COMPLEX ROBOT SYSTEMS LAB

Body Plan of Soft Robots

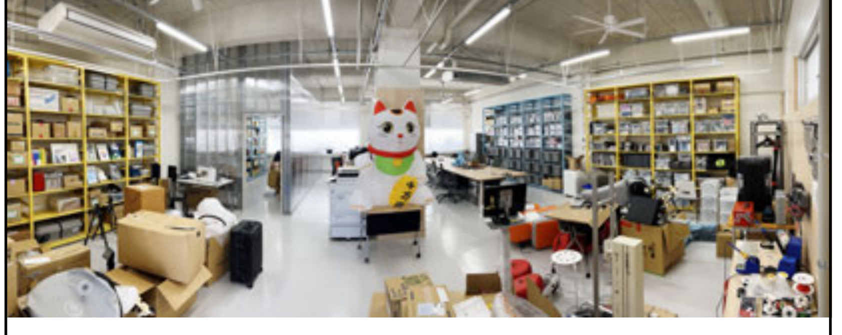
Ryuma Niiyama
Associate Professor, Meiji University

1

COMPLEX ROBOT SYSTEMS LAB

複雑ロボットシステム研究室（新山研究室）

2



3

Industrial Robot Arm

https://www.fanuc.co.jp/ja/product/robot/f_r_large.html
https://www.yaskawa.com/products/robotics/robots-with-iec/articulated-robots
https://kawasakirobotics.com/jp/
https://epson.com/industrial-robots-factory-automation
https://www.mitsubishielectric.com.au/product/robots/

5

State of the Art of Hard Robotics

- Trajectory planning + MPC (Model Predictive Control)?

6

Collaborative Robot


Universal Robot, UR5


Kuka, LBR IIWA


Rethink Robotics, The Baxter & Sawyer


Kawada, Nextage

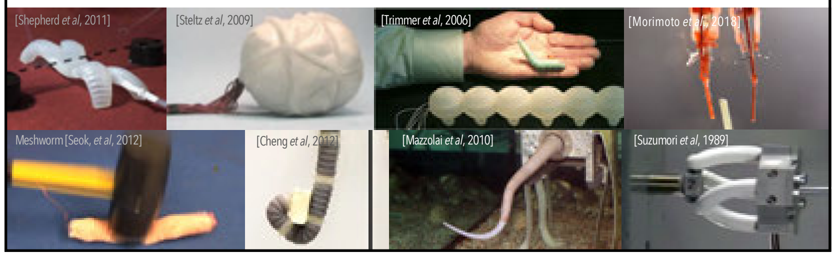

ABB, YuMi


Fanuc, CR-35iA

7

Soft Robotics

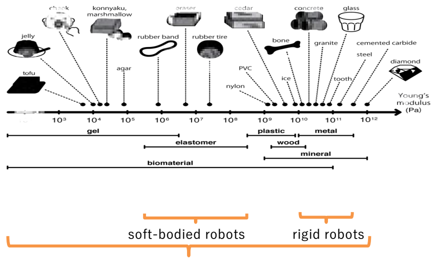
Emerging research field that focuses on the transformations in robot mechanisms and control by
leveraging the unique properties of soft materials.
(not limited to fully soft-bodied robots)



10

Use both “hard” and “soft”

- Right material for the right job, expanding design options
  - From metals to elastomers, from single materials to composites



11

Hard vs. Soft

Classic Hard Actuators

- Assembly of rigid rigid bodies
- Output: Rotation, translation
- One of the components:
  Actuator, transmission, and effector
- Powerful, large machines

Soft Actuators

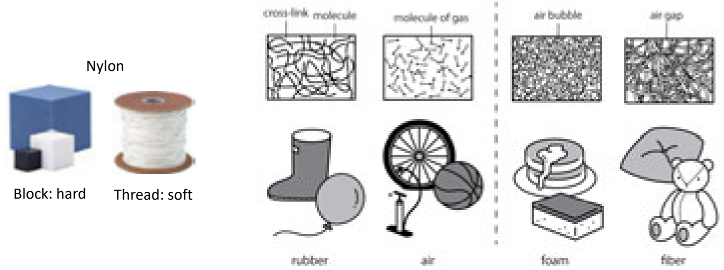
- Soft material with embedded structure
- Output: 3D Deformation, especially bending and contraction
- Actuator and body is fused
- low output force, small




13

Soft Materials, Soft Structures

- Soft material: elastomer, gel, fluid (water, oil, air)
- Soft structure: thin (film, fiber), foamed



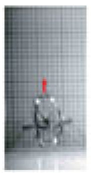
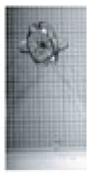
14

Function of Softness

- Deformation
  - Safety
  - Adaptability
  - Store and release elastic energy, entropic elasticity


Inflatable Arm
[Sanan *et al.*, 2011]


Jamming Gripper
EMPIRE



Crawling and Jumping Soft Robot
[Matsuyama, *et al.*, 2007]

15

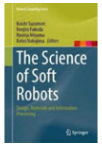
Advanced Functions

- Transformation
  - Phase-transition, jamming transition
  - Growth, self-healing
  - Biodegradable, edible
- Embodied Intelligence
  - Morphological Computation: memory, generate time series data

16

Textbook

鈴森 康一、中嶋 浩平、新山 龍馬、舛屋 賢 編著
『ソフトロボット学入門　基本構成と柔軟物体の数理』
（オーム社、2023年）



Koichi Suzumori, Kenjiro Fukuda, Ryuma Niiyama, Kohei Nakajima Ed.
“The Science of Soft Robots”
(Springer, 2023)

Single Author


細田 耕
『柔らかヒューマノイド』
（化学同人、2016年）


新山 龍馬
『やわらかいロボット』
（金子書房、2018年）

鈴森 康一
『いいかげんなロボット』
（化学同人、2021年）

Handbook

古川 英光、川上 勝 監修
『やわらかものづくりハンドブック』
（NTS、2022年）

日本ロボット学会編
ロボット工学ハンドブック第3版
（コロナ社、2023年2月）

17

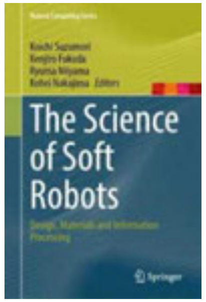
Textbook: Science of Soft Robots

1. Introduction

PART I Design of Soft Robots
2. Soft Mechanisms
3. Biological Mechanisms
4. Soft Manipulation and Locomotion

PART II Soft Materials
5. Basics of Polymer
6. Biological material
7. Flexible and Stretchable Electronics and Photonics
8. Soft actuators

PART III Autonomous Soft Robots
9. Modeling and Control of Continuum Body
10. Material Intelligence
11. Information Processing using Soft Body Dynamics



Koichi Suzumori, Kenjiro Fukuda, Ryuma Niiyama, Kohei Nakajima Ed.
“The Science of Soft Robots”
(Springer, 2023)

18

Matthew Borgatti, Kari Love
“Soft Robotics”
（Make Community, 2018）

Collection of academic papers

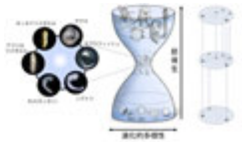
19

ロボットアーキテクチャ
ROBOT ARCHITECTURE

20

Body Plan

- 生物の個体発生における身体構造、諸器官の配置
- 動物の形態
  - 左右相称動物、特に脊椎動物の三胚葉性の体制
  - 体節と四肢の発生、横紋筋の起源
  - 脳・神経系の発生、神経誘導

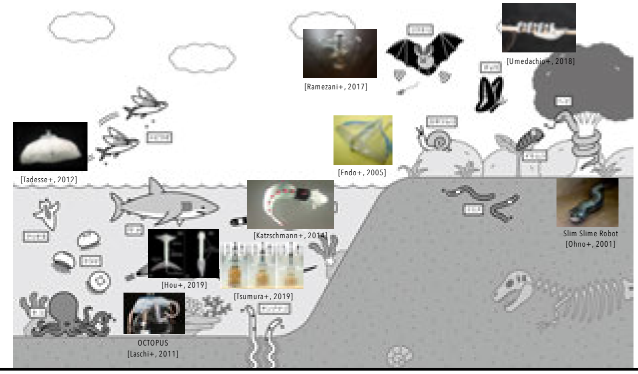


[Irie., 2017]

[Zuniga *et al.*, 2015]

21

Bio-inspired Soft Robots



22

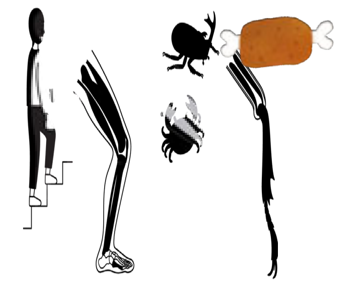
Locomotion

- Terrestrial locomotion
  - Legged
  - Limbless crawling: snake, snail
  - Rolling: caterpillar
- Aerial Locomotion
  - Flapping: bee, bird
  - Gliding
- Aquatic locomotion
  - Flotage: water strider
  - Swimming : fish, eel, dolphin, salamander, penguin
    - Undulation
    - Fin
  - Jet Propulsion: squid, octopus, cuttlefish
- “Artificial” Locomotion
  - Wheel, Continuous Track
  - Jet Propulsion (gas)

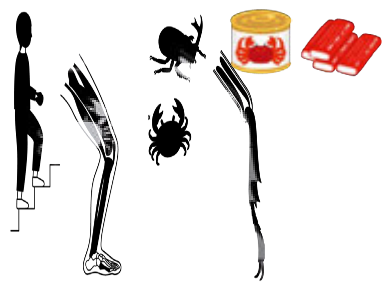
23

Musculoskeletal System

Endo-skeletal System 内骨格



Exo-skeletal System 外骨格

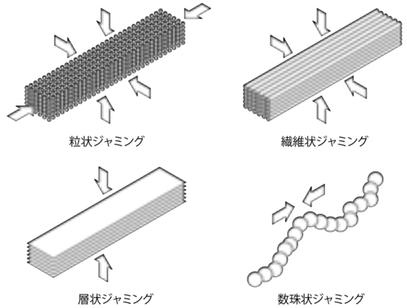


26

27

Jamming

- Granular, fiber, layer/laminar, beads



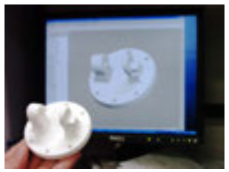
28

Digital Fabrication

- Making Robots with 3D Printer

Kawada Robotics, Nextage

Hack Rod by Primordial Research Project, Autodesk, and Bandito Brothers, 2016.



Stratasys Objet24

29

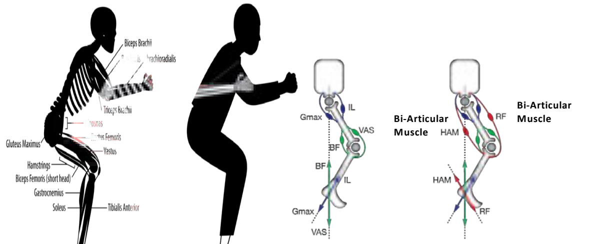
筋骨格ロボット

MUSCULOSKELETAL ROBOT

31

Human Musculoskeletal System

- Muscle-Tendon Complex (MTC)
  - Mono- and multi-articular muscles
  - Very difficult to emulate MTC in electric motors



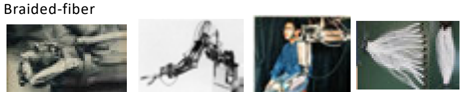
(a) Independently driven joints with mono-articular muscles
(b) combination of mono-articular muscles and bi-articular muscles

32

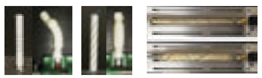
33

Pneumatic Artificial Muscles (PAM)

Braided-fiber


McKibben Muscle, 1957
Bridgestone-Hitach Arm 1984
Rubbertuator [Noritsugu *et al.*, 1995]
Small-diameter PAM [Suzumori *et al.*, 2011]

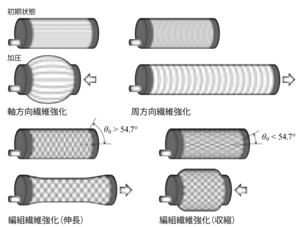
General


[Hirai *et al.*, 2001]
[Krishman, 2015]

Parallel-fiber


Warsaw-type, 1968
WAP-1, 1968
Pleated PAM [Daerden *et al.*, 2001]
[Nakamura *et al.*, 2009]

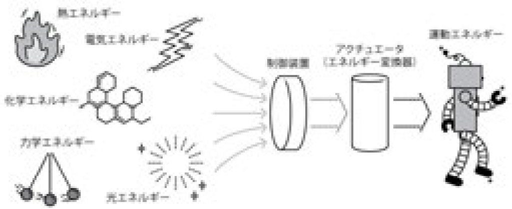
Fiber-reinforced PAM Family



34

Actuator

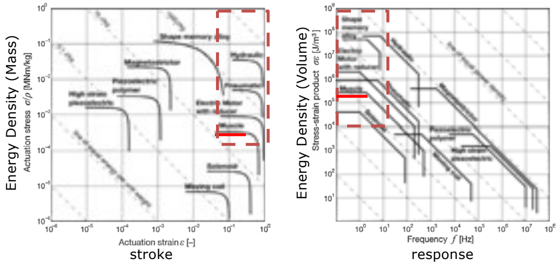
- Actuators are Energy Converters
  - Output mechanical energy
  - The input energy can be anything
  - Controlled by information



35

Actuator Comparison

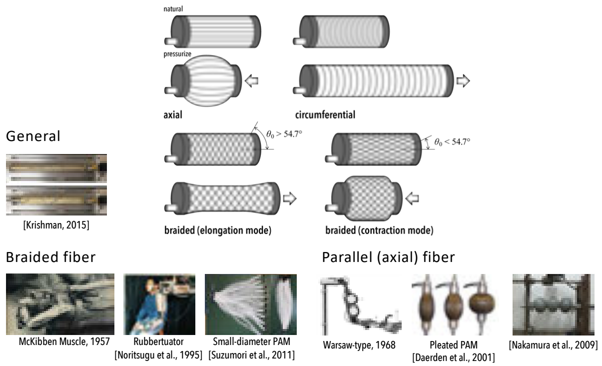
- Challenges of Soft Acuators:
  small displacement, slow, low durability, poor availability



[Huber *et al.*, 1997] [Granosik *et al.*, 2005] [谷江, 1984] [Zupan *et al.*, 2002] [Bell *et al.*, 2005]

36

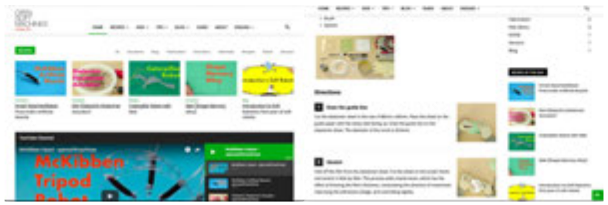
Fiber-reinforced Pneumatic Muscles

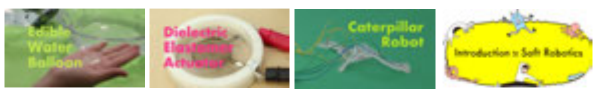


37

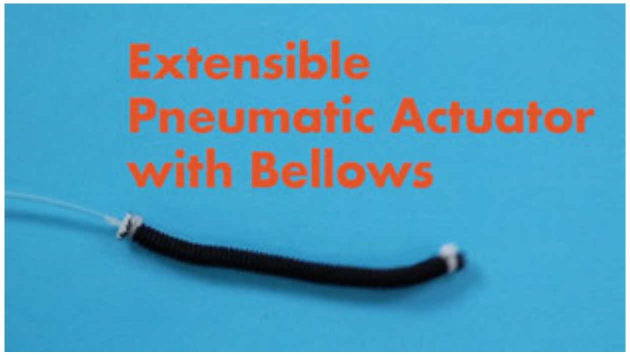
Open Soft Machines

http://opensoftmachines.com





38

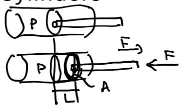


39

Output Work of Fluidic Actuators

仕事

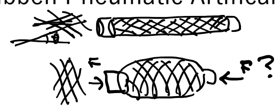
- Pneumatic Cylinders



$W_{out} = FL$

$W_{in} = PAL = PV$

- McKibben Pneumatic Artifical Muscles



$dW_{in} = dW_{out}$

$-FdL = PdV$

$\rightarrow F = -P\frac{dV(\theta)}{dL(\theta)}$

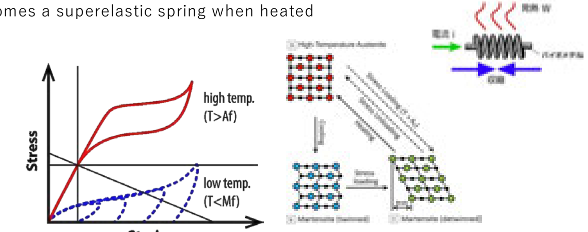
$V = f(\theta)$
$L = f_2(\theta)$

40

40

Shape Memory Alloy

- SMA
  - Ni-Ti Alloy
  - Products: Nitinol, Muscle Wires, Flexinol, and BioMetal
  - Binary, nonlinear, and hysteresis because it is based on crystalline phase transition
  - Becomes a superelastic spring when heated

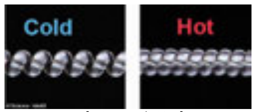


[Dadbakhsh *et al.*, 2014]

41

Shape Memory Polymer (SMP)

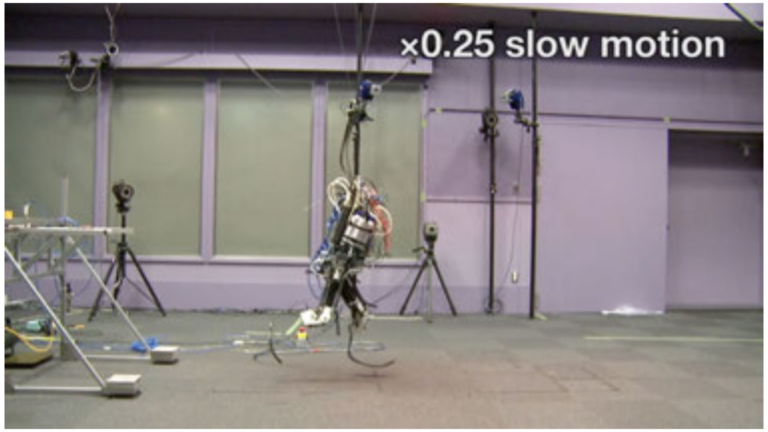
- SMP
  - Principle
    - Shape recovery by entropic elasticity when heated above the glass transition temperature Tg.
    - Shape recovery by heating above the melting point Tm, blended with a material with a low melting point.
- Crystalline polymer formed with stretching
  - Not like SMA, it works by softening
  - One-time motion: Shrink tube/film
  - Actuator: Rubber band, Twisted and Coiled Polymer (TCP)



[Haines *et al.*, 2014]

42

43



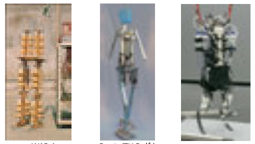
[Niiyama *et al.*, 2010]

44

Approaches to Human Motor Skills

Embodied Layer

- Biomechanics
- Passive Dynamic Walking
- Sensory-motor coupling
- Uncertain environment
- Emergent behaviors



WAP-1 [Kato et al. 1972] | Denis (TU Delft) [M. Wisse et al. 2005] | Athlete Robot [Niiyama et al., 2010]

Controller and Planning Layer

- Well-defined movement
  e.g. bipedal locomotion
- Torque, Angle, Posture

ASIMO | Atlas | Digit

45

Musculoskeletal Robots

2002-2010 **2011–2013** **2014–present**

Remote handshake robot
[Niiyama *et al.*, ICRA 2007]
[Niiyama *et al.*, ICRA 2009 WS]
[Niiyama *et al.*, 2010]
[Niiyama *et al.*, CLAWAR 2009]
[Nishikawa *et al.*, 2014]
[Nishikawa *et al.*, AMAM 2013]
[Fujita *et al.*, ICISIP 2017]
[Dwindra *et al.*, ROBIO 2018]
Ars Electronica 2009
[Nishikawa *et al.*, AMAM 2011]
[Yamada *et al.*, IROS 2011]
[Nishikawa *et al.*, ICRA 2016]
[Chen *et al.*, ROBIO 2017]
[Ushigome *et al.*, VRMM 2010]
[Niiyama *et al.*, 2012]
[Niiyama *et al.*, Humanoids 2010]
[Nishikawa *et al.*, Humanoids 2015]
[Ishii *et al.*, IROS 2018]

46

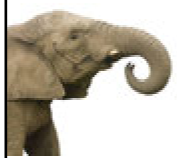
連続ロボットアーム

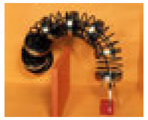
CONTINUUM ROBOT ARM

47

Continuum Robot Arm

- 骨や関節のないロボットアーム
  巻きつき把持、障害物の多い環境
- 課題：リーチング、制御



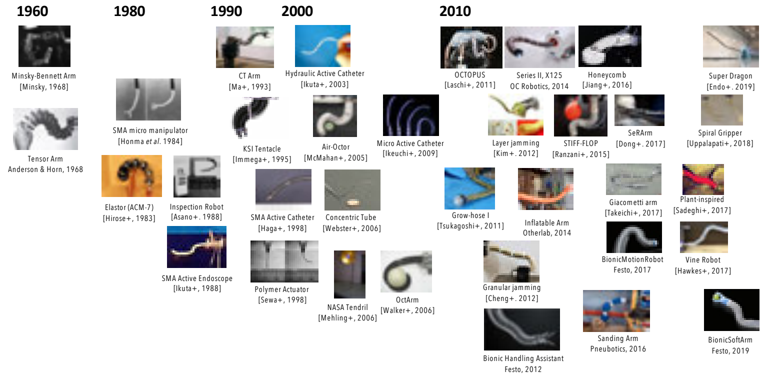

Elastor [Hirose+, 1983]


OctArm [Walker+, 2006]

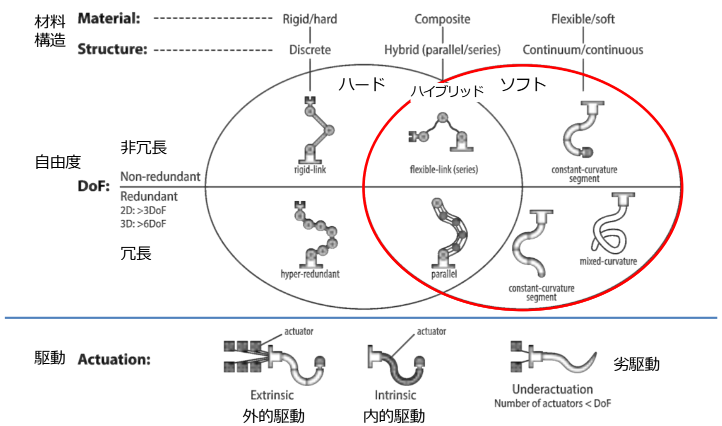

STIFF-FLOP [Ranzani+, 2015]

48

History



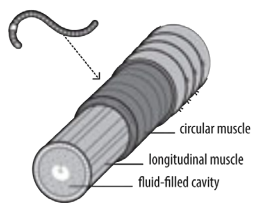
49

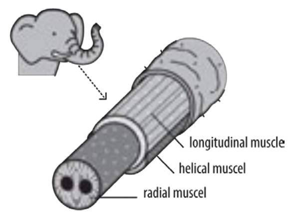


50

Soft Skeletal Sytem

- Hydrostatic Skeleton
  液体包骨格
  - Fluid-filled bladder surrounded by muscles
- Muscular Hydrostat
  筋肉包骨格
  - Muscle-filled hydrostatic skeleton

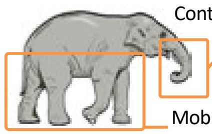


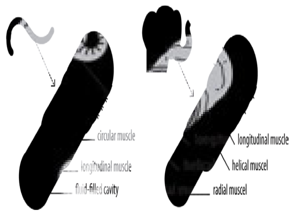


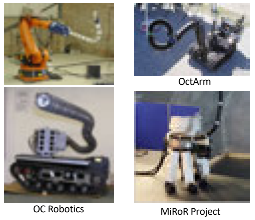
51

Elephant's Trunk

- Muscular Hydrostat
  筋肉包骨格
  - Muscle-filled hydrostatic skeleton



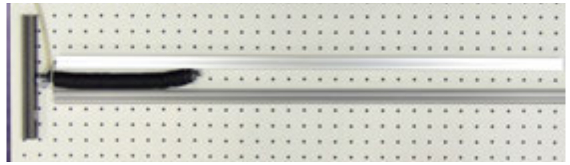


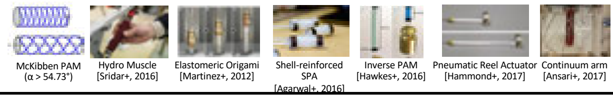


52

Extensible Soft Actuator

- EPAB (Extensible Pneumatic Actuator with Bellows)
  [Yukisawa *et al.*, ROBIO2017]

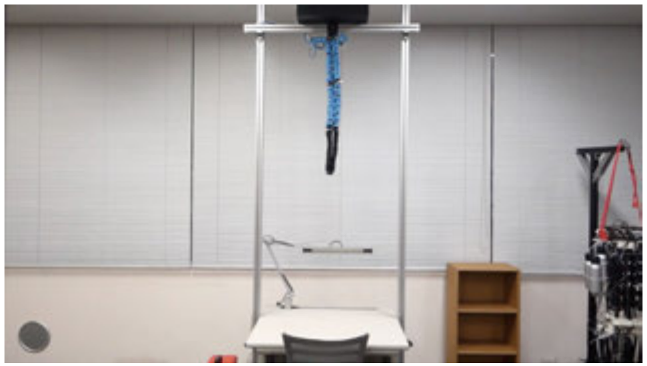




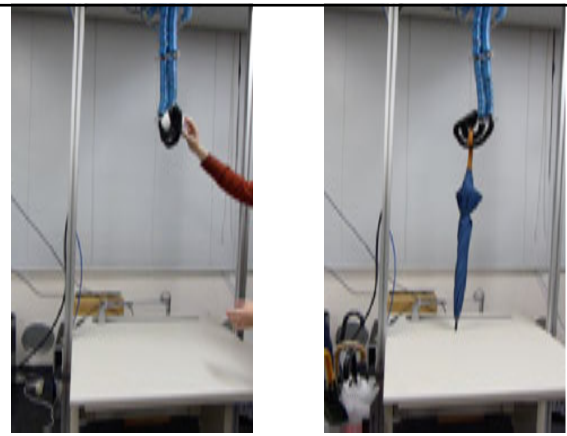
53

Ceiling Continuum Arm

[Yukisawa *et al.*, ROBIO 2017]
[Yukisawa *et al.*, RoboSoft 2018]



54



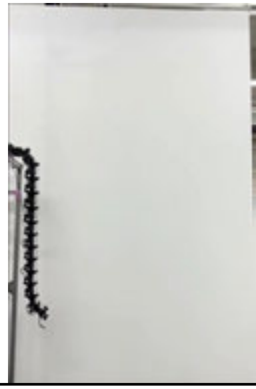
Throwing a ball **Pulling out an umbrella**

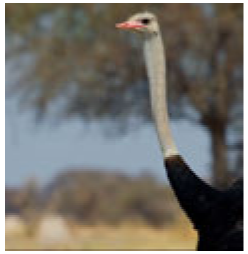
55

Maze Tasks (feedforward control)

56

Hybrid RobOstrich Manipulator





[Manome *et al.*, 2024]

https://www.youtube.com/watch?v=KL6ZmgbG-z8

57

57

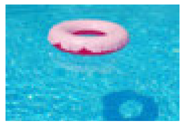
インフレータブルロボット

INFLATABLE ROBOTS

58

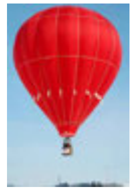
Inflatables

Rubber balloon



Swim ring

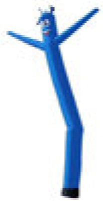
Inflatable castle



Hot air balloon

Foil balloon

Inflatable boat



Wacky waving tube

Inflatable dome

59

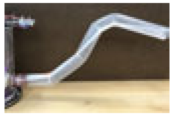
Inflatable Robots

Robots using a membrane structure supported by internal pressure.
Large, lightweight, and can be folded by deflating.


Inflatable robot arm, Otherlab, 2011


Inflatable arm [Sanan, *et al.*, 2011]


Inflatable arm, iRobot, 2012


Vine-inspired robot [Hawkes+, 2017]


Baymax, Disney, 2014


Soft upper body [Alspach+, 2015]


King Louie, Pneubotics [Best+, 2015]


Isoperimetric soft robot [Usevitch+, 2020]

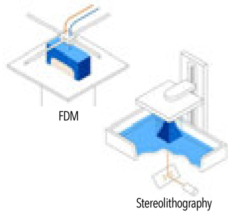
60

Why membrane-based robots?

- Fabrication Challenges of 3D Soft Robots
- Start from 2D: compact, affordable, ease of production

Raise the dimension from 2D to 3D

Layering: 3D Printing



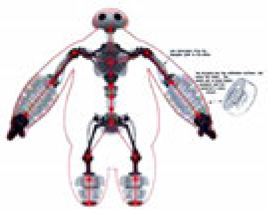
Folding: Origami Robots


Origami Robot [Felton *et al.* 2014]

Blowing: Inflatable Robots

61

Baymax from "Big Hero 6"

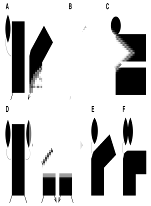


62

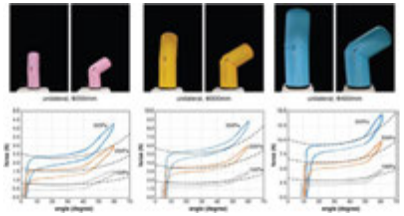

WPI-CMU team
Atlas robot with inflatable suit

63

Inflatable Joint



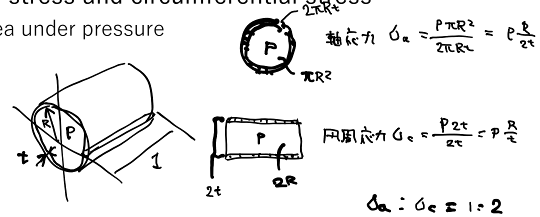
- Blower-powered Soft Inflatable Joints [Seong *et al.*, RoboSoft 2019]
  - Active control of the internal pressure
  - Driven by tendon wires pulled by linear actuators
  - Theoretical models for both unilateral and bilateral joints



64

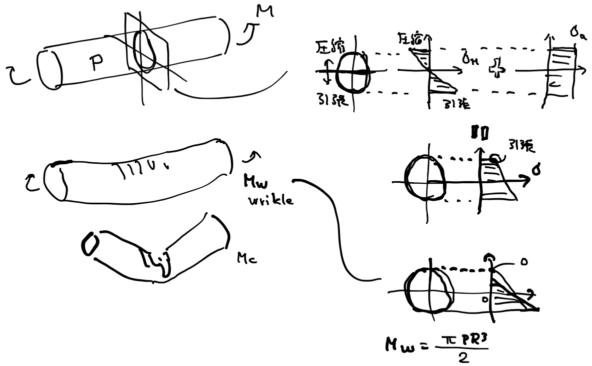
Theory of thin-walled cylinder

- Axial stress and circumferential stress
  - Area under pressure



65

Inflatable beams subjected to bending



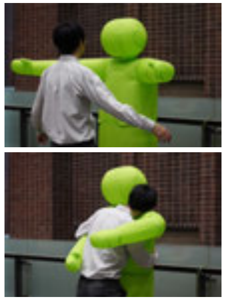
66

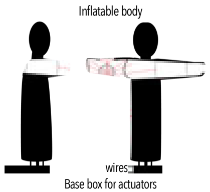
Physical Human–Robot Interaction

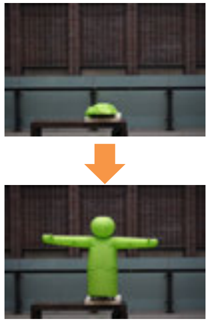
67

pHRI (physical human-robot interaction)

- Inflatable Humanoid Robot, 6 DoF



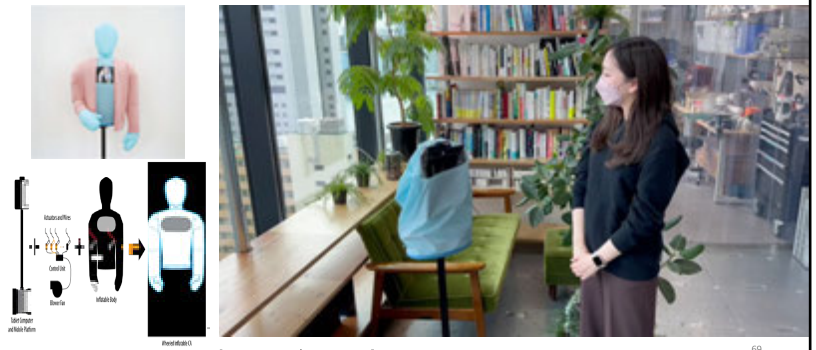




68

68

Avatar Application



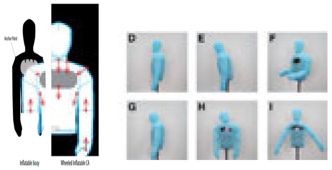
[Niiyama *et al.*, IJAT 2023]

69

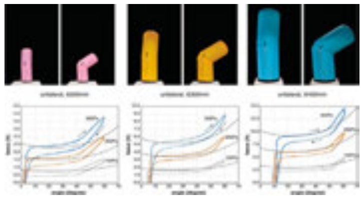
69

Background Technologies

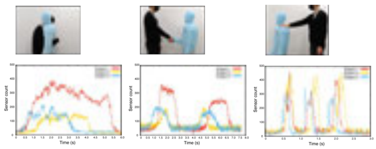
- Tendon-driven inflatable joint
- Gestures by deformation
- Embedded sensors



Possible gestures



Tendon-driven inflatable joint in different scale.



Capacitance-based tactile sensor on the shoulder.

70

Summary

- Softness expands the possibilities of robotics
  - Deformation and transfromation
  - Continuum Body
  - Soft Body Plan

71