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Effect of Joints Structure of Transformable Spacecraft on Attitude Change Utilizing Non-holonomic Constrain

可変構造宇宙機の関節構造が非ホロノミック拘束を利用した姿勢変化に与える影響

Kyushu University
〇TAKEUCHI Saki
BANDO Mai
HOKAMOTO Shinji

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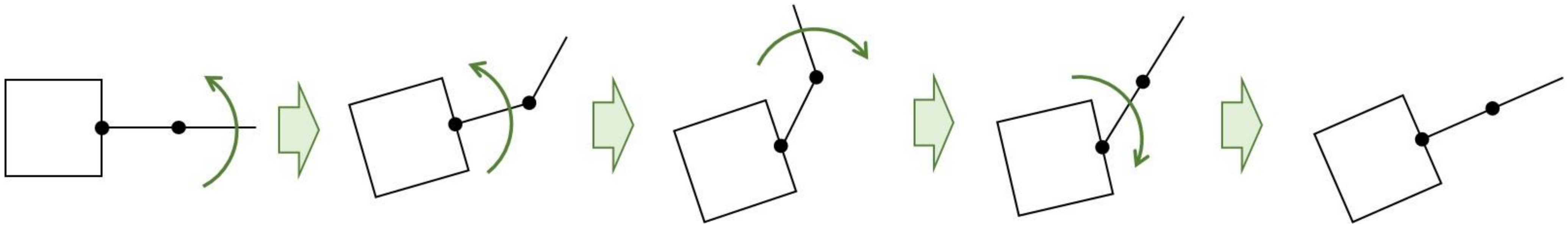
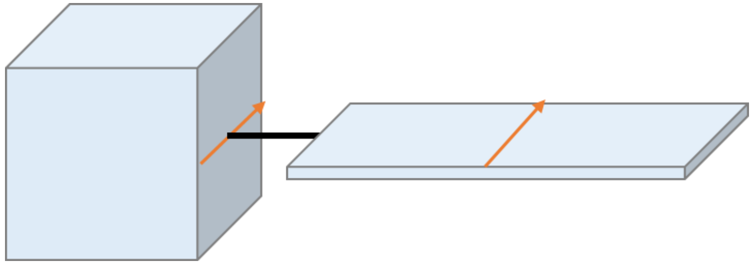
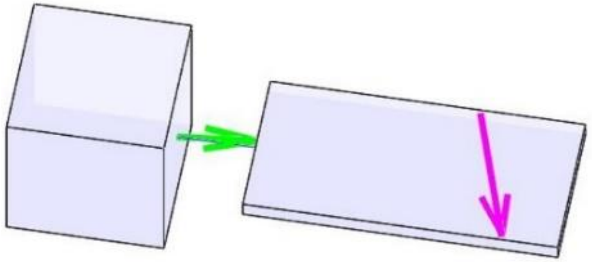
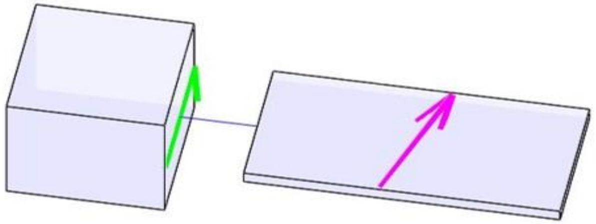




Generally used structure



The optimized structure



Slightly changed
from the optimized structure

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Background

Devices for the attitude control

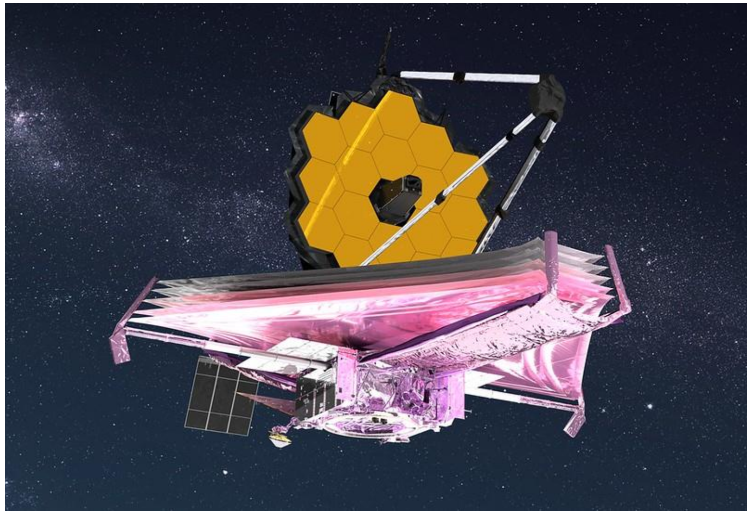
- Thruster, Control Momentum Gyro, Reaction Wheel
- having sufficiently high accuracy
  enough to perform missions

[Issue]

Loss of control performance
due to failure and running out of propellant

[example] James Webb Space Telescope[1]

- Carries propellant sized for 10 years
- No guarantee for more than 5 years operation term



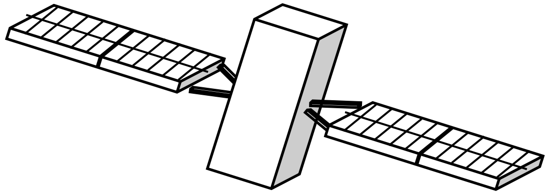
James Webb Space Telescope

https://www.flickr.com/photos/nasawebbtelescope/51412123217/in/album-72157624413830771/

[1] Gardner, J., Mather, J., Doyon, R., Greenhouse, M., Hammet, H., et al., Space Science Reviews., 123 (4), 2006, pp. 485–606.

Background

Control by devices



This term is limited.

launching

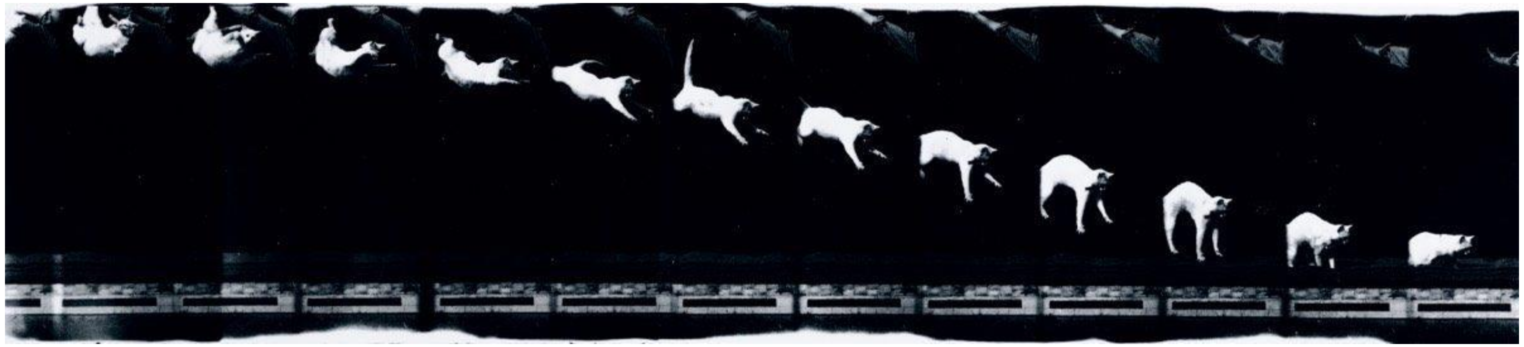
Device failure
or
Propellant depletion

Continue the Mission
by **non-holonomic feature**

The operation term is extended.

Background

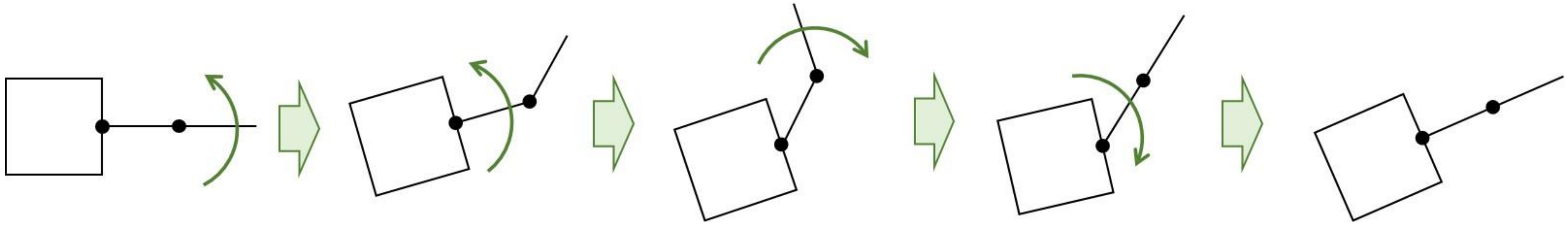
- Non-holonomic constrain
  - Not describing only by generalized coordinate system and time
  - Include differential parameters and is non-integrable
- Non-holonomic turn
  - **Attitude change caused by internal forces** such as a falling cat
  - Able to find the motion that achieves the desired attitude change



taken by
Etienne-Jules Marey
(1830-1904)

Background

- Apply non-holonomic feature to spacecraft

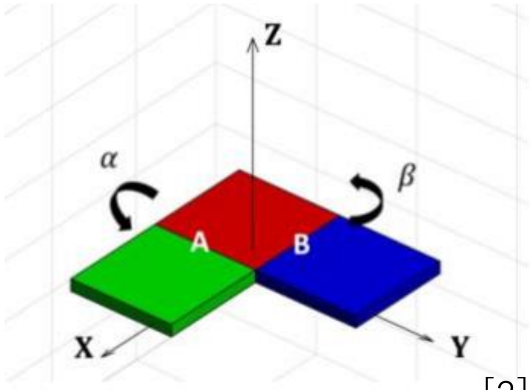


The shape does not change in the body-fixed coordinate system.
However, **the attitude can be changed** in the inertial coordinate system.

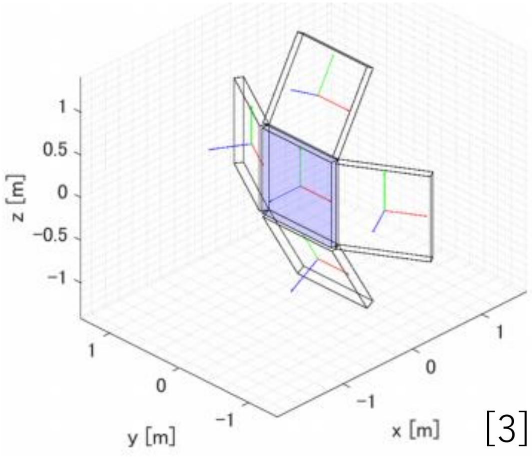
Purpose

- Control methods based on the numerical analysis and learning have been mainly studied.

- The structure is predefined without deep consideration.
    - The motion generated by the non-holonomic control is quantifiable by Lie Brocket, the degree is generally small
    - The structural configuration affects the control coefficients on non-holonomic constraint.



[2]



[3]

[2]Kaoru Ohashi, Toshihiro Chujo, and Junichiro Kawaguchi. In 28th Workshop on JAXA Astrodynamics and Flight Mechanics, 2018
[3] Yuki Kubo, Yoshihiro Chujo, Javier Hernando-Ayuso, and Junichiro Kawaguchi. In 69th International Astronautical Congress of the International Astronautical Federation, 2018.

Purpose

In this study,

- **Confirm the effect of structural optimization**

Difficulties

- Non-holonomic system does not constraint the initial and final state.
- The roundabout trajectory is often compelling.

→Evaluation value includes attitude changes by several trajectories.

- The spacecraft has several movable part, thus,

  the number of design parameters becomes large.

→ The optimization is conducted as an iteration of optimization.

Derivation of the Attitude Change

Governing equations when no external forces/torques acts

- The Mass center of the whole system

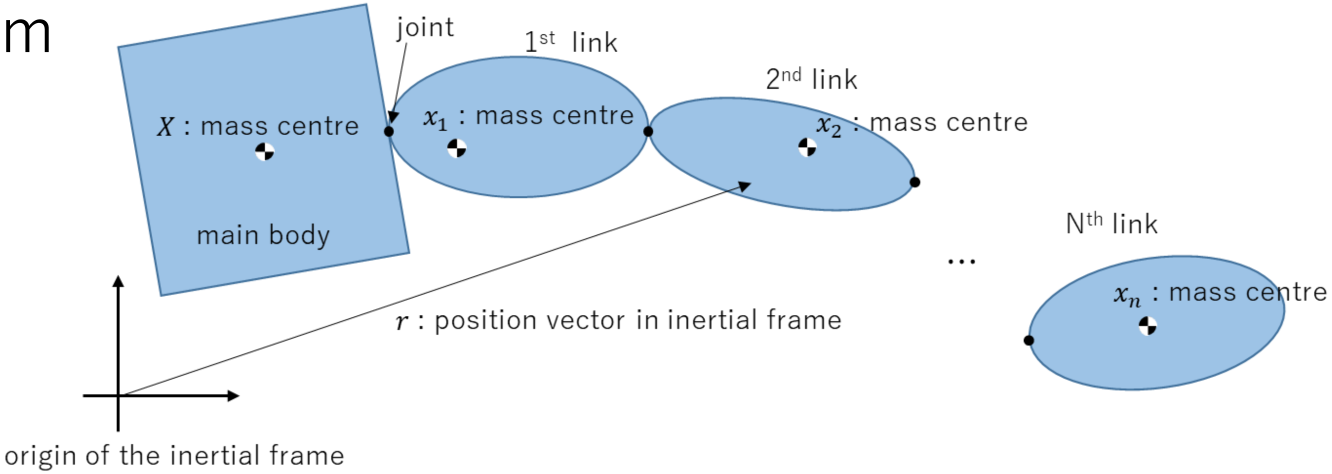
$$\left(\frac{1}{M_{\text{system}}}\right)\left(M\boldsymbol{X}+\sum m_i\boldsymbol{x}_i\right)=0$$

- Angular momentum conservation

$$\int_{body}\boldsymbol{R}\times\dot{\boldsymbol{R}}\,dM+\sum\left(\int_{link}\boldsymbol{r}\times\dot{\boldsymbol{r}}\,dm\right)=const.$$

- Kinematics

$$\dot{q}=\frac{1}{2}Q(q)\omega$$



$\boldsymbol{x}$: the position of the mass center
$\boldsymbol{r}$: position
m : mass
ϕ : joint angle
$\dot{\phi}$: angular velocity of the joint

Derivation of the Attitude Change

- The angular velocity of the main body

$$\boldsymbol{\omega} = f\left(\boldsymbol{X}, \phi, \dot{\phi}, \text{structual parameter}\right)$$

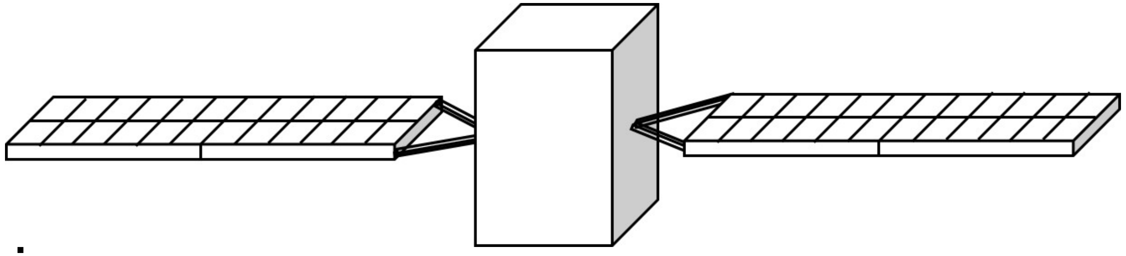
- The angular velocity is integrated after converting it into the derivative of the attitude angle.

- The attitude change is determined

when the trajectory in joint space is decided.

Problem Setting

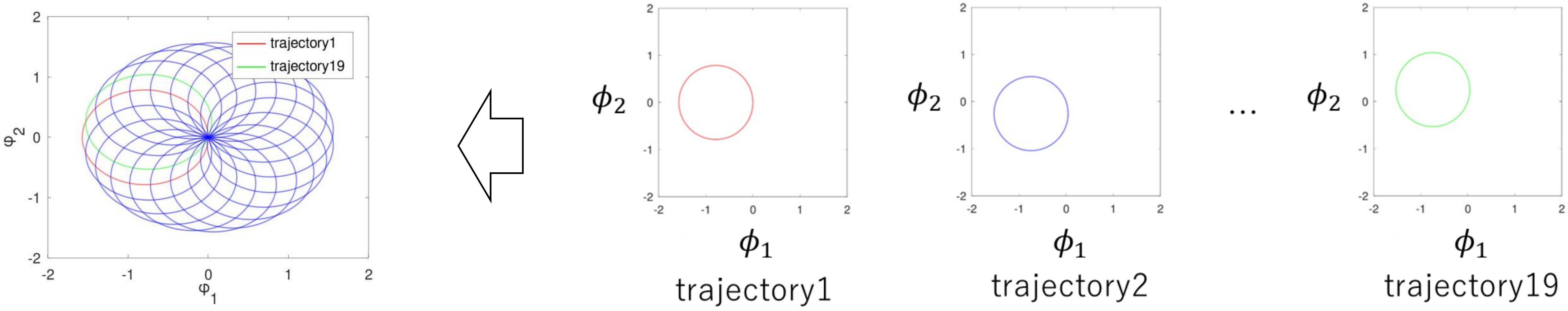
- Considering spacecraft with solar panels
  - ➢Structural parameter
    optimized parameters
  - ➢The initial attitude
    when it deploys solar panels to maximize power generation



  - ➢The trajectories
    a circle in two dimensions

Problem Setting

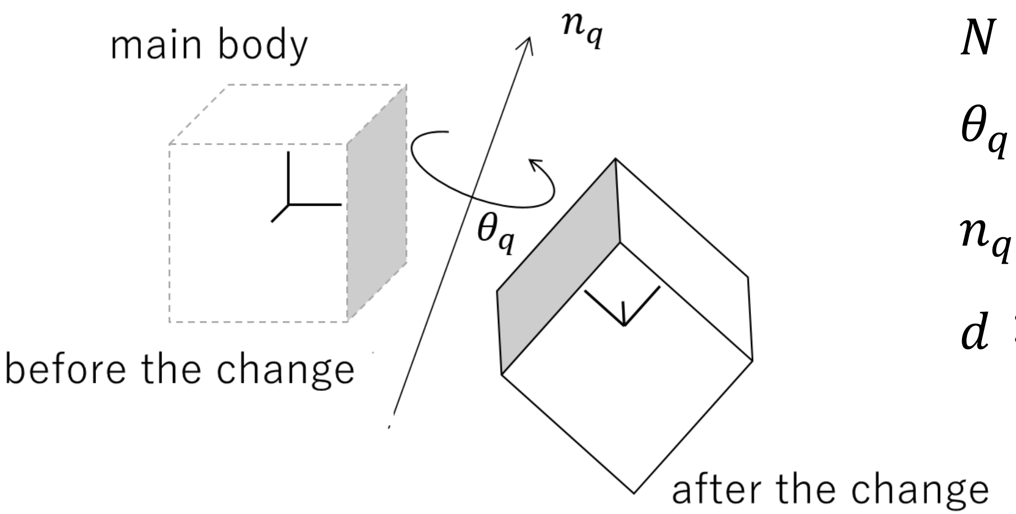
- The trajectories (joint’s rotational motion)

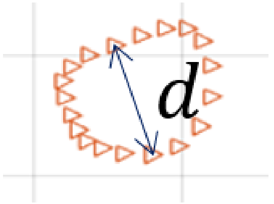


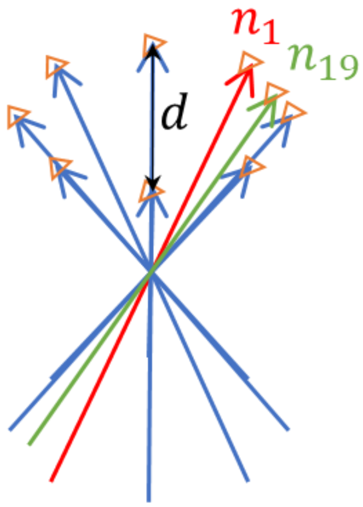
Problem Setting –Evaluation Value

- Maximize the Evaluation Value

$$\max J = \frac{1}{N}\sum_{i=1}^{N} {\theta_{q}}_{i}^{2} * \min d$$







N : the number of trajectory

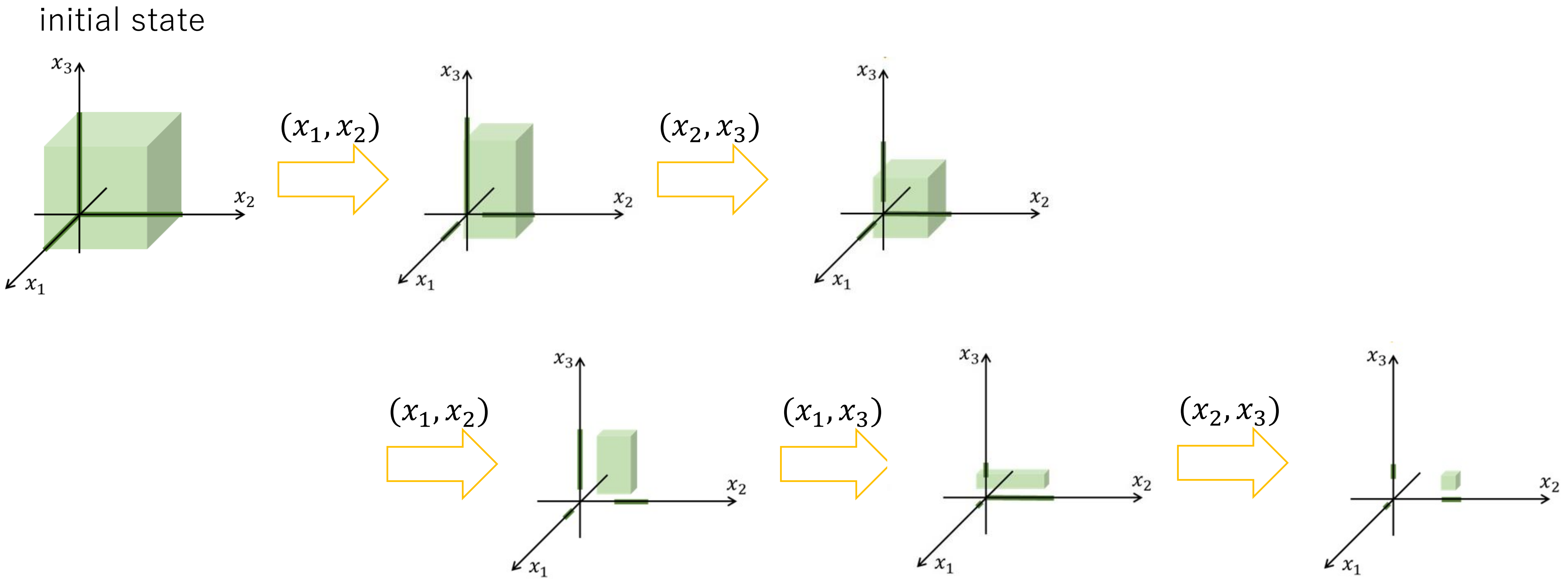
θ_q : the minimum rotational angle

n_q : unit vector indicates rotational axis

d : the square norm of the vectors between the trajectories to be originated

Optimization Method -Concept

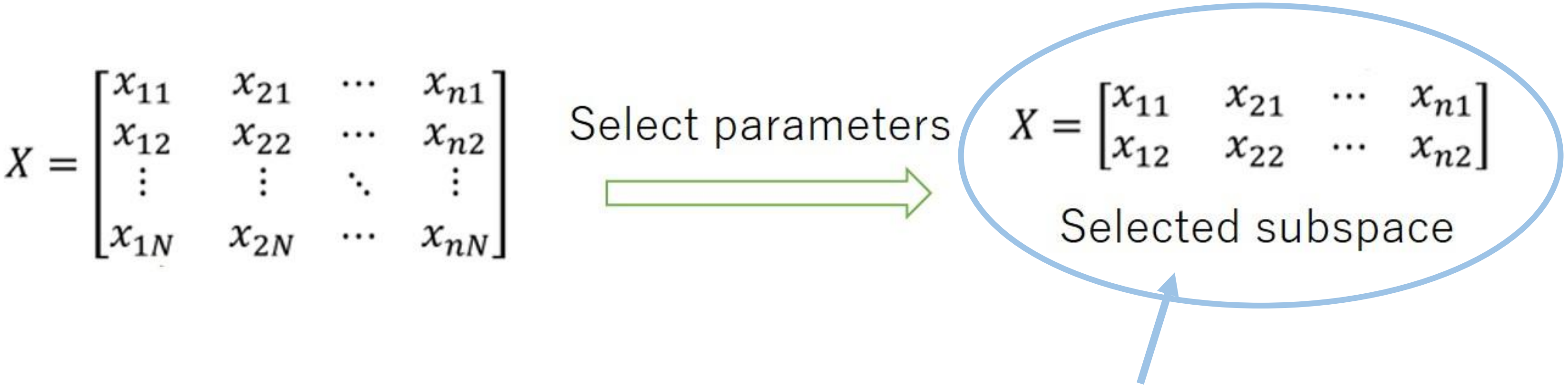
- Iterate optimizations in subspace composed of selected parameters



Optimization Method -Concept

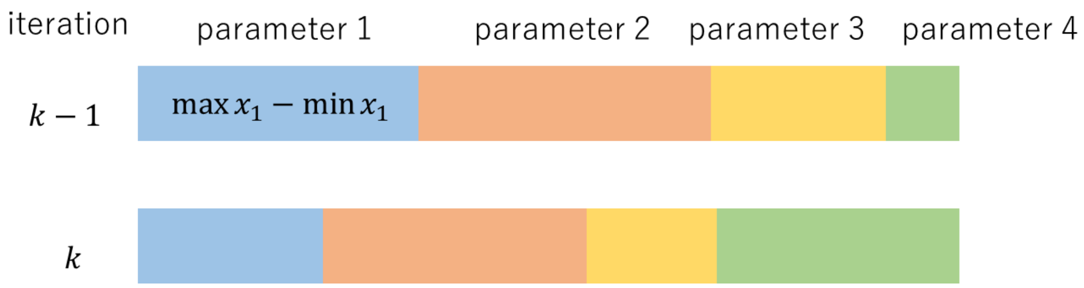
- Iterate optimizations in subspace composed of selected parameters
- consist of two parts;

  "parameter selection" and "optimization"

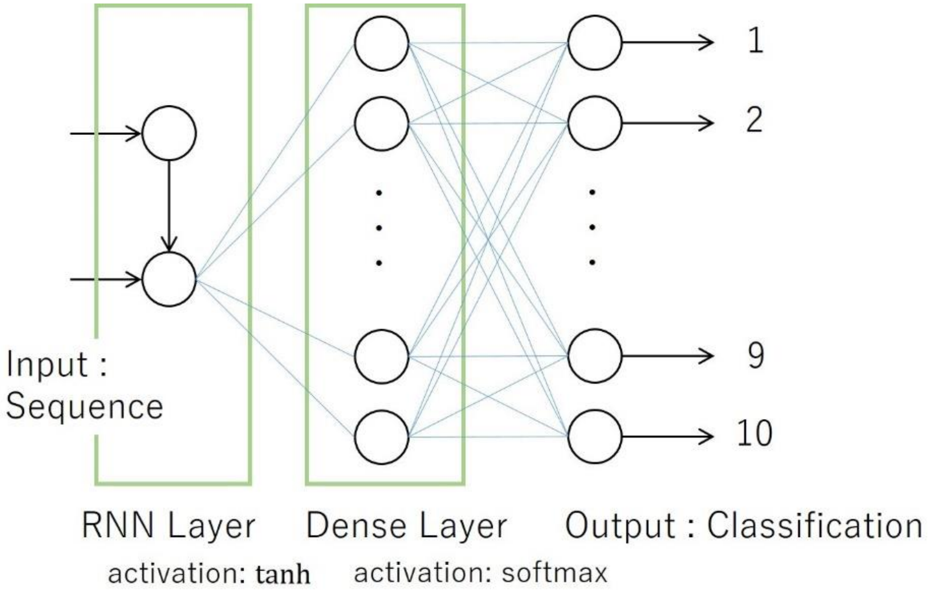


–Parameter Selection Process

- Dimensional selection part uses the Neural Network Model
  - Classification
  - Input: the ratio of parameter width



  - Output:
    combination of the selected parameters
    (parameter1, parameter2),⋯

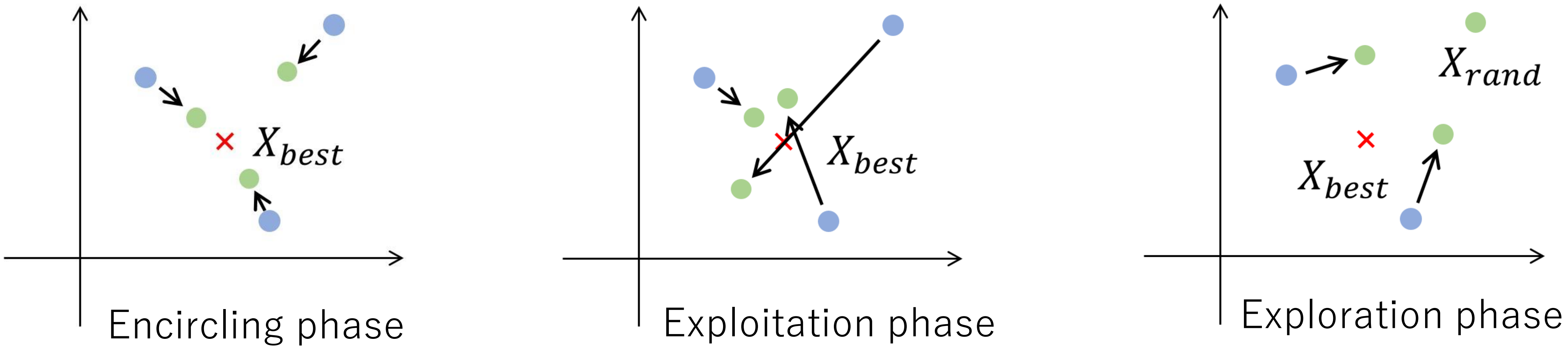


the diagram of NN structure

–Optimization Process

- Algorithm : primarily based upon the Whale Optimization Algorithm[4]
  - Metaheuristic (not requiring gradient descent)
  - Excellent **convergence** and **search capability** around the estimated optimal solution
  - Several candidate solutions are updated

    through three probabilistically determined phase

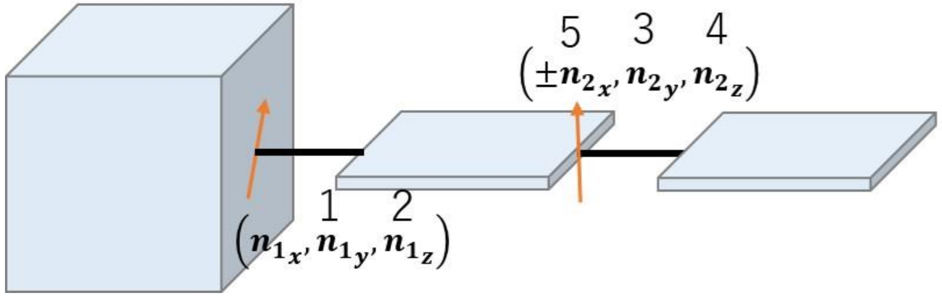


[4] Mirjlili, S., and Lewis, A, Advances in Engineering Software, 95, 2016, pp. 51–6

Numerical Example – System

- Model : one cubic main body with a rectangular panel
- Optimized structural configuration parameters :

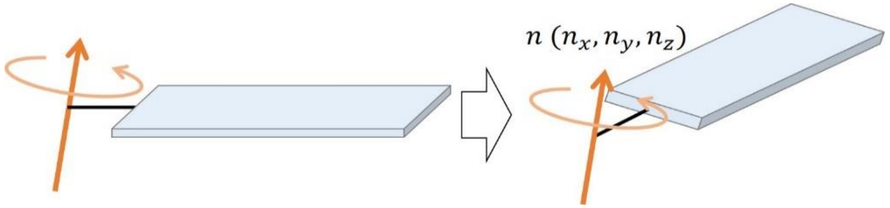
  the direction of the 1st joint n_{1y}, n_{1z}, the direction of the 2nd joint n_{2y}, n_{2z}



Specifications of model

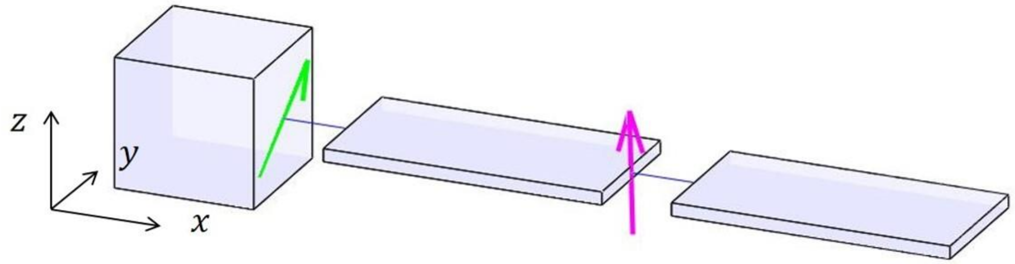
	geometry	mass [kg]	length [m]
main body	cube	100	2
connection part	-	0	0.5
panel	rectangle	5	2×1×0.5

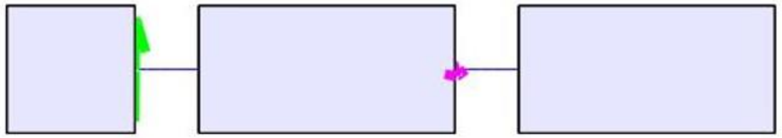
Possible movement (1 DOF)

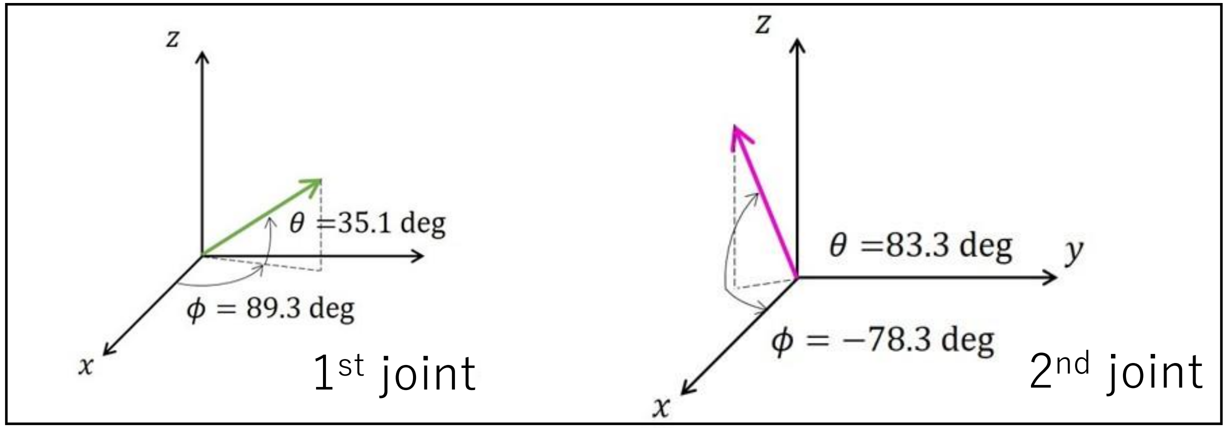


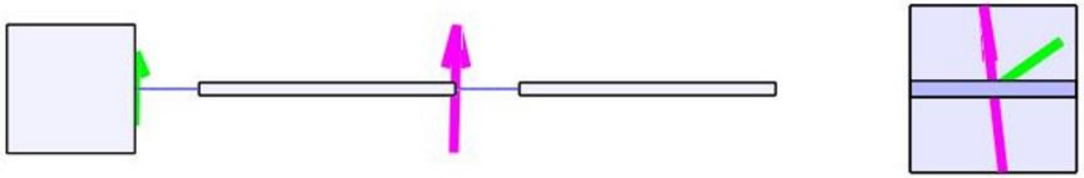
Numerical Example –Optimized Structure

- The optimized structural configuration





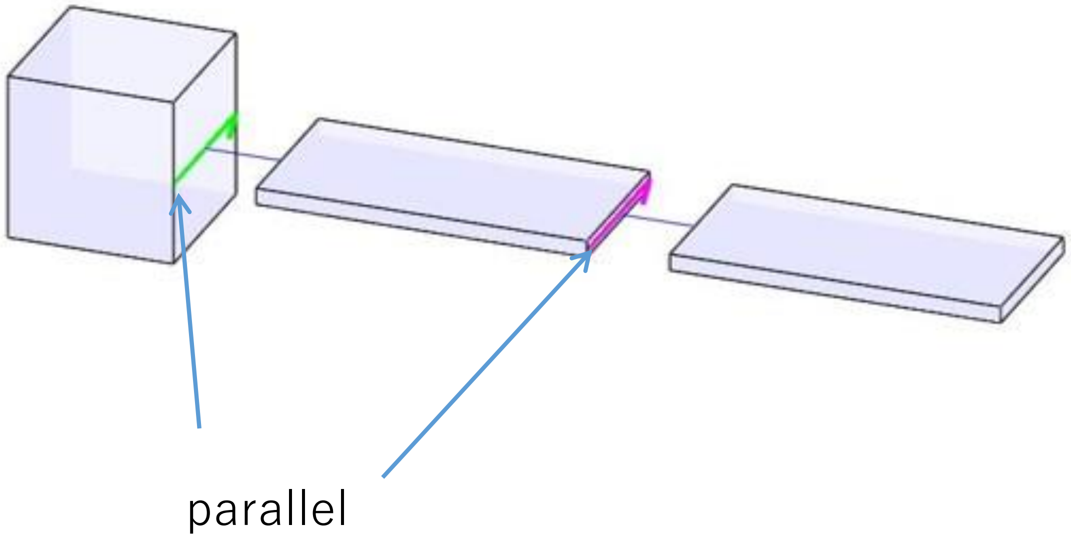




Numerical Example –"Feasible structure"

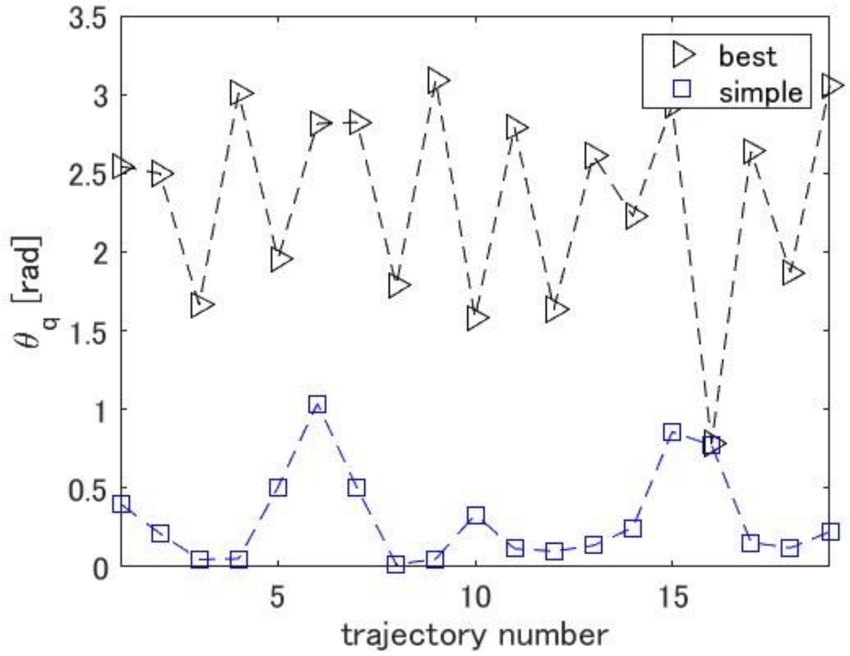
- "Simple structure" is introduced to the comparison

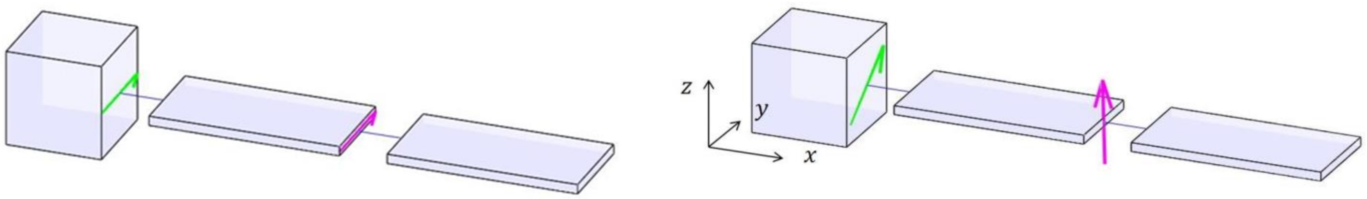
simple structure



Numerical Example –Comparison

- Compare “simple” and “optimized” structure





simple

optimized

	simple	optimized
the average of θ[rad]	0.3099	2.3323
n times of simple	-	7.53

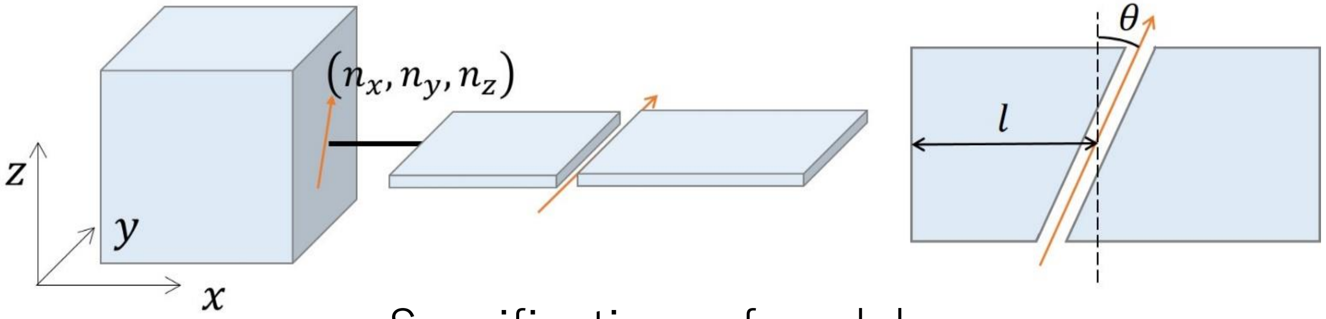
- Optimization makes larger attitude change possible

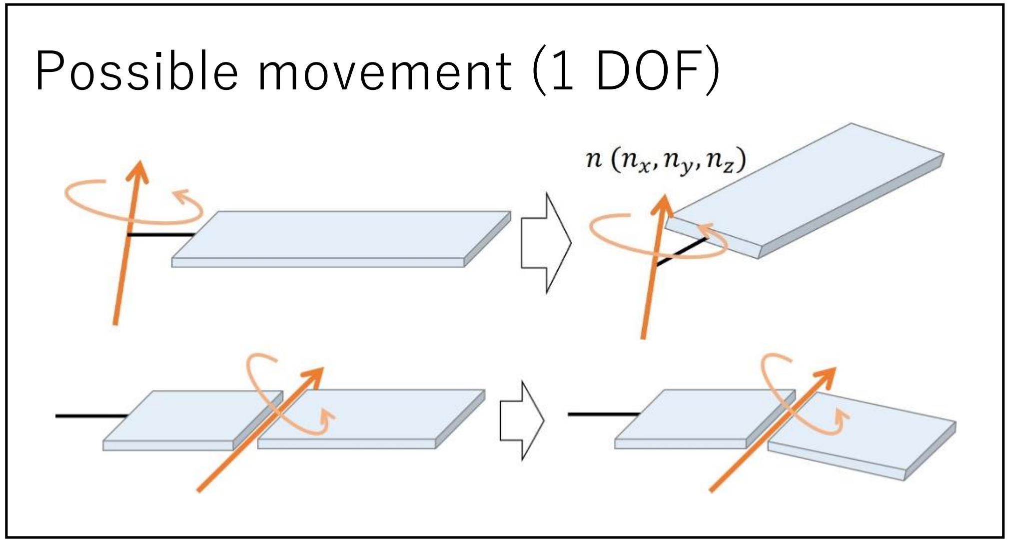
Numerical Example – System

- Model : one cubic main body with a rectangular panel
- Optimized structural configuration parameters : $n_y, n_z,\ l,\ \theta$

  -the direction of the 1st joint n_{1y}, n_{1z}

  - the direction of the 2nd joint θ, and the position l



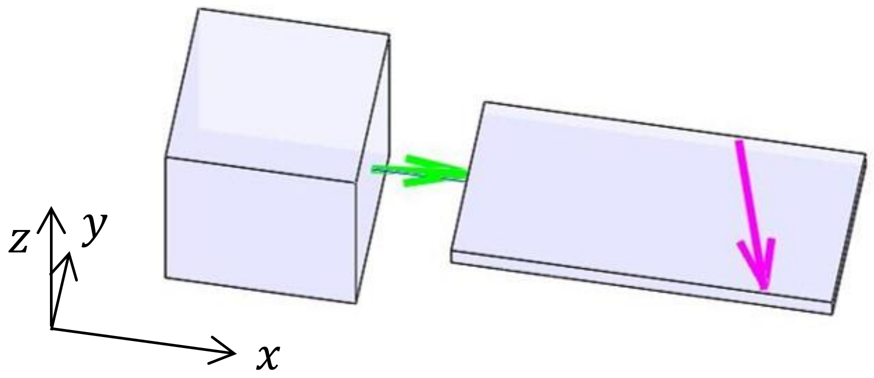


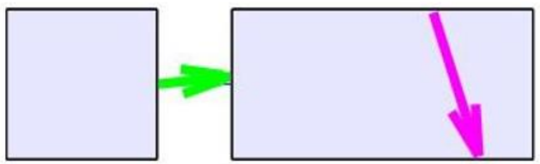
Specifications of model

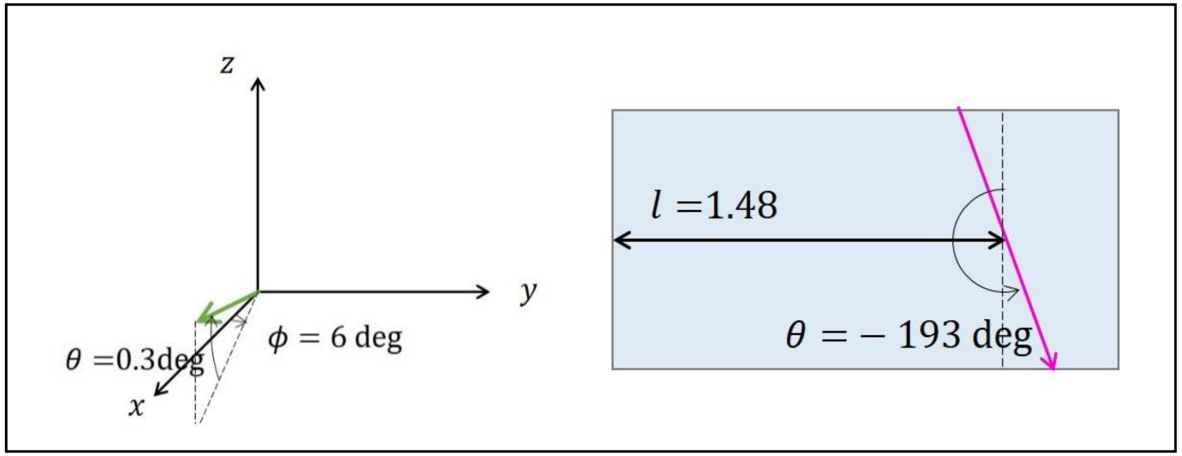
	geometry	mass [kg]	length [m]
main body	cube	100	2
connection part	-	0	0.5
panel	rectangle	10	2×1×0.5

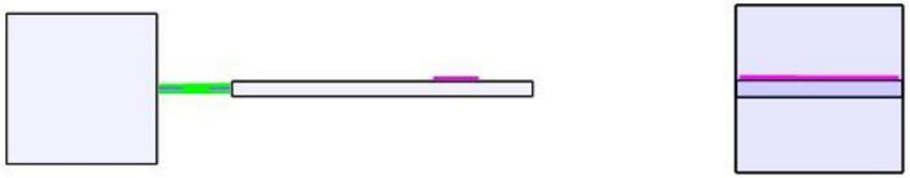
Numerical Example –Optimized Structure

- The optimized structural configuration





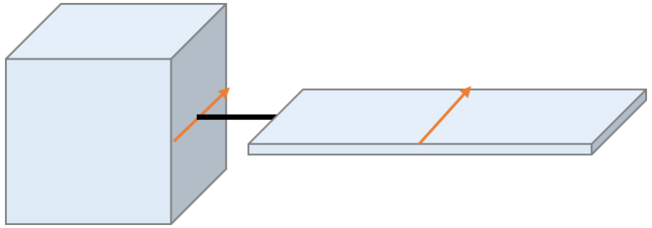




Numerical Example –"Feasible structure"

- "Simple structure" and "feasible structure" are introduced

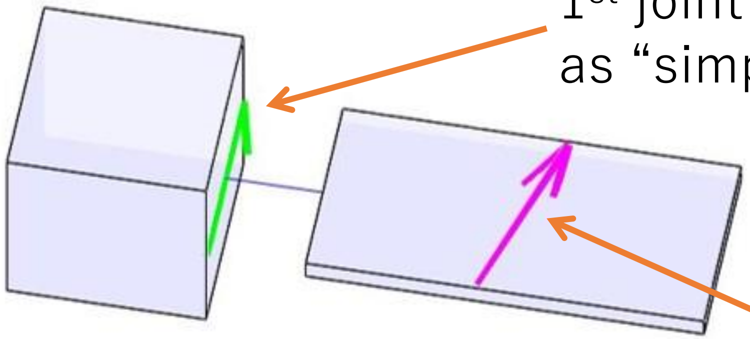
simple structure



Specifications of configurations

	simple	optimized	feasible
azimuth angle [deg]	90	0.3	90
elevation angle [deg]	0	6	0
l $[m]$	1	1.48	1
θ [deg]	0	-193	17

feasible structure

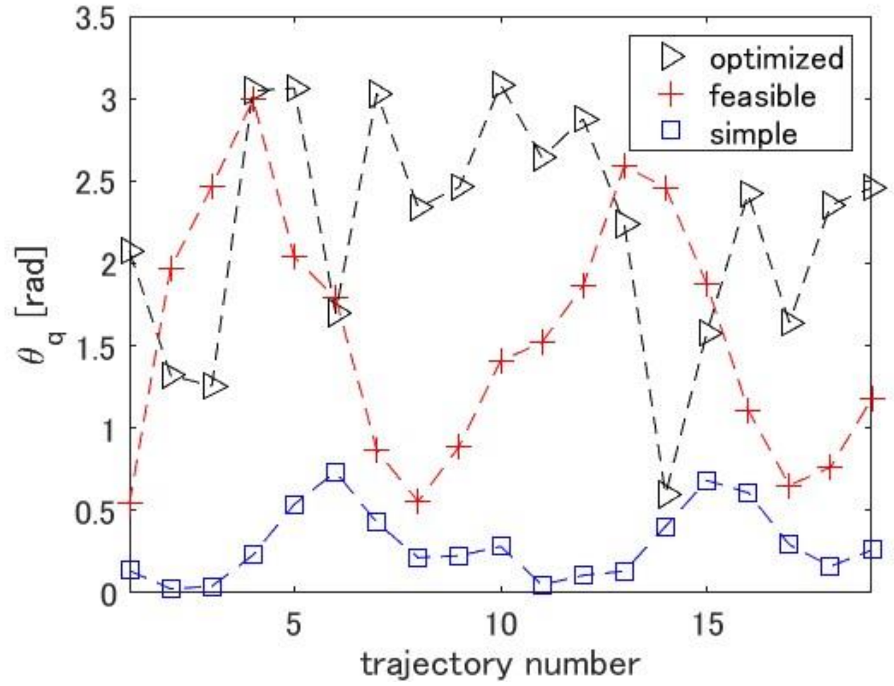


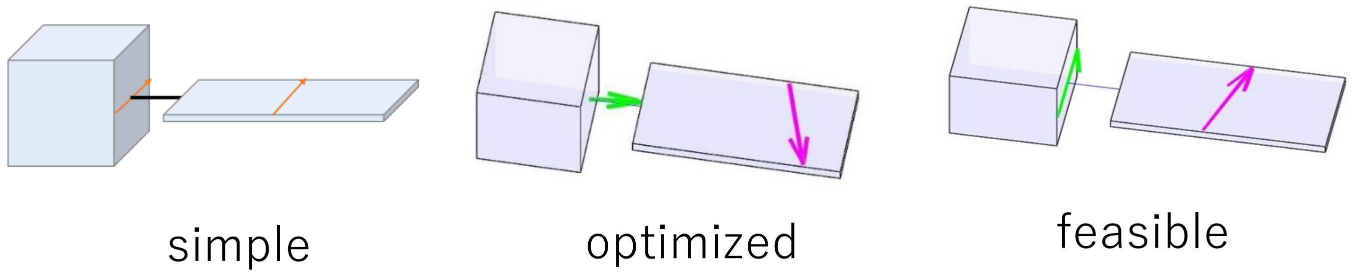
1st joint is reflected as "simple structure"

2nd joint is reflected as "optimized structure"(θ) and "simple structure"(l)

Numerical Example –Comparison

- Compare “simple”, “optimized”, and “feasible” structure





	simple	optimized	feasible
the average of θ[rad]	0.2837	2.2121	1.15538
n times of simple	-	8.00	4.07

- Optimization makes larger attitude change possible

Conclusion

- The optimized structural configuration is obtained by the proposed optimization method.

- Considering the structure contributes to making large attitude change possible.
  - The optimized structure achieves an 8-fold larger attitude change.
  - Even a slight change in one structural configuration has an effect.