Soft End-Effectors and Their Applications

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Agenda

- What is robotic end-effector?
- Why soft robotic end-effectors are important?
- What are the existing soft robotic end-effectors?
- How to make soft robotic end-effectors?
- How to model and simulate soft robotic end-effectors?
- What are the potential applications of soft robotic end-effectors?
- Soft robotic end-effectors developed by our group
- Future research directions
- Report

What is robotic end-effector (EE)?

An **end effector** is the device at the end of a robotic arm, designed to **interact with the environment**. The exact nature of this device depends on the application of the robot.

Robotic hand

Robotic gripper

Suction pad

Other tools

Image from Google

Examples of Robotic EE

SCHMALZ

NBK

SMC

On-Robot

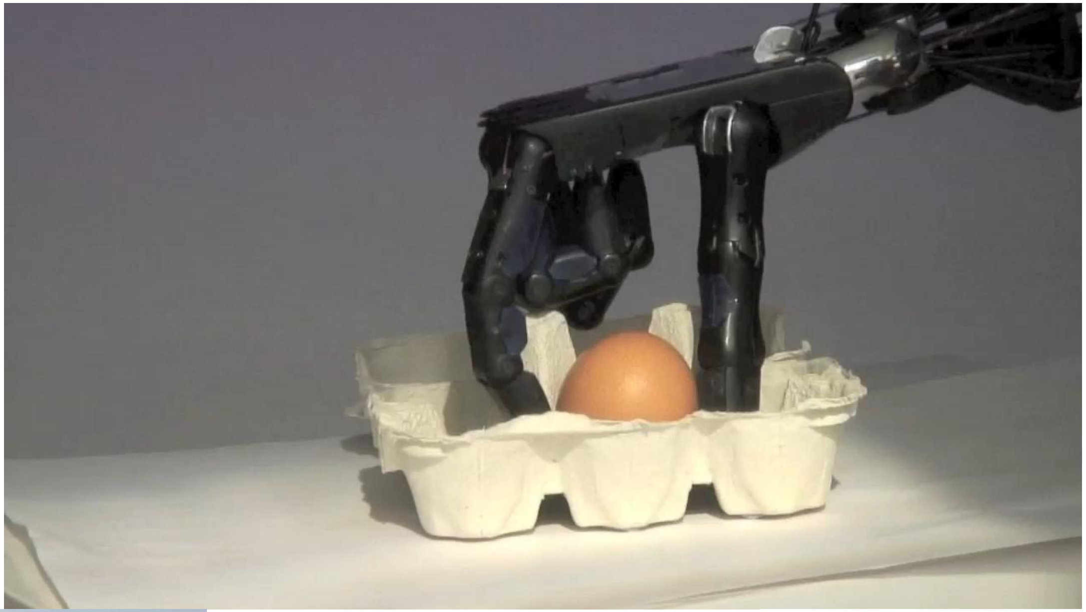
Barrett TECH

ROBOTIQ

Shadow Robot

Images from Google

Examples of Performance



Videos from YouTube

①
https://www.youtube.com/watch?v=bzPcQc0eTQU
②
https://www.youtube.com/watch?v=IqrBi6_1cFs
③
https://www.youtube.com/watch?v=orqitN4HJTA

Features of Conventional EEs

RITSUMEIKAN

	Parallel gripper	Suction pad	Dexterous hand
Pros	High speed Low cost Easy to control	High adaptability High speed Low cost Easy to control Light weight	High adaptability
Cons	Low adaptability Relatively high weight	Require flat surface to suck	Low speed High cost Hard to control

Why soft robotic EEs are important?

Images from Google

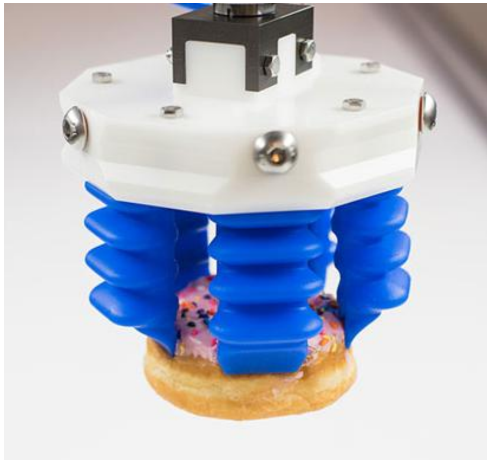
High speed handling

?

High speed handling of objects with large varieties in physical properties, such as size, shape, hardness, friction, fragility, …

What are the existing soft robotic EEs?→Commercial ones

RITSUMEIKAN

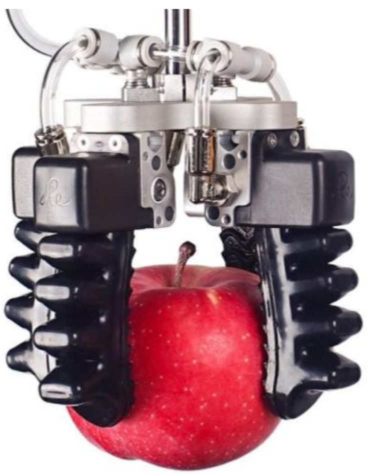


Soft Robotics Inc

SoftGripping Inc

Soft Robot Tech co., LTD

Piab AB Inc



RoChu (China)

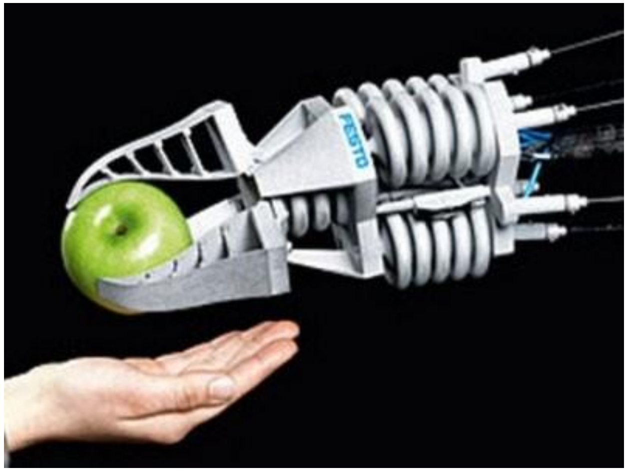
Schmalz

NITTA

OnRobot

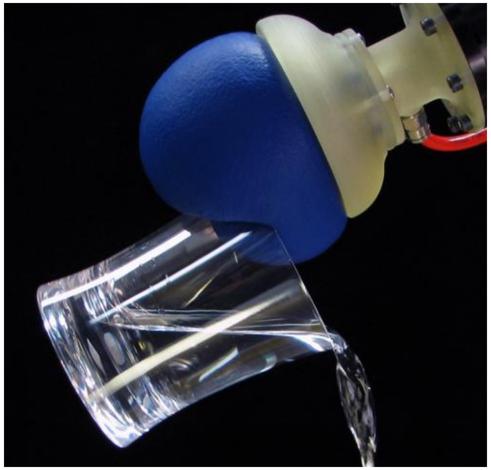
Images from Google

What are the existing soft robotic EEs?→Commercial ones

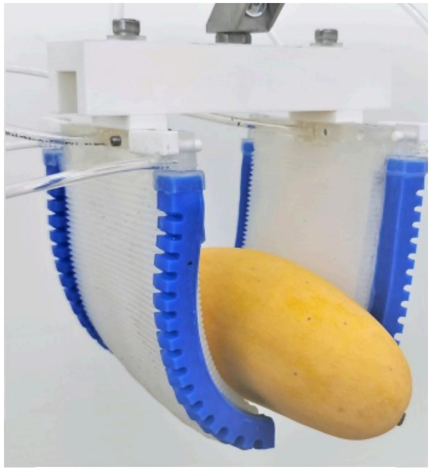


FESTO (Fin gripper)

Bridgestone (Artificial muscle)



Jamming gripper (USA)



IPI (Singapore)

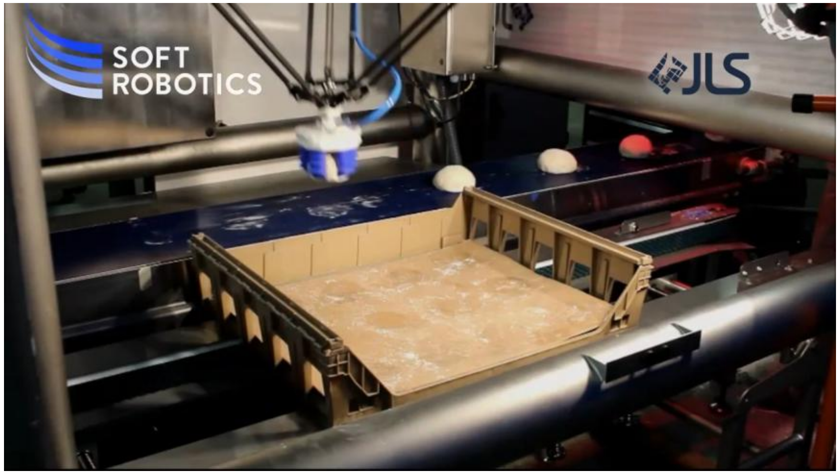
Ubiros Gripper (UK)

FESTO Soft Gripper

RoChu (China)

Images from Google

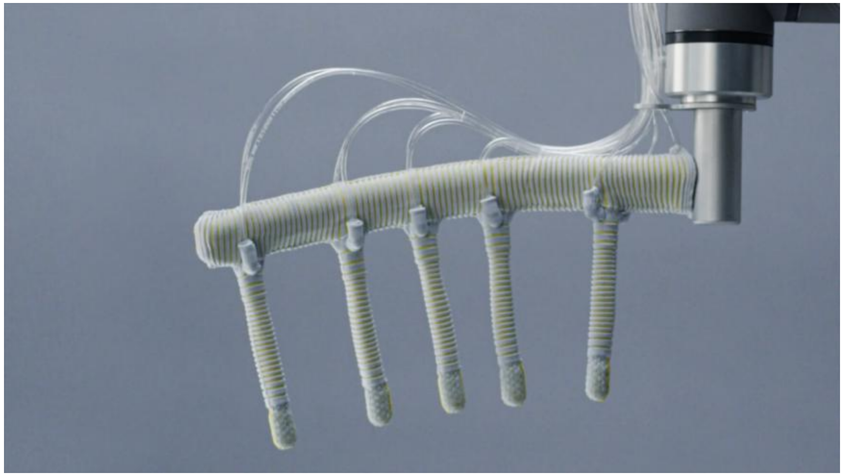
Examples of Performances



***m*Grip,** Soft Robotics Inc.

Jamming gripper

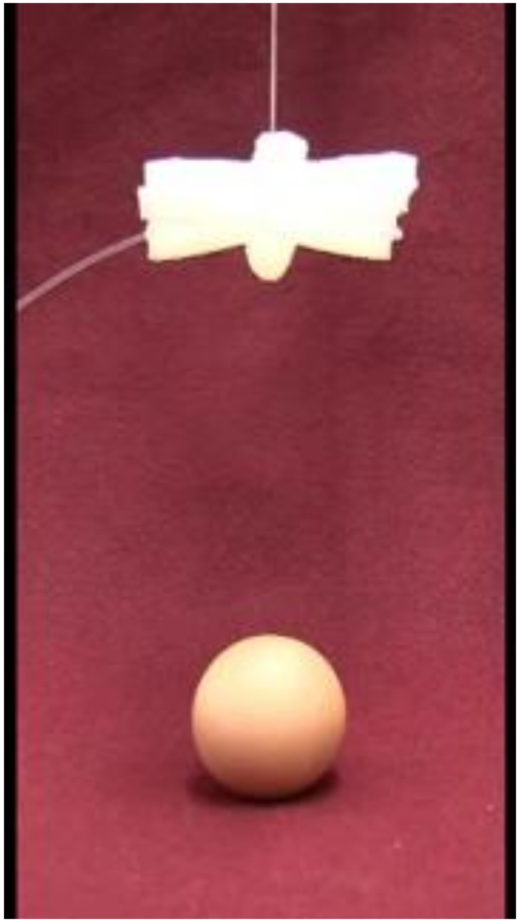
SOFTmatics hand, NITTA



SOFTmatics hand, NITTA

Videos from YouTube

Existing researches on soft EEs

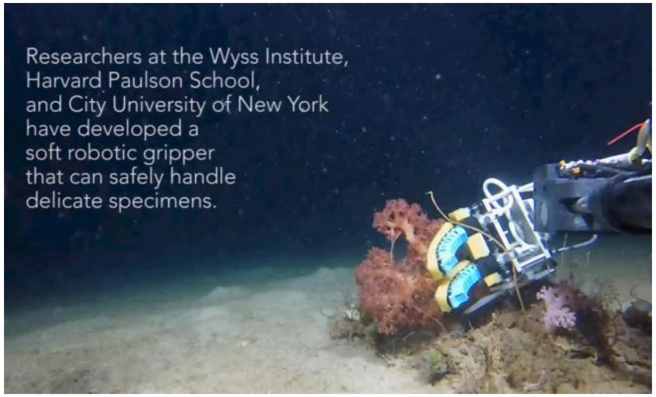


Whitesides et al.,
Harvard Univ., 2011

Suzumori et al.,
TIT, 1991

Rus et al.,
MIT., 2019

Cecilia et al.,
IIT, 2016



Wood et al.,
Harvard Univ., 2016

Videos from YouTube

A nice review of soft EEs

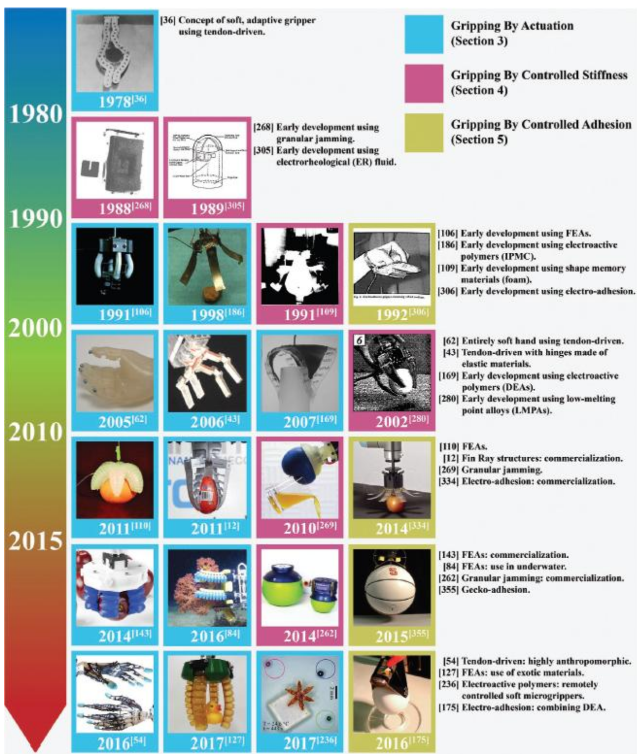
REVIEW

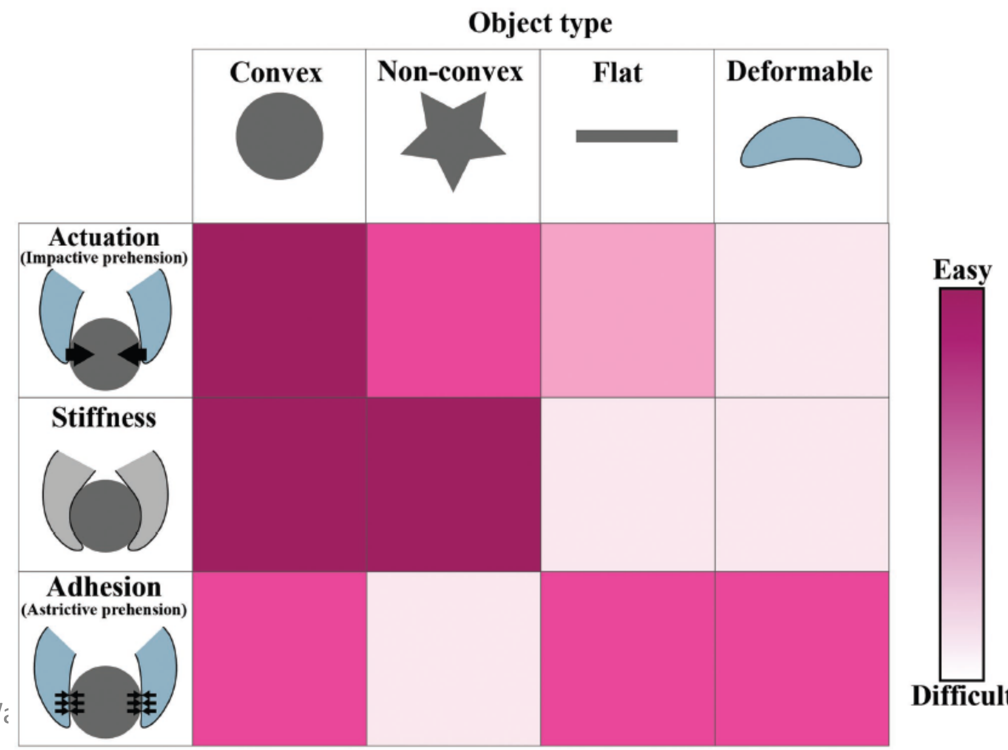
ADVANCED MATERIALS
www.advmat.de

Soft Grippers

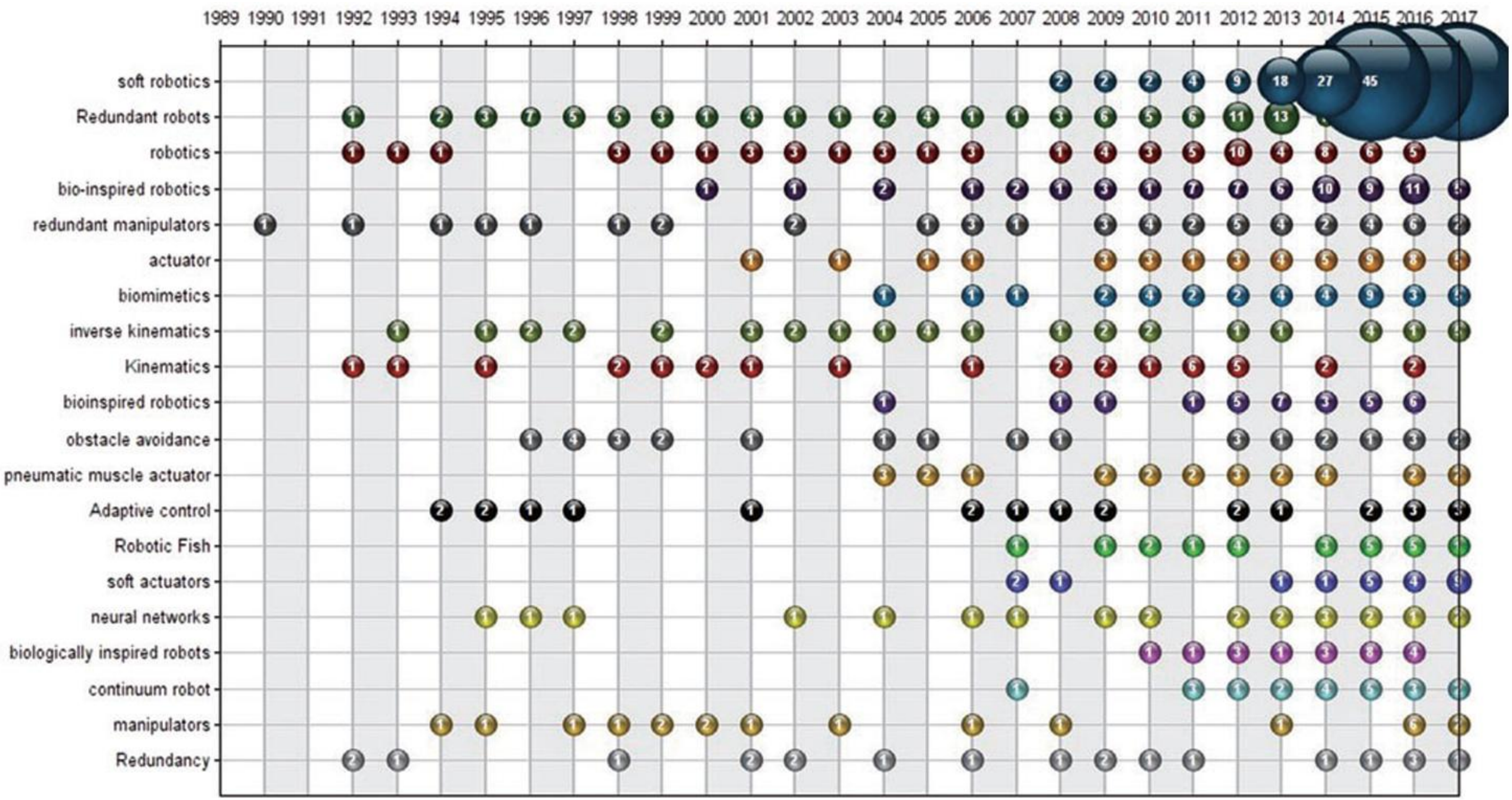
Soft Robotic Grippers

*Jun Shintake, Vito Cacucciolo, Dario Floreano, and Herbert Shea**





Keywords related with soft robotics



G. Bao, et al., Soft Robotics, 2018

Features of Soft EEs

RITSUMEIKAN

Rigid EE

- large
- Heavy
- Hard
- Expensive
- Hard to use
- Structured environmental
- Not safe
- Hard to fabricate

Soft EE

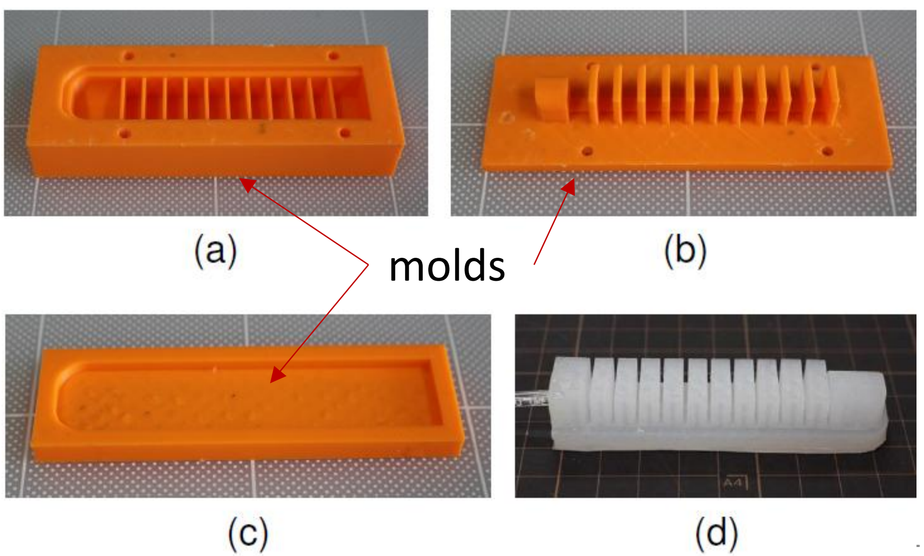
- Small
- Light
- Soft
- Inexpensive
- Easy to use
- Non-Structured environmental
- Safe
- Easy to fabricate

How to fabricate soft EE?

RITSUMEIKAN

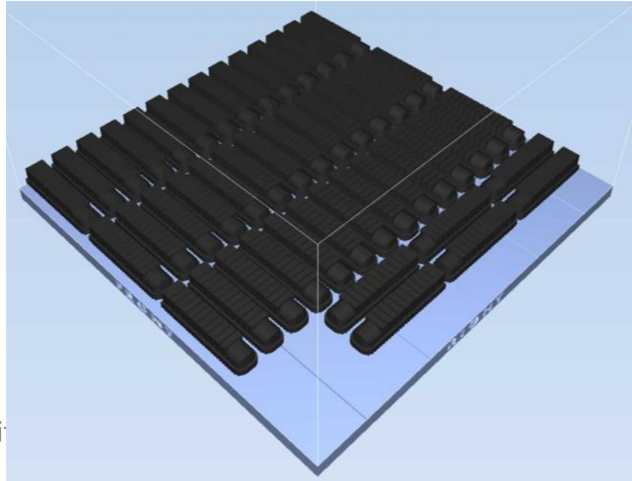
Casting

Liquid silicone



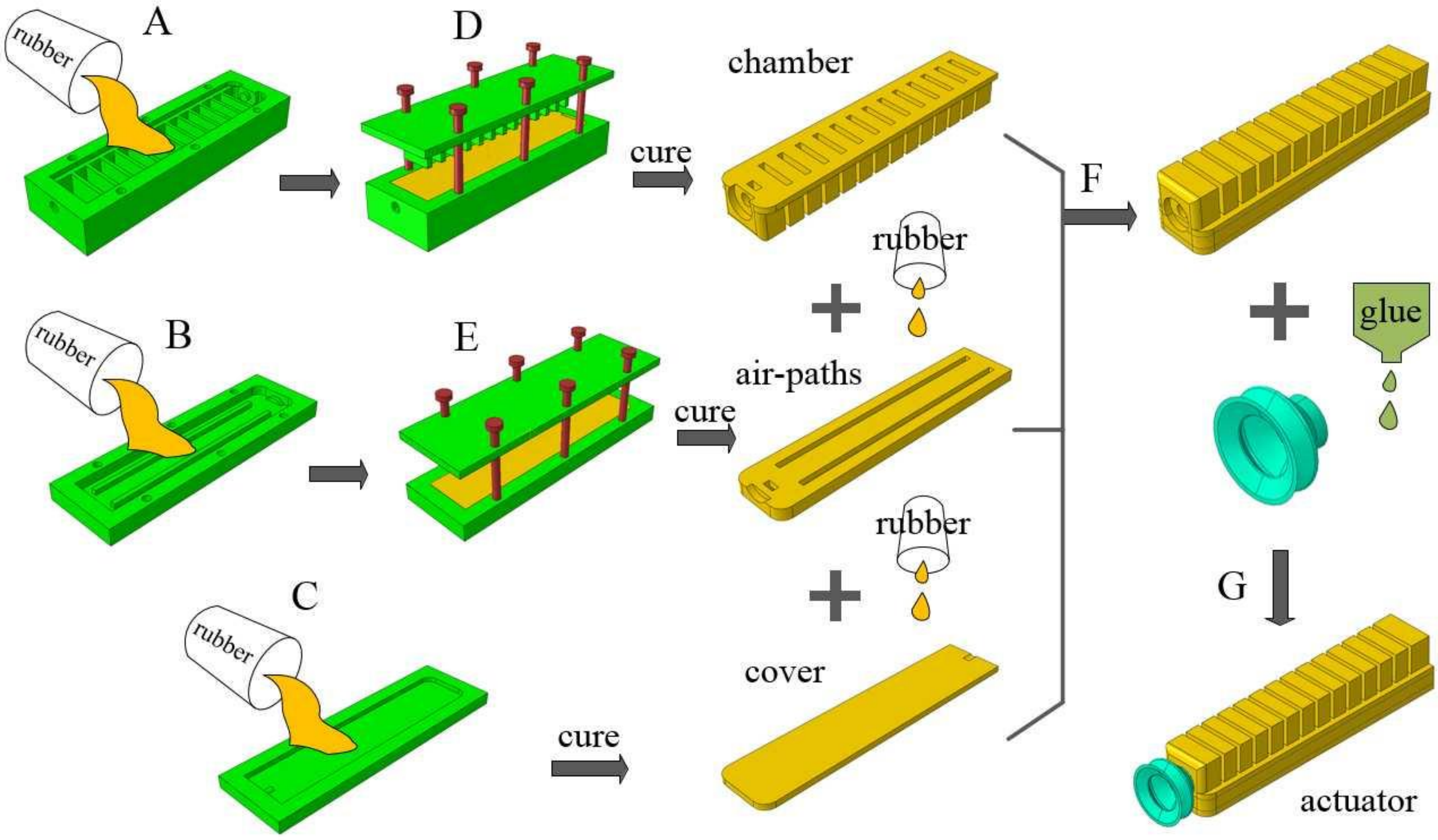
3D printing

Objet350 Connex (Stratasys)

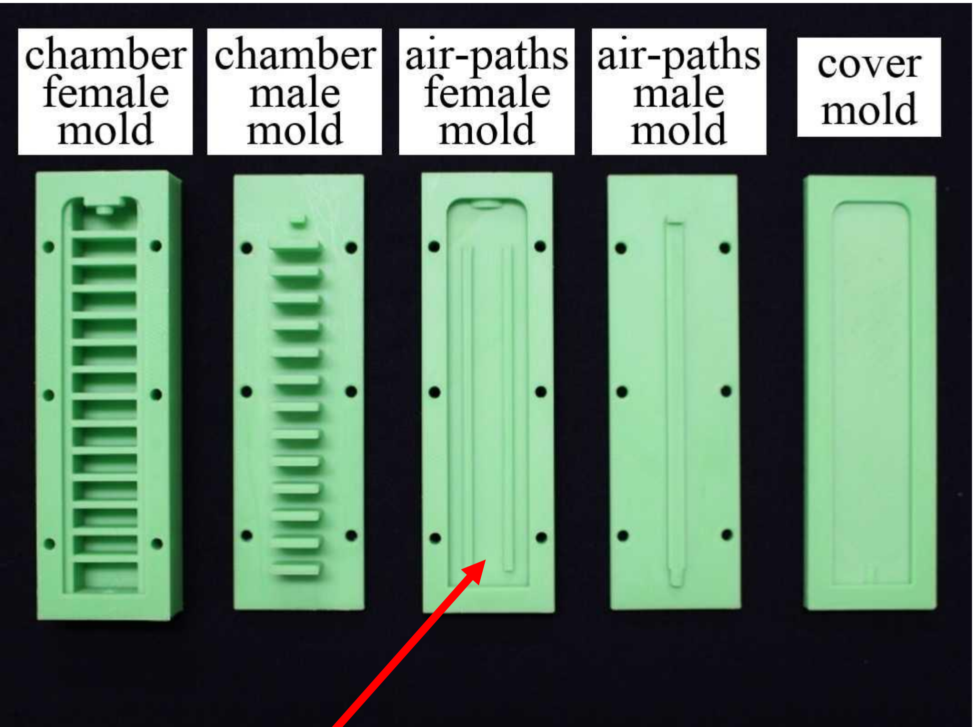


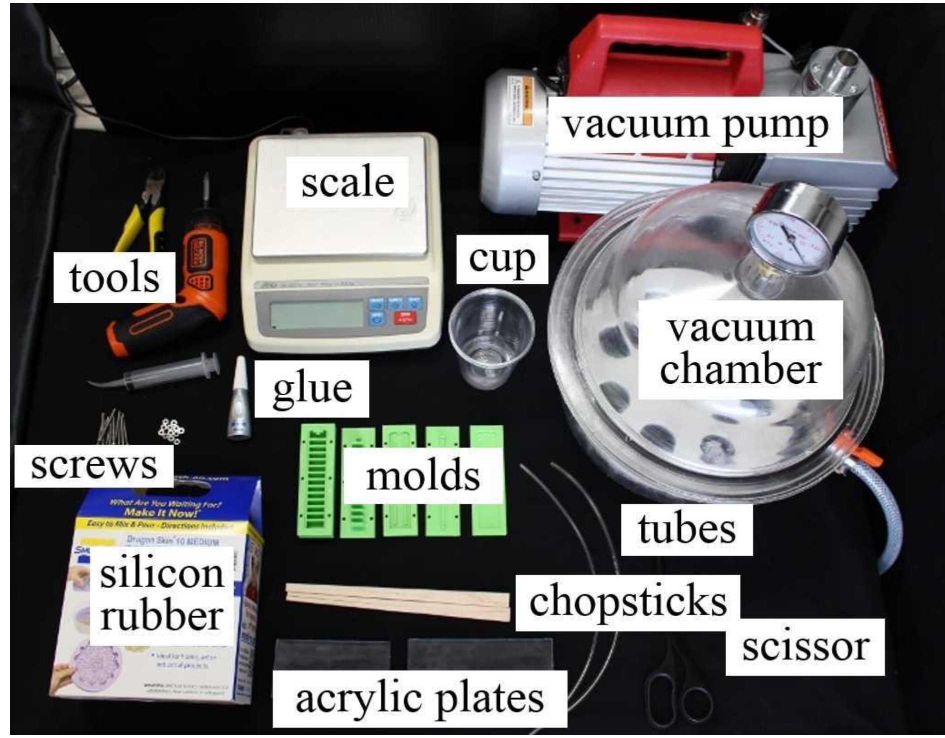
48 soft fingers

Example of casting

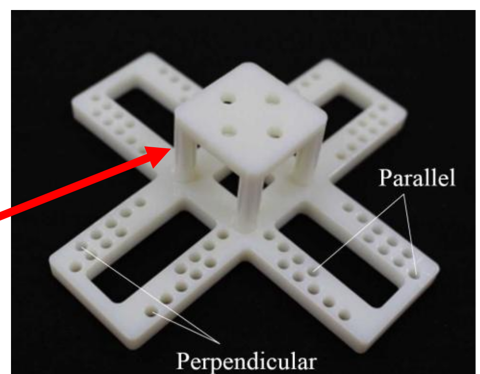


Things that you need





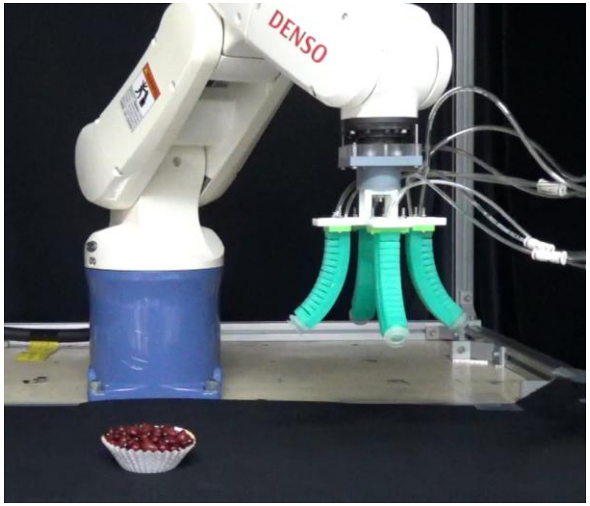
ABS or PLA



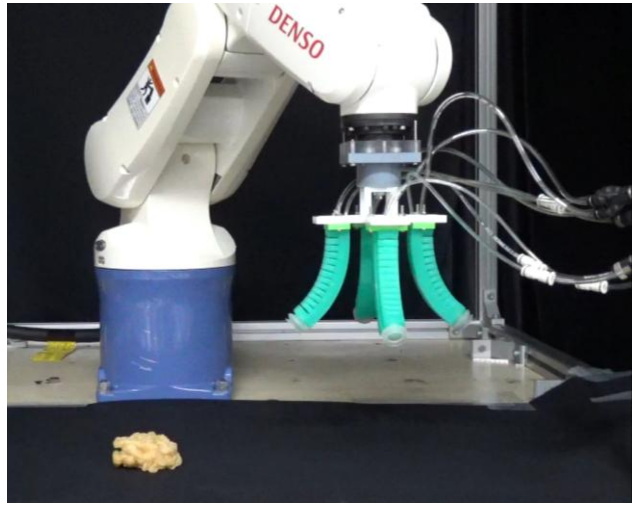
VeroWhite
Stratasys, Objet

Fabrication process

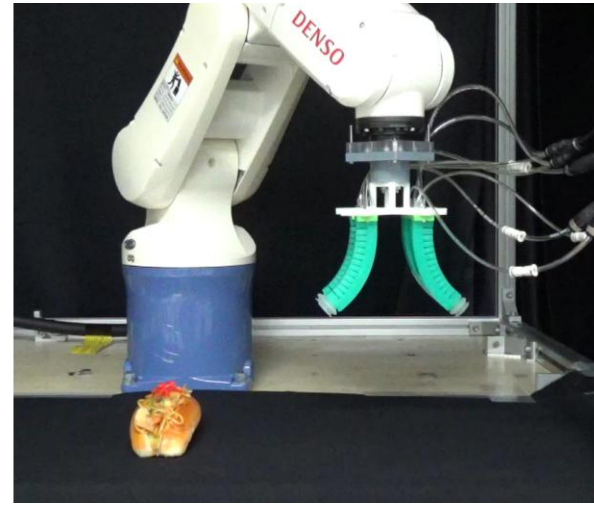
Performance of fabricated gripper



Grasping: red beans



Grasping: fried chicken



Grasping: hot dog

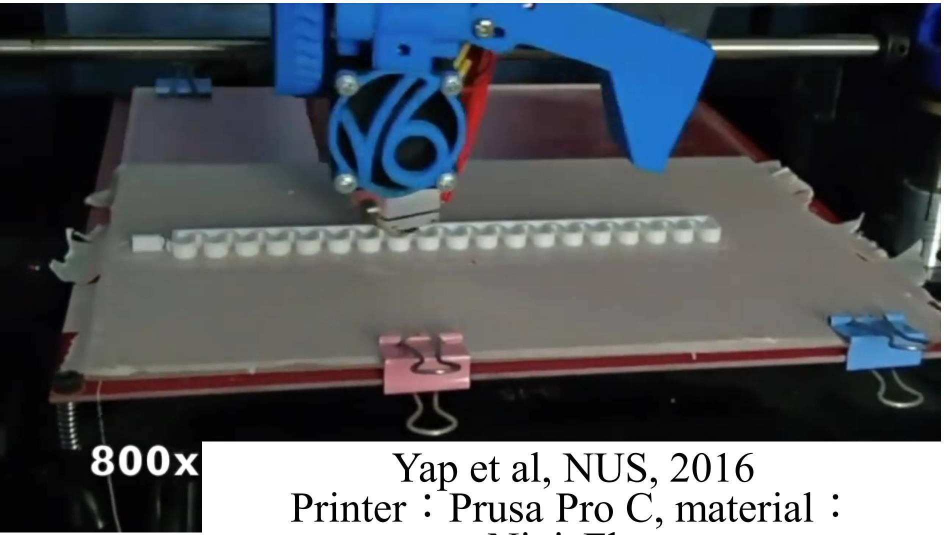
Suction: frozen hamburger

Suction: Mac Air

Bento packaging test

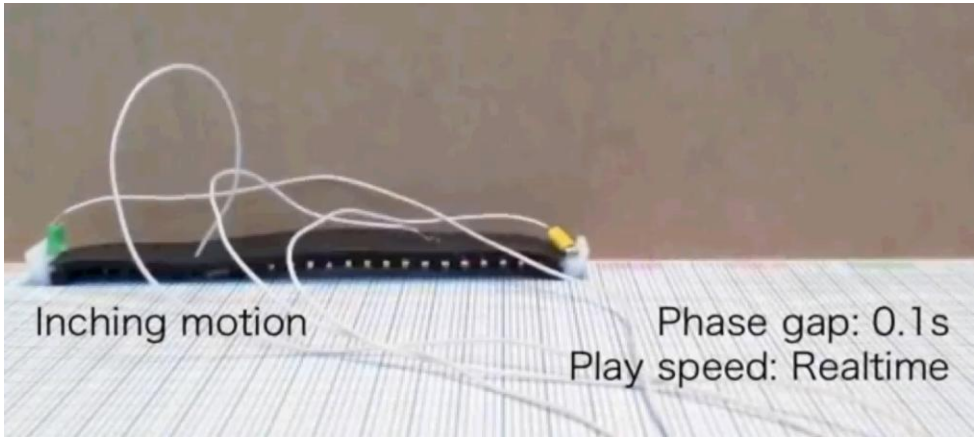
Examples of 3D printing

RITSUMEIKAN



Yap et al, NUS, 2016
Printer：Prusa Pro C, material：NinjaFlex

Umedachi, et al., 2013, Printer：Stratasys Objet 500, material：TangoBlackPlus

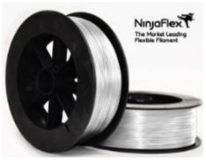


Raye et al, NUS, 2022
Printer：Prusa Pro C, material：NinjaFlex

Tolley et al., UC San Diego, 2017, Printer：Stratasys Objet 350, material: TangoBlackPlus

Videos from YouTube

3D printers that can be used to print soft materials

Printer name	Approach	Material	Hardness	Example
 Prusa	FDM	 NinjaFlex	Shore A85	
 Keyence Agilista	InkJet	Silicone like	Shore A60	
 Stratasys Objet	PolyJet	Rubber-like	Shore A27～Shore A95, 14 levels	
 MITS M3DS	DLP	Rubber-like	Shore A2～A50	
 RepRap L320	LAM	Liquid silicone rubber	Shore A30, A50, A70	

Manual casting vs. 3D printing

	Manual casting	3D printing
Pros	Durability Material candidates	Uniformity Efficiency Customizability
Cons	Uniformity Efficiency Customizability	Durability Material candidates

Cost

How to model and simulate soft EE?

Finite Element Model

Self coded models

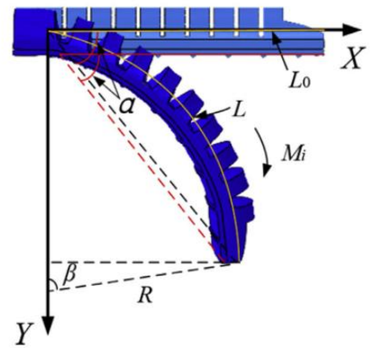
Ansys

SIMULIA ABAQUS

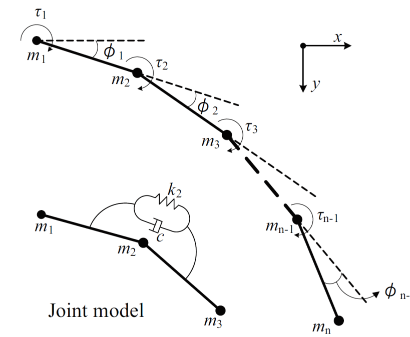
COMSOL MULTIPHYSICS®

SOFA

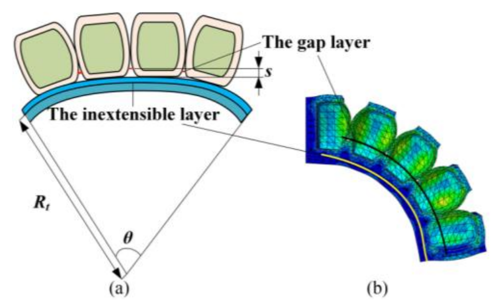
Other Models



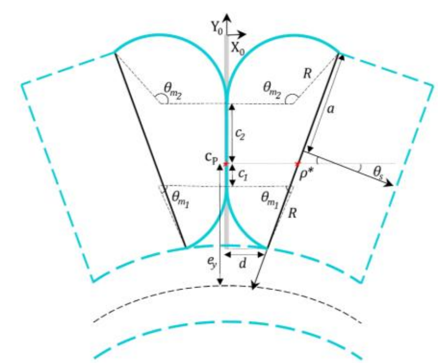
Beam constant curvature model



Line-segment model



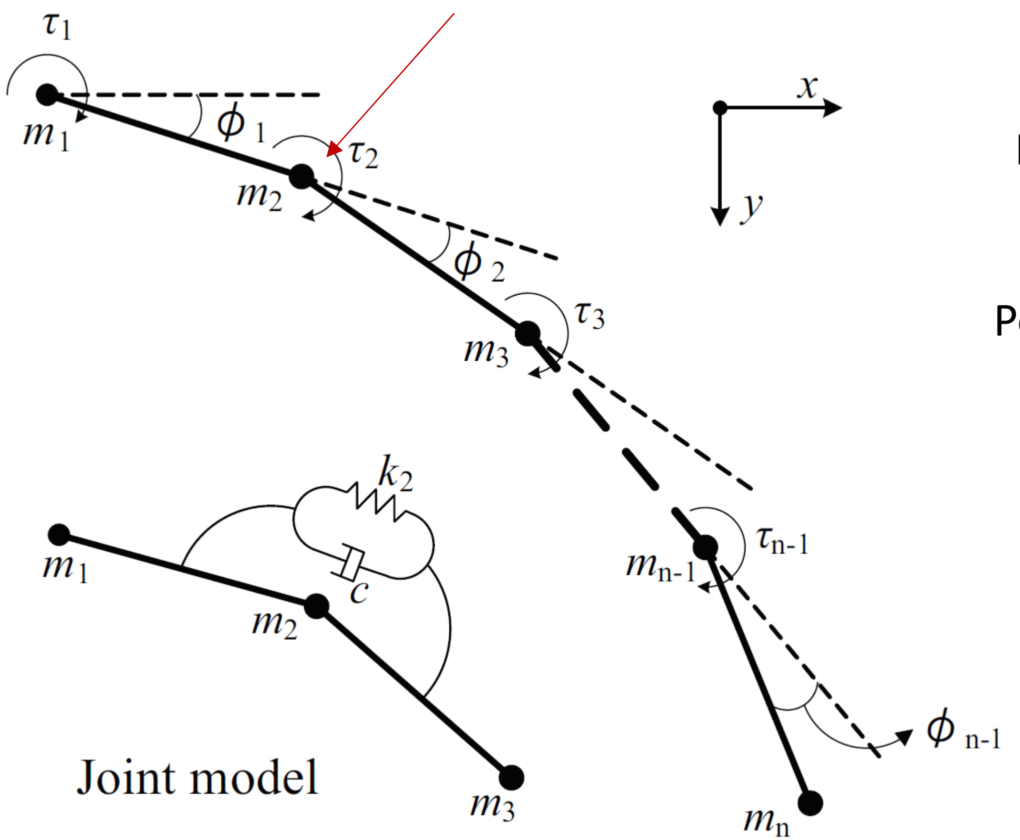
Serially connected constant curvature model



Finite strain membrane model

Line-Segment Model

$$\tau_i(P) = (a_i P + b_i)P,$$



Kinetic energy: $$T = \frac{1}{2}\sum_{i=1}^{n} m_i(\dot{x}_i^2 + \dot{y}_i^2).$$

Flexural energy: $$U_{flex} = \frac{1}{2}\sum_{i=1}^{n-1} k_i \phi_i^2.$$

Potential energy: $$U_{grav} = \sum_{i=1}^{n} m_i g y_i.$$

External work: $$W_{pres} = \sum_{i=1}^{n-1} \tau_i(P)\phi_i.$$

The Lagrangian:

$$L = T - U_{flex} - U_{grav} + W_{pres} + \sum_{i=1}^{n-1} \lambda_i R_i,$$

Line-Segment Model

Constraint: $R_i(x_i, x_{i+1}, y_i, y_{i+1}) \triangleq \{X_i^2 + Y_i^2\}^{\frac{1}{2}} - L_i,$

Constraint stabilization method: $\ddot{R}_i + 2\gamma \dot{R}_i + \gamma^2 R_i = 0, \quad (i = 1, 2, \cdots, n-1)$

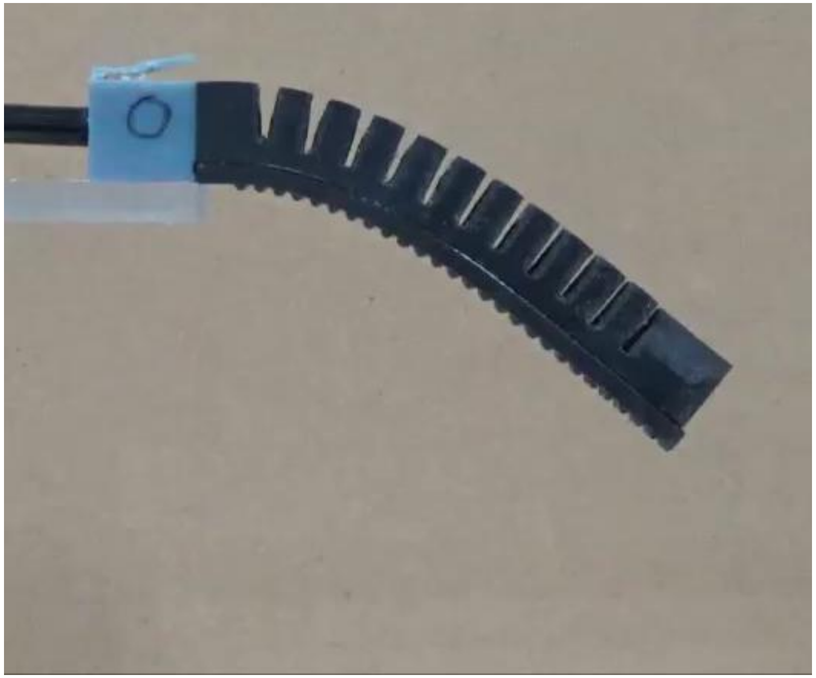
$$\frac{\partial L}{\partial x_i} - \frac{\mathrm{d}}{\mathrm{d}t}\frac{\partial L}{\partial \dot{x}_i} = 0,$$
$$\frac{\partial L}{\partial y_i} - \frac{\mathrm{d}}{\mathrm{d}t}\frac{\partial L}{\partial \dot{y}_i} = 0.$$

Lagrangian dynamics

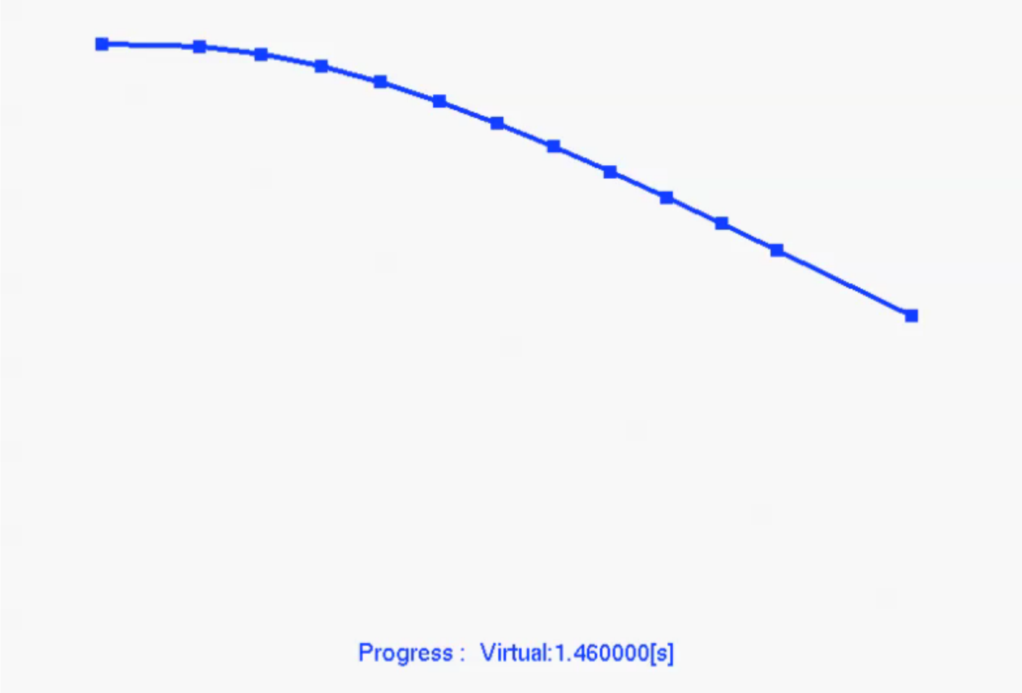
$$\begin{bmatrix} \mathbf{I} & \mathbf{0} & \mathbf{0} & \mathbf{0} & \mathbf{0} \\ \mathbf{0} & \mathbf{I} & \mathbf{0} & \mathbf{0} & \mathbf{0} \\ \mathbf{0} & \mathbf{0} & \mathbf{M} & \mathbf{0} & \mathbf{A}_x \\ \mathbf{0} & \mathbf{0} & \mathbf{0} & \mathbf{M} & \mathbf{A}_y \\ \mathbf{0} & \mathbf{0} & \mathbf{A}_x^{\mathrm{T}} & \mathbf{A}_y^{\mathrm{T}} & \mathbf{0} \end{bmatrix} \begin{bmatrix} \dot{\mathbf{x}} \\ \dot{\mathbf{y}} \\ \dot{\mathbf{v}}_x \\ \dot{\mathbf{v}}_y \\ \lambda \end{bmatrix} = \begin{bmatrix} \mathbf{v}_x \\ \mathbf{v}_y \\ \mathbf{F}_x \\ \mathbf{F}_y \\ \mathbf{F}_c \end{bmatrix}$$

Line-segment model

Simulation



Experiment

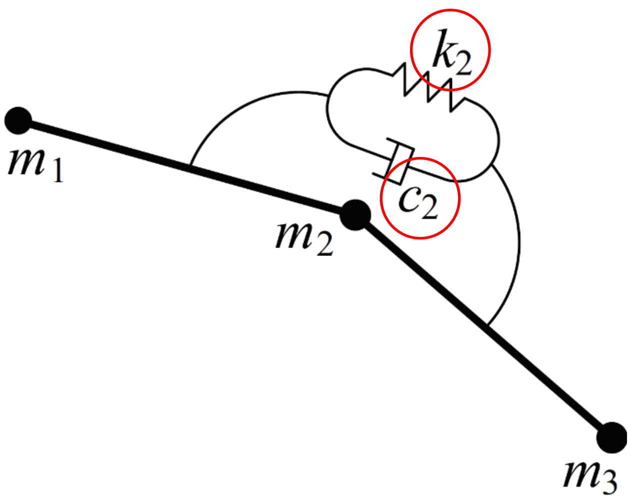


Simulation

Z. Wang, et al., IEEE RAL, 2017

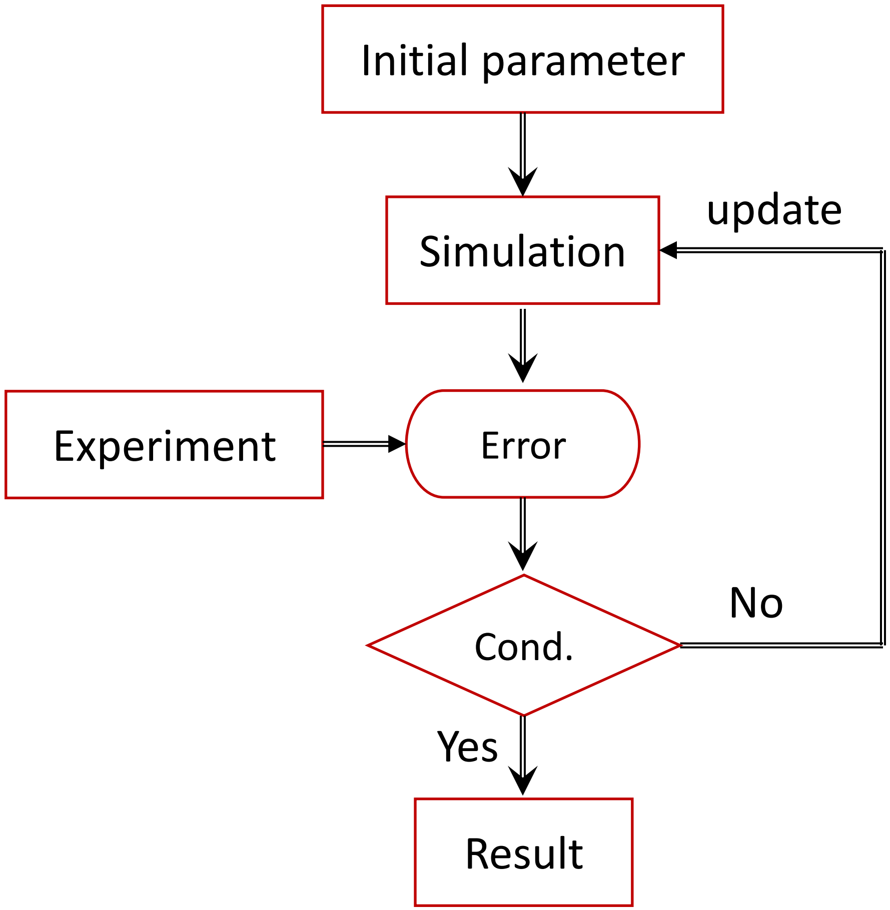
Parameter Identification

Unknown parameters

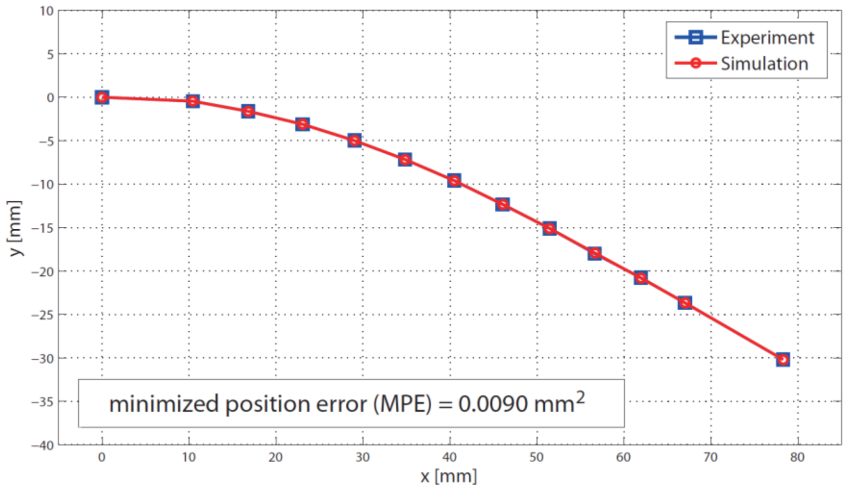


$$\tau_i(P) = (a_i P + b_i) P,$$

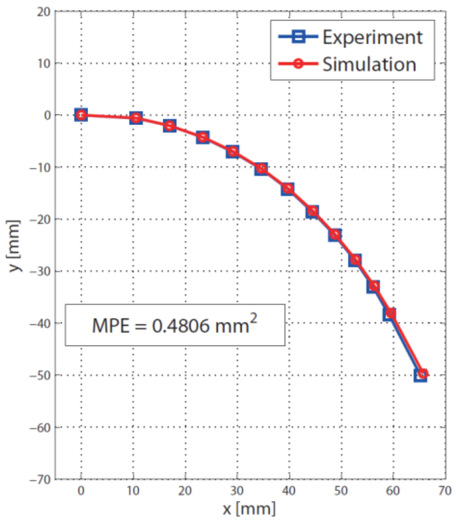
Optimization based method



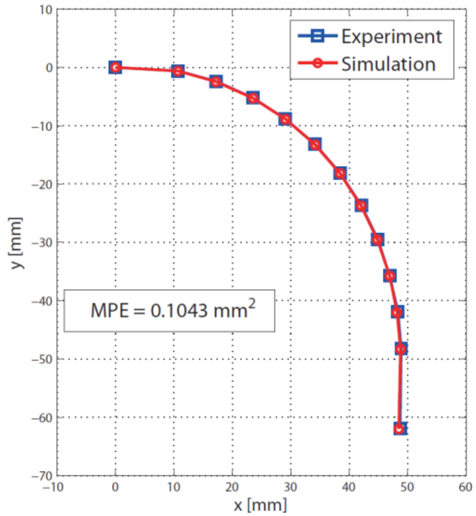
Identification results and validation



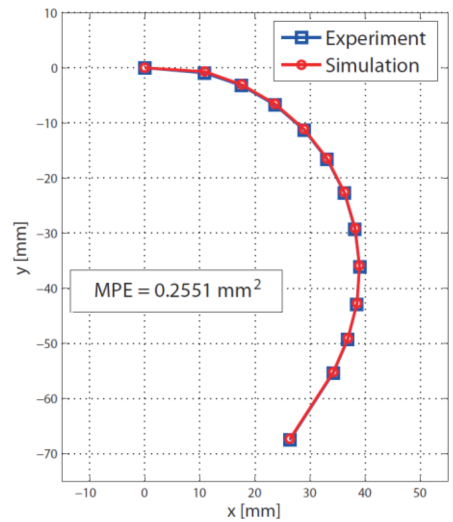
Under gravity



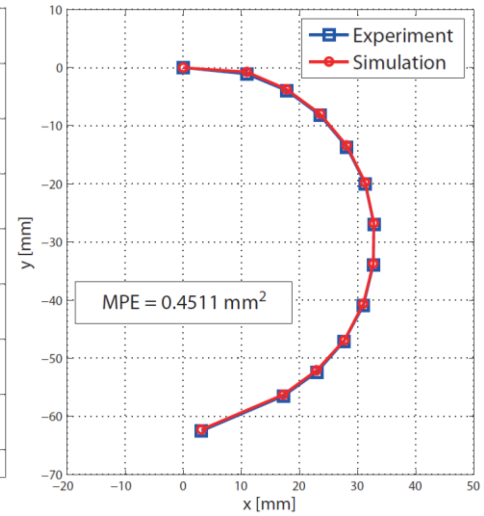
P = 10 kPa



P = 20 kPa

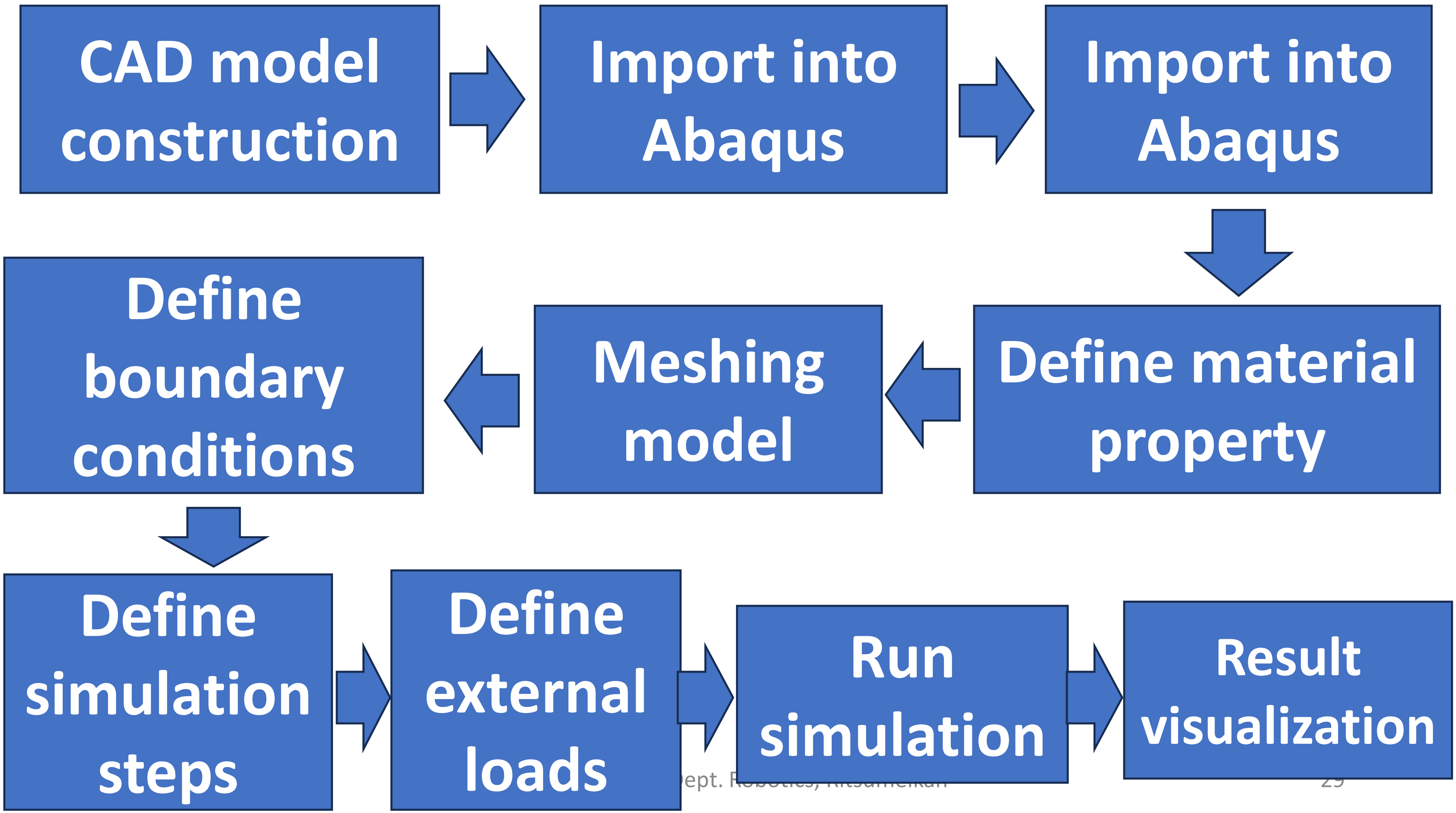


P = 30 kPa

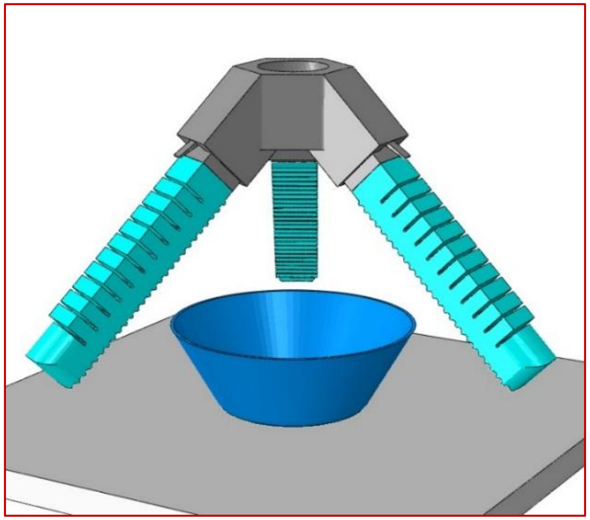


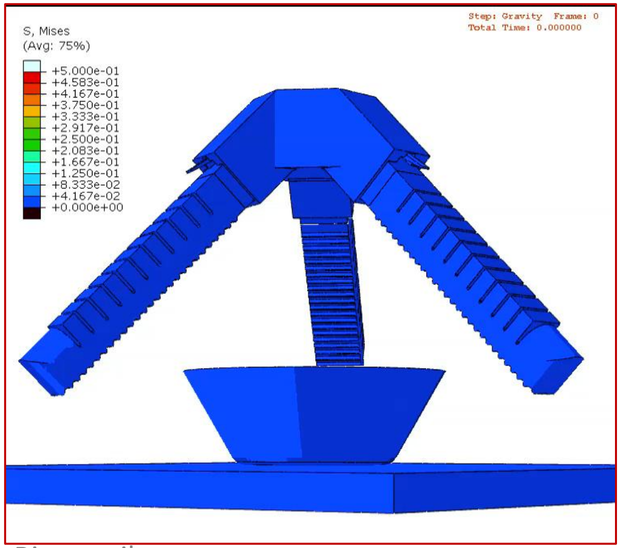
P = 40 kPa

Finite Element Modeling (Abaqus)

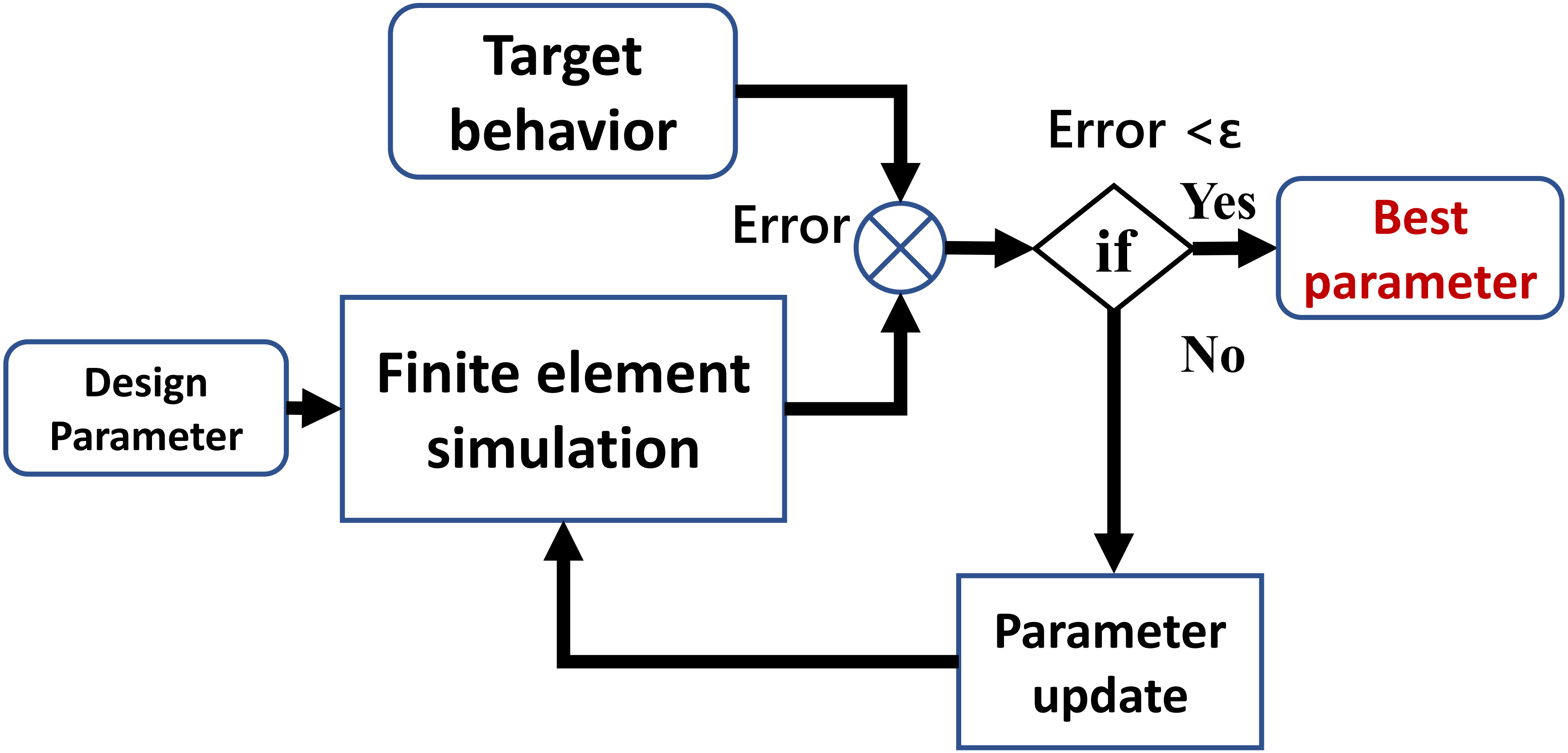


Example of Finite Element Simulation

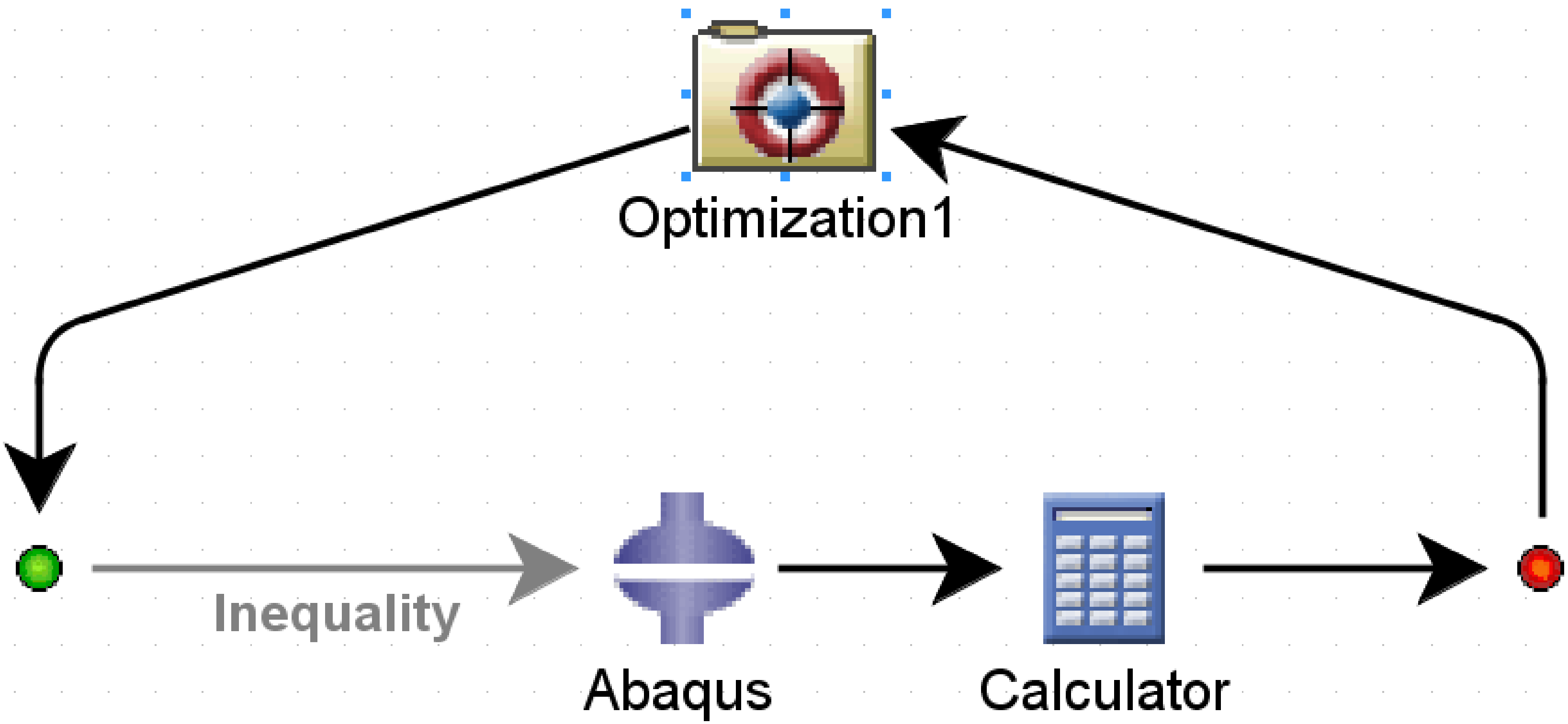




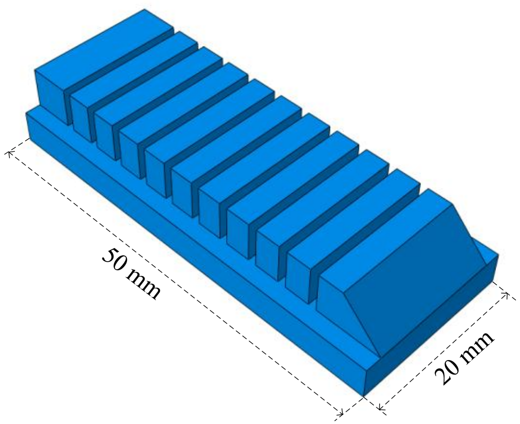
Parameter Identification Method

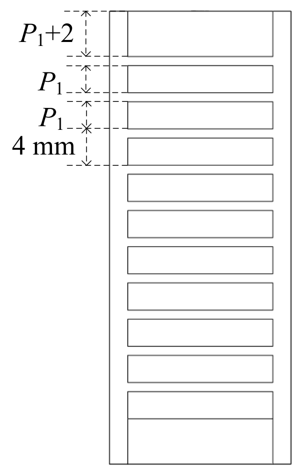


Parameter Identification using Abaqus and Isight

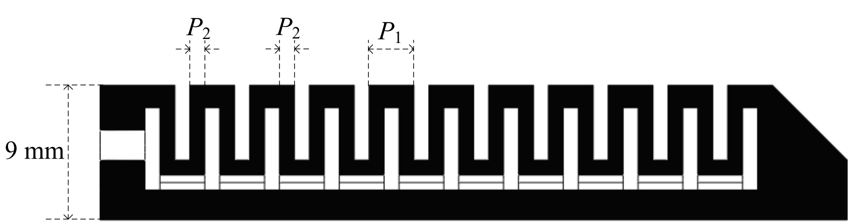


Example of Design Optimization





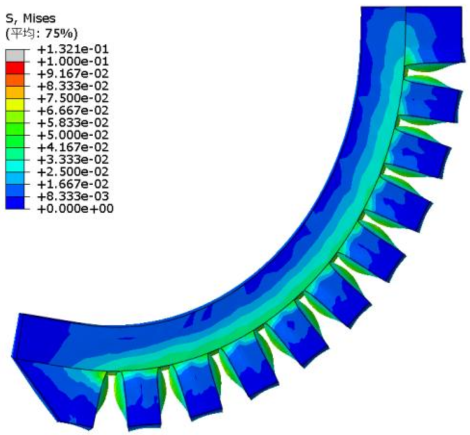
Design parameters： [P1, P2]



Design parameterization

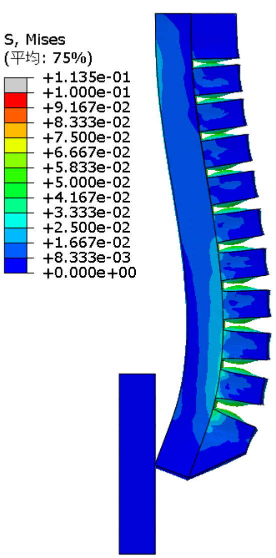
Free deformation

Initial parameters:
P1 = 3.0 mm
P2 = 1.0 mm



Grasping case

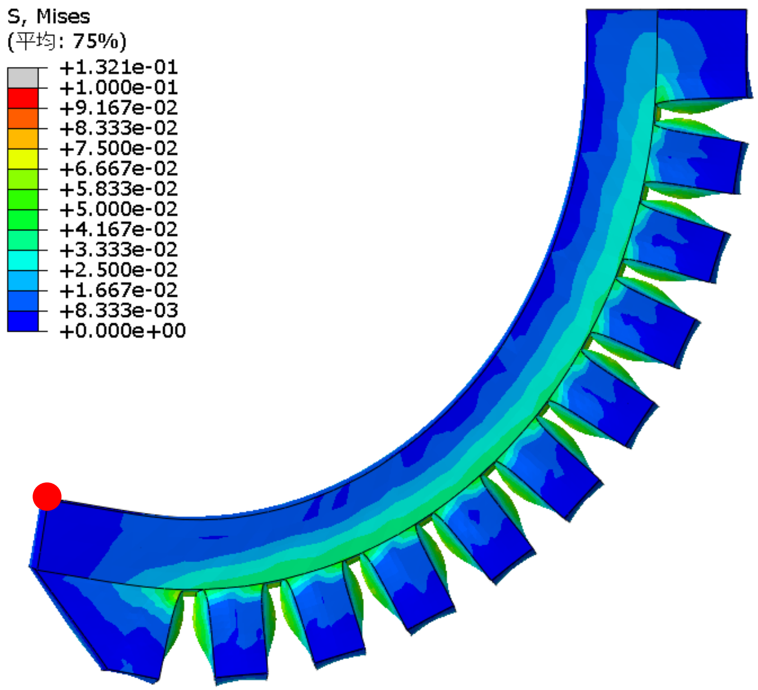
Initial parameters:
P1 = 3.0 mm
P2 = 1.0 mm



Optimization Results
--- Maximum Bending

Initial parameters:

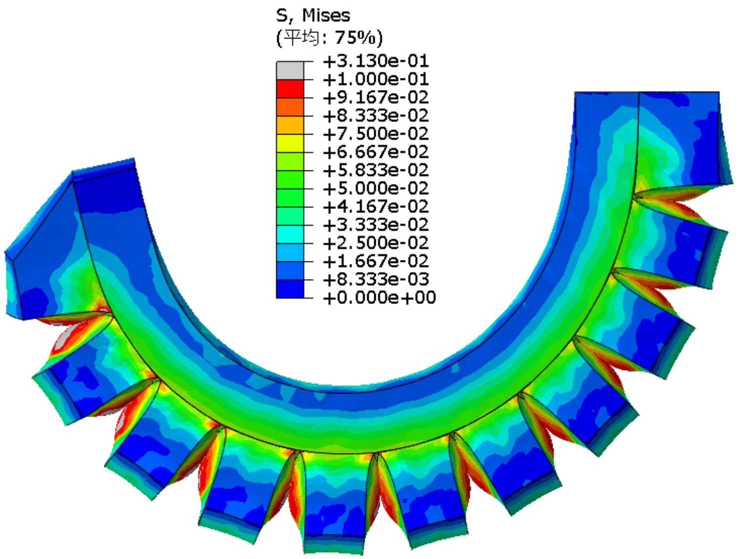
P1 = 3mm, P2 = 1mm



Deformation = 22.38 mm

Optimized parameters:

P1 = 3.8mm, P2 = 0.6mm

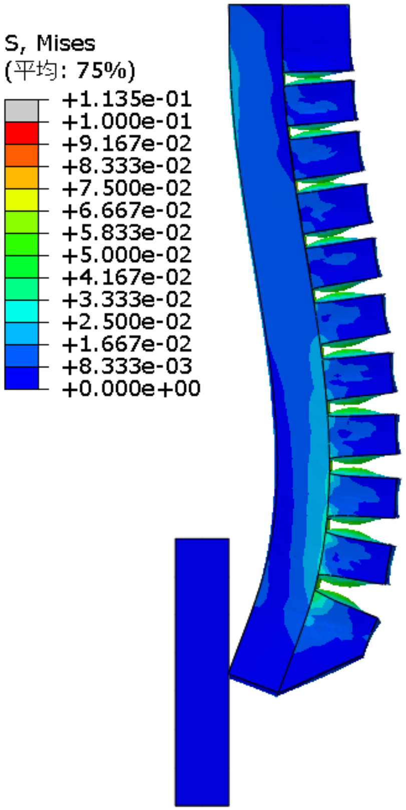


Deformation = 45.47 mm

Optimization Results --- Maximum Force

Initial parameters:

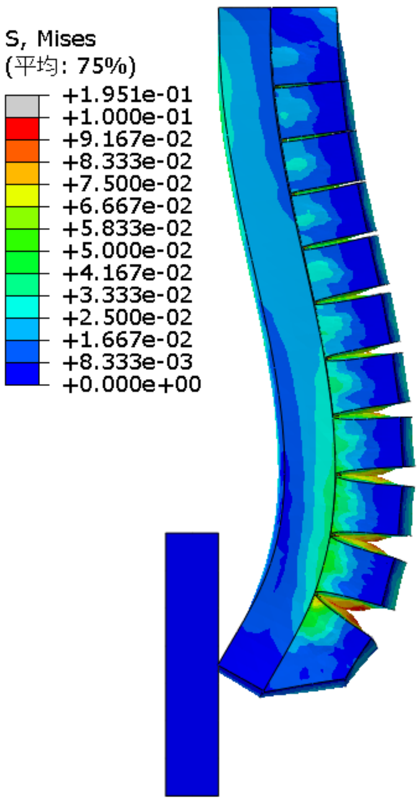
P1 = 3mm, P2 = 1mm



Force = 57.3 mN

Optimized parameters:

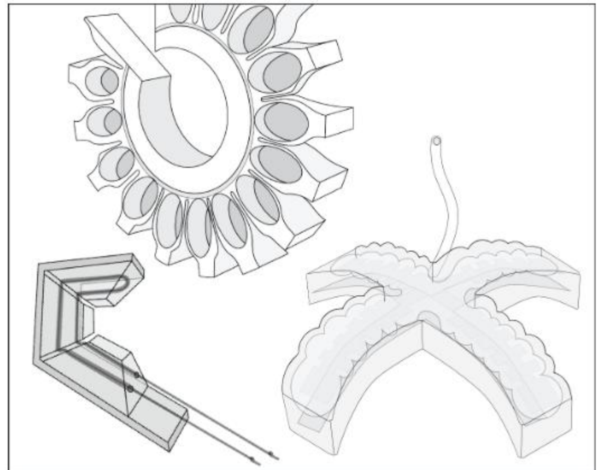
P1 = 3.8mm, P2 = 0.6mm



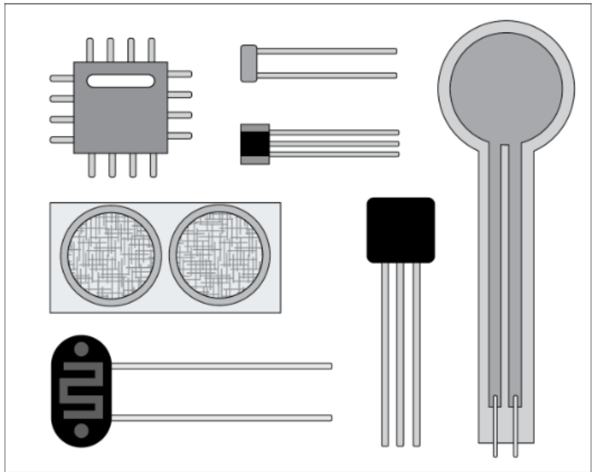
Force = 108.6 mN

Learning Resources

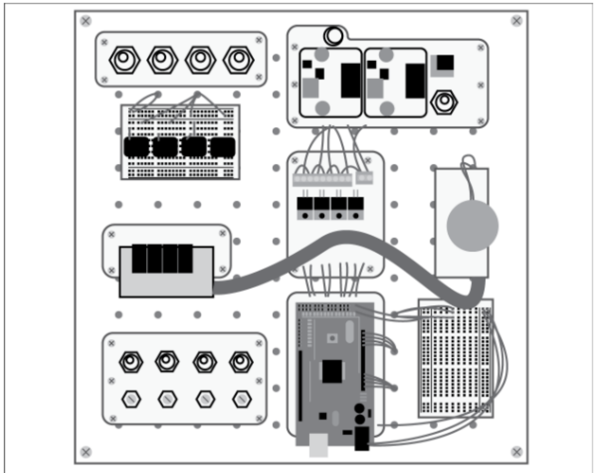
soft robotics toolkit



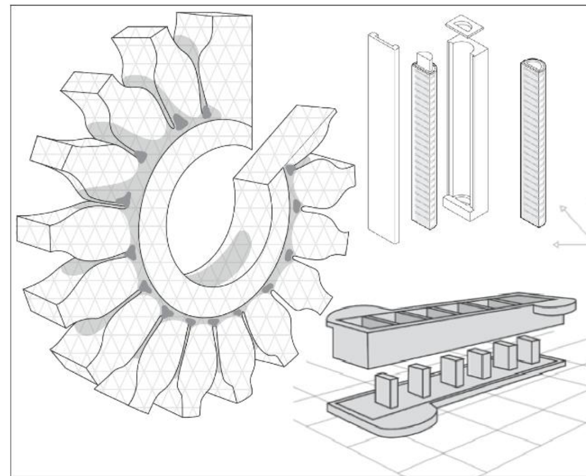
Actuators



Sensors



Controls



Modeling and Manufacturing

Soft Robotics Toolkit---Actuator

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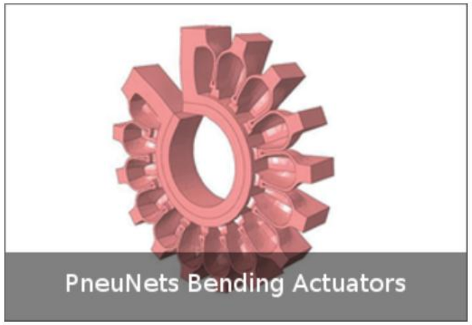
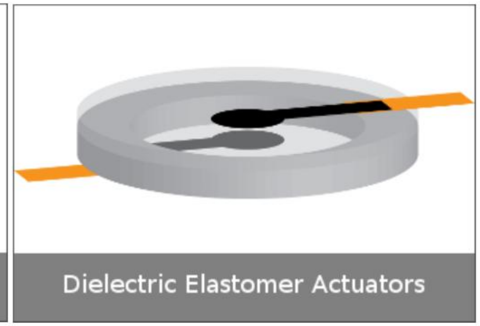

PneuNets Bending Actuators

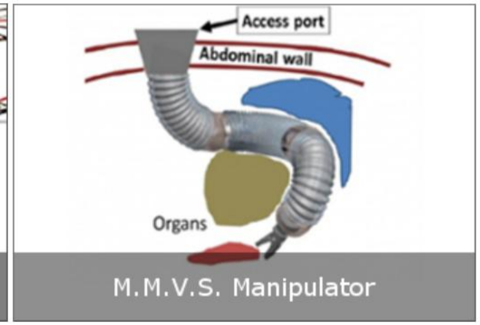

Fiber-Reinforced Actuators


Dielectric Elastomer Actuators

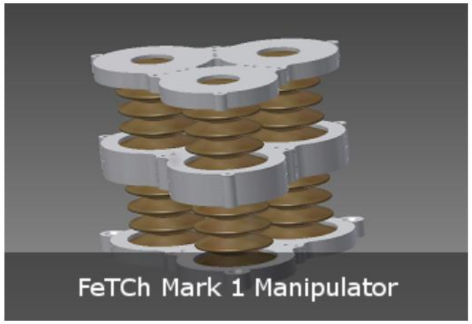

Combustion-Driven Actuators


Pneumatic Artificial Muscles


SDM Fingers

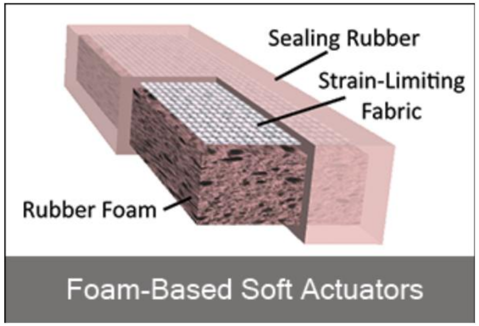


M.M.V.S. Manipulator

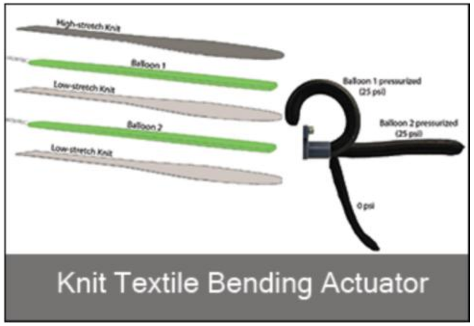

FeTCh Mark 1 Manipulator


HPN Manipulator


3D Printed Soft Gripper Stiffened by Passive Particle Jamming



Foam-Based Soft Actuators


Knit Textile Bending Actuator

What Are Potential Applications?

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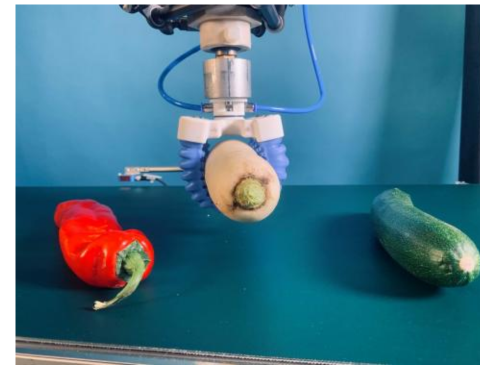
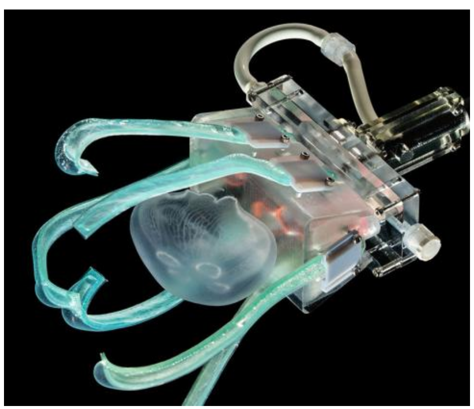
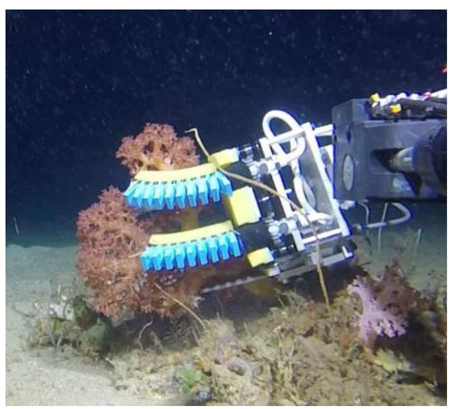
Food industry

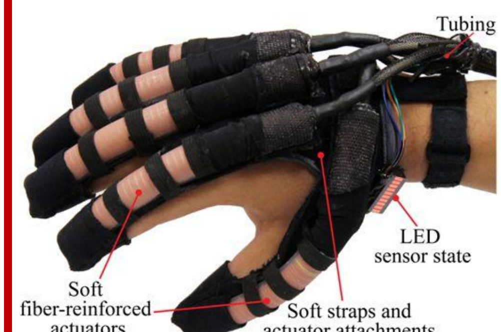

Agriculture and Fishery

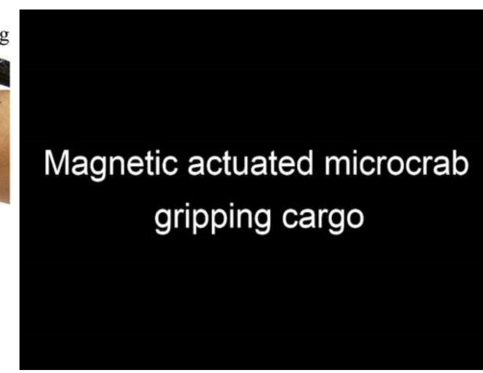


Living creature grasping

Biomedical application





Main Applications that We are Focusing on

Automation Challenges in the Food Industry and Agriculture

① Grasping

1. Too many categories
2. Large differences
3. Complex properties
4. Soft and fragile

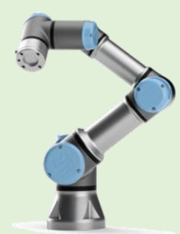
② Recognition

Random picking scenario

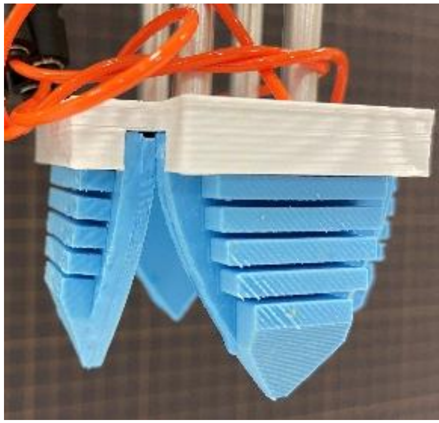
③ Application

1. Food compatibility
2. High speed motion
3. Durability
4. Contamination
5. Sterilization
6. Ease of use

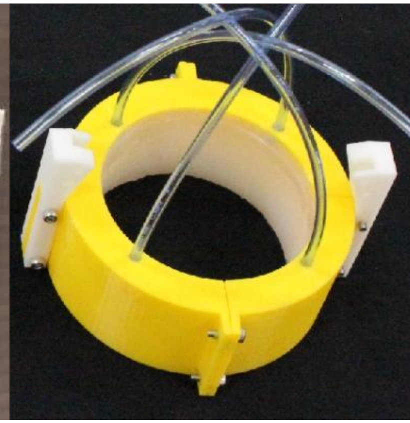
④ Cost

Hardware	Software	SI
 	Recognition Machine learning Image processing Conveyor tracking	System Integration Maintenance

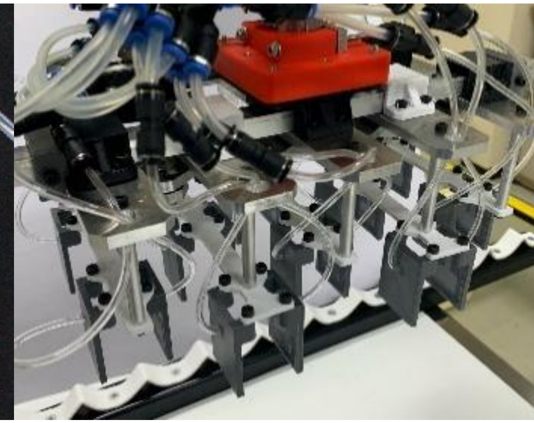
Soft robotic end-effectors developed by our group



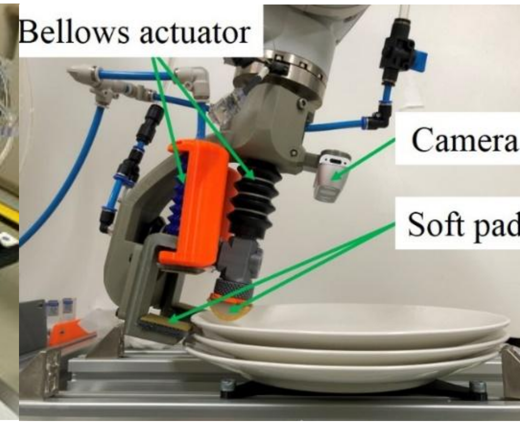
Wrapping gripper



Circular shell gripper



Parallel shell gripper

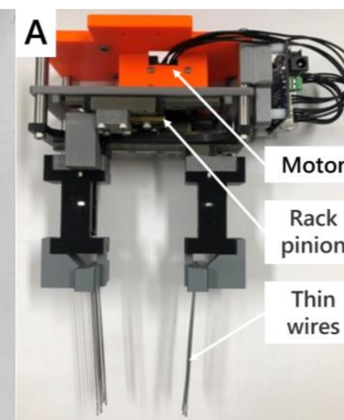


Dishwashing hand

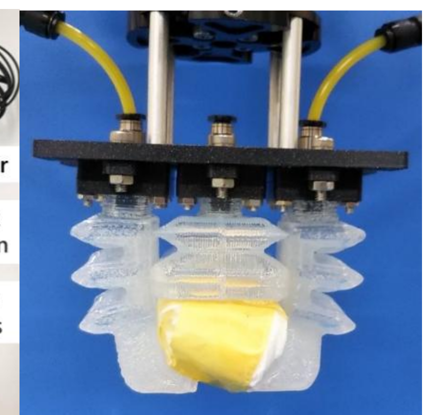
Needle gripper

Scooping-binding gripper

Bellows gripper



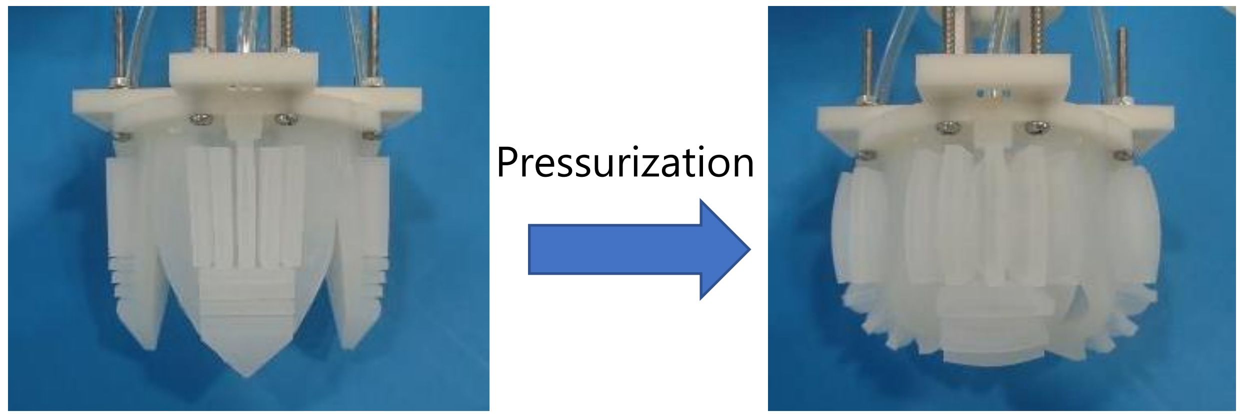
Multi-wire gripper



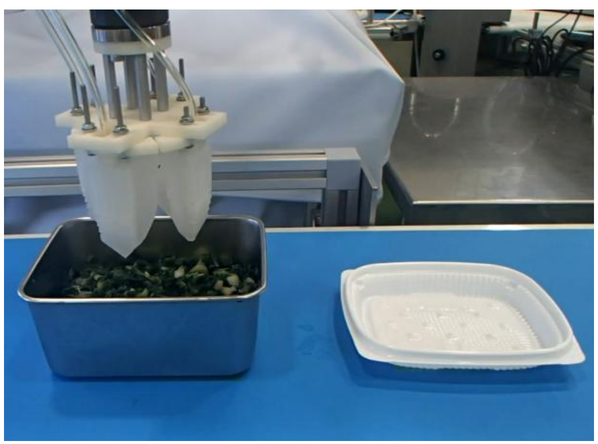
Shovel gripper

1. Wrapping gripper

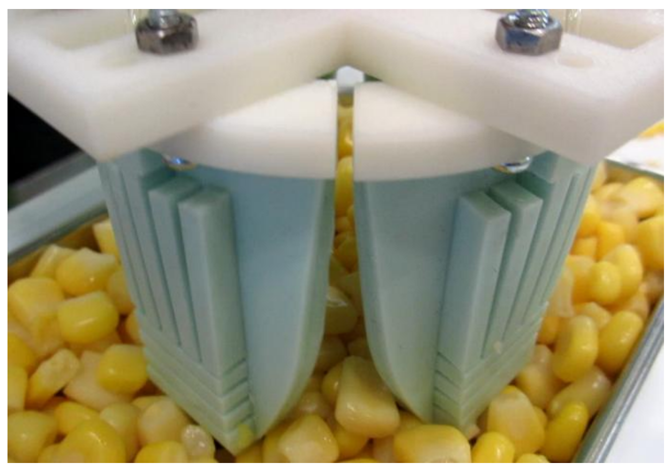
Granular food



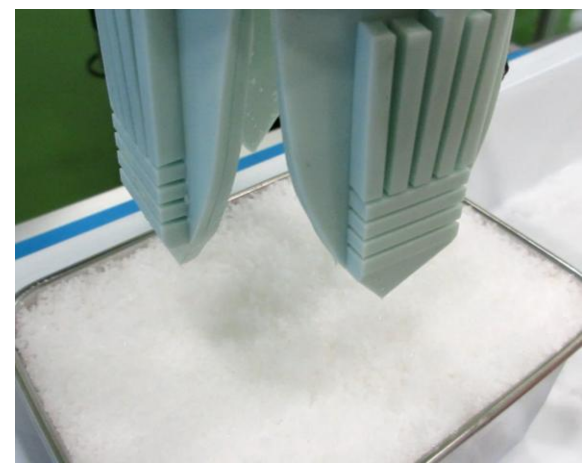
Wrapping gripper



Grasping of chopped green onion



Grasping of corn

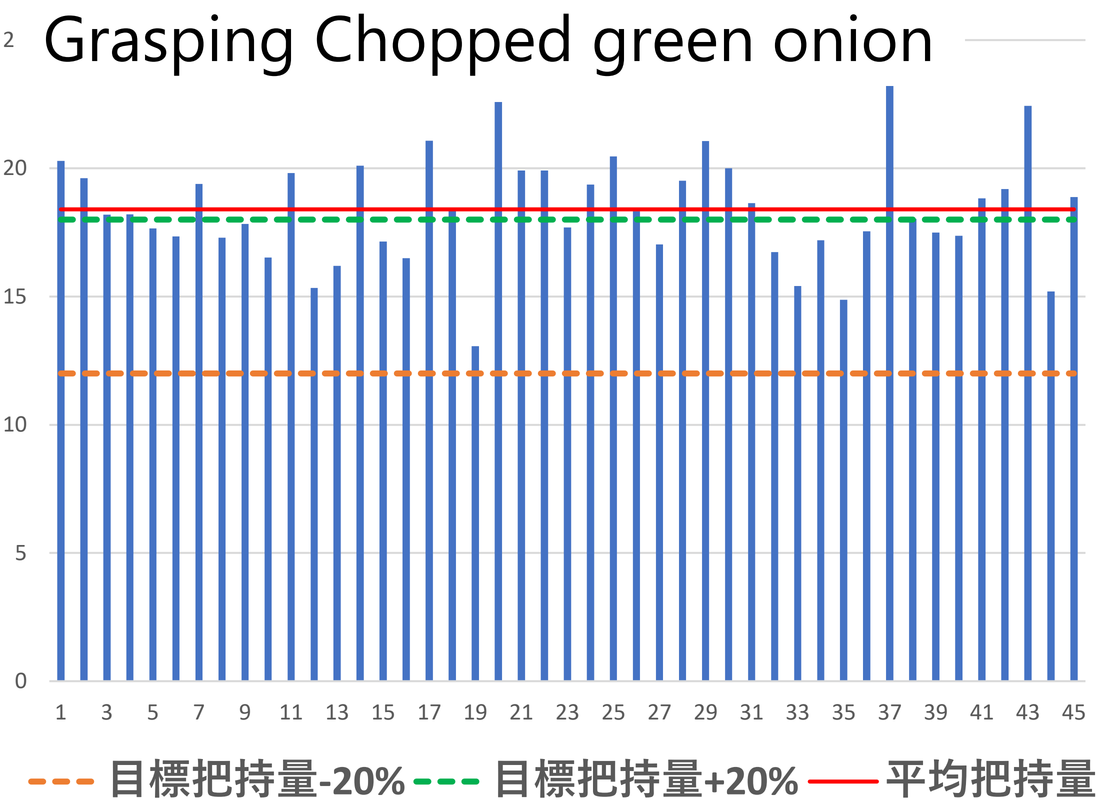


Grasping of salt

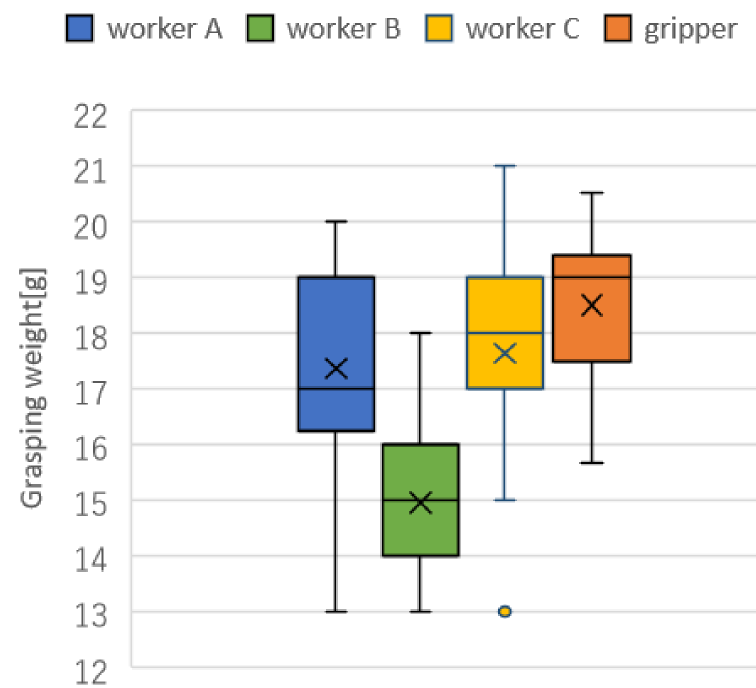
Kuriyama et al., IEEE RoboSoft 2019

System Performance

Grasping results of specified weight



Average	STD [g]	RSTD
18.4 g	2.09 g	11.4%

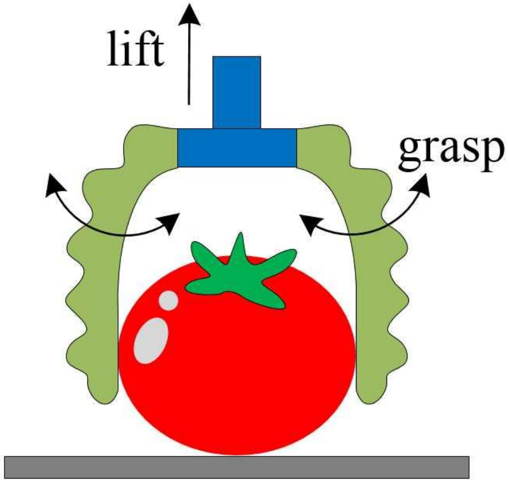


Results comparison with human worker

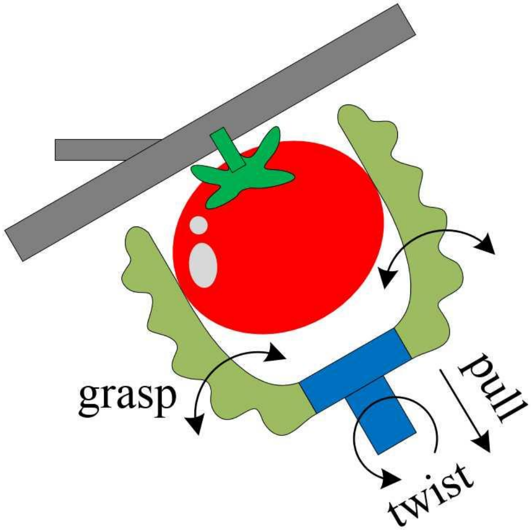
2. Circular shell gripper

Daifuku mochi

Harvesting tomato



Grasping and lifting

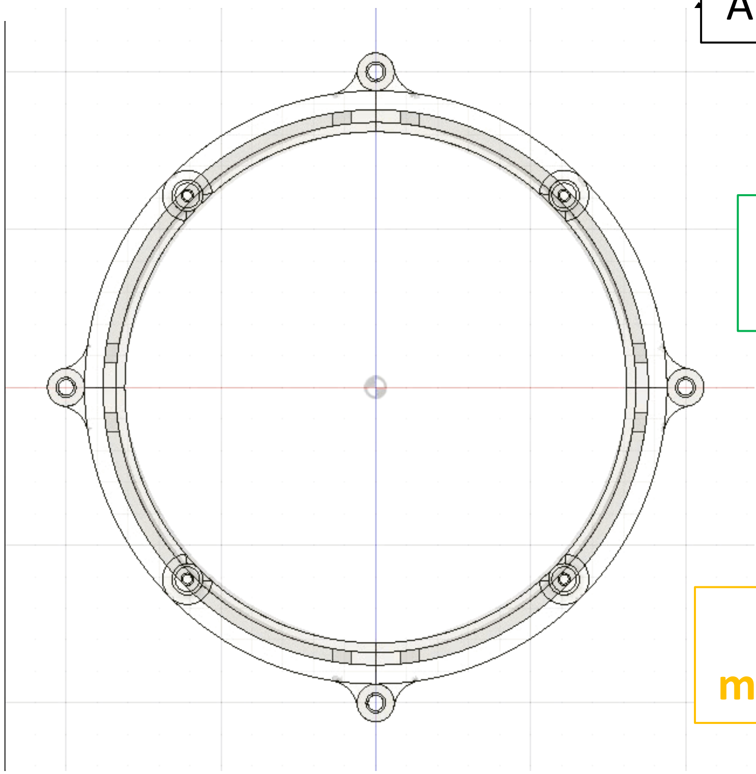


Pulling while twisting

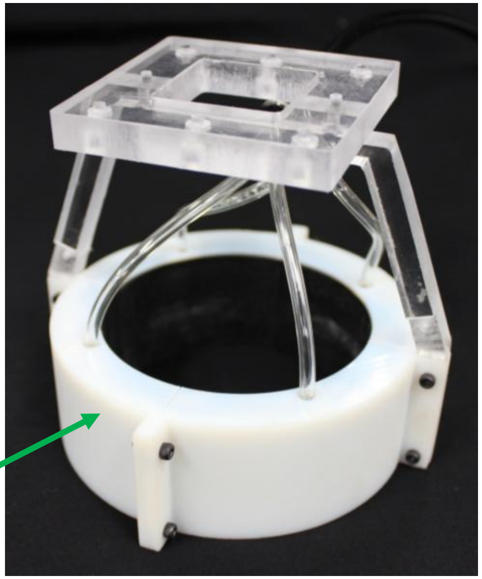
A gripper capable of doing both

Idea of shell gripper

Air chamber

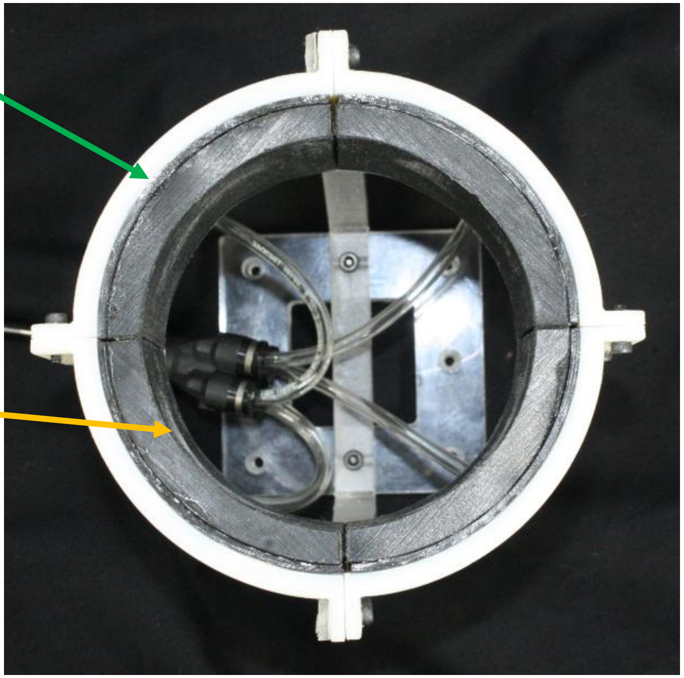


Shell gripper image



Rigid shell

Soft membrane



Fabricated shell gripper

Grasping performances

Circular shell gripper for handling food products

Zhongkui Wang, Kanegae Ryo, Shinichi Hirai
Ritsumeikan University, Japan

Wang et al., Soft Robotics, 2021

3. Parallel shell gripper

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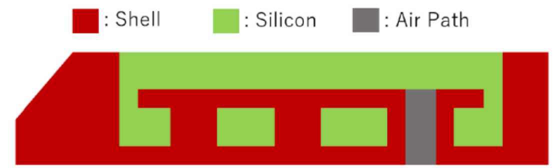
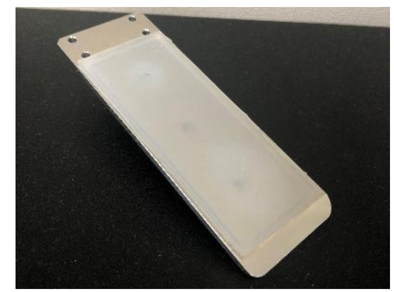
Cucumber packaging by human

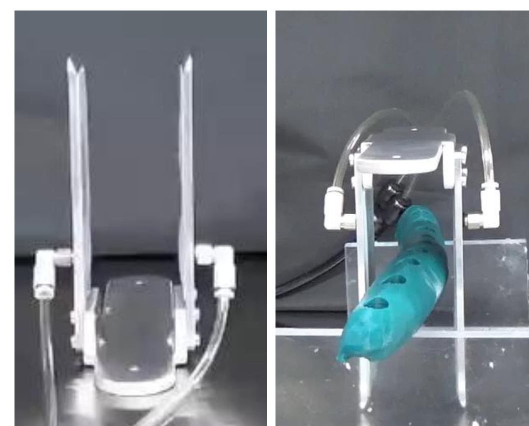
Parallel shell gripper



Cross-section view



Prototype

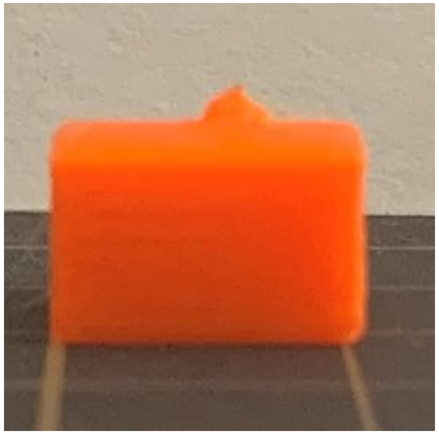


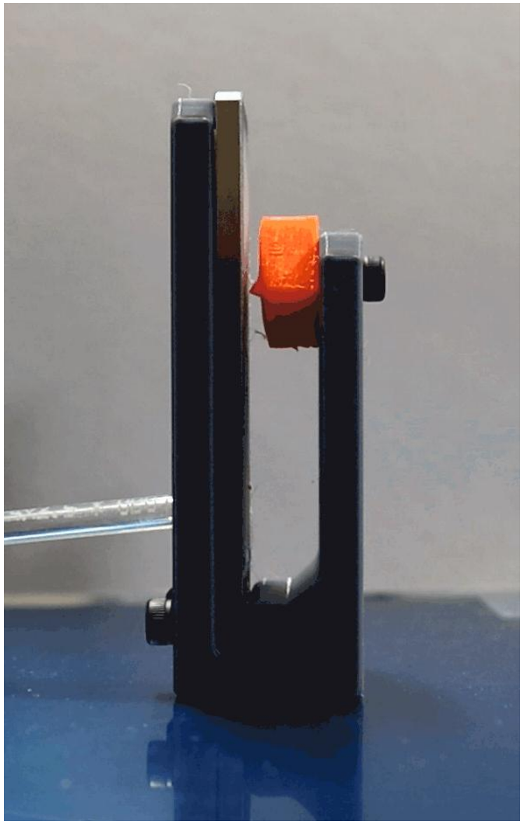
Grasping test

System requirements：

1. Productively: 30 t / day
2. Grasping
3. Takt time: 7 sec
4. No damage to product
5. Durable to thorns
6. Small gaps among products
7. Adaptable to differences
8. Grasping failure detection
9. Remote monitoring
10. Low cost

Durability tests



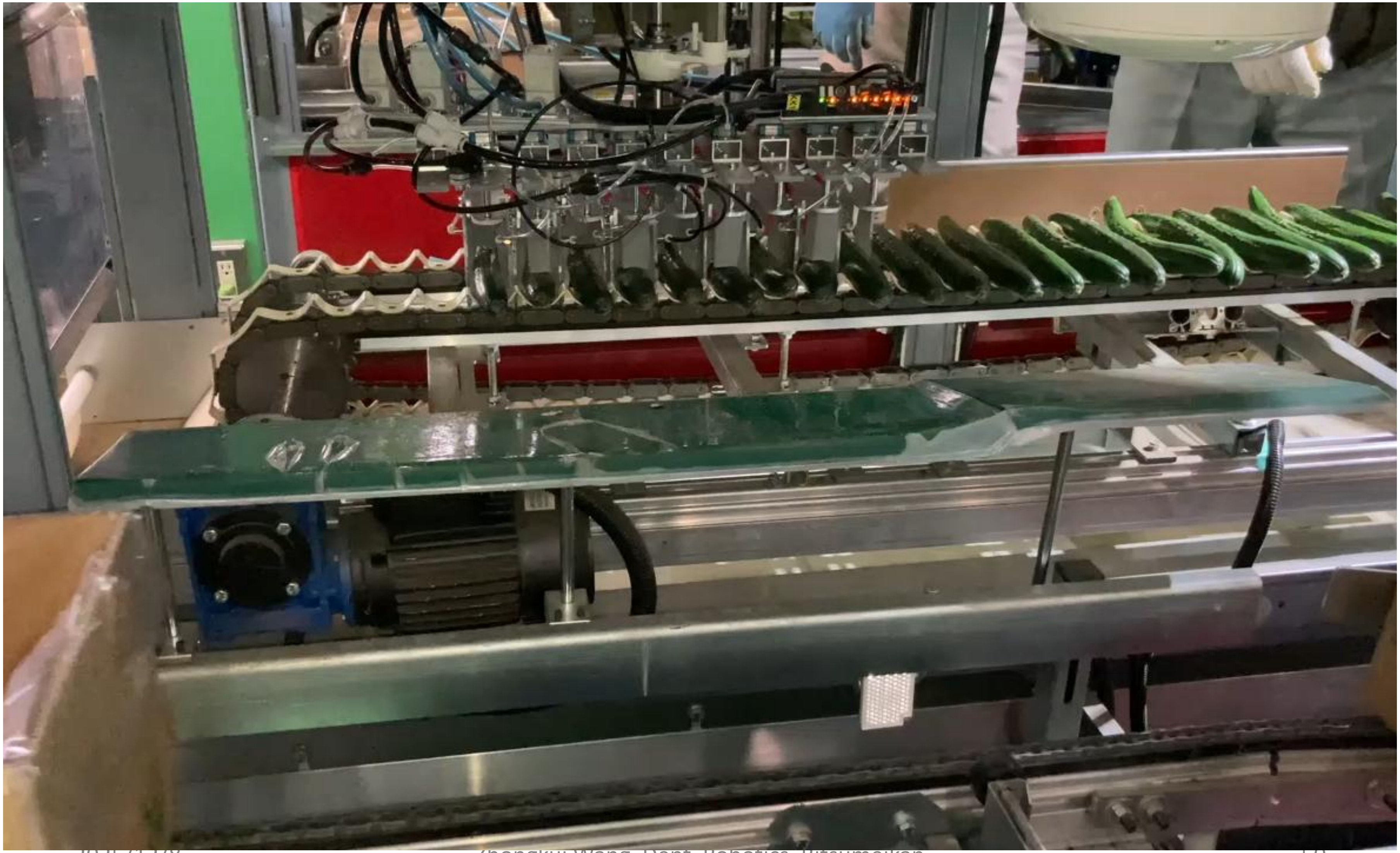


Sample of cucumber thorn

材質	SUS304		
印加圧力 [kPa]	18	16	14
ふくらみ量（算出値）[mm]	9.75	8.77	7.78
耐用回数	15015	16779	10 万回以上

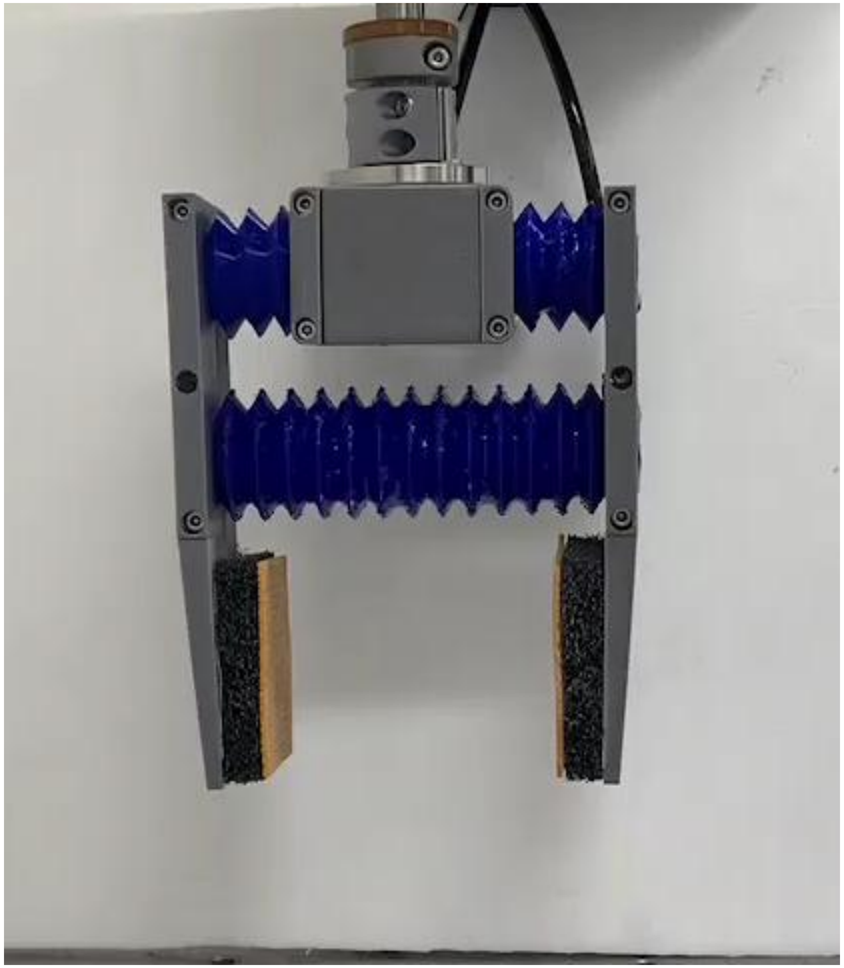
Kanegae et al., IEEE RCAR 2020

Field experiment



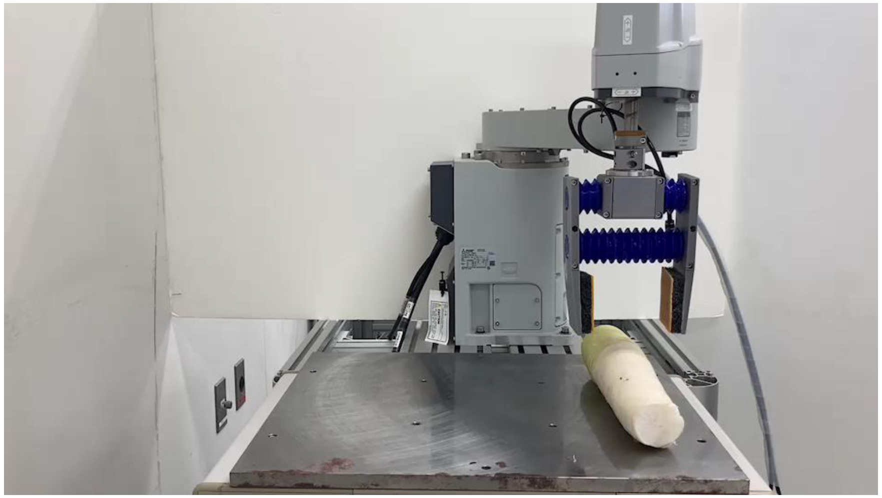
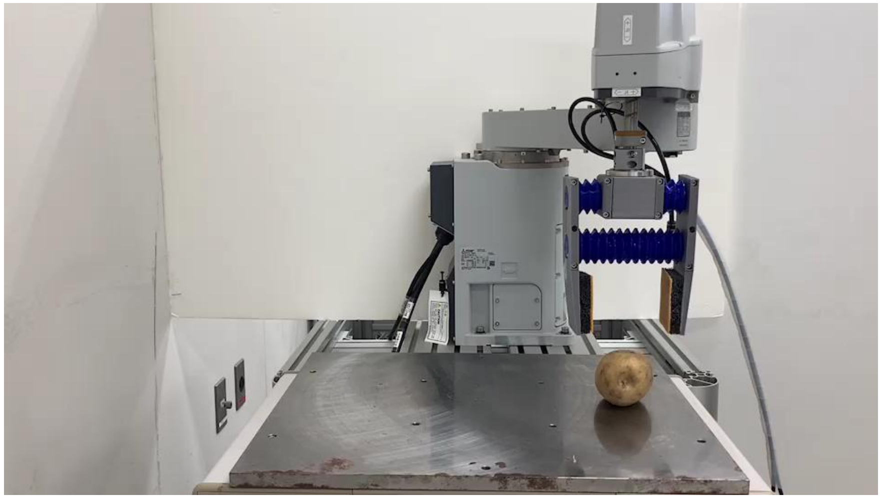
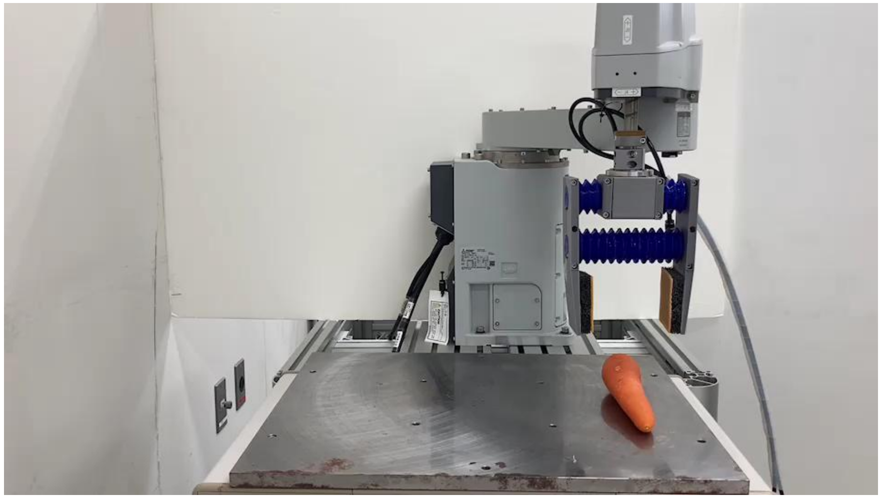
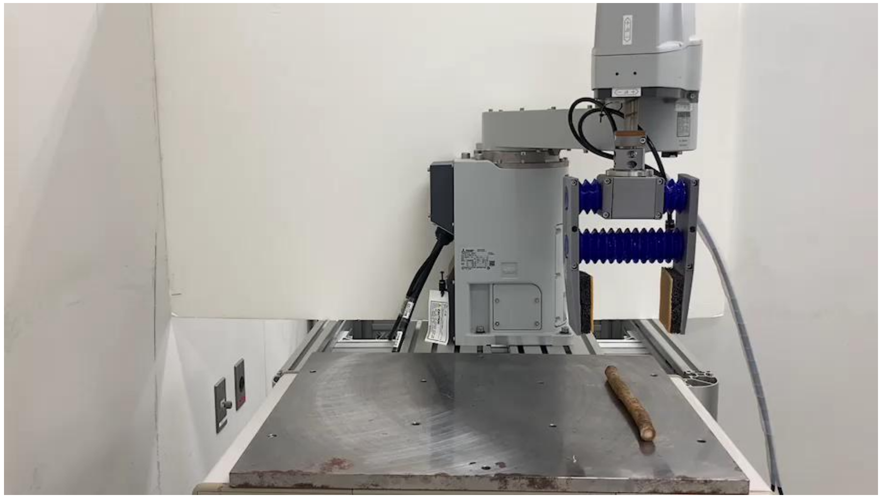
4. Soft bellows hand

Arrangement of white radish

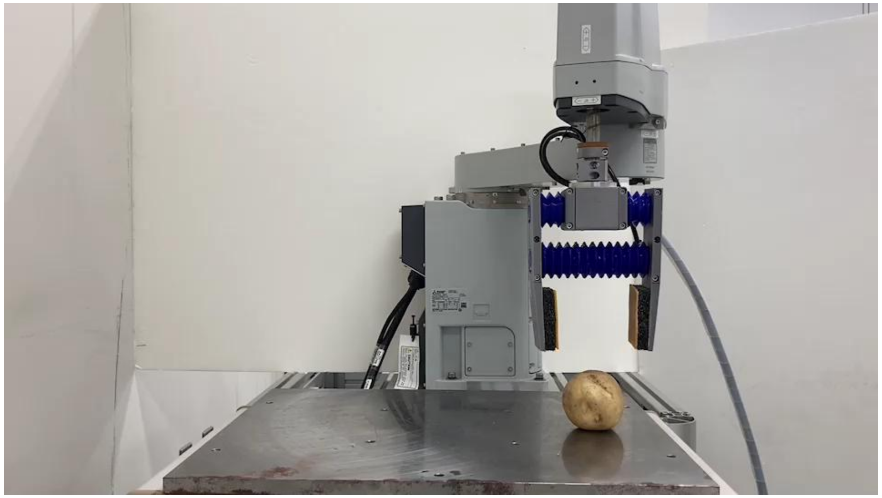


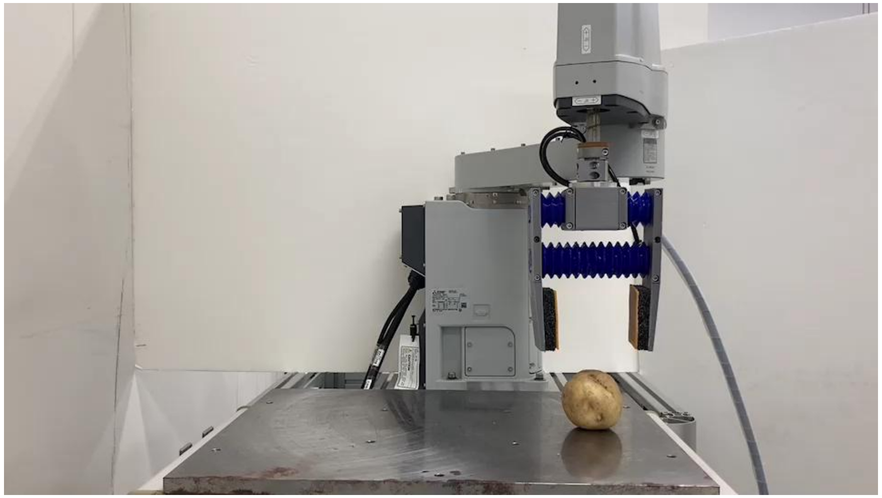
Soft bellows hand

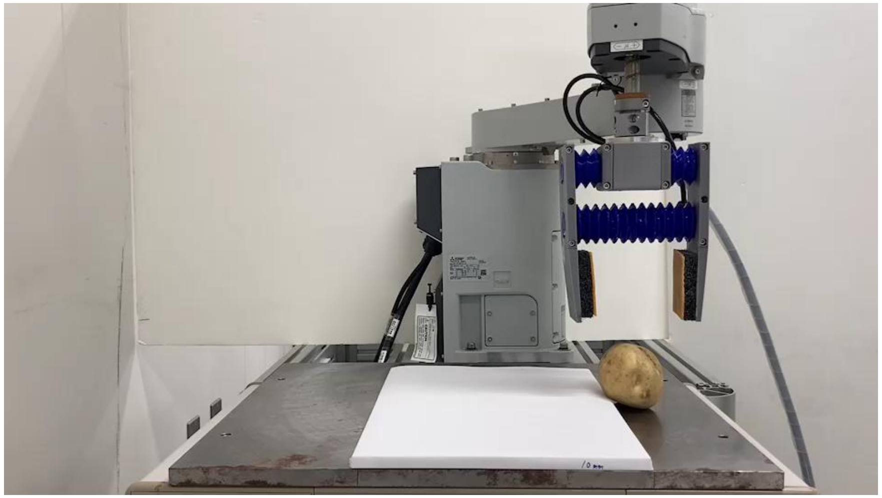
Grasping of agricultural products

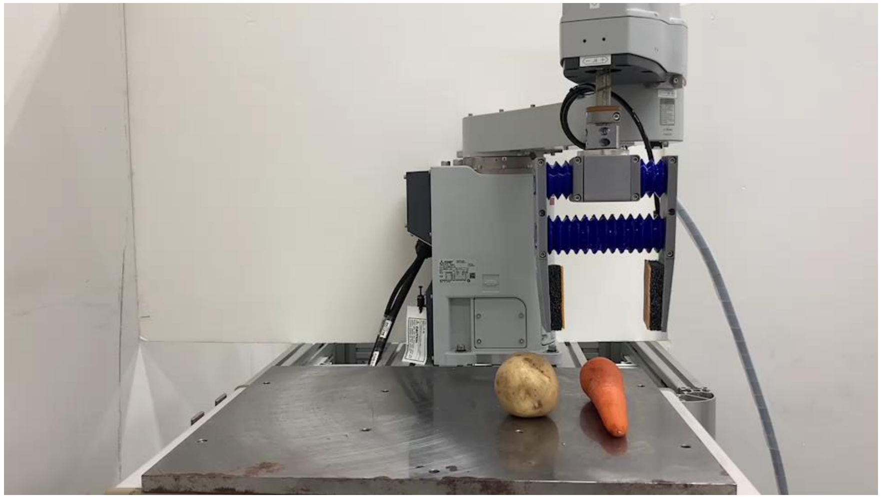





Grasping with contact





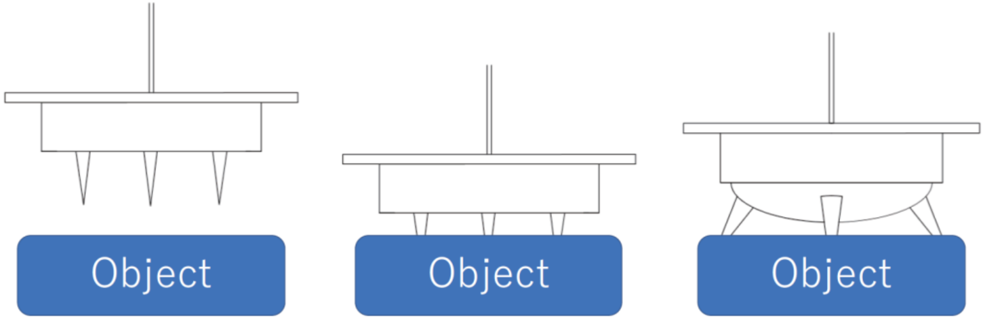




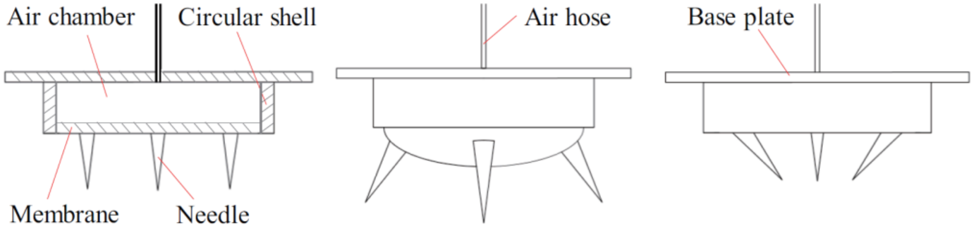
5. Needle gripper

Removing defective product from tray

Idea of needle gripper

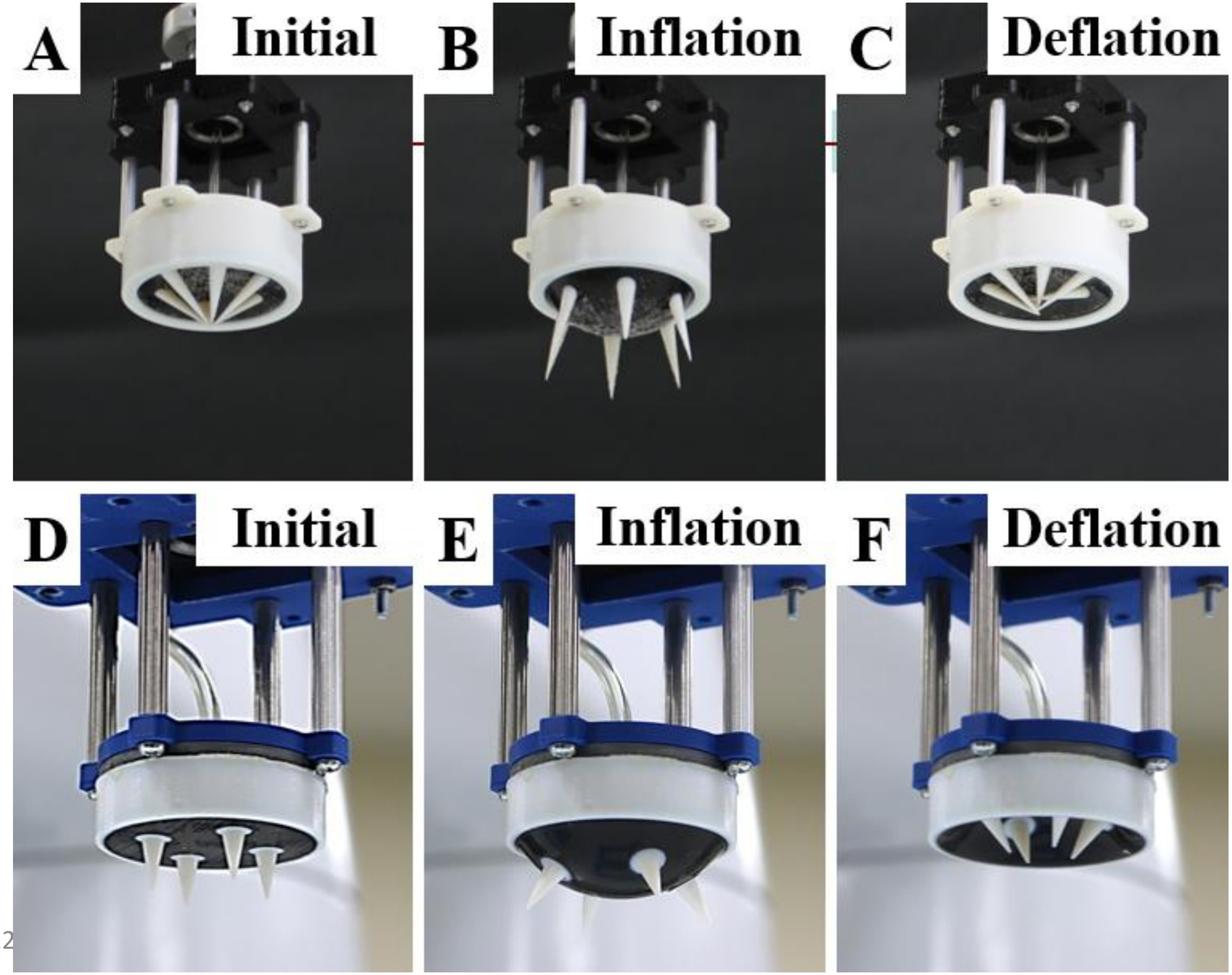


Grasping by piercing

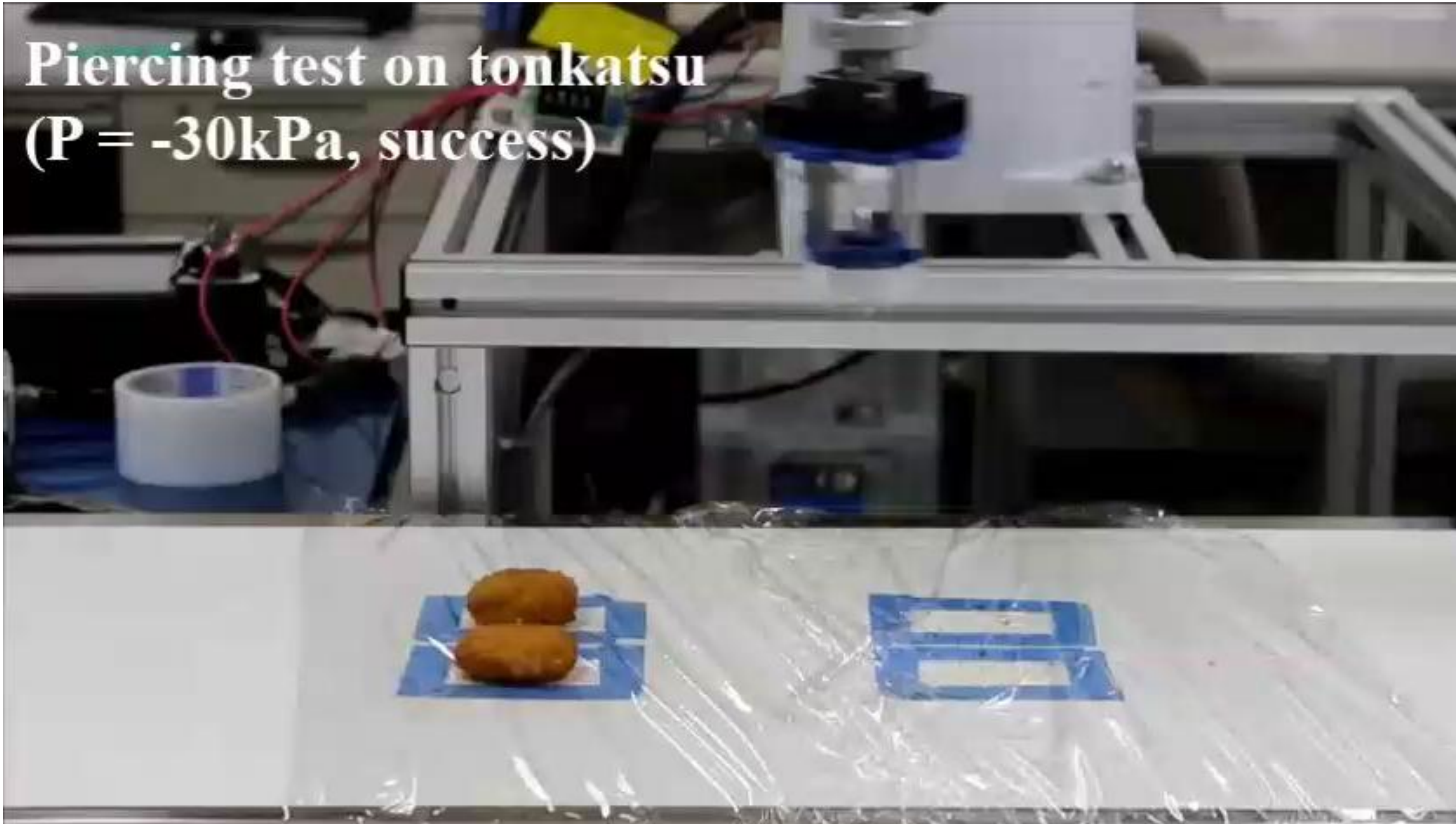


Grasping by pinching

Fabricated needle gripper



Grasping by piercing



Grasping by pinching

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Makiyama et al., IEEE RCAR 2020

6. Multi-wire hand

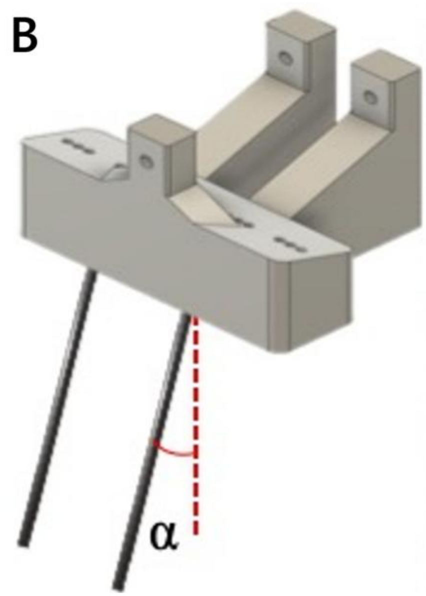
Arrangement by human

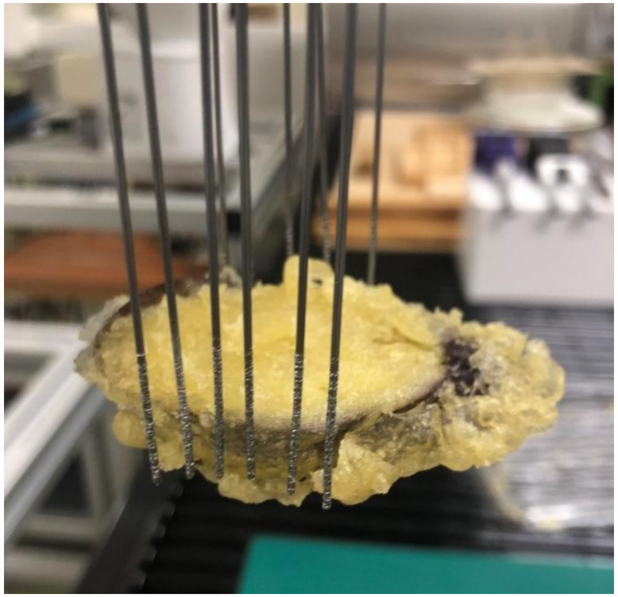
Arrangement target

Task definition

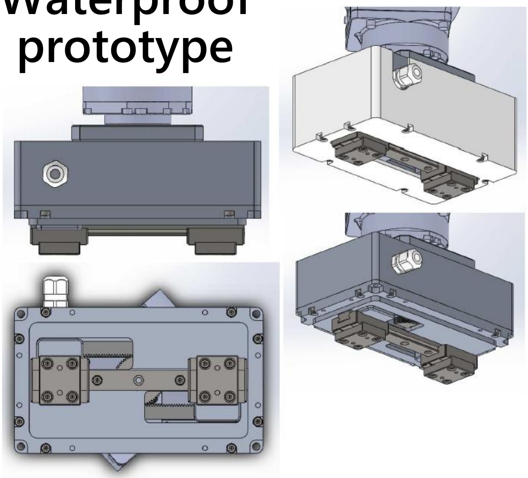
- 5 categories tempura
- Minimum grasping force
- Shrimp tail upward
- No overlap among objects
- 3D arrangement
- High speed

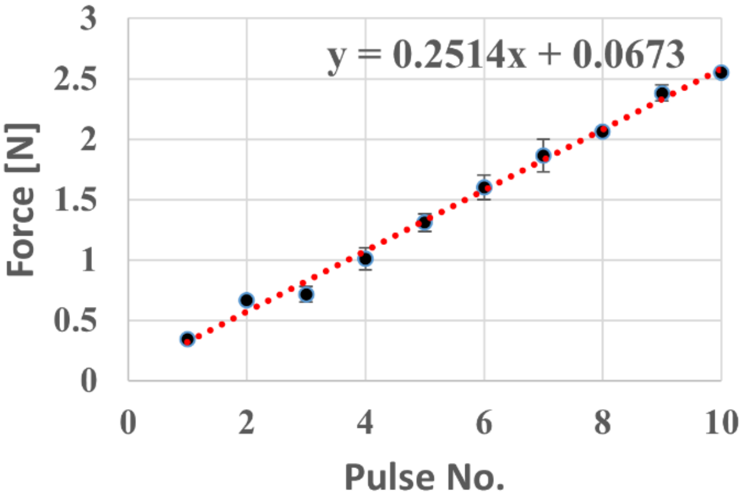
Idea of multi-wire hand





Waterproof prototype

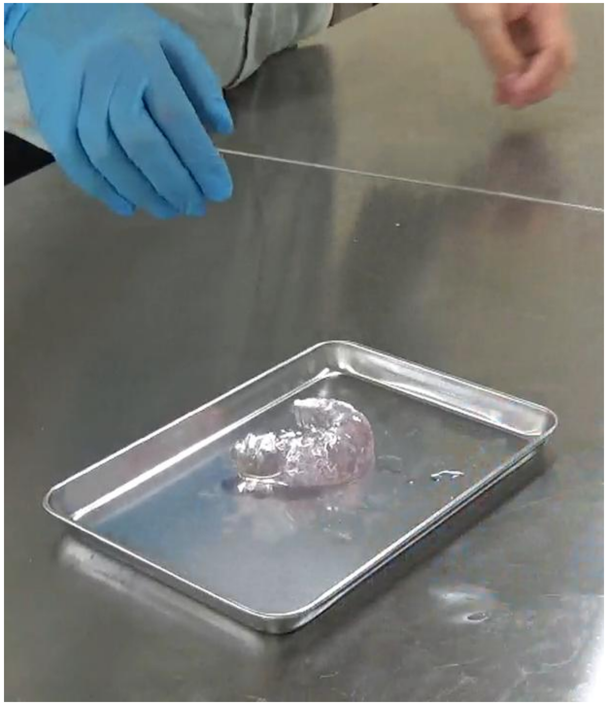


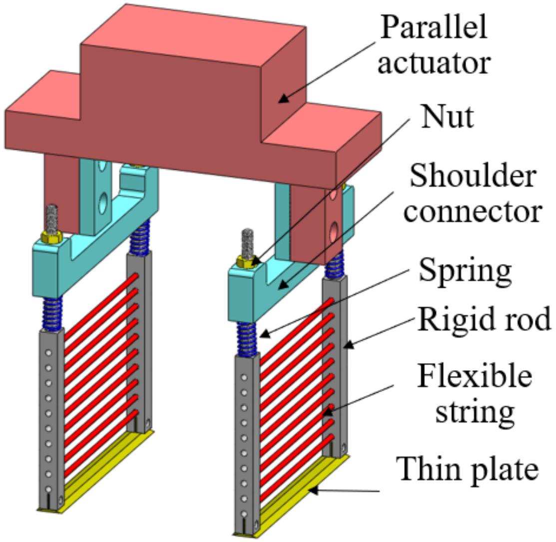


Minimum force without sensor
≒0.35 N

Automatic food arrangement

7. Scooping-binding hand





Gripper design

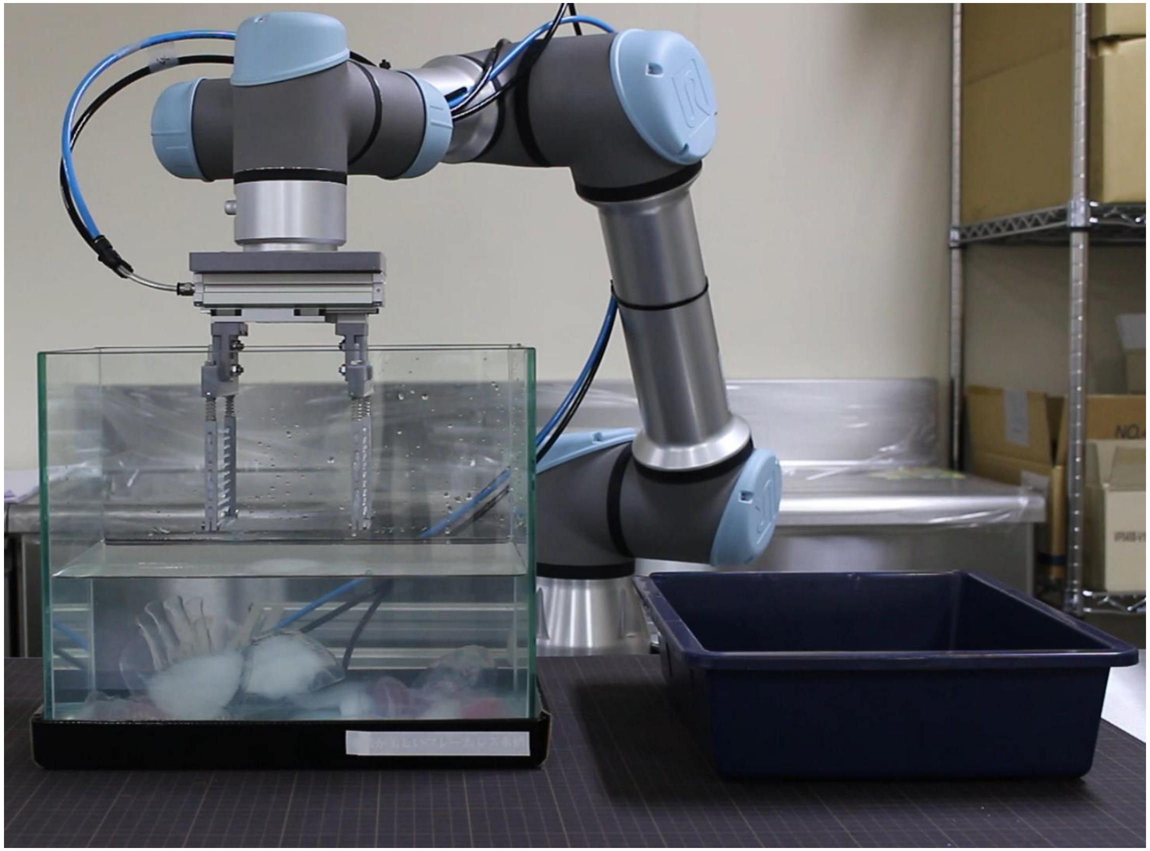
ゲルサンプル(タコの足)の把持
(Gel sample: octopus leg)

掬い込みハンド
Scooping-Binding hand

掬い込みハンドでの把持
Grasping using the scooping-binding hand

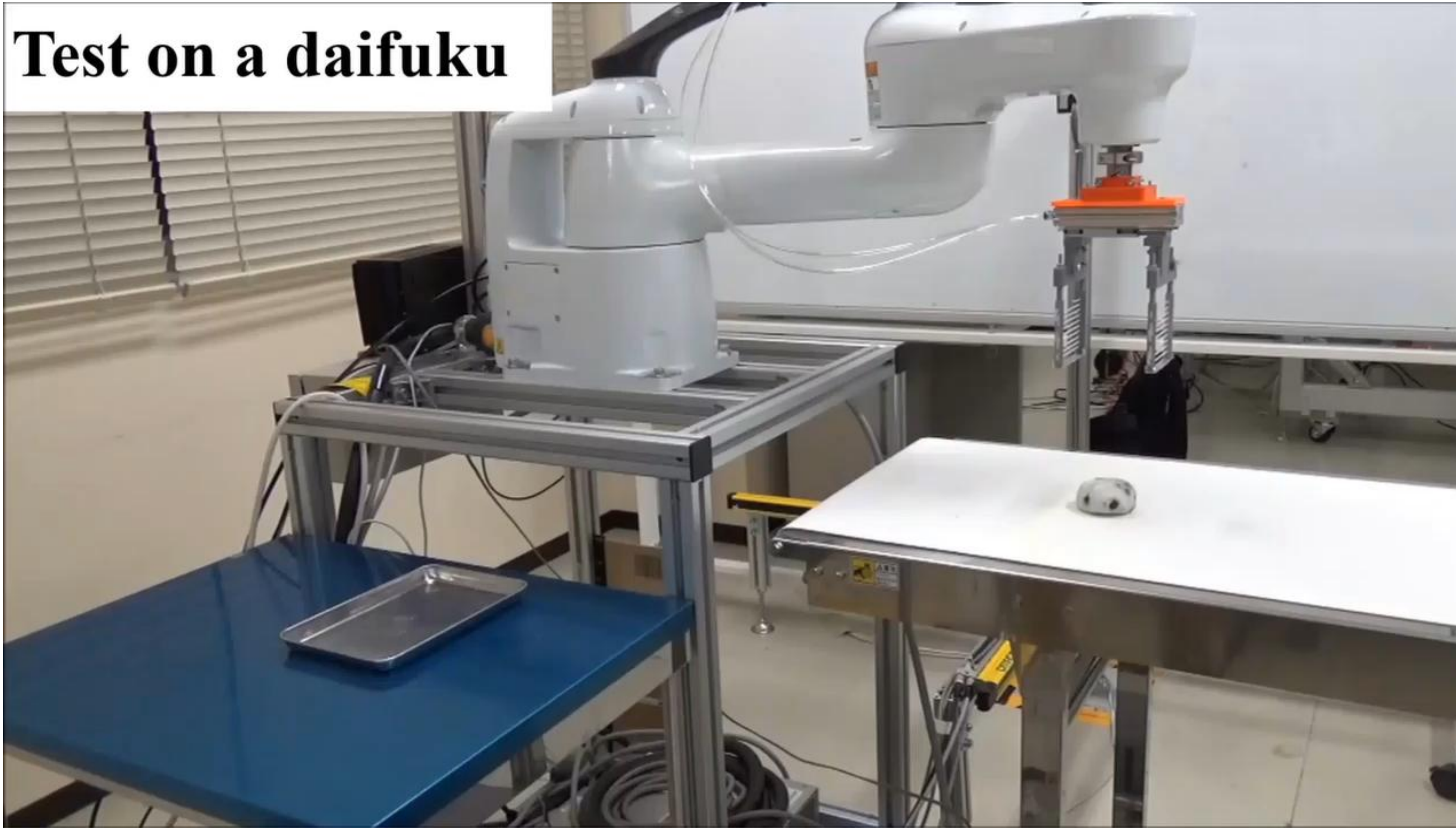
Grasping gel jellyfish

ゲルクラゲサンプル
Gel sample of a jellyfish



水中でのゲルクラゲ把持
Grasping the gel jellyfish from a water tank

Grasping various food products



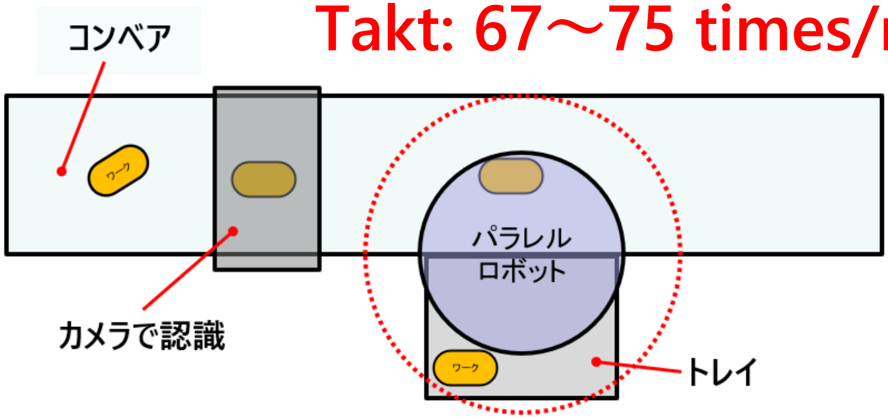
Wang et al., Front. Robot. AI, 2021

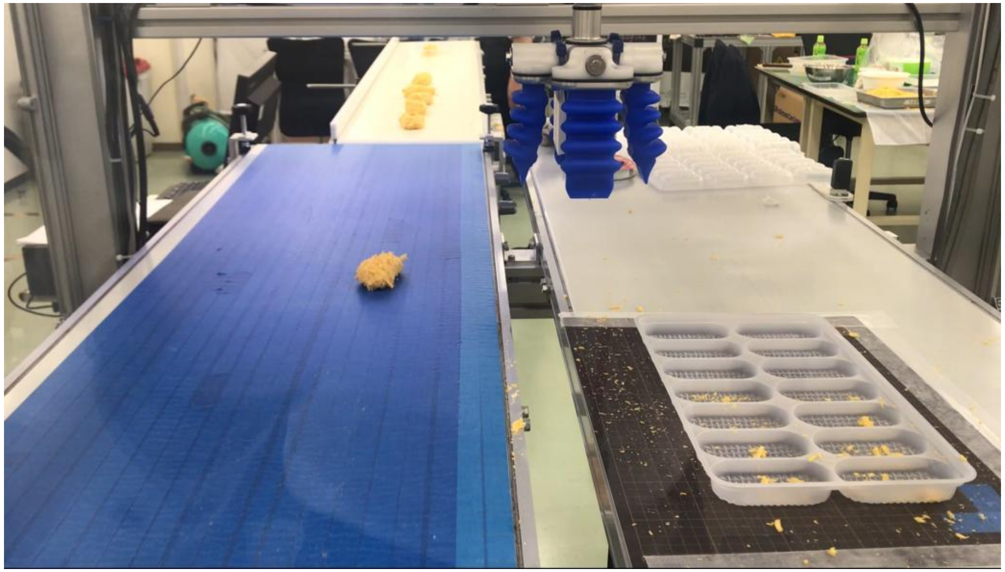
8. High-speed food handling

Commercial gripper

Bread-crumbs coated oyster

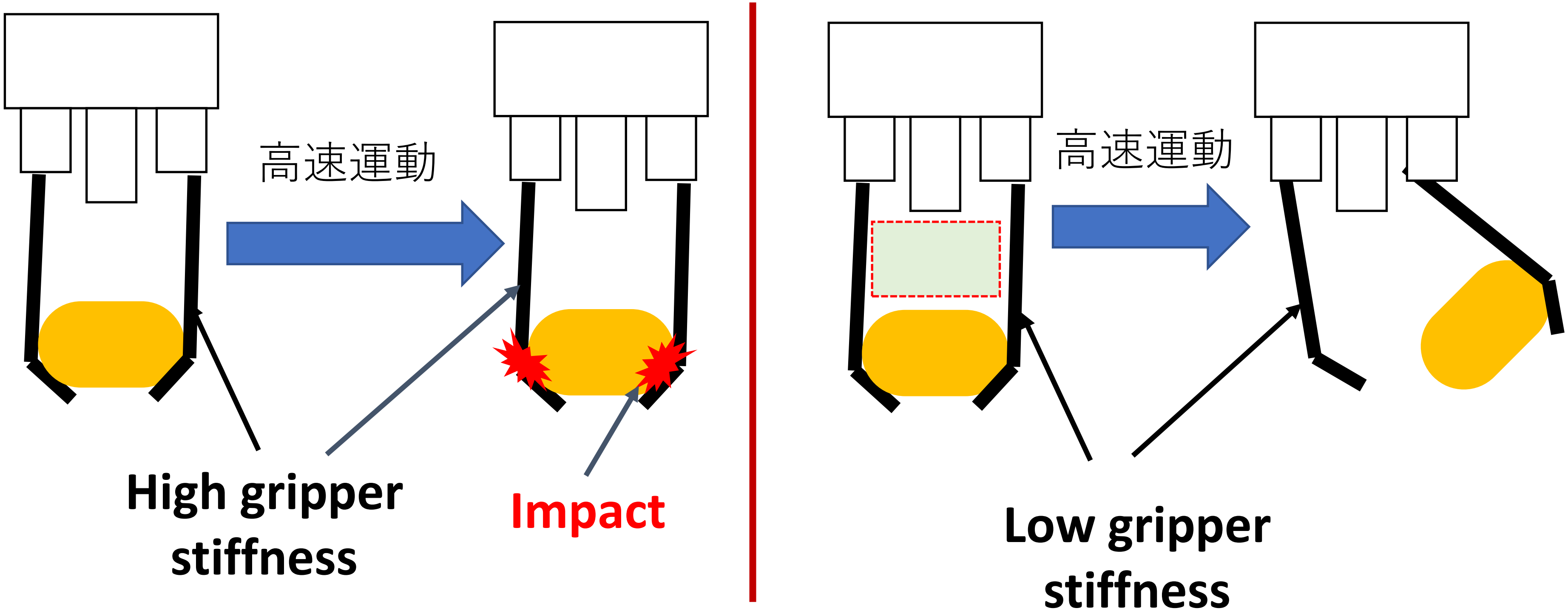
Takt: 67～75 times/min





Failed to handle at 70 times/min

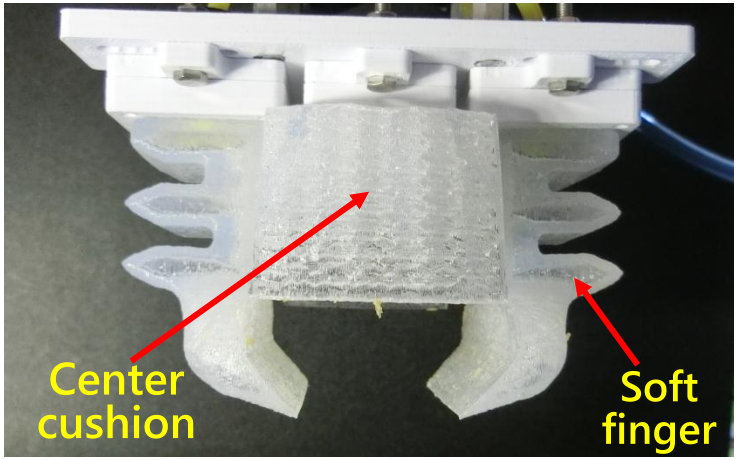
Reason of grasping failure



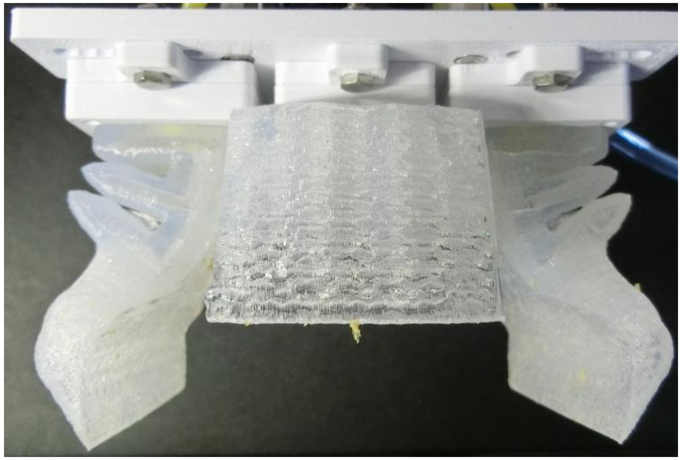
- **Appropriate gripper stiffness is required**
- **Constraining the movement of the target**

Shovel gripper

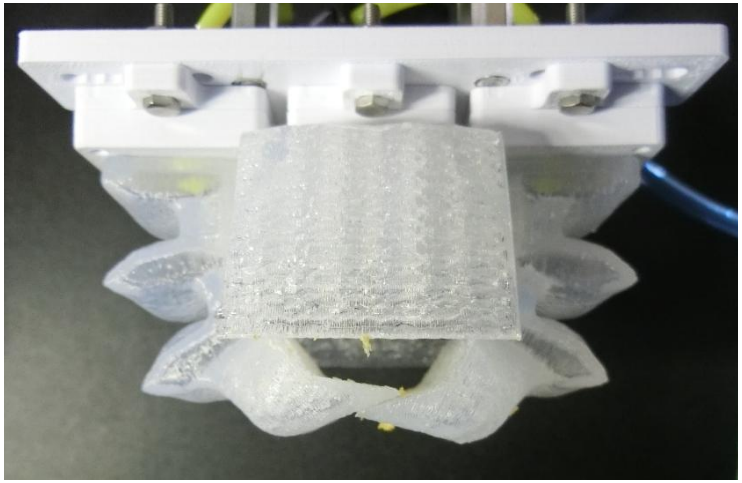
Initial state

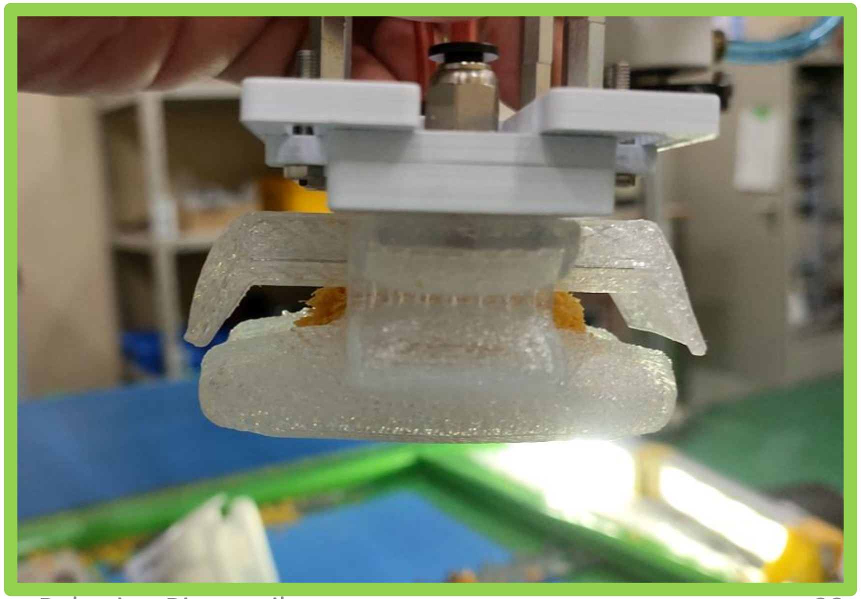


Open state



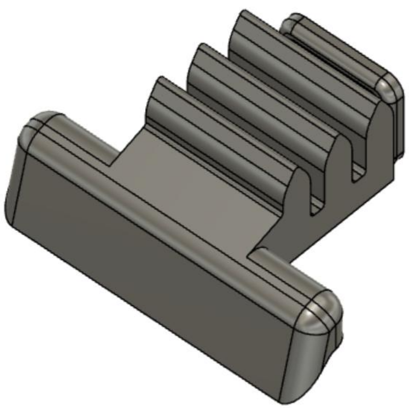
Close state

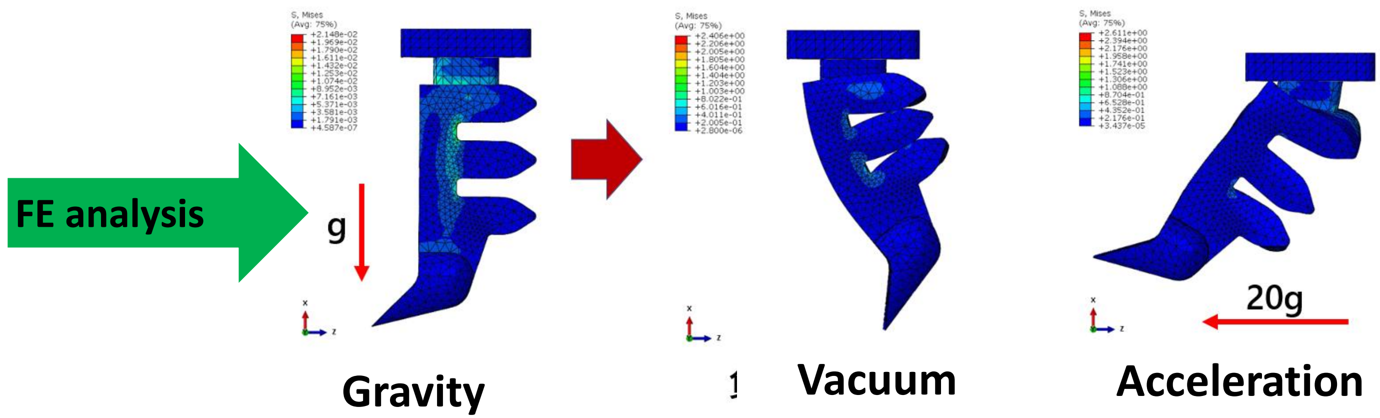


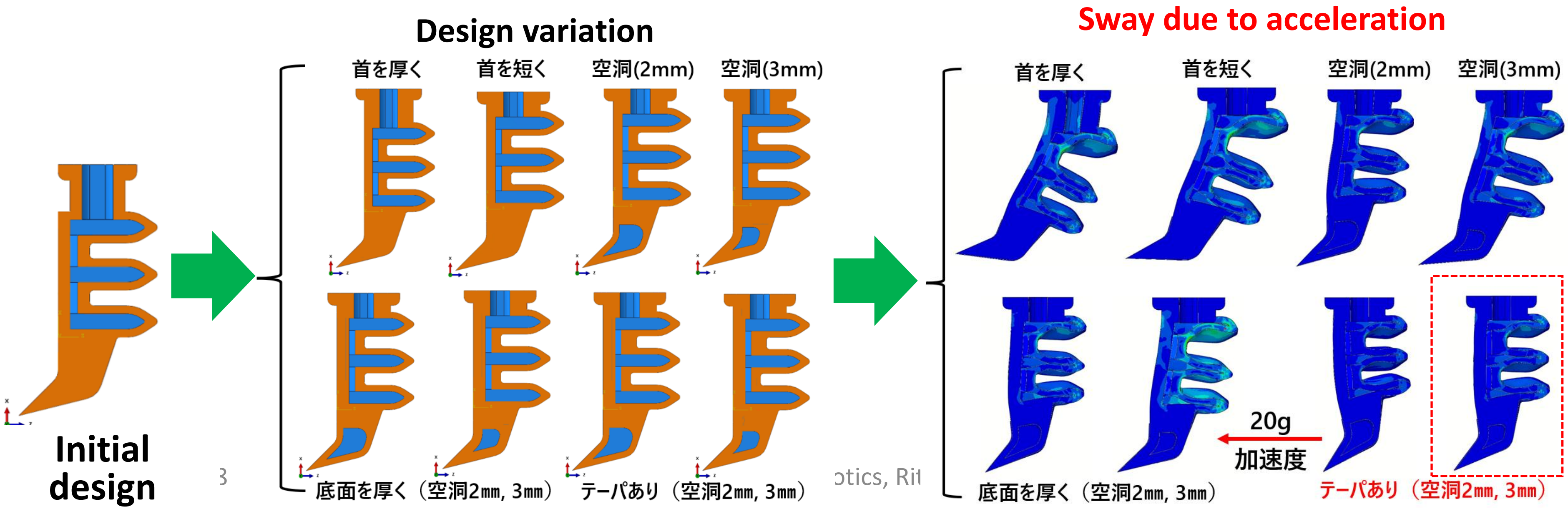


Design of gripper stiffness

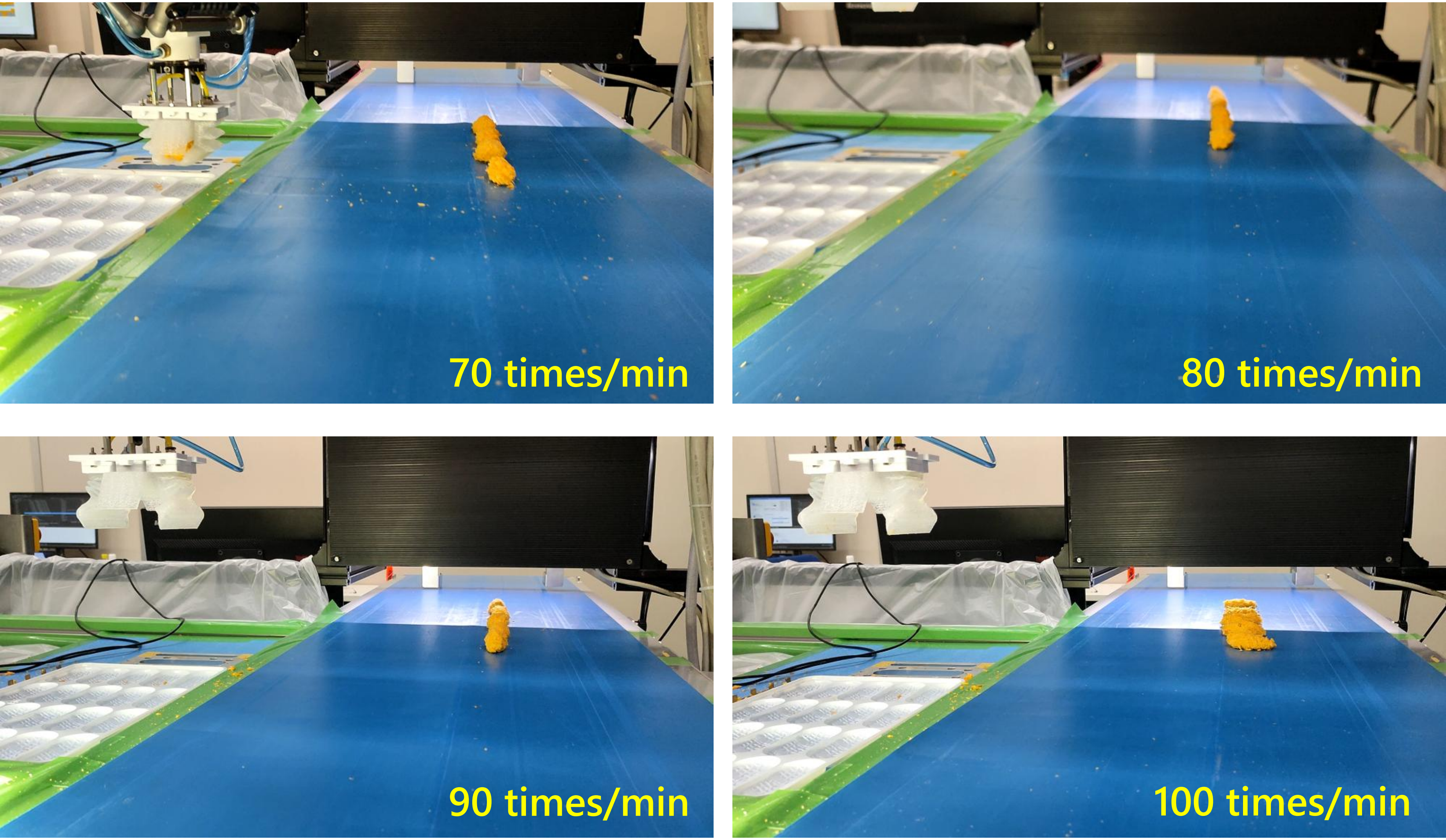
Target： Contact area ↑ Stiffness ↑



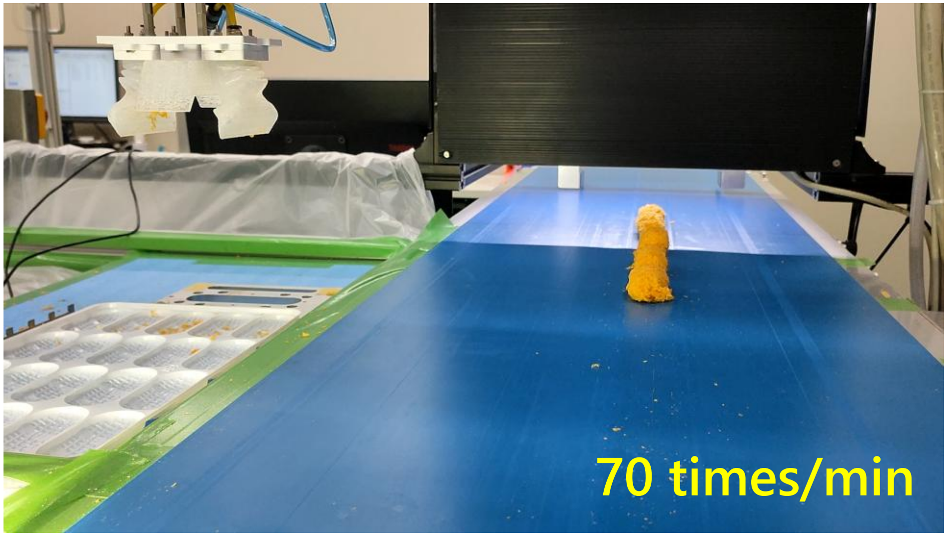


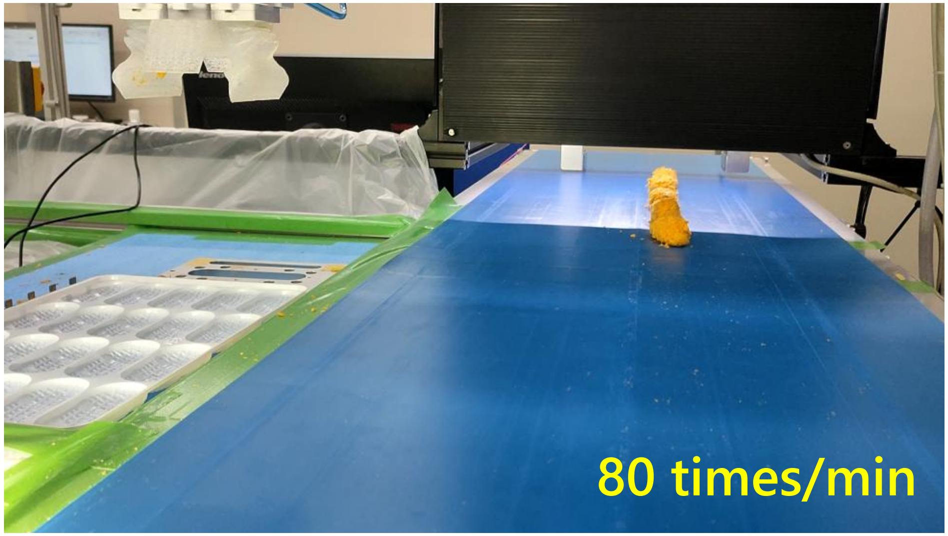


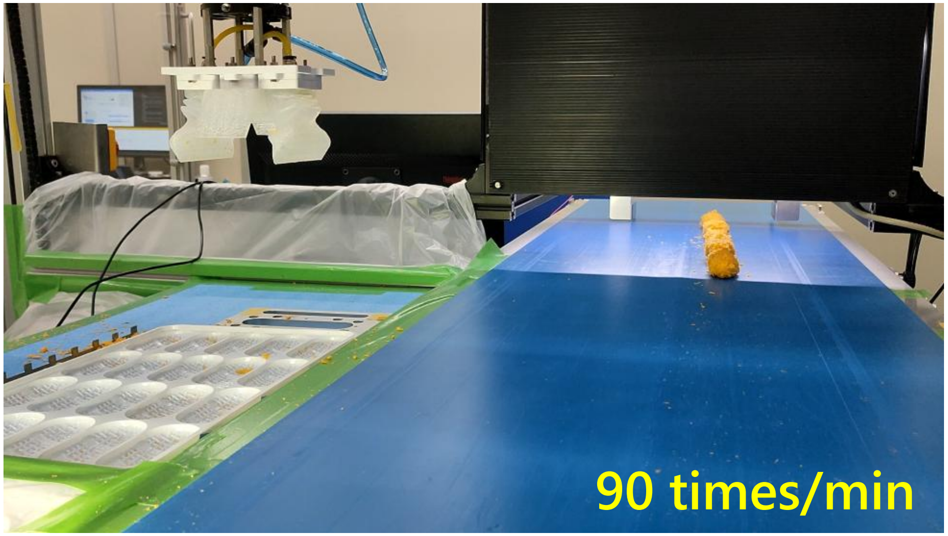
Handling tests (16 g target)

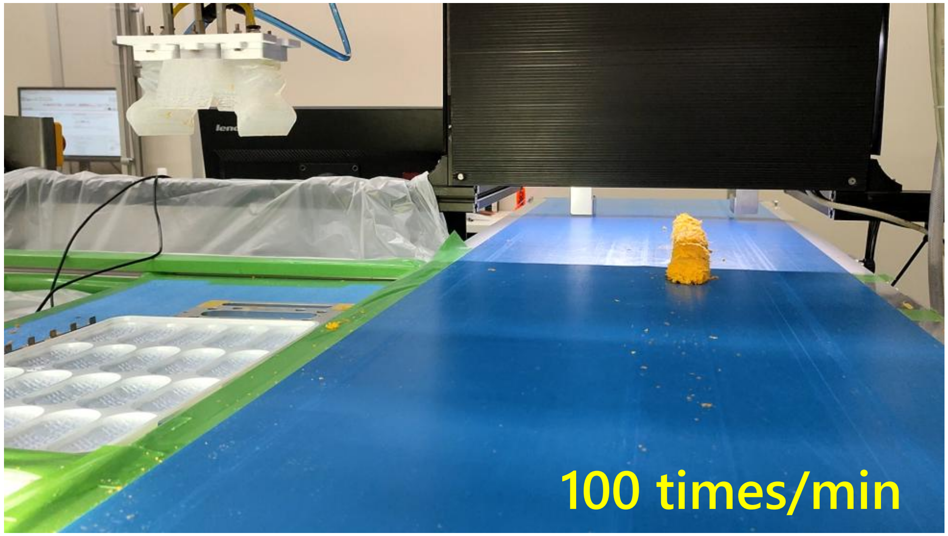


Handling tests (40 g target)









Production Line Implementation

Y. Zhang, Z. Wang, et al., Journal of Field Robotics, 2024

Food handling competition

Teams

No.	チーム名	大学
①	ADMP Gripper	National University of Singapore (NUS)
②	SNAP ROBOTICS	Singapore University of Technology and Design (SUTD)
③	FANTASTIC	University of Bristol (UoB)
④	SIRSLAB	Italia Institute of Technology (IIT)
⑤	FLIPPER	École Polytechnique Fédérale de Lausanne (EPFL)
⑥	TEAM RITSUMEIKAN	Ritsumeikan University



NUS team

Ritsumeikan Team

Competition results

順位	点数	大学
1	170	Singapore University of Technology and Design (SUTD)
2	108	Ritsmeikan University
3	91	École Polytechnique Fédérale de Lausanne (EPFL)
4	30	National University of Singapore (NUS)
5	29	University of Bristol (UoB)
6	23	Italia Institute of Technology (IIT)

Award

IEEE
IEEE Robotics & Automation Society
6TH IEEE-RAS INTERNATIONAL CONFERENCE ON SOFT ROBOTICS
Singapore, 3 – 7 April 2023
Best Manipulation Award
- 2nd Prize -
Presented to
TEAM RITSUMEIKAN
ROBOSOFT
Marcello Calisti
Competition Chair
Albert Causo
Competition Chair

Competition at ICRA 2024

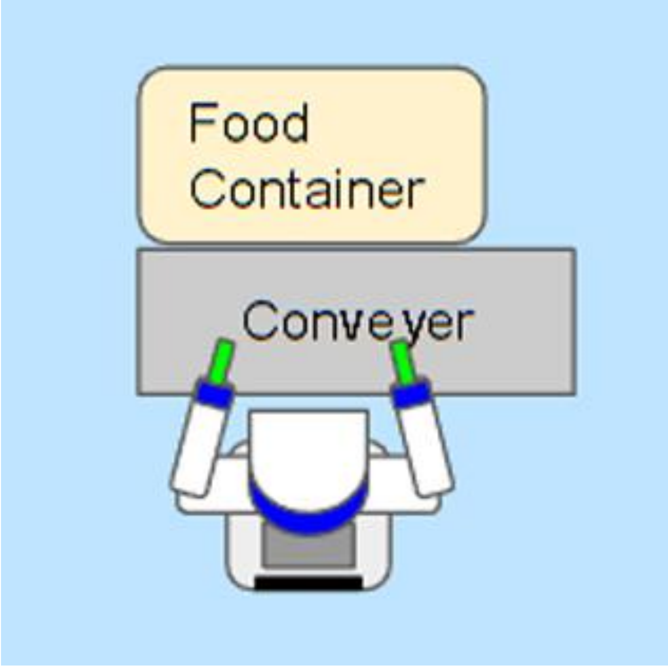
RITSUMEIKAN

ICRA2024

YOKOHAMA | JAPAN

Competition	5/13	5/14	5/15	5/16
The BARN Challenge 2024				
Food Topping Challenge				
Robotic Sim2Real Challenge				
IEEE RAS Quadruped Robot Challenges (QRC)				
MathWorks Minidrone Competition – ICRA 2024				
GPR2024: Crowdsourced Map Association for Large-scale Environments				
Bots & Bento | The first Robotic Pallet Handling Competition				
ICRA 2024 Robotic Grasping and Manipulation Competitions				
WRS Future Convenience Store Challenge in Cyber Space				
The 16th F1TENTH Autonomous Grand Prix				
The RoboDrive Challenge				

Food Topping Challenge

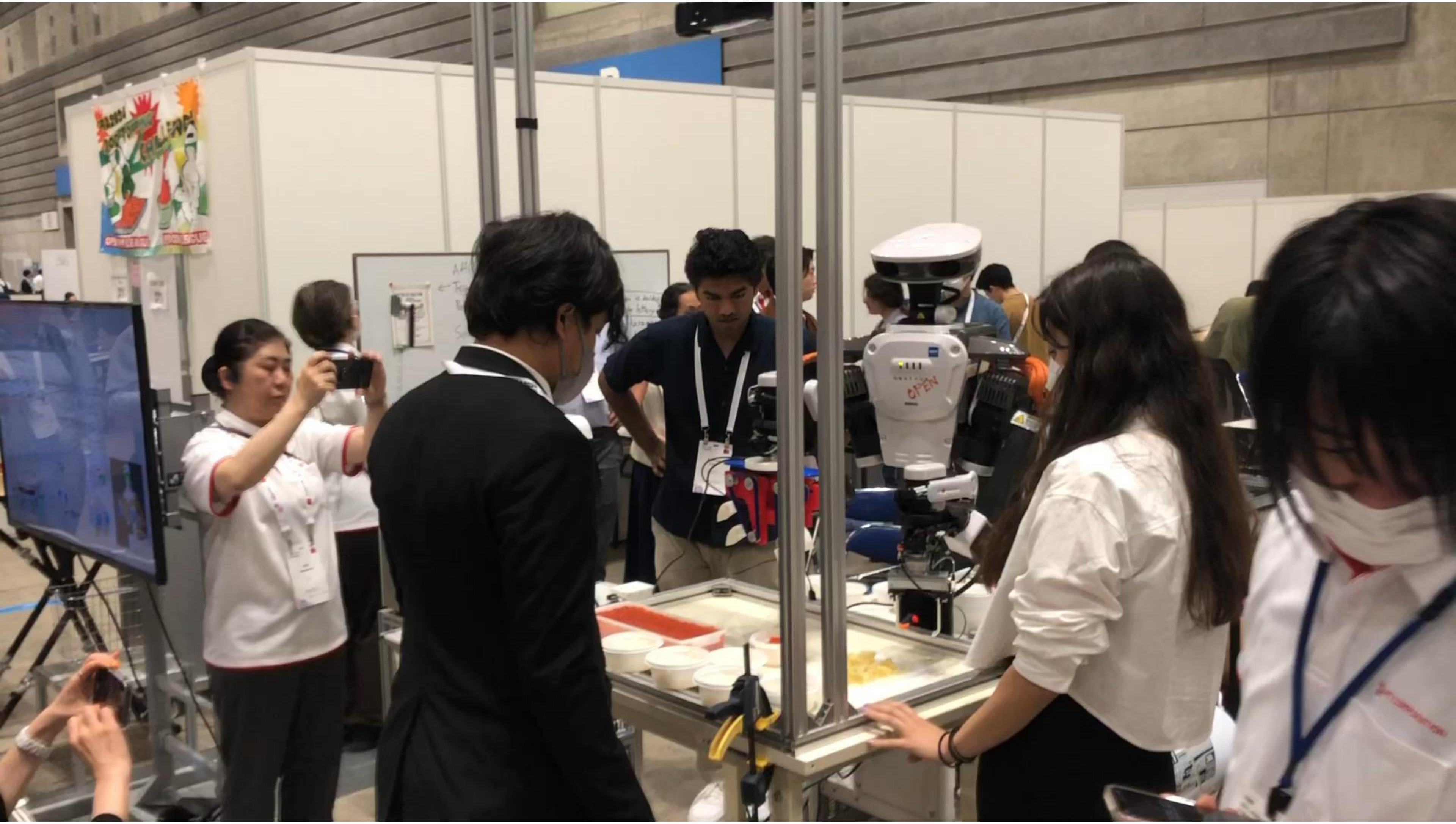


1) Speed of serving 10 dishes.
2) Accuracy weight of bowls.(Weight is also important factor because of food products.)
3) Visual of bowls（Judges want to eat the bowls, beautiful, no missing items）
4) Food loss, cost perspective. The team with the least amount of salmon roe spilled shall be rated higher.

All Teams

No.	Team name	Affiliation	Country
①	Team OSCAR	Osaka Univ.	Japan
②	Tokyo Metropolitan	Tokyo Metropolitan Univ.	Japan
③	University of Cambridge	University of Cambridge	U.K.
④	SWEL	Yamagata Univ.	Japan
⑤	Team Ritsumeikan 1	Ritsumeikan Univ.	Japan
⑥	GRIPS smart robotics	Smart Robotics Co. Ltd.	Japan
⑦	Team Ritsumeikan 2	Ritsumeikan Univ.	Japan
⑧	Motion Control Lab	Tsukuba Univ.	Japan

Performance (Osaka Univ.)

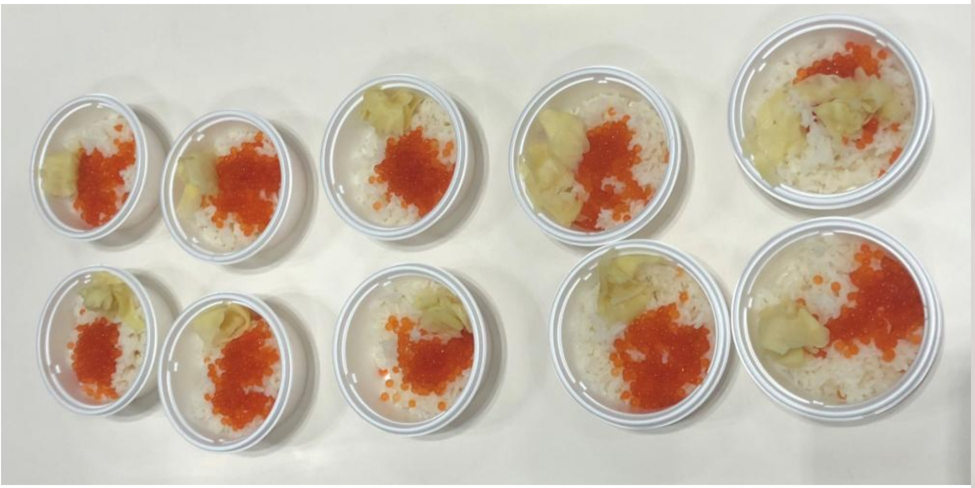


Performance (Ritsumeikan Univ., team 1)

Performance (Ritsumeikan Univ., team 2)

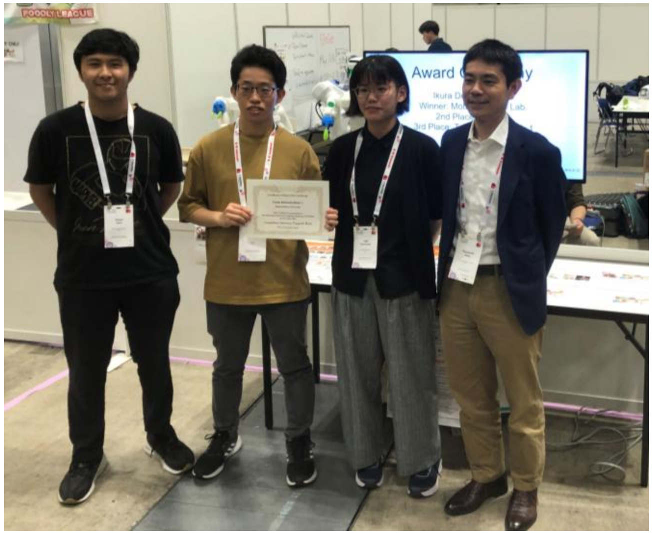
Results

Osaka Univ.



1st	Tsukuba Univ.
2nd	Osaka Univ.
3rd	Ritsumeikan Univ.

Award ceremony




Future possible directions

- New EE ideas for handling various food and agricultural products at **high-speed**, especially **fragile and heavy** products;
- New EE ideas for handling **living creatures**;
- Easy and **effective models** for helping the control and design of soft EE;
- New **fabrication methods** that is easy accessible, efficient, and suitable for EE commercialization;
- New and **smart materials** that can change its properties according to tasks, e.g., 4D material.

Report

- Think of one target object that is difficult to handle by conventional EEs;
- Write down the reason **why it is difficult** to grasp;
- Propose a soft robotic EE that can handle the object at **high-speed**;
- If possible, make a CAD design and insert the drawing; at least make a handwritten sketch;
- Submit a PDF file through **moodle+R**
- Submission deadline: **Dec. 26 (FRI), 23:55**