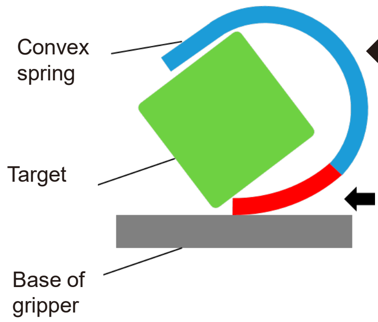
Design of convex spring for gripper

Ideal motion:

"Enclose the target before contact, then tighten it up"

➡ Different requirement is given to each part of spring





End tip side

Fast propagation of inflexion point

⇒Fast tightening up

Root side

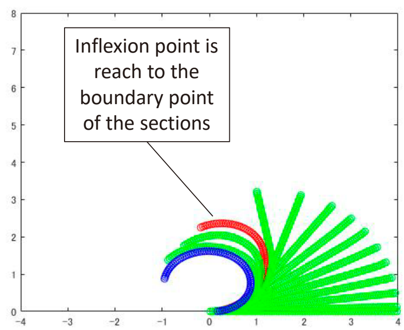
Slow propagation of inflexion point

⇒ Inhibiting end tip coiling before enclosing

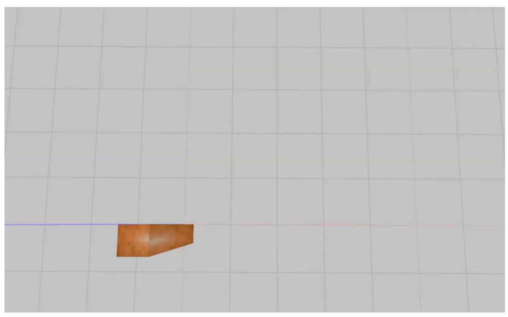
This is achieved by changing the curvature of the cross-sectional shape.

Design of convex spring for gripper

Simulation results with different cross-sectional curvature in the middle of the spring



History of spring motion

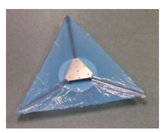


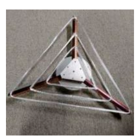
Simulation result (1/5 speed)

An ideal motion of convex spring is obtained by selecting and combining the spring parameters.

Next issue

Construction of a mechanical model of a mechanism that combines a membrane or net with a convex spring.





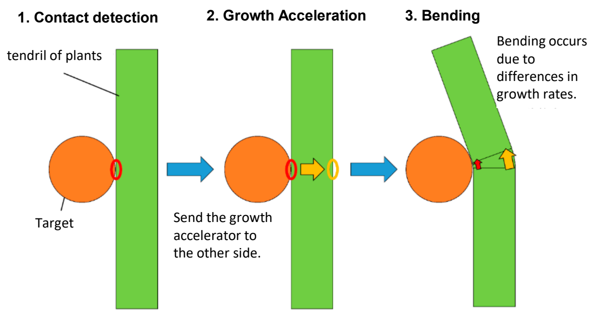
Twining mechanism that mimics a plant

Twining characteristics of plants

Thigmotropism of tendril of plants

The main control system (the brain) is not responsible for the movement, but the reflex response of each cell group to contact achieves the coiling movement as a whole.

Tendril of plants



Repeat steps 1 to 3 to achieve winding.

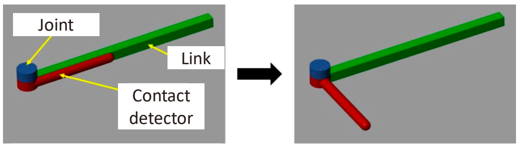
- Applying this property to a multi-link arm enables adaptive wrapping around a target.
- Each link is controlled independently by its own contact detection, so each link has the characteristics of a swarm robot.
  - **Easy to modularize.**
  - **Various configurations can be taken according to the target.**

Purpose

Design and algorithm of an adaptive winding mechanism based on a thigmotropism of tendril is discussed.

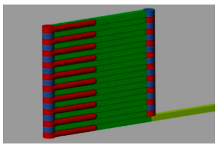
Concept design of twining mechanism

Module unit

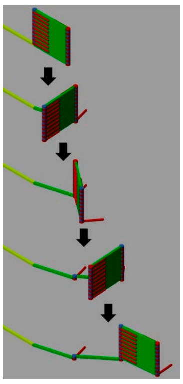


Stored state Deployed state

Integration design



Stored state of twining mechanism



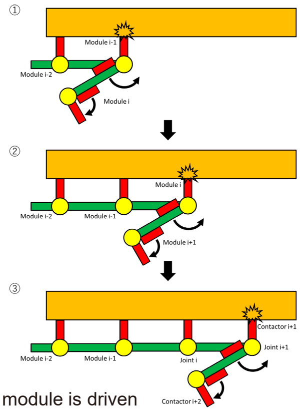
Growth and twining motion

Algorithm for target caging

① Contactor i-1 contacts to the target
- Module i-2 stops Joint i-2 motion
- Module i-1 starts Joint i-1 motion
- Module i deploys Contactor i

② Contactor i contacts to the target
- Module i-1 stops Joint i-1 motion
- Module i starts Joint i motion
- Module i+1 deploys Contactor i+1

③ Contactor i+1 contacts the target
- Module i stops Joint i motion
- Module i+1 starts Joint i+1 motion
- Module i+2 deploys Contactor i+2

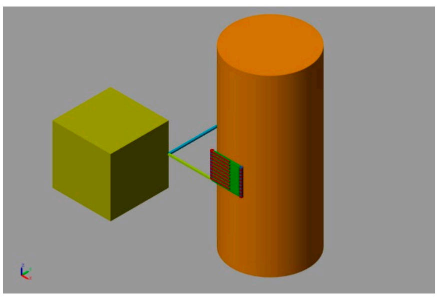


Caging operation is achieved when each module is driven based on its own and neighboring modules' contact history.

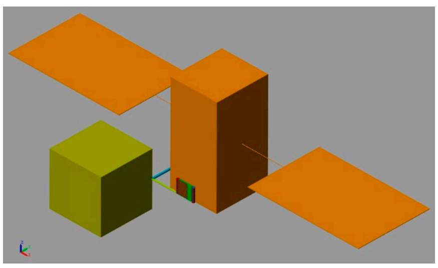
Algorithm for target tightening

- ✓ It does not drive when two or more of them are not in contact continuously.
- ✓ When the front and rear of the motor are in contact and the motor itself is not in contact, it drives in the opposite direction of the winding direction.
- ✓ Otherwise, it is driven in the winding direction.

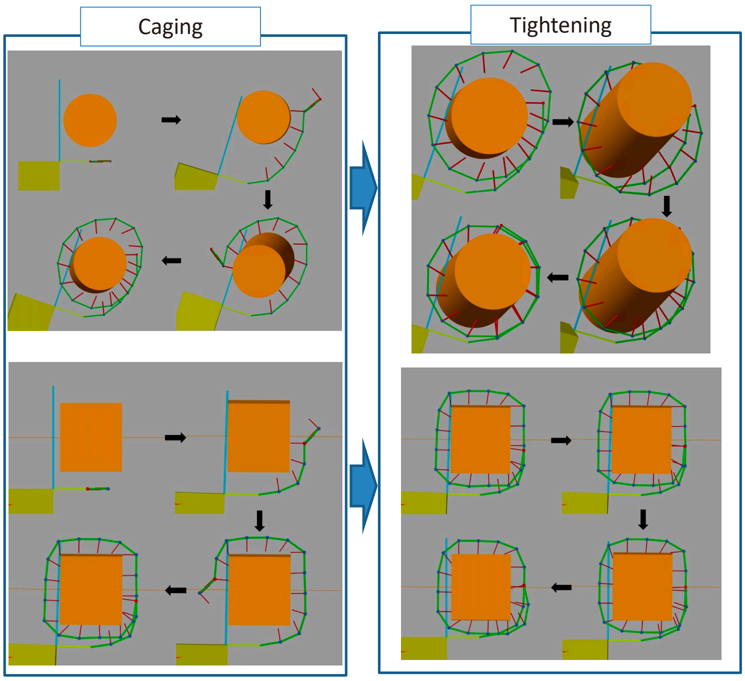
Simulation



Capture of cylindrical targets (rockets)



Capture of box-shaped target (satellite)

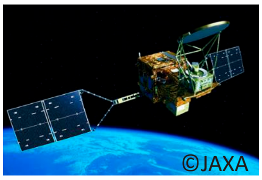


Low contact force truss gripper

Acknowledgement
2017-2019 Joint research of JAXA-Tokyo Tech
「Research on Deorbit Device Attaching System for Large Scale Debris」

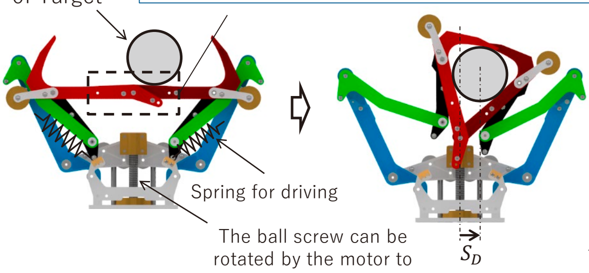
Low contact force truss gripper

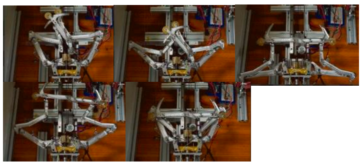
Assumed target :
Rockets and satellites with rod-like structures such as truss-type PAF (e.g. Cosmos 3M)



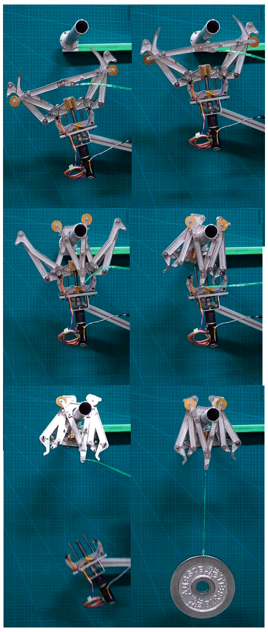
Concept :
Hand and mounting mechanism for attaching a device by simply pressing down.

Model 2018





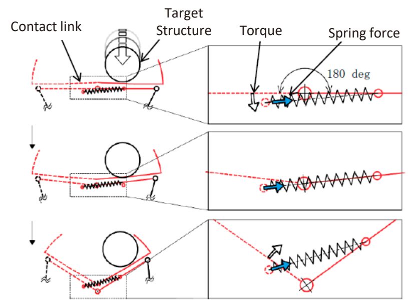
Reversing the disconnection motor restores the initial state.

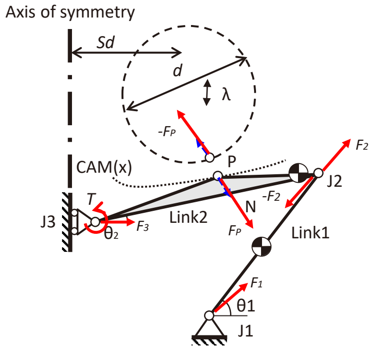


Capture and separation motion

Dynamics modeling of Low contact force truss gripper

The condition for the mechanism to work:
Work exceeding the elastic energy in the open state of the mechanism is given from the outside.

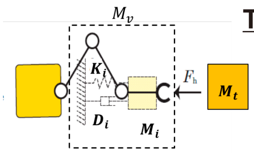




Requirement for energy K to be given to gripper

- Minimum energy required to actuate the EE K_{min}
- Maximum allowable energy K_{max} to avoid causing structural failure

$$K_{min} \leq K \leq K_{max}$$

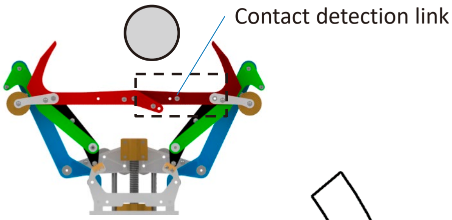


Transfer energy

When the virtual mass due to the mechanical impedance of the robot arm (Nakanishi, 2010) matches the virtual mass of the target contact point (Asada, 1983), impedance matching occurs and the transfer energy is maximized.

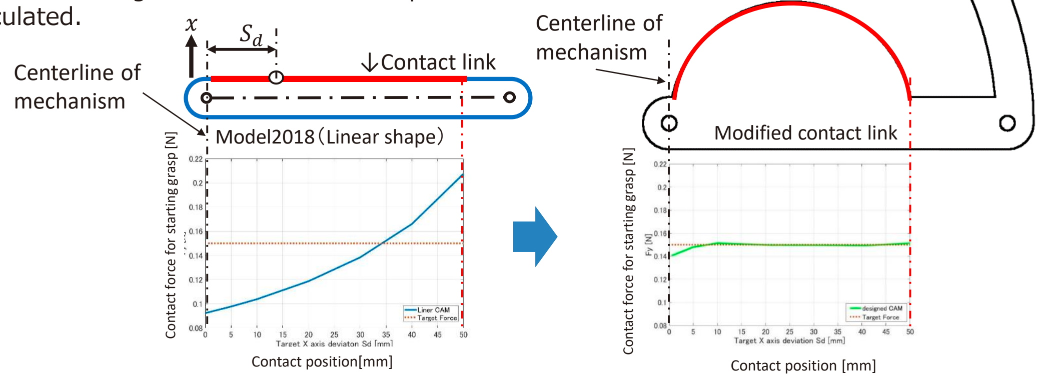
Low contact force truss gripper

Improvement of the shape of the contact



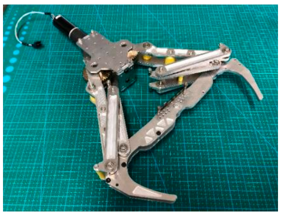
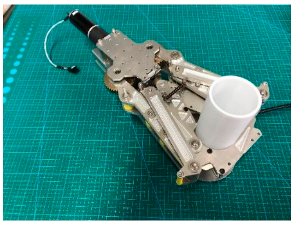
When the contact detection link is a straight line, the amount of work due to the contact force changes depending on the position of the contact.

From the dynamics model, the shape in which the hand moves regardless of the contact position was calculated.



Relationship between the contact point and contact force for starting grasp

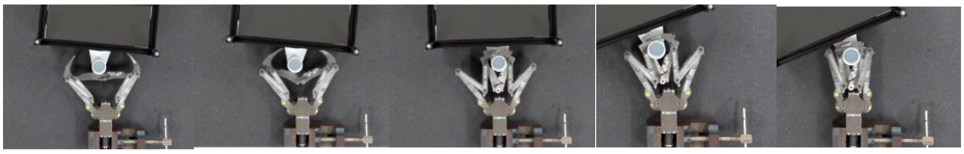
Low contact force truss gripper (Model 2020)

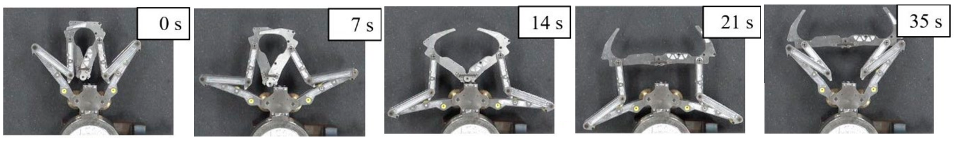
Modification of gripper

- Suitable for debris removal devices that require higher restraint forces than tether attachment.
- Self-locking fixation by worm gear.
- Improved operational stability by changing the contact link shape.

Grasping a free-floating target

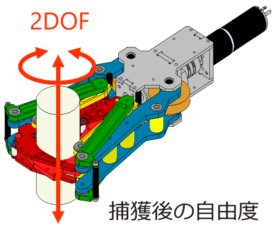


Recovery motion



Low contact force truss gripper

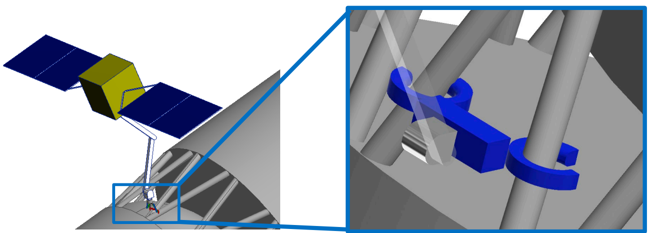
Extension to 6DOF constraints



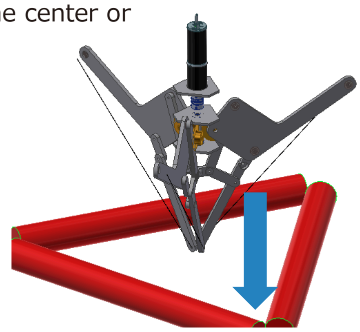
- When using a thruster as a deorbit device (when a controlled deorbit is required, such as for large debris), it is necessary to ensure that all six degrees of freedom are constrained.
- Fixation by friction is difficult to guarantee because it depends on surface conditions.

Realization of 6DOF constraint by grasping multiple trusses simultaneously

We are considering a mechanism for capturing by pressing against the center or the base of the V-shaped section of the truss.



トラス把持イメージ



Summary

- The purpose of this study is to establish debris grasping strategies and methods, and non-cooperative grasping mechanisms (end-effector and arm).
- The mechanical analysis and design of a debris wrapping mechanism using a bistable convex were clarified.
- A mechanism that mimics the twining motion of plants is being investigated.
- The mechanical analysis and design of a hand that can grasp a truss structure by simply pushing on it are clarified.

2017-2019 Joint research of JAXA-Tokyo Tech "Research on Deorbit Device Attaching System for Large Scale Debris."