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 are 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.

Robot hand

Robot gripper

Suction pad

Other tools

Image from Google

Examples of Robotic EE

SCHMALZ

NBK

SMC

UR

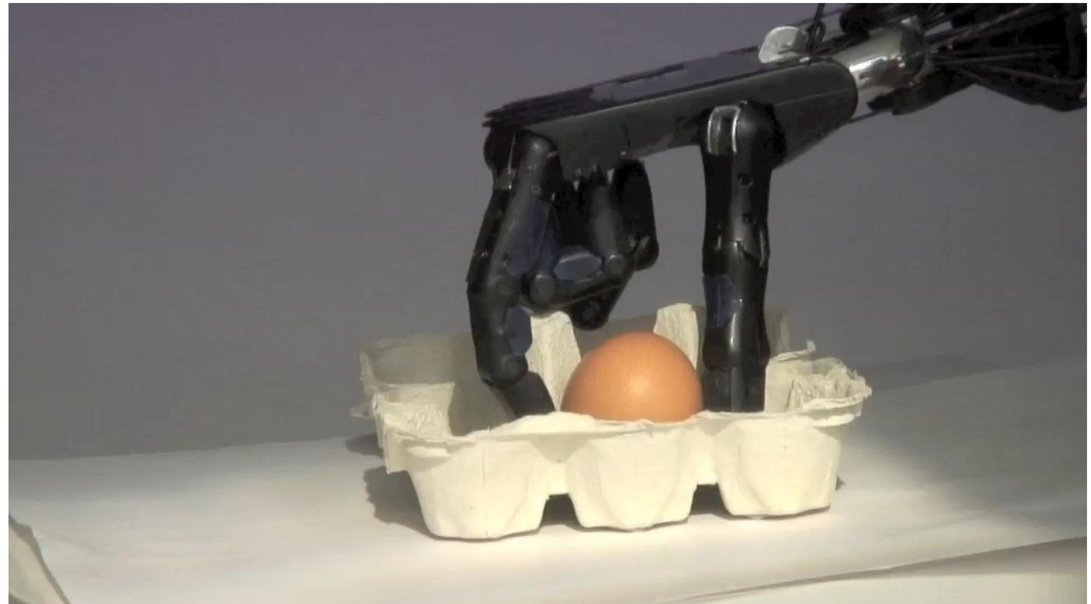
Barrett TECH

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 Existing EE

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	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?

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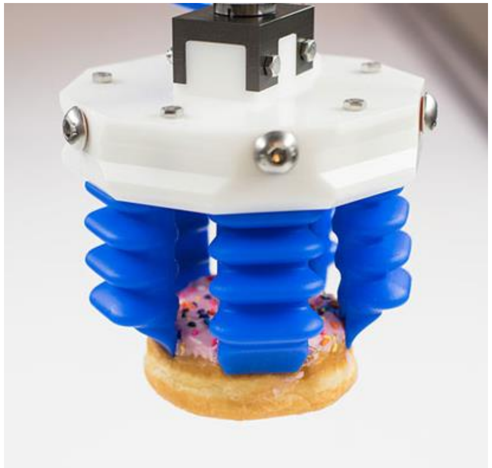
Images from Google

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

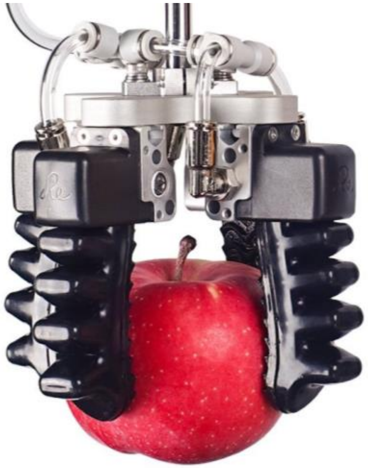


Soft Robotics Inc

SoftGripping Inc

Soft Robot Tech co., LTD

Piab AB Inc



RoChu (China)

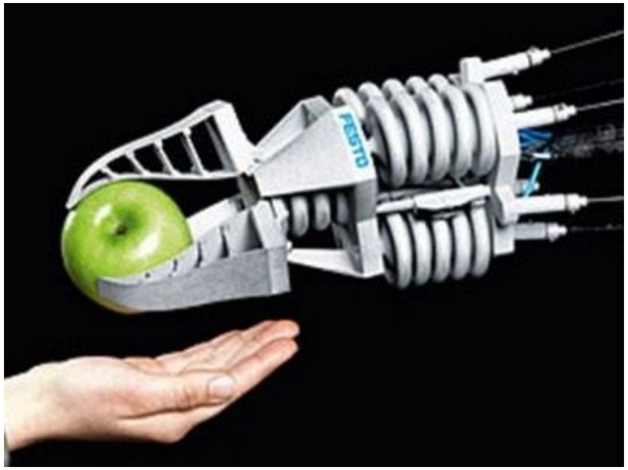
Schmalz

ニッタ

OnRobot

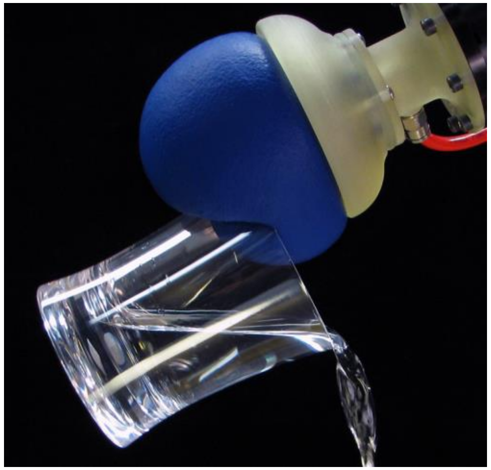
Images from Google

What are the existing soft robotic EEs?→Commercial ones

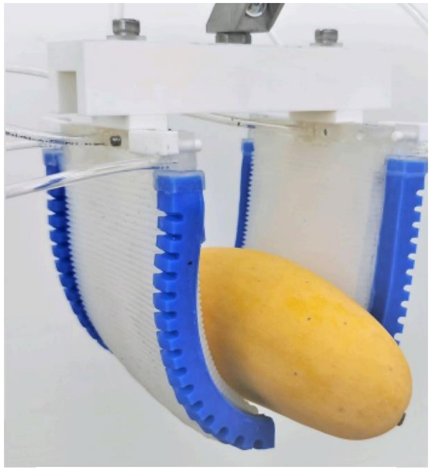


FESTO (Fin gripper)

Bridgestone (Artificial muscle)



Jamming gripper (USA)



IPI (Singapore)

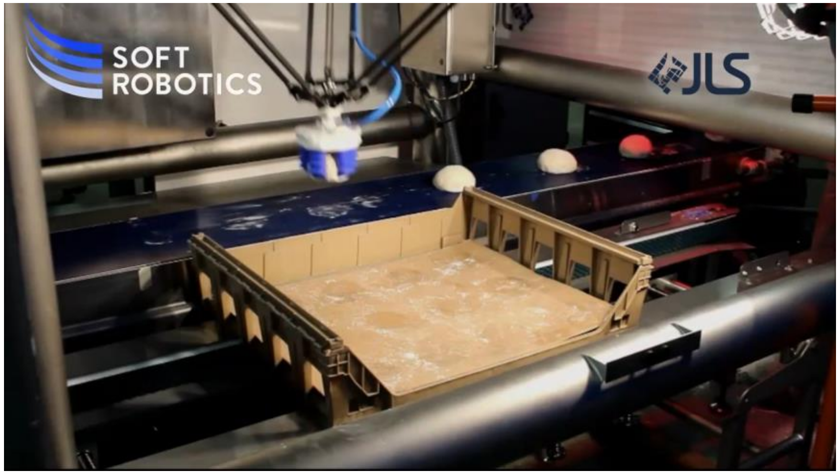
Ubiros Gripper (UK)

FESTO Soft Gripper

RoChu (China)

Images from Google

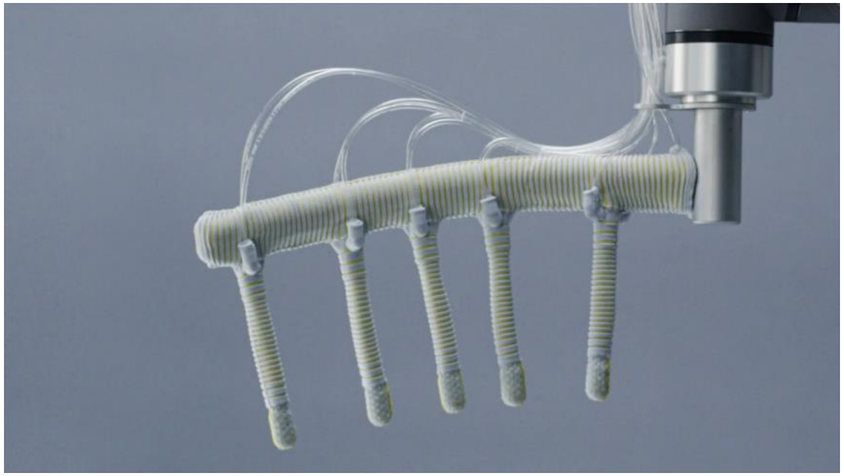
Examples of Performances



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

Jamming gripper

SOFTmatics hand, NITTA



SOFTmatics hand, NITTA

Videos from YouTube

Existing researches on soft EEs

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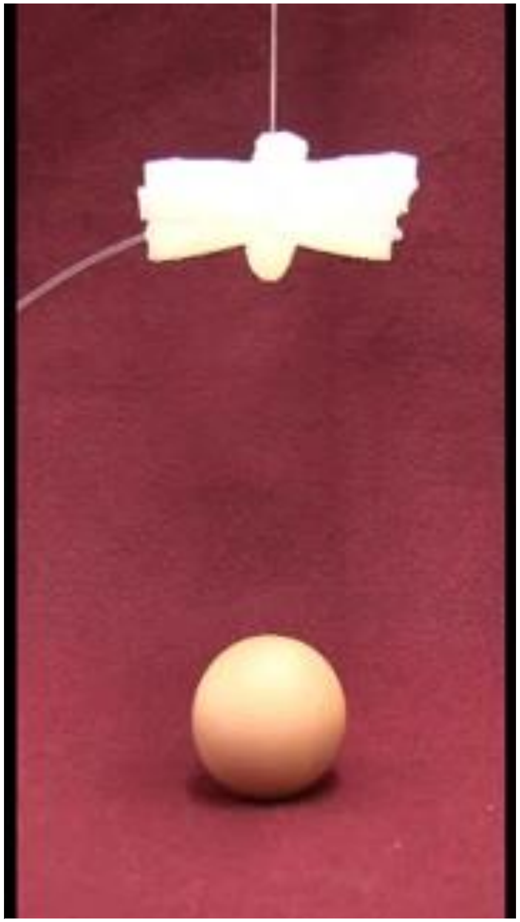
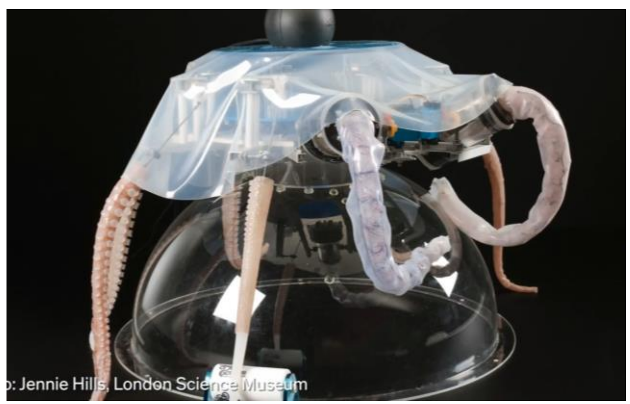


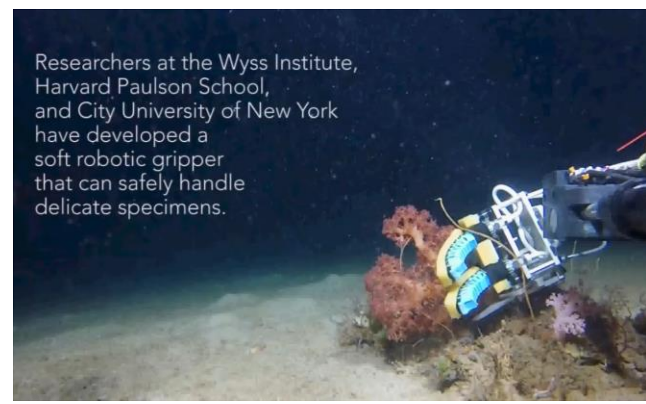
Whitesides et al.,
Harvard Univ., 2011

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

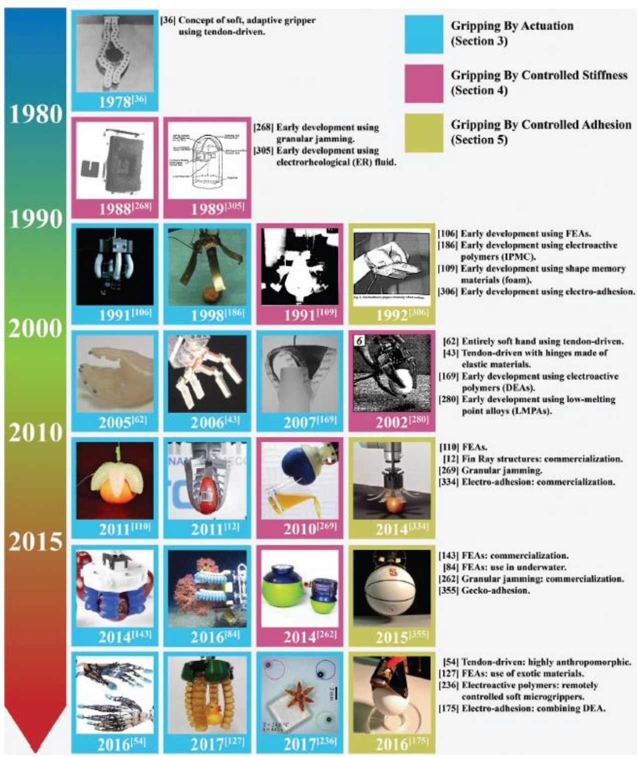
Soft Grippers

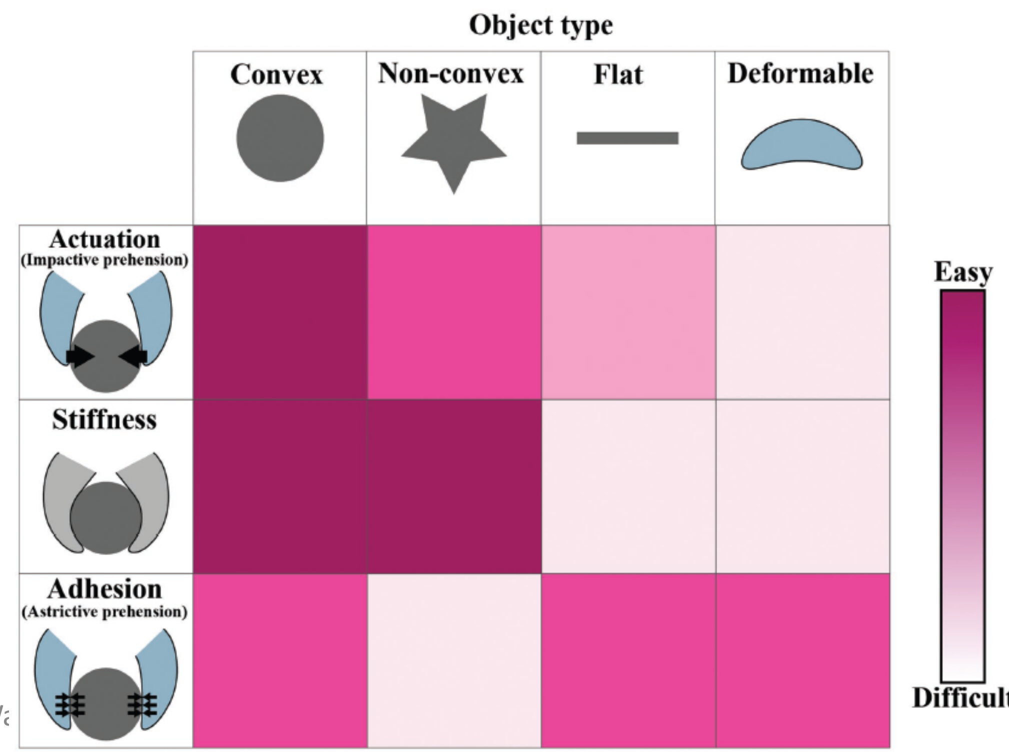
ADVANCED MATERIALS

www.advmat.de

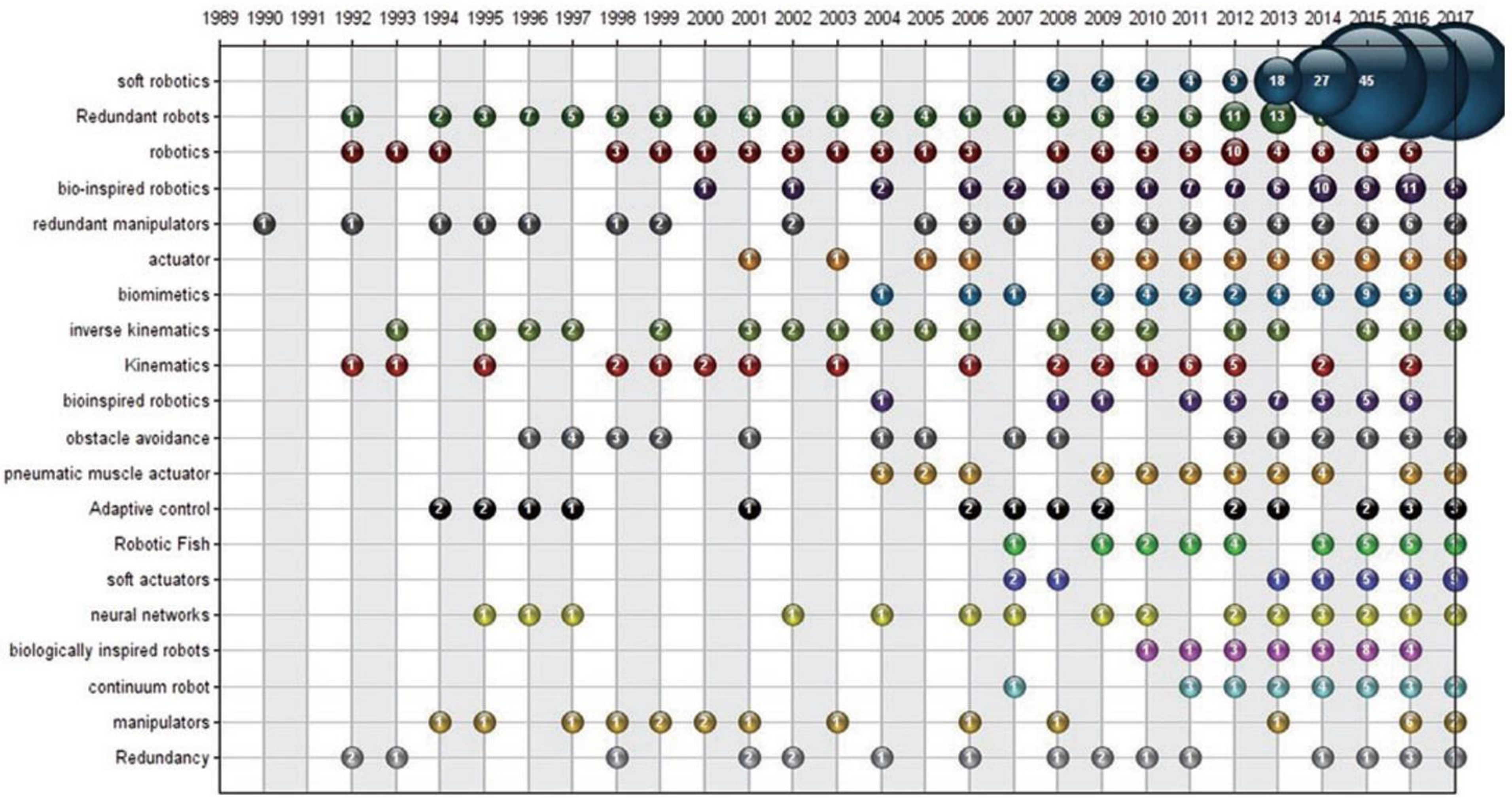
Soft Robotic Grippers

*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

Rigid EE

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

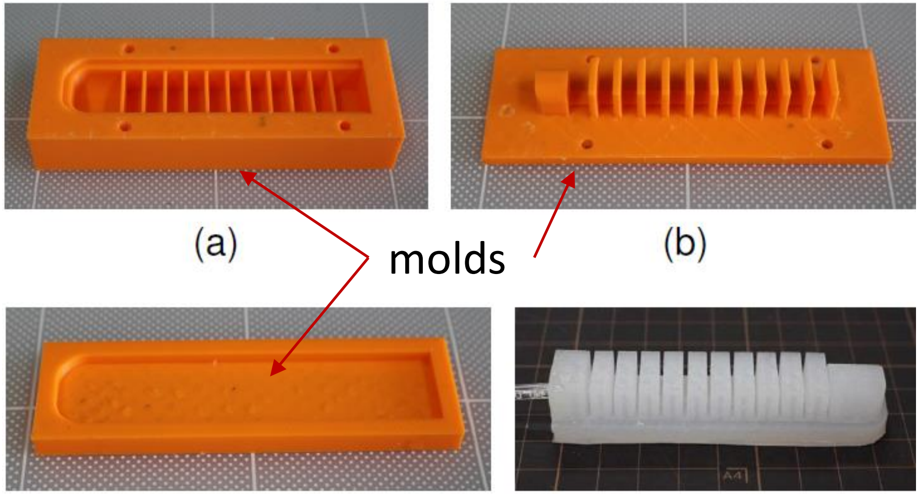
Soft EE

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

How to fabricate soft EE?

Casting

Liquid silicone



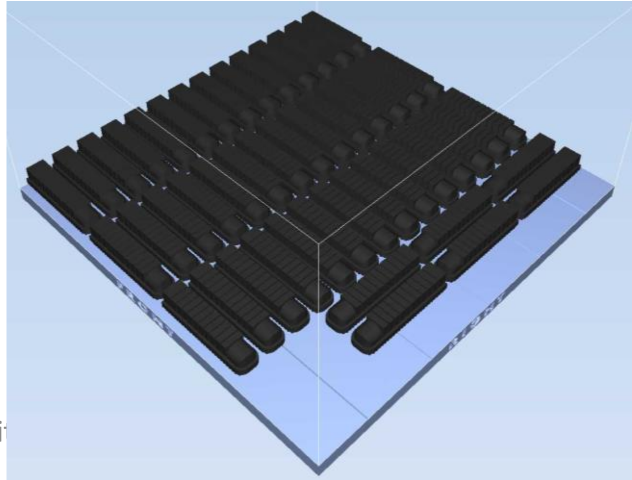
(a) (b)

molds

(c) (d)

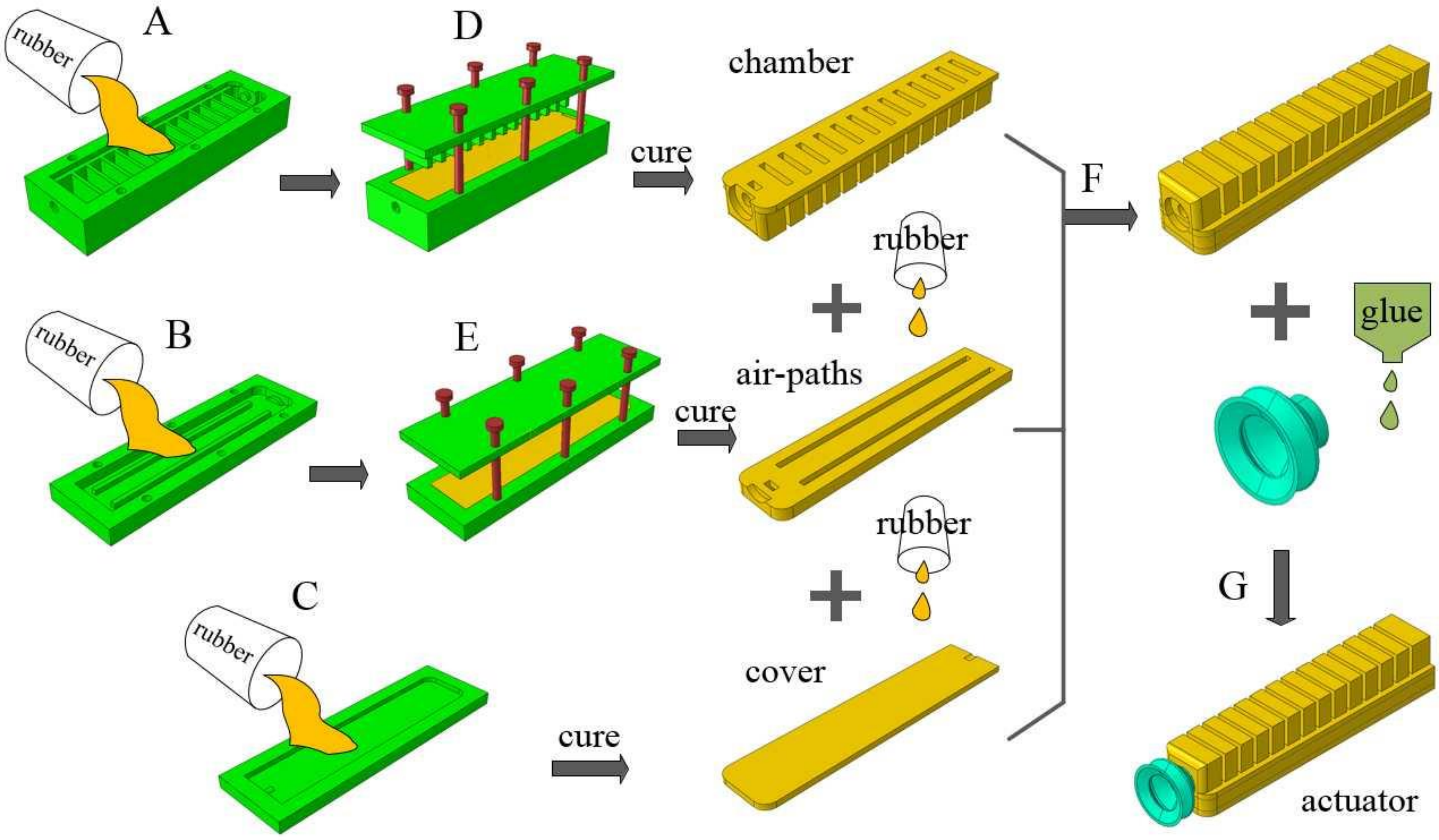
3D printing

Objet350 Connex (Stratasys)

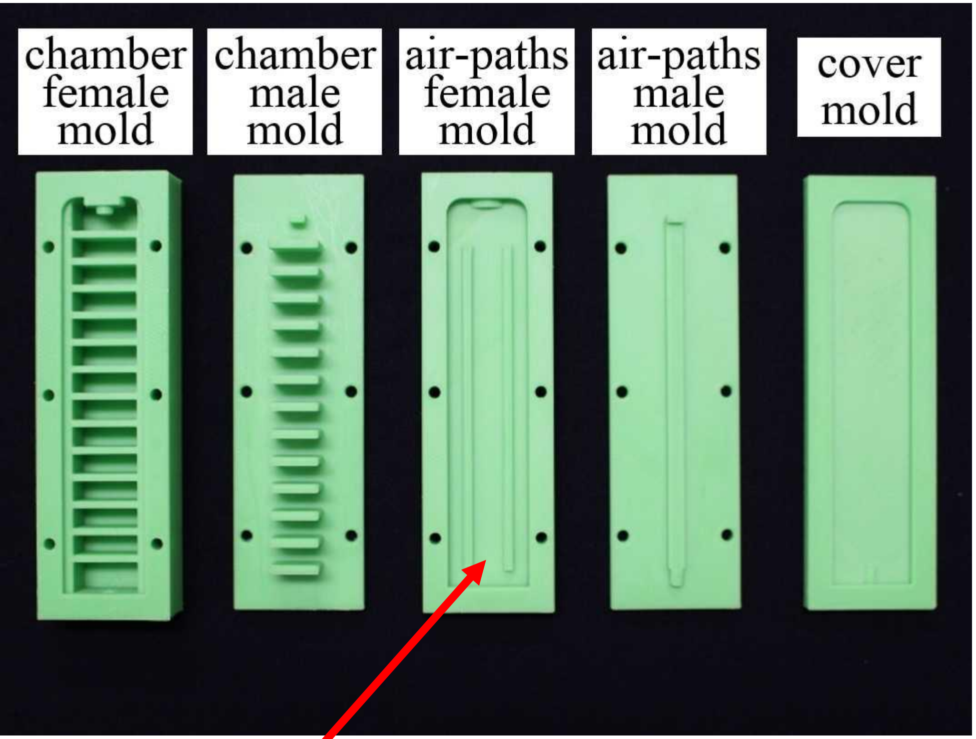


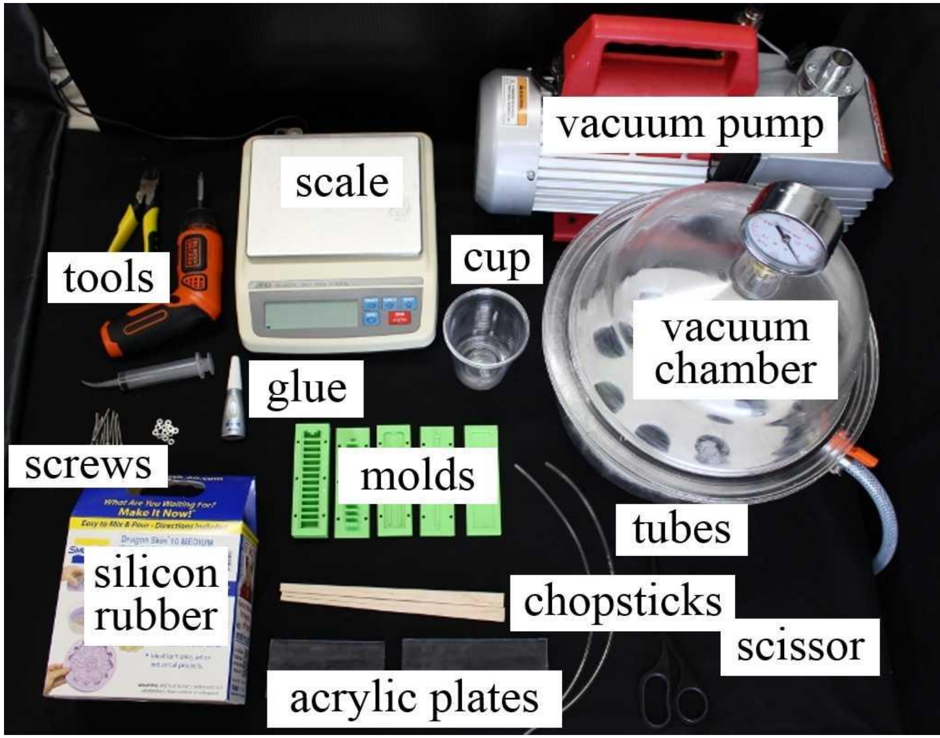
48 soft fingers

Example of casting

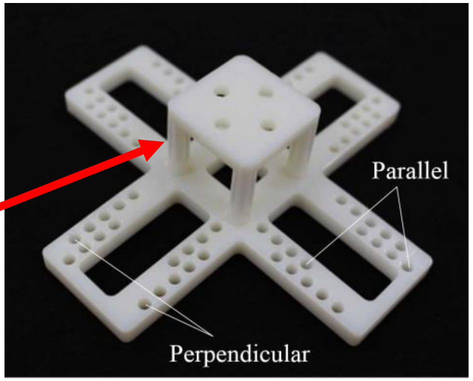


Things that you need





ABS or PLA



VeroWhite
Stratasys, Objet

Fabrication process

Performance of fabricated gripper

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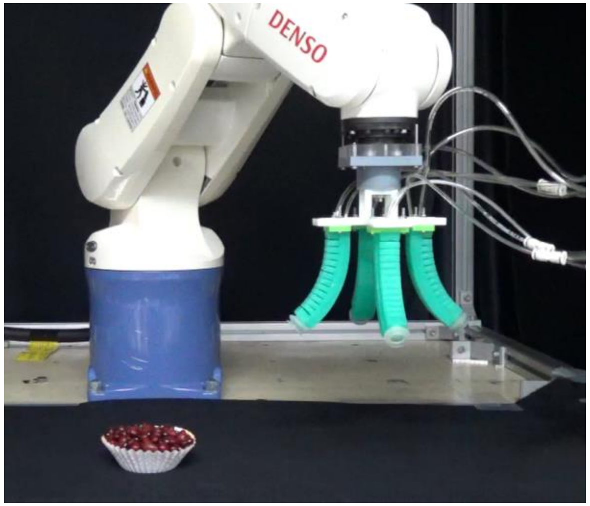
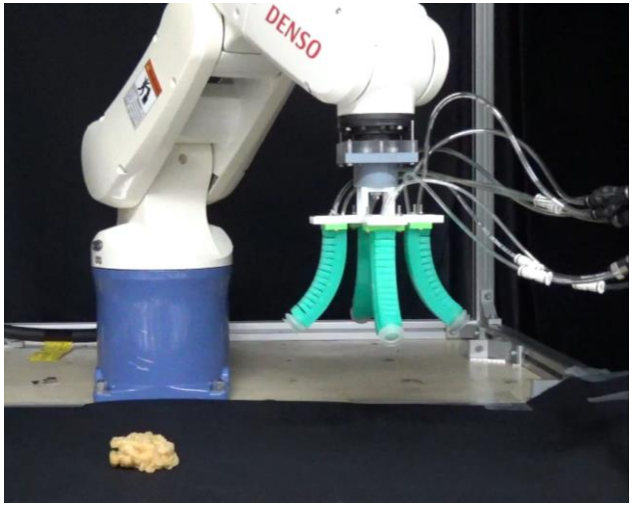
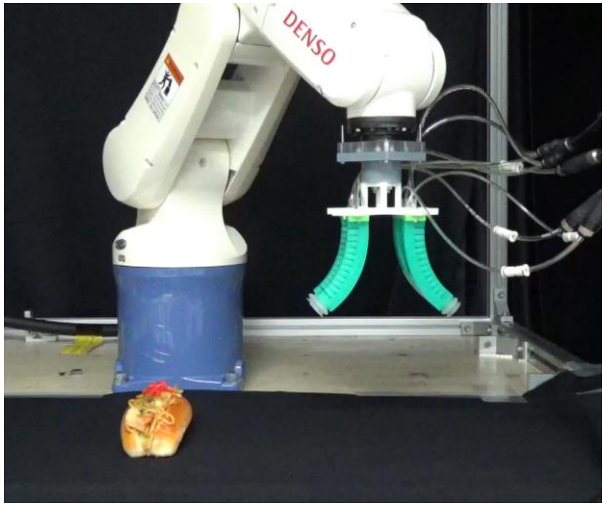


Grasping: red beans

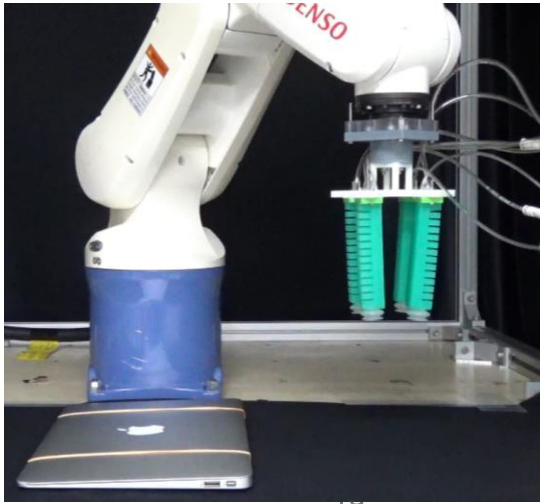


Grasping: fried chicken



Grasping: hot dog

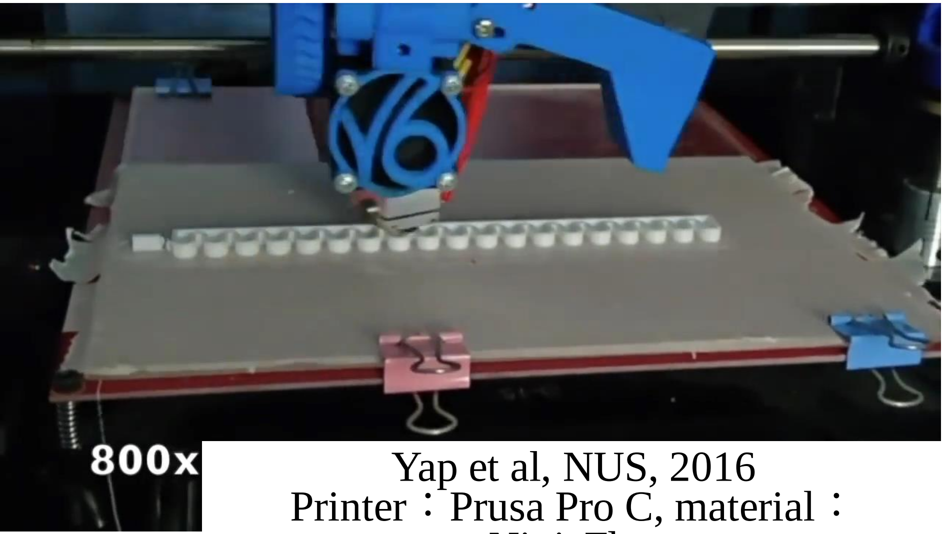
Suction: frozen hamburger



Suction: Mac Air

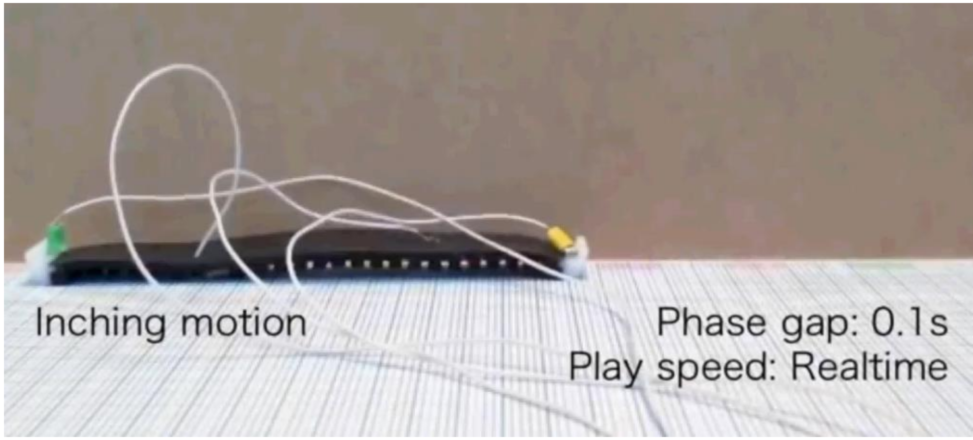
Bento packaging test

Examples of 3D printing



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

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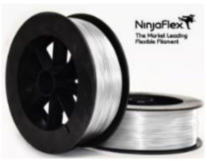
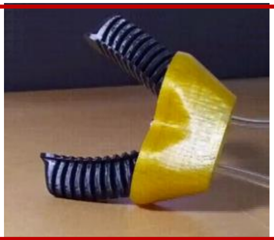
Printer name	Approach	Material	Hardness	Example
 Prusa	FDM	 NinjaFlex	Shore A85	
 Keyence Agilista	InkJet	Silicone like	Shore A60	
 Stratasys Objet	PolyJet	Rubber-like	Shore A27～Shore A95, 14 levels	
 MITS M3DS	DLP	Rubber-like	Shore A2～A50	
 RepRap L320	LAM	Liquid silicone rubber	Shore A30, A50, A70	

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?

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Finite Element Model

Self coded models

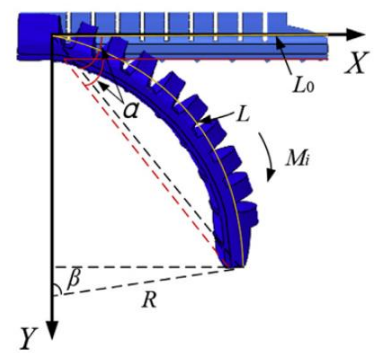
Ansys

SIMULIA ABAQUS

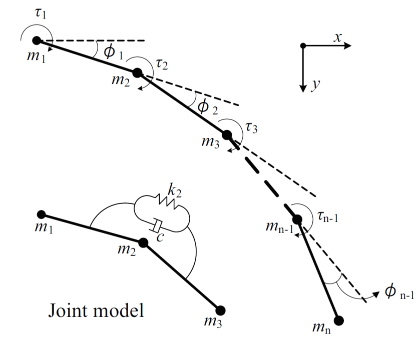
COMSOL MULTIPHYSICS

SOFA

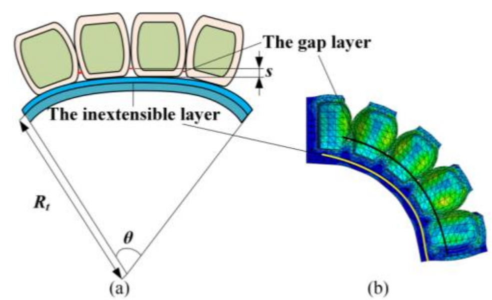
Other Models



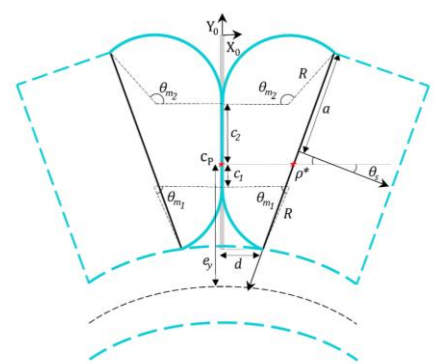
Beam constant curvature model



Line-segment model

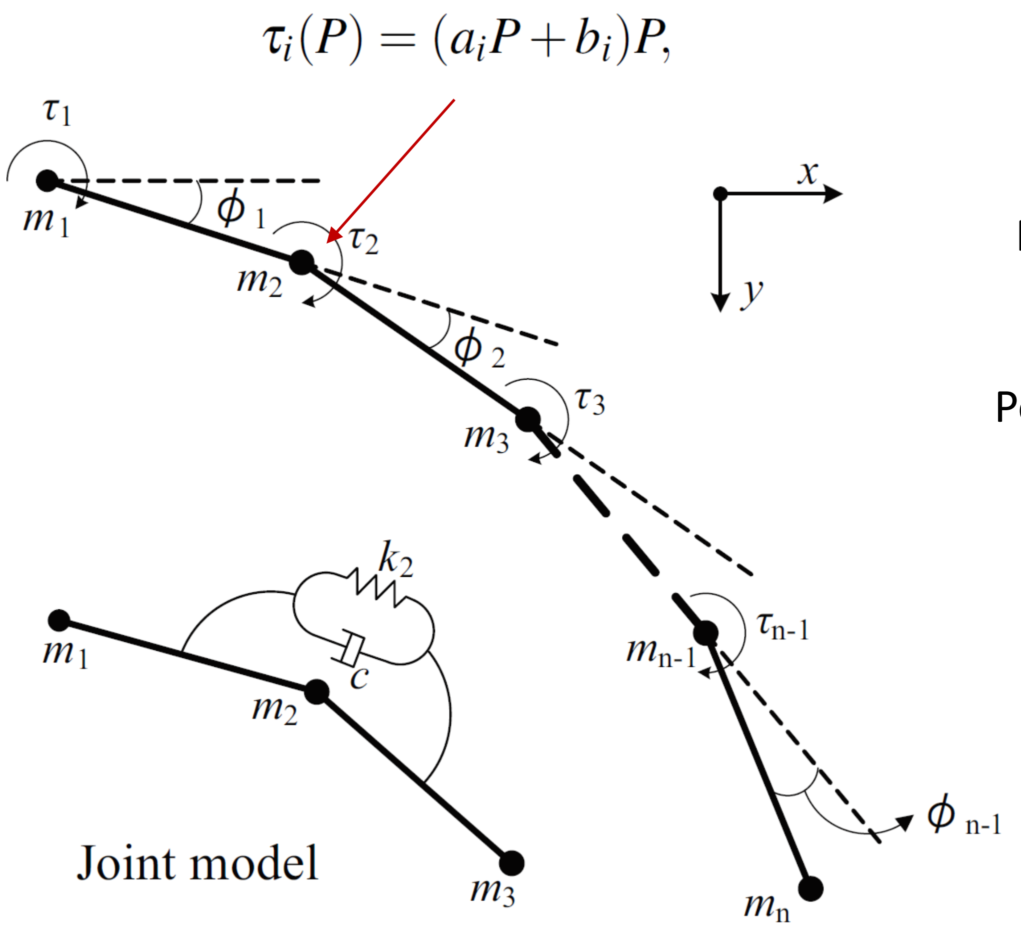


Serially connected constant curvature model



Finite strain membrane model

Line-Segment Model



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

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

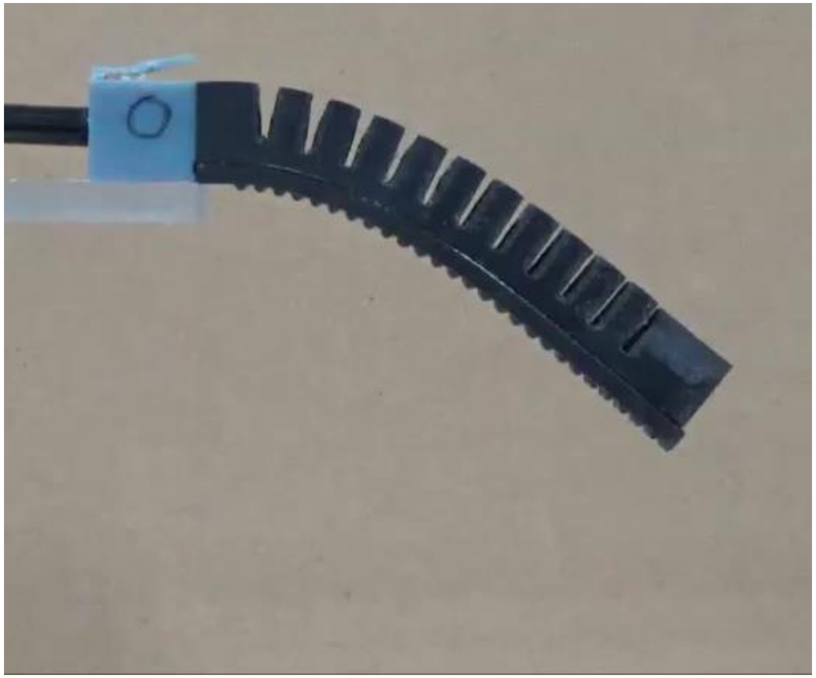
$$\frac{\partial L}{\partial y_i} - \frac{\mathrm{d}}{\mathrm{d}t}\frac{\partial L}{\partial \dot{y}_i} = 0.$$

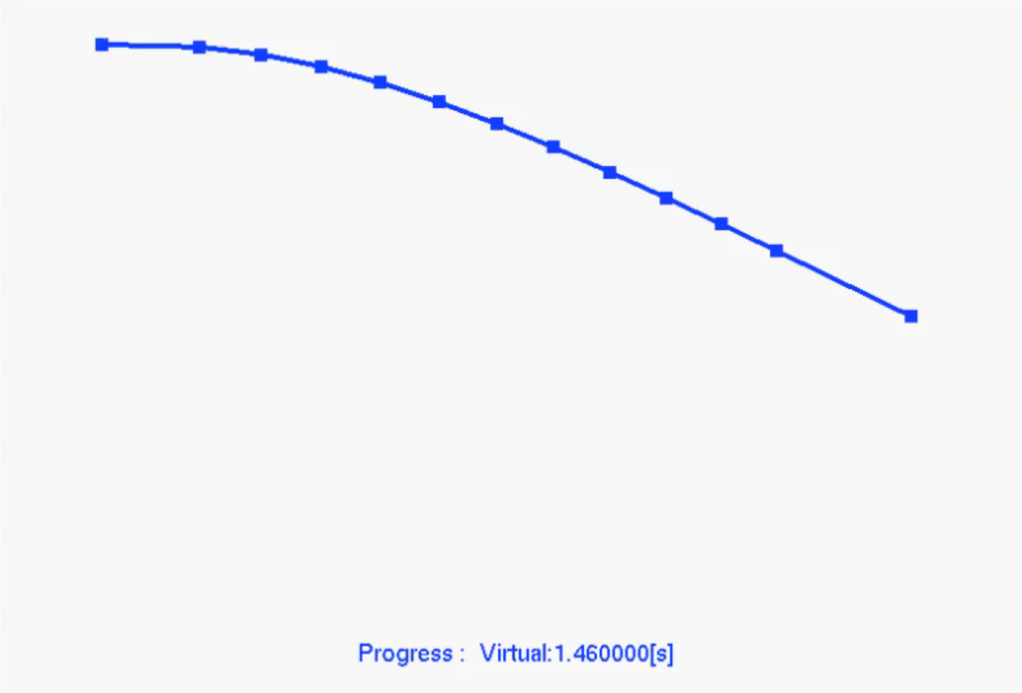
Lagrangian dynamics

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

Line-segment model

Simulation





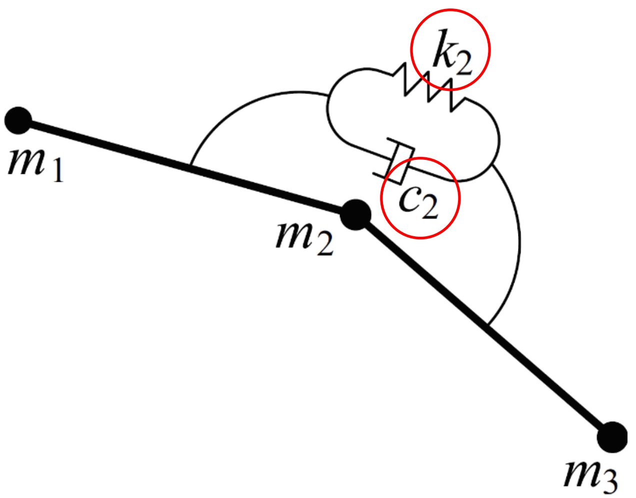
Experiment

Simulation

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

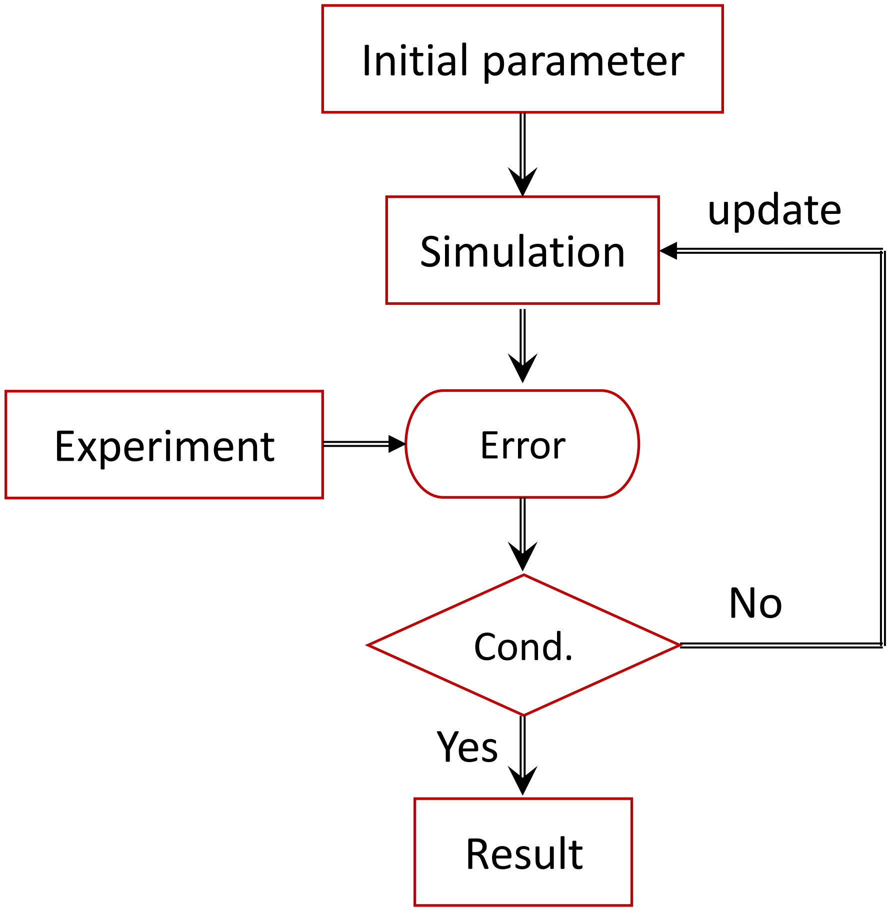
Parameter Identification

Unknown parameters

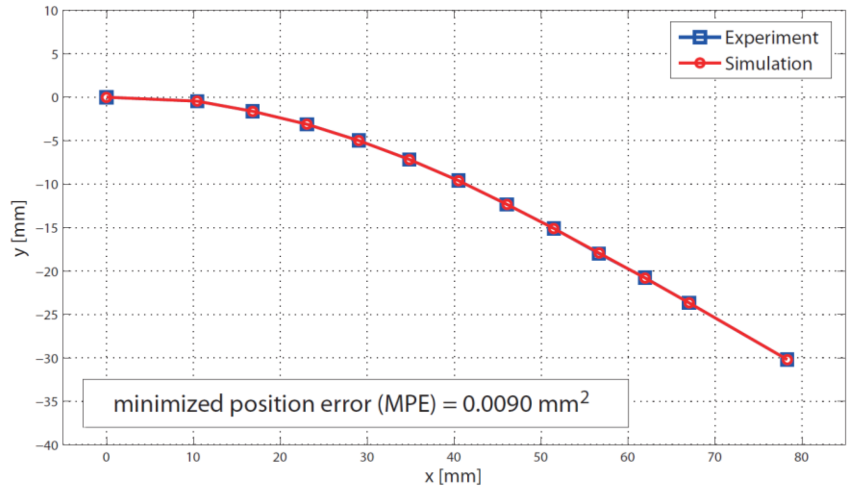


$$\tau_i(P) = (a_i P + b_i) P,$$

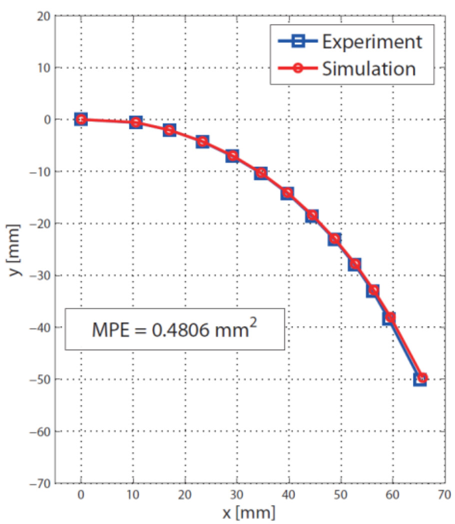
Optimization based method



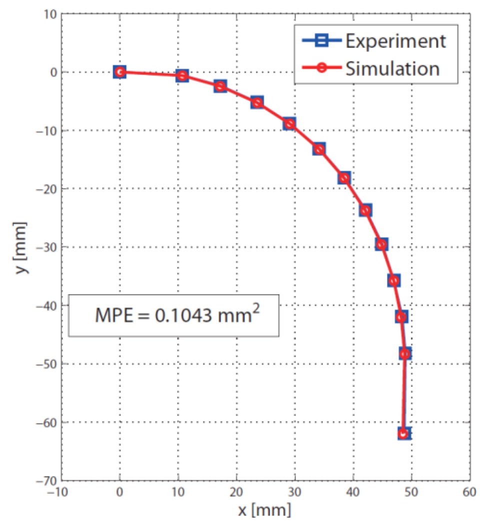
Identification results and validation



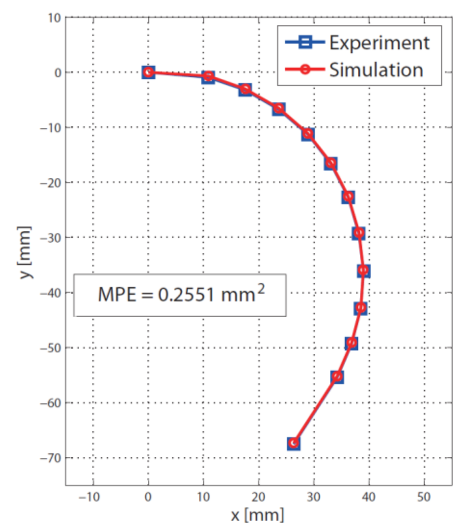
Under gravity



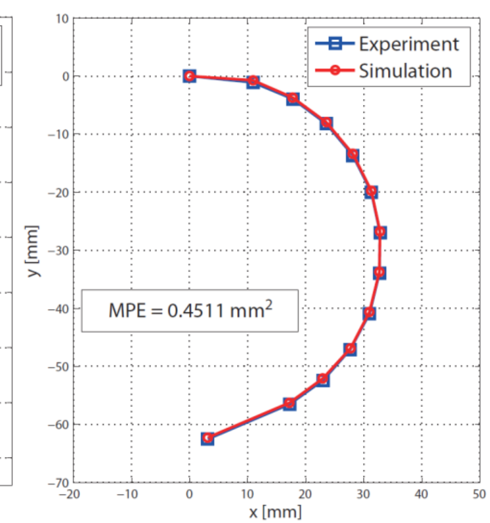
P = 10 kPa



P = 20 kPa

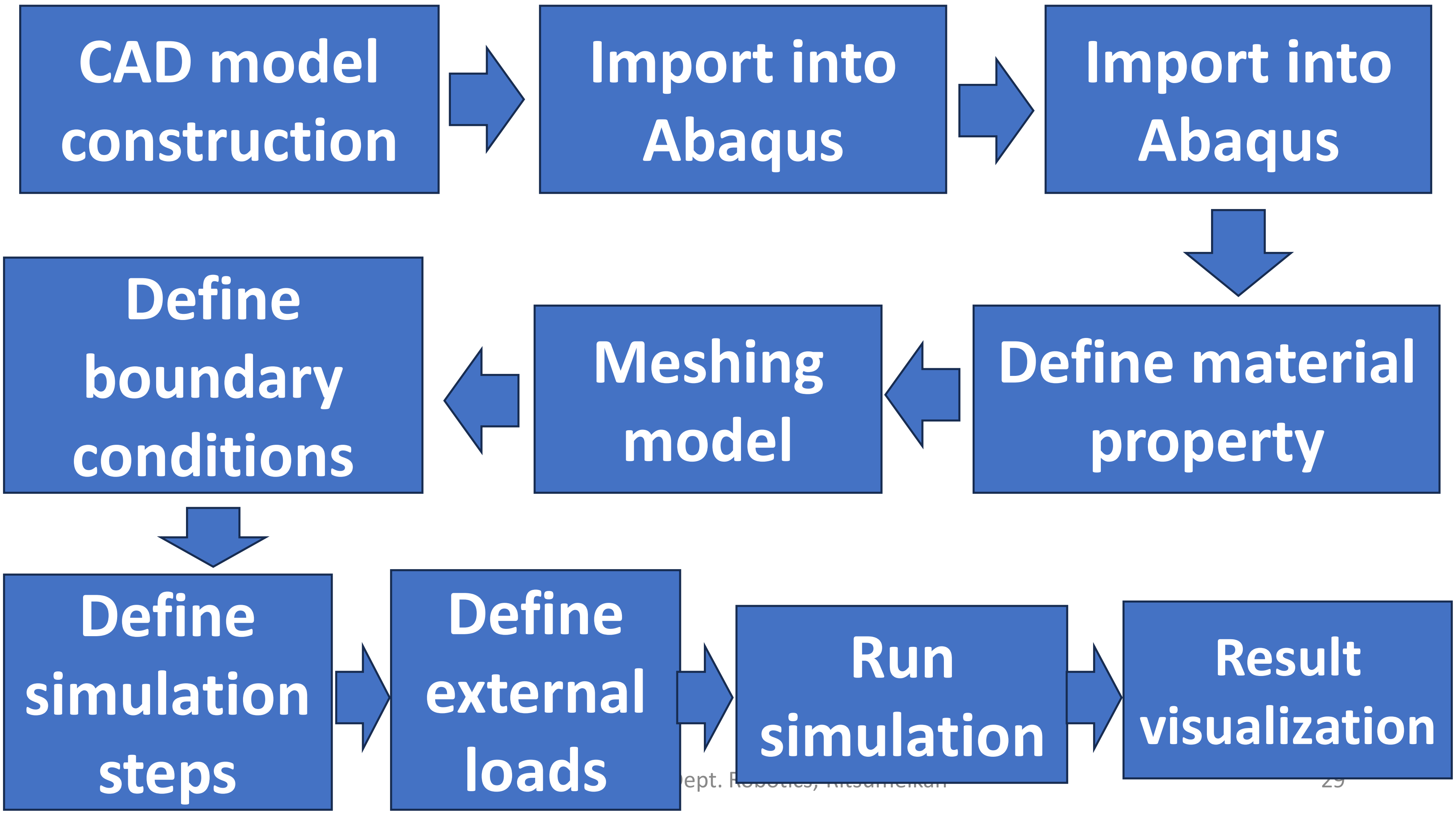


P = 30 kPa

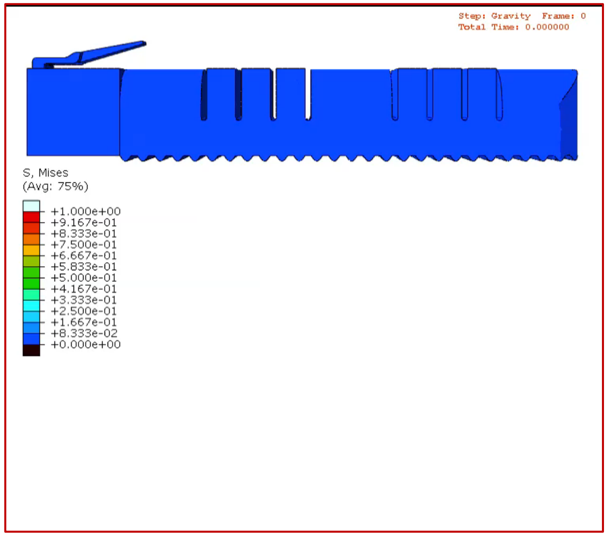


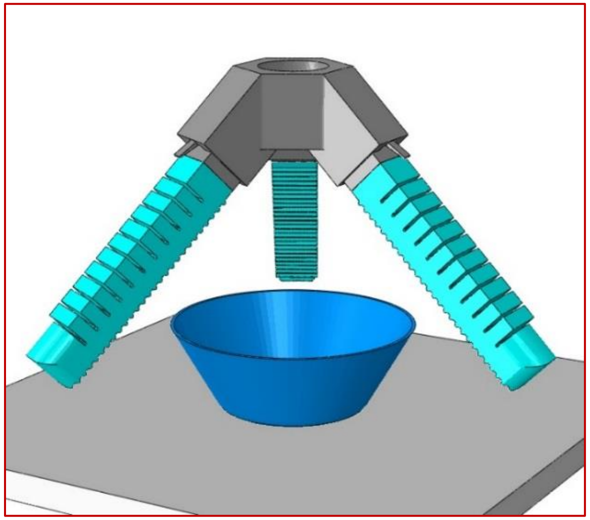
P = 40 kPa

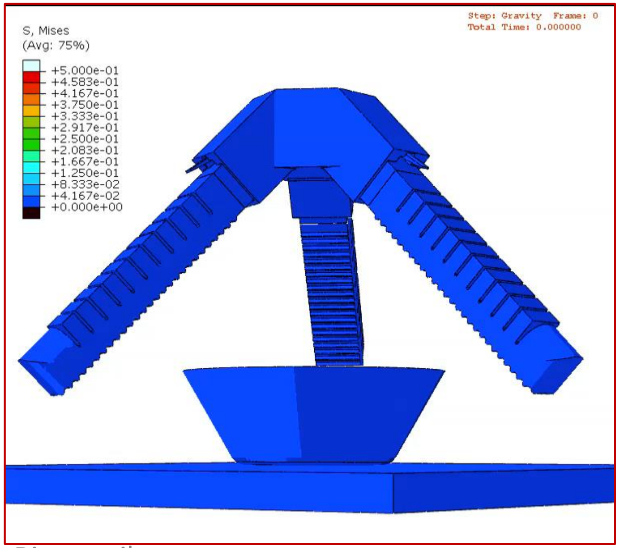
Finite Element Modeling (Abaqus)



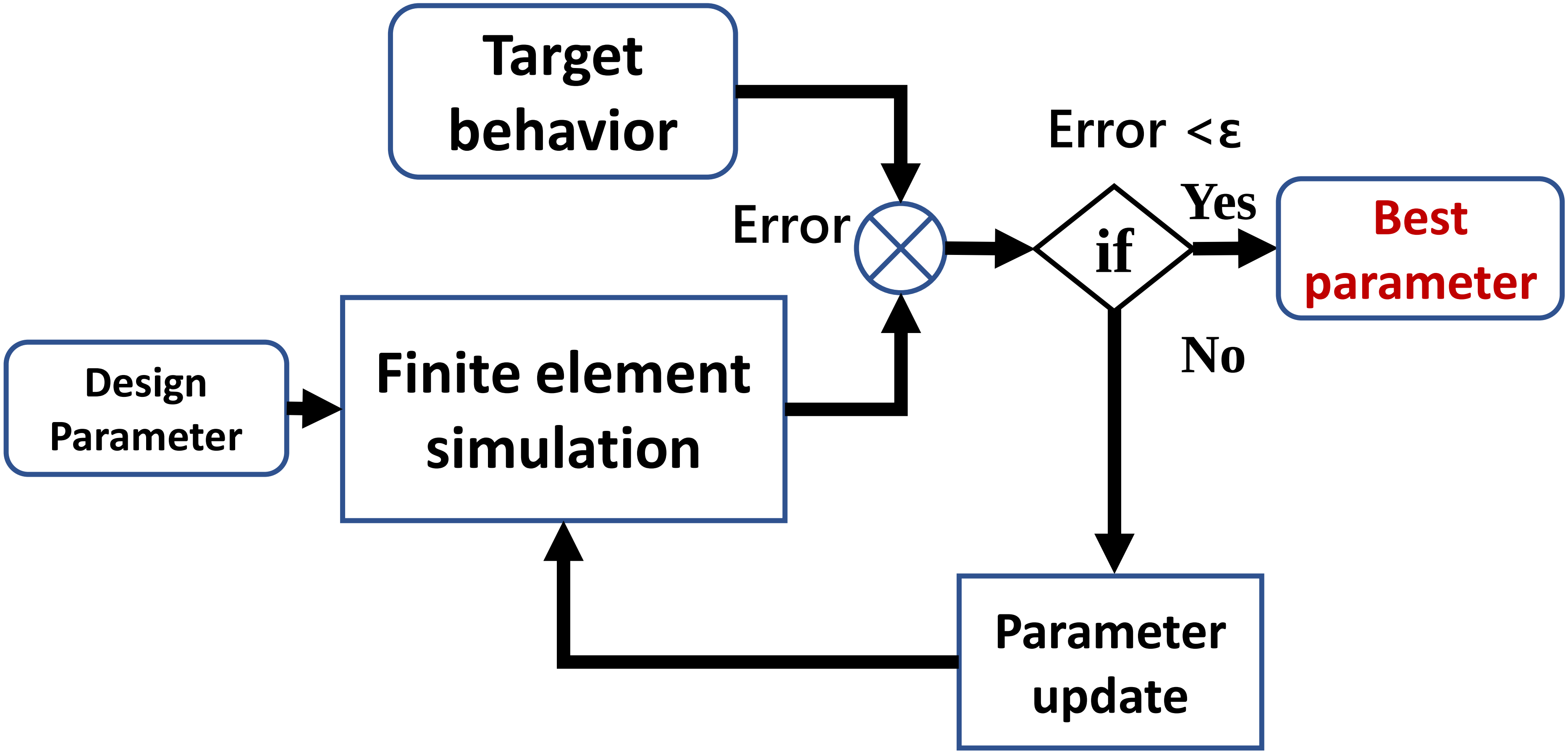
Example of Finite Element Simulation



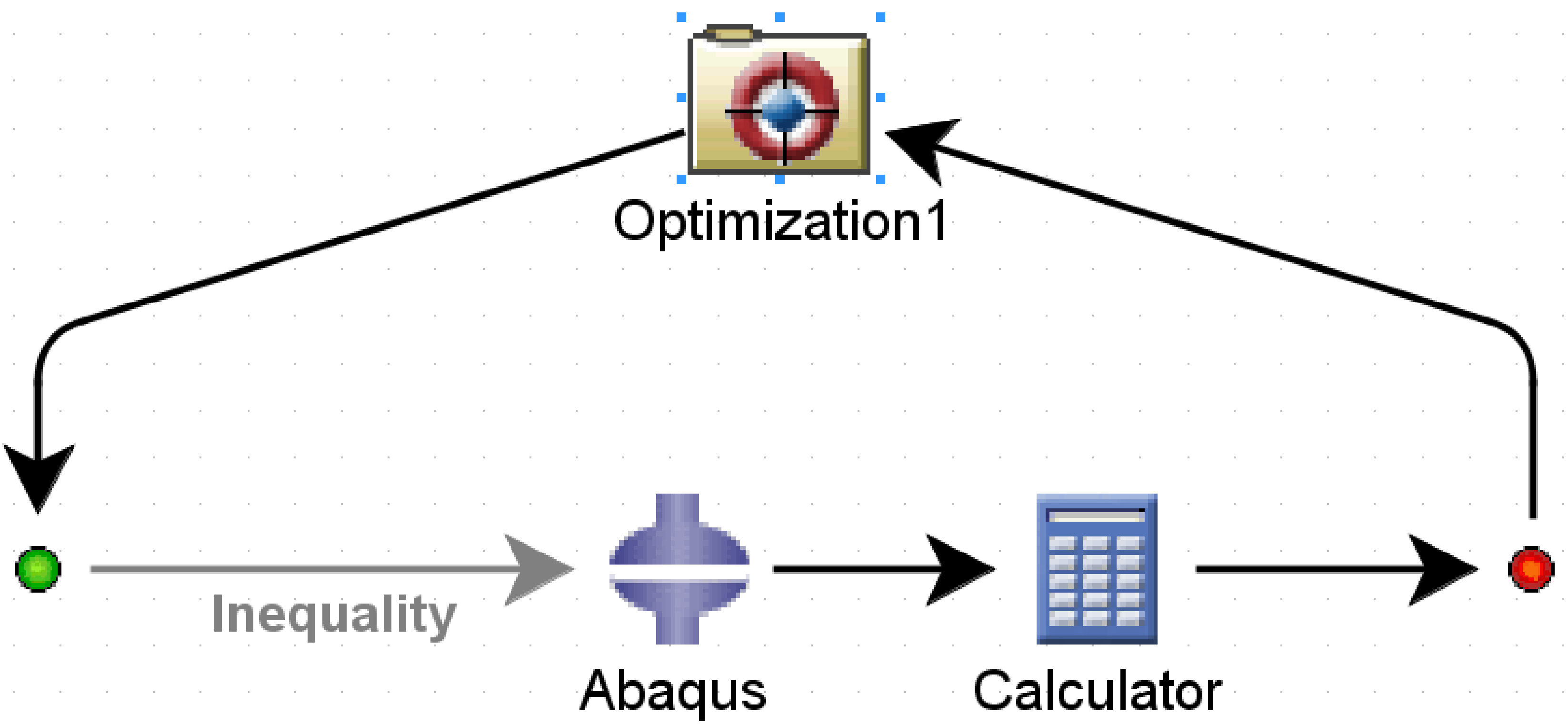




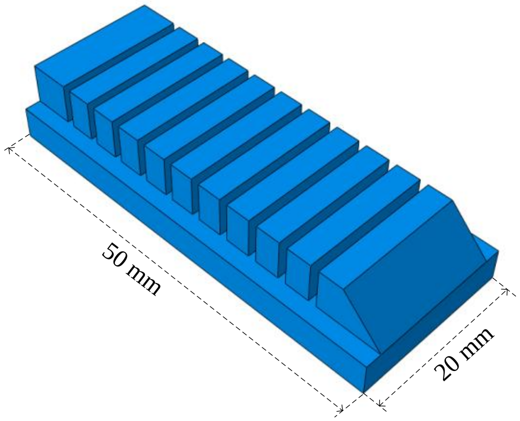
Parameter Identification Method

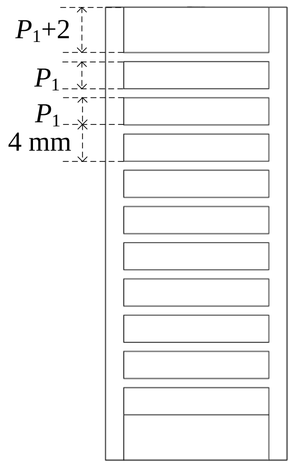


Parameter Identification using Abaqus and Isight

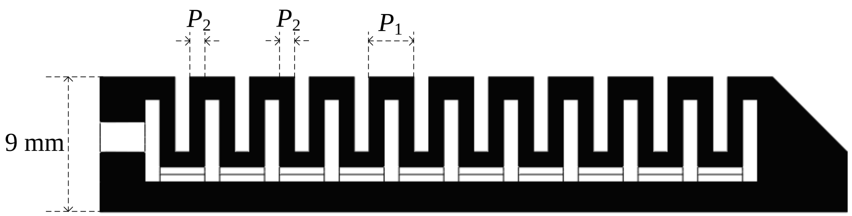


Example of Design Optimization





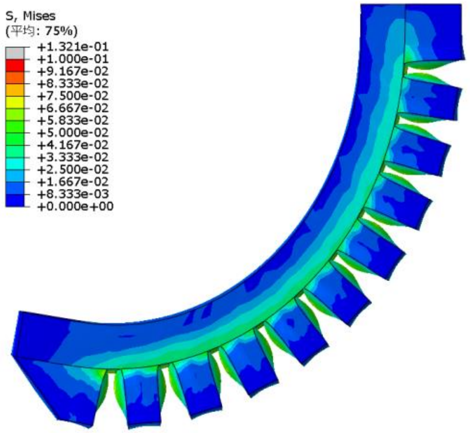
Design parameters： [P1, P2]



Design parameterization

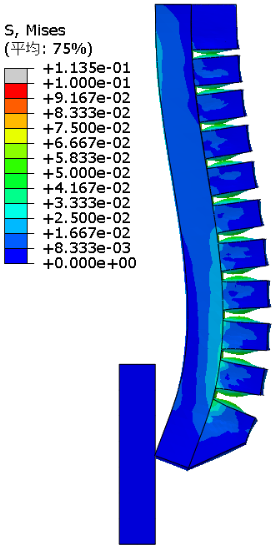
Free deformation

Initial parameters:
P1 = 3.0 mm
P2 = 1.0 mm



Grasping case

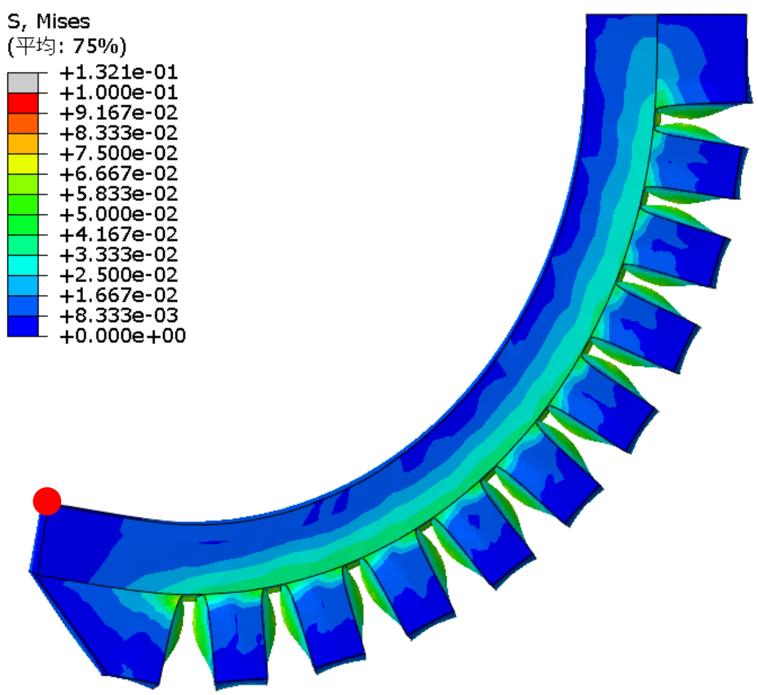
Initial parameters:
P1 = 3.0 mm
P2 = 1.0 mm



Optimization Results --- Maximum Bending

Initial parameters:

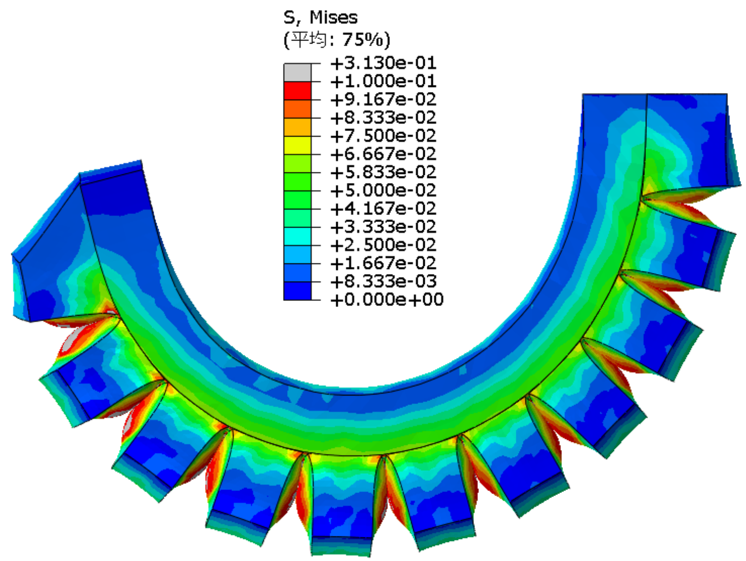
P1 = 3mm, P2 = 1mm



Deformation = 22.38 mm

Optimized parameters:

P1 = 3.8mm, P2 = 0.6mm

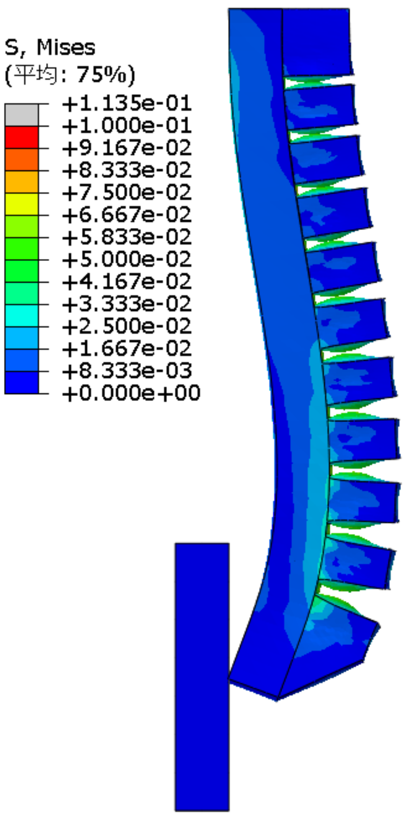


Deformation = 45.47 mm

Optimization Results --- Maximum Force

Initial parameters:

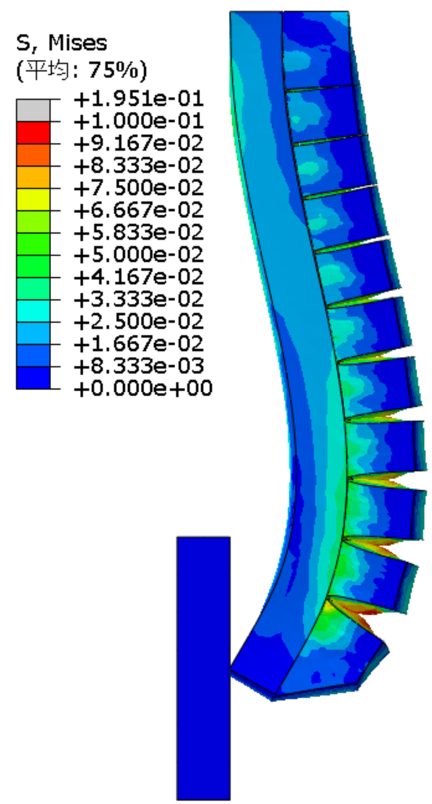
P1 = 3mm, P2 = 1mm



Force = 57.3 mN

Optimized parameters:

P1 = 3.8mm, P2 = 0.6mm



Force = 108.6 mN

Learning Resources

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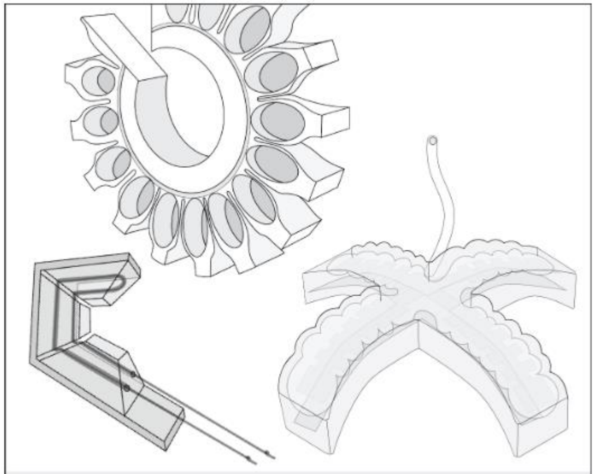
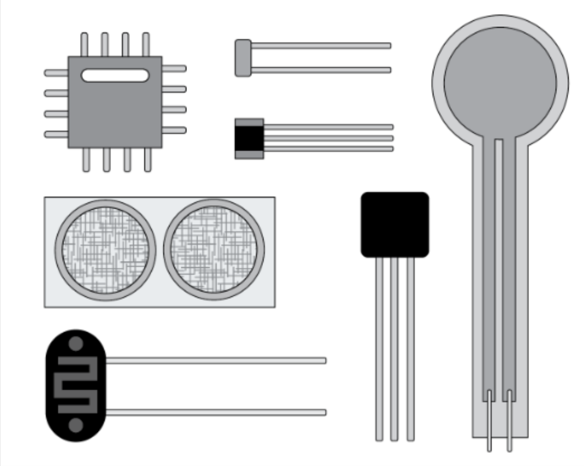
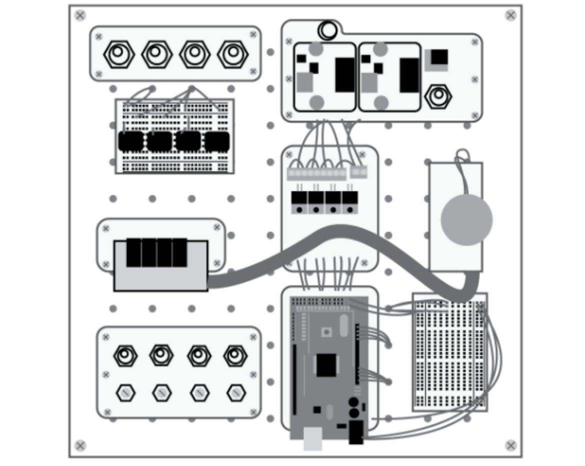
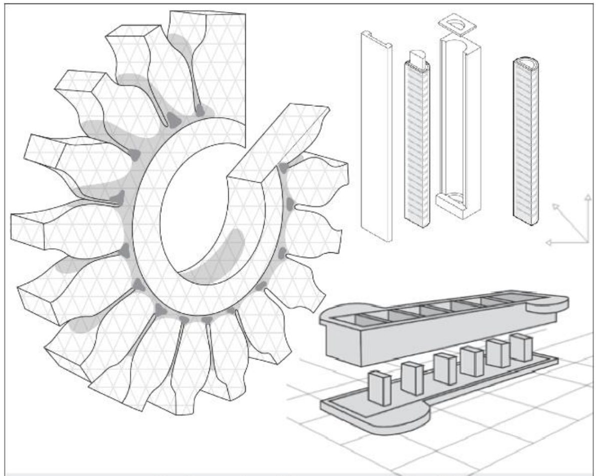
soft robotics toolkit

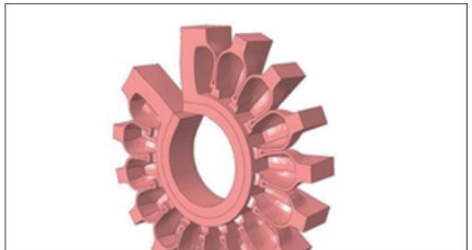

Actuators


Sensors

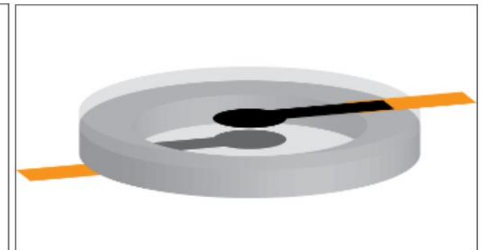

Controls

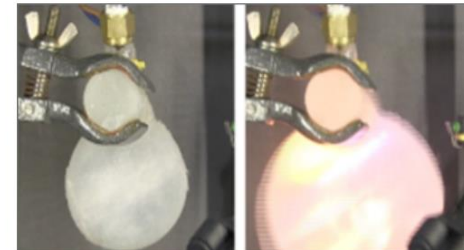

Modeling and Manufacturing

Soft Robotics Toolkit---Actuator

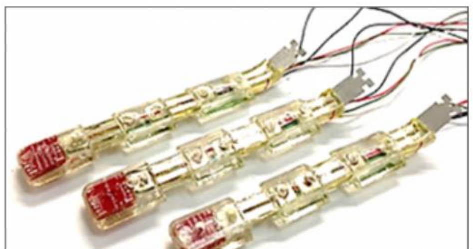

PneuNets Bending Actuators

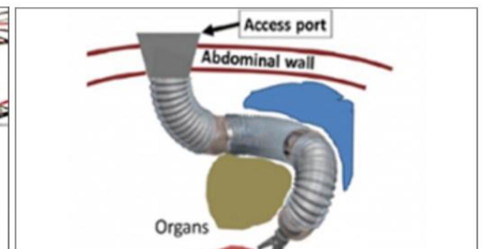

Fiber-Reinforced Actuators


Dielectric Elastomer Actuators

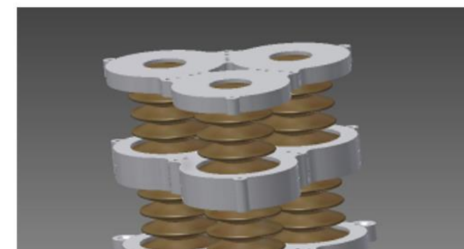

Combustion-Driven Actuators


Pneumatic Artificial Muscles


SDM Fingers

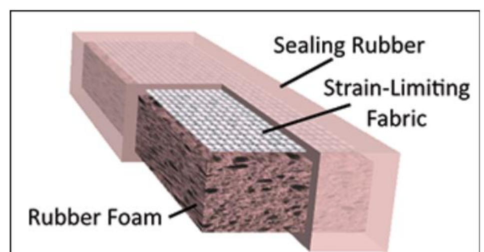


M.M.V.S. Manipulator

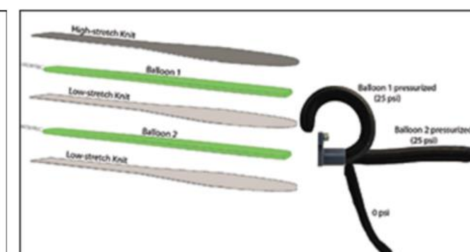

FeTCh Mark 1 Manipulator


HPN Manipulator


3D Printed Soft Gripper Stiffened by Passive Particle Jamming



Foam-Based Soft Actuators



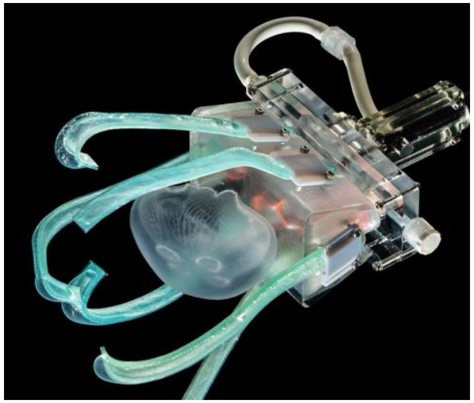
Knit Textile Bending Actuator

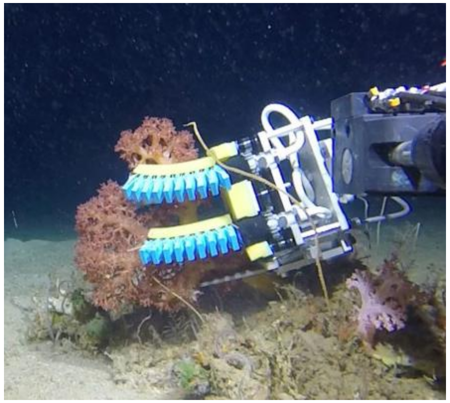
What Are Potential Applications?

Food industry

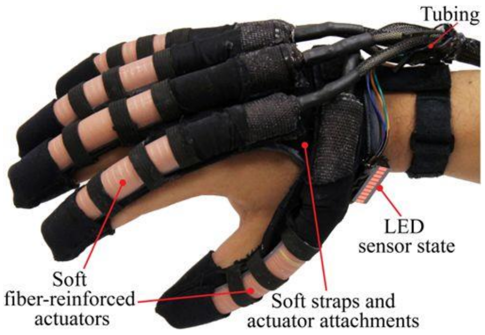
Agriculture and Fishery

Living creature grasping





Biomedical application



Main Applications that We are Focusing on

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Automation Challenges in the Food Industry and Agriculture

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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

Recognition
Machine learning
Image processing
Conveyor tracking

SI

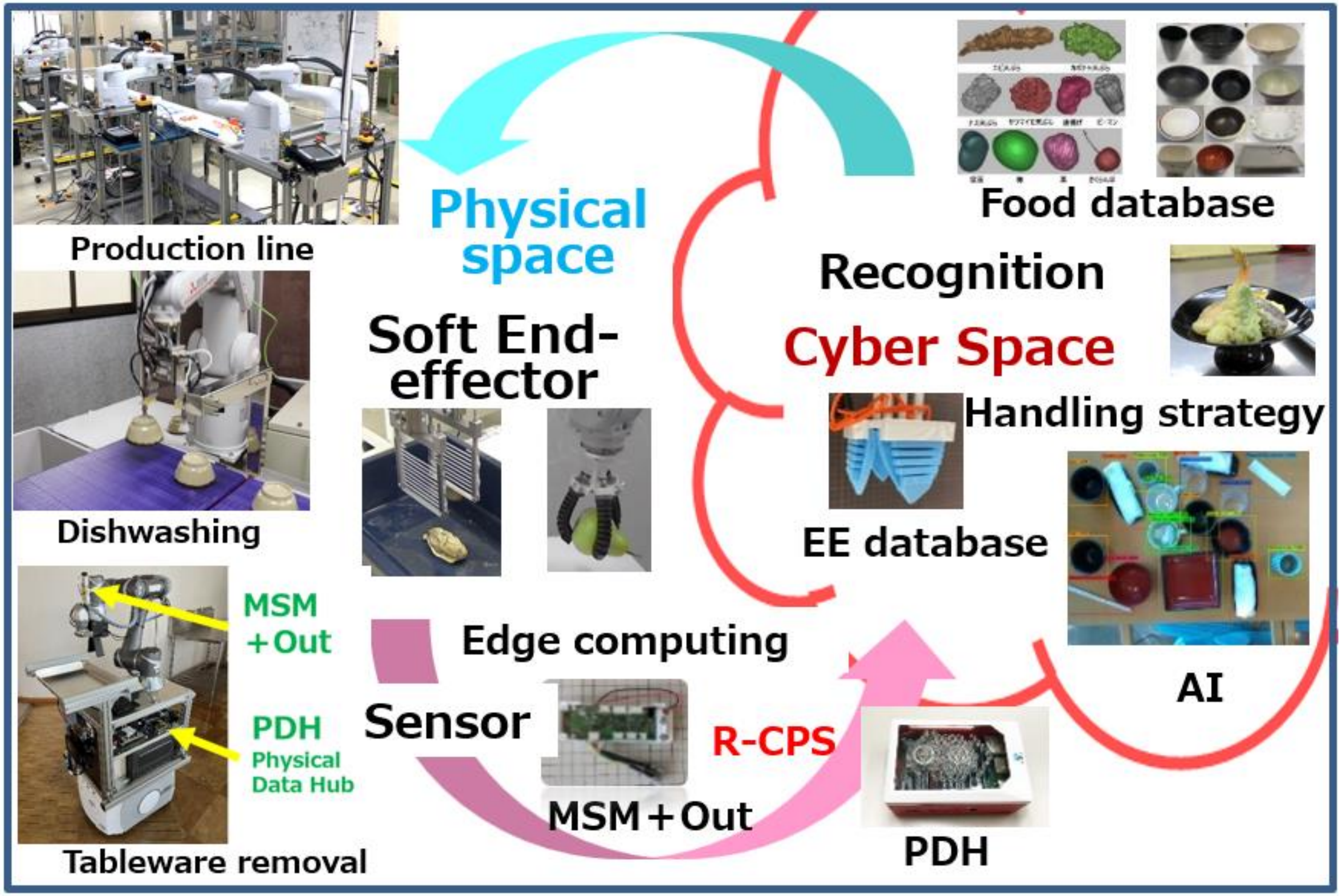
System Integration

Maintenance

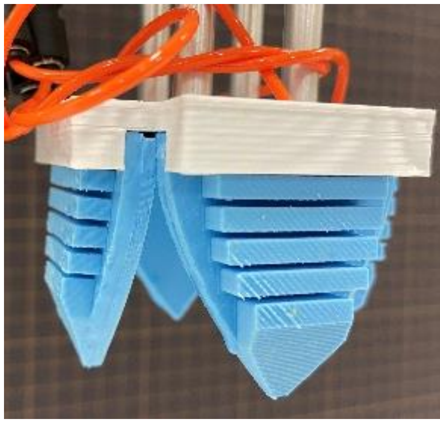
SIP Project

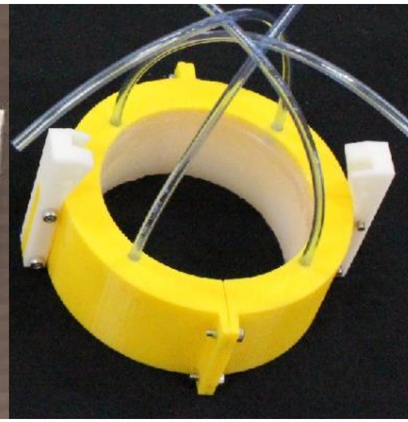
Cross-Ministerial Strategic Innovation Promotion Program

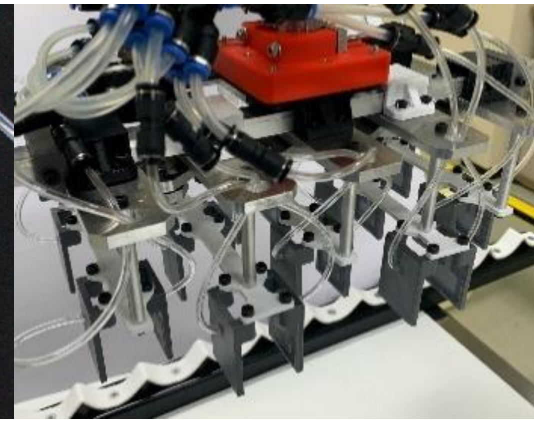
Title: Soft End-Effector System (SSES) for Cyber Physical System (CPS) Construction

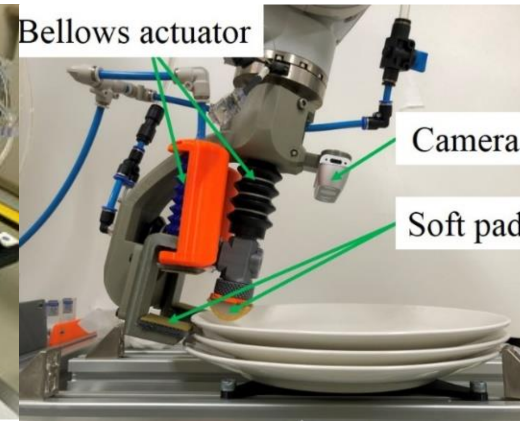


Soft robotic end-effectors developed by our group


Wrapping gripper


Circular shell gripper


Parallel shell gripper

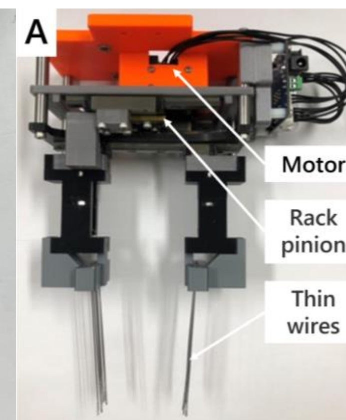


Dishwashing hand

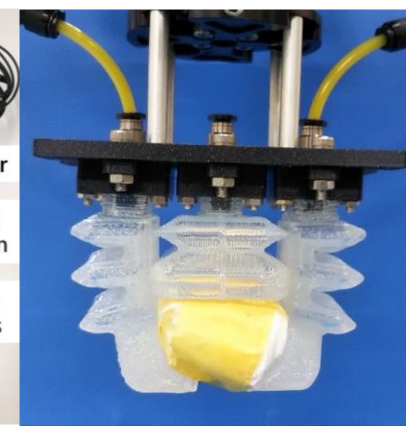

Needle gripper


Scooping-binding gripper


Bellows gripper



Multi-wire gripper


Shovel gripper