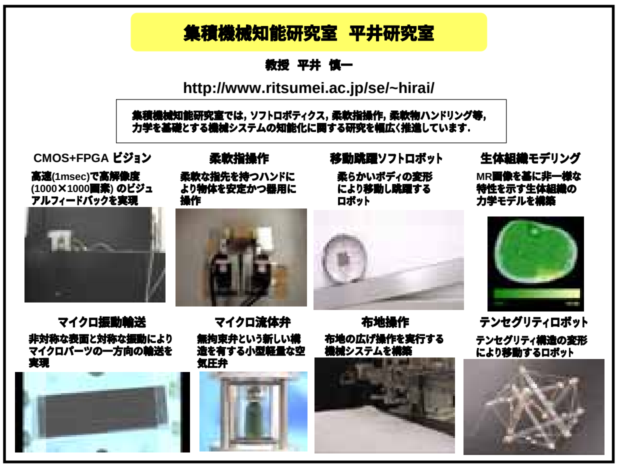
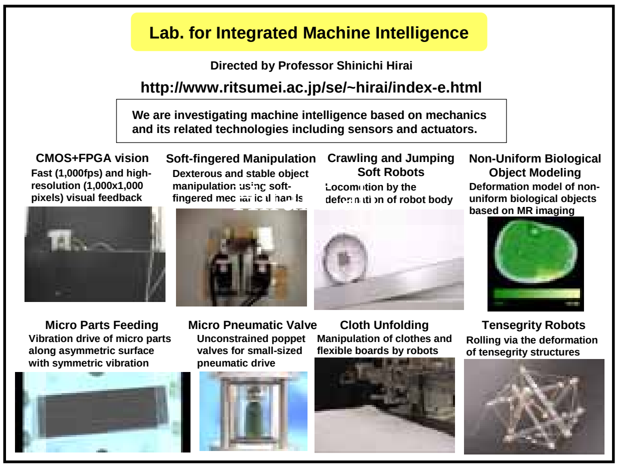
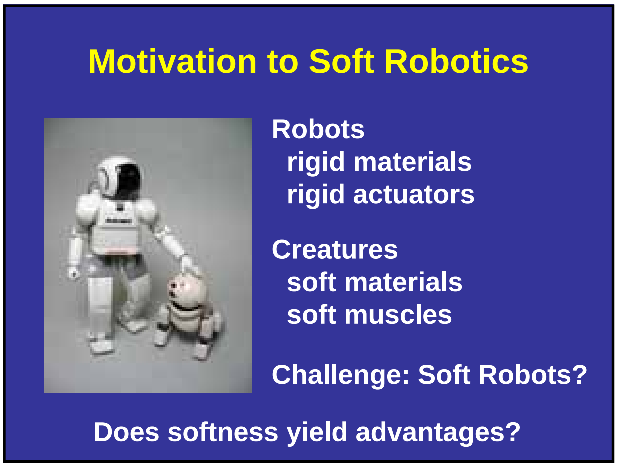
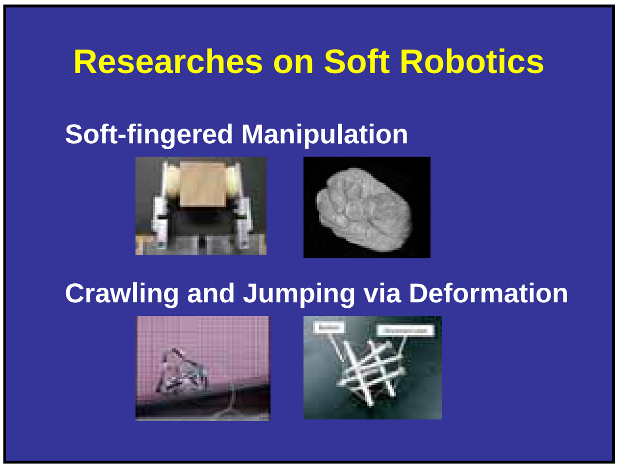
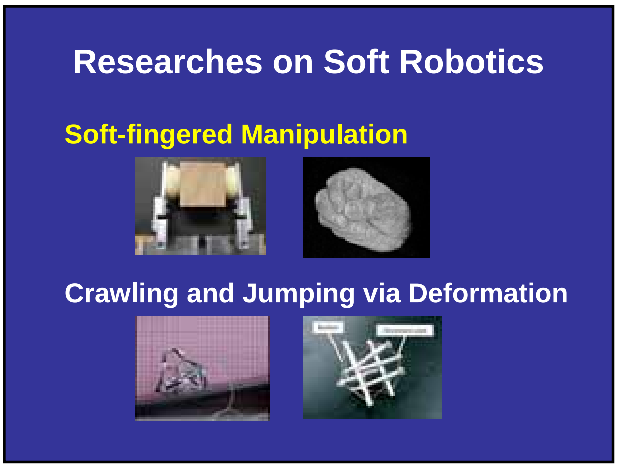

特殊講義 I　2010/05/28
ソフトロボティクス
Soft Robotics
平井　慎一
集積機械知能研究室
http://www.ritsumei.ac.jp/se/~hirai/


集積機械知能研究室　平井研究室
教授　平井　慎一
http://www.ritsumei.ac.jp/se/~hirai/
集積機械知能研究室では，ソフトロボティクス，柔軟指操作，柔軟物ハンドリング等，力学を基礎とする機械システムの知能化に関する研究を幅広く推進しています．
CMOS+FPGA ビジョン
高速(1msec)で高解像度(1000×1000画素) のビジュアルフィードバックを実現
柔軟指操作
柔軟な指先を持つハンドにより物体を安定かつ器用に操作
移動跳躍ソフトロボット
柔らかいボディの変形により移動し跳躍するロボット
生体組織モデリング
MR画像を基に非一様な特性を示す生体組織の力学モデルを構築
マイクロ振動輸送
非対称な表面と対称な振動によりマイクロパーツの一方向の輸送を実現
マイクロ流体弁
無拘束弁という新しい構造を有する小型軽量な空気圧弁
布地操作
布地の広げ操作を実行する機械システムを構築
テンセグリティロボット
テンセグリティ構造の変形により移動するロボット


Lab. for Integrated Machine Intelligence
Directed by Professor Shinichi Hirai
http://www.ritsumei.ac.jp/se/~hirai/index-e.html
We are investigating machine intelligence based on mechanics and its related technologies including sensors and actuators.
CMOS+FPGA vision
Fast (1,000fps) and high-resolution (1,000x1,000 pixels) visual feedback
Soft-fingered Manipulation
Dexterous and stable object manipulation using soft-fingered mechanical hands
Crawling and Jumping Soft Robots
Locomotion by the deformation of robot body
Non-Uniform Biological Object Modeling
Deformation model of non-uniform biological objects based on MR imaging
Micro Parts Feeding
Vibration drive of micro parts along asymmetric surface with symmetric vibration
Micro Pneumatic Valve
Unconstrained poppet valves for small-sized pneumatic drive
Cloth Unfolding
Manipulation of clothes and flexible boards by robots
Tensegrity Robots
Rolling via the deformation of tensegrity structures


Motivation to Soft Robotics
Robots
rigid materials
rigid actuators
Creatures
soft materials
soft muscles
Challenge: Soft Robots?
Does softness yield advantages?


Researches on Soft Robotics
Soft-fingered Manipulation
Crawling and Jumping via Deformation


Researches on Soft Robotics
Soft-fingered Manipulation
Crawling and Jumping via Deformation

Why human dexterity

Humans exhibit outstanding dexterity

Science
source of dexterity

Engineering
dexterous hands

Why human dexterity

Background (1/2)

Humans exhibit outstanding dexterity

What's the sources of dexterity

- brain-nerve system
- binocular eyes
- tactile receptors
- else?

Background (2/2)

Human finger

soft fingertip
hard fingernail on the reverse side

Differs from animals

Does this structure contribute to dexterity?

Soft fingertips reduce DOFs

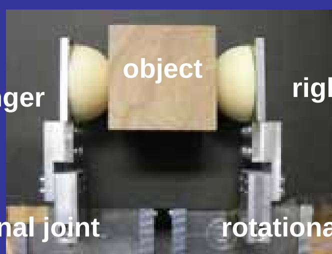
rigid fingertips

soft fingertips

	rigid fingertips	soft fingertips
grasping force	A pair of 1-DOF fingers (2DOF)	A single 1-DOF finger (1DOF)
grasping force & object orientation	1 DOF and 2-DOF fingers (3DOF)	A pair of 1-DOF fingers (2DOF)

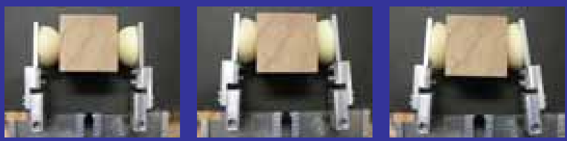
Observations (1/3)

Ability of a pair of 1-DOF fingers with hemispherical soft tips and hard back plates



Observations (2/3)

move two fingertips inward

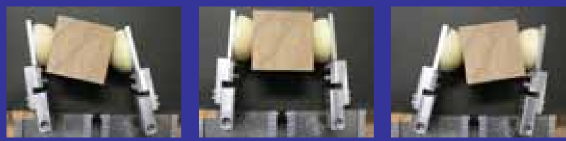


small deformation (grasping force) → large deformation (grasping force)

Can control grasping force

Observations (3/3)

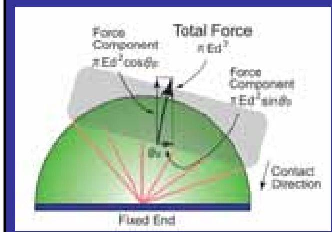
rotate two fingertips in the same direction



Can control object orientation

Modeling (1/3)

Old model: Radially distributed model



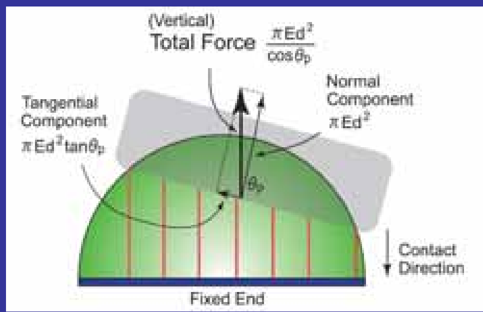
Contact force passes the center of hemisphere

Two fingertips cause non-zero moment around the object

The **3rd DOF** to cancel out the moment

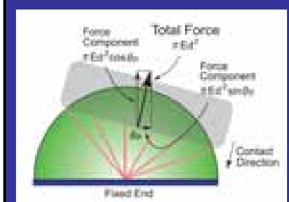
Modeling (2/3)

Our model: Parallel distributed model

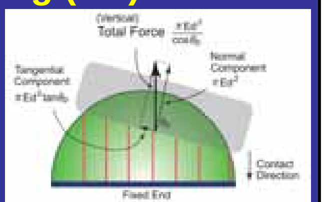


Inoue and Hirai, IEEE TRO, 22-6, 2006

Modeling (3/3)



radial



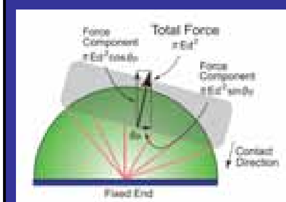
parallel

$$F_{\mathrm{radial}} = \pi E d^2$$

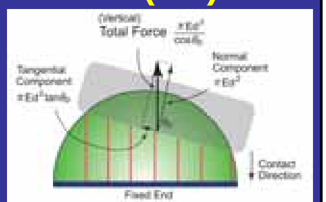
$$F_{\mathrm{perp}} = \frac{\pi E d^2}{\cos\theta_{\mathrm{p}}}$$

Force depends on object orientation

Model verification (1/2)



radial



parallel

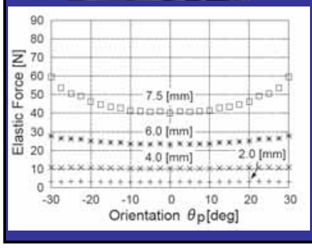
$$F_{\mathrm{radial}} = \pi E d^2$$

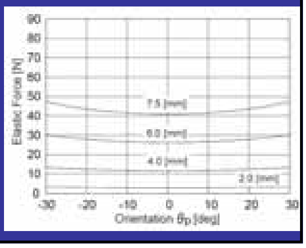
$$F_{\mathrm{perp}} = \frac{\pi E d^2}{\cos\theta_{\mathrm{p}}}$$

Examine if force depends on orientation

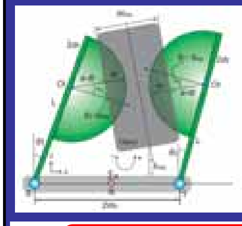
Model verification (2/2)

parallel model





Simulation (1/3)



Inoue and Hirai, Experimental Robotics X, Springer, 2008

dynamic simulation based on Lagrange formulation

object

left fingertip right fingertip

$$T = \frac{1}{2}m_{\mathrm{obj}}(\dot{x}_{\mathrm{obj}}^2 + \dot{y}_{\mathrm{obj}}^2) + \frac{1}{2}I_{\mathrm{obj}}\dot{\theta}_{\mathrm{obj}}^2 + \frac{1}{2}I_{\mathrm{finger}}\dot{\theta}_1^2 + \frac{1}{2}I_{\mathrm{finger}}\dot{\theta}_2^2$$

$$U = U_{\mathrm{parallel}}(d_{n1}, d_{t1}, \theta_1 - \theta_{\mathrm{obj}}) + U_{\mathrm{parallel}}(d_{n2}, d_{t2}, \theta_2 + \theta_{\mathrm{obj}}) + m_{\mathrm{obj}} g y_{\mathrm{obj}}$$

Simulation (2/3)

Lagrangian

$$\mathcal{L} = T - U + \lambda_1^{\mathrm{H}} C_1^{\mathrm{H}} + \lambda_2^{\mathrm{H}} C_2^{\mathrm{H}}$$

holonomic

non-holonomic

object

$$\frac{d}{dt}\frac{\partial \mathcal{L}}{\partial \dot{x}_{\mathrm{obj}}} - \frac{\partial \mathcal{L}}{\partial x_{\mathrm{obj}}} = \frac{\partial}{\partial \dot{x}_{\mathrm{obj}}}(\lambda_1^N C_1^N + \lambda_2^N C_2^N)$$

$$\frac{d}{dt}\frac{\partial \mathcal{L}}{\partial \dot{y}_{\mathrm{obj}}} - \frac{\partial \mathcal{L}}{\partial y_{\mathrm{obj}}} = \frac{\partial}{\partial \dot{y}_{\mathrm{obj}}}(\lambda_1^N C_1^N + \lambda_2^N C_2^N)$$

$$\frac{d}{dt}\frac{\partial \mathcal{L}}{\partial \dot{\theta}_{\mathrm{obj}}} - \frac{\partial \mathcal{L}}{\partial \theta_{\mathrm{obj}}} = \frac{\partial}{\partial \dot{\theta}_{\mathrm{obj}}}(\lambda_1^N C_1^N + \lambda_2^N C_2^N)$$

fingers

$$\frac{d}{dt}\frac{\partial \mathcal{L}}{\partial \dot{\theta}_1} - \frac{\partial \mathcal{L}}{\partial \theta_1} = \frac{\partial}{\partial \dot{\theta}_1}(\lambda_1^N C_1^N + \lambda_2^N C_2^N)$$

$$\frac{d}{dt}\frac{\partial \mathcal{L}}{\partial \dot{\theta}_2} - \frac{\partial \mathcal{L}}{\partial \theta_2} = \frac{\partial}{\partial \dot{\theta}_2}(\lambda_1^N C_1^N + \lambda_2^N C_2^N)$$

fingertips

normal

$$\frac{d}{dt}\frac{\partial \mathcal{L}}{\partial \dot{d}_{n1}} - \frac{\partial \mathcal{L}}{\partial d_{n1}} = \frac{\partial}{\partial \dot{d}_{n1}}(\lambda_1^N C_1^N + \lambda_2^N C_2^N)$$

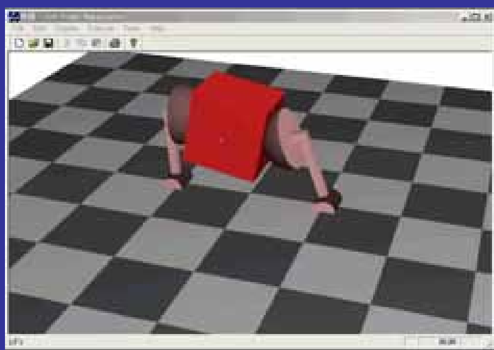
$$\frac{d}{dt}\frac{\partial \mathcal{L}}{\partial \dot{d}_{n2}} - \frac{\partial \mathcal{L}}{\partial d_{n2}} = \frac{\partial}{\partial \dot{d}_{n2}}(\lambda_1^N C_1^N + \lambda_2^N C_2^N)$$

tangential

$$\frac{d}{dt}\frac{\partial \mathcal{L}}{\partial \dot{d}_{t1}} - \frac{\partial \mathcal{L}}{\partial d_{t1}} = \frac{\partial}{\partial \dot{d}_{t1}}(\lambda_1^N C_1^N + \lambda_2^N C_2^N)$$

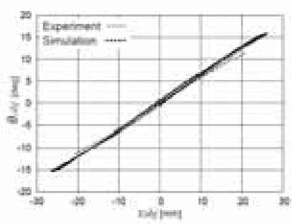
$$\frac{d}{dt}\frac{\partial \mathcal{L}}{\partial \dot{d}_{t2}} - \frac{\partial \mathcal{L}}{\partial d_{t2}} = \frac{\partial}{\partial \dot{d}_{t2}}(\lambda_1^N C_1^N + \lambda_2^N C_2^N)$$

Simulation (3/3)

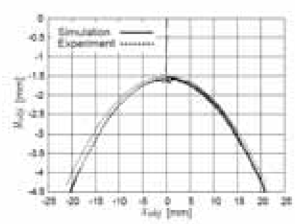


Experiment

Comparison



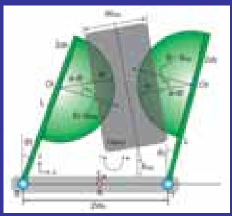
(a) orientation



(b) position

simulation vs experiment

Radial vs parallel models



Sum of two fingertip potential energies around equilibrium point with two joints fixed

Radial model --- saddle point

Parallel model --- local minimum
no continuous feedback needed

Discussion

- **Parallel distributed model**
  with tangential deformation meets observations
- **Experimental model verification**
  force magnitude depends on object orientation
- **Dynamics of manipulation process**
  simulation and experiment validate parallel model

See for details

Mechanics and Control of Soft-fingered Manipulation

Takahiro Inoue and Shinichi Hirai
Springer-Verlag 978-1-84800-980-6

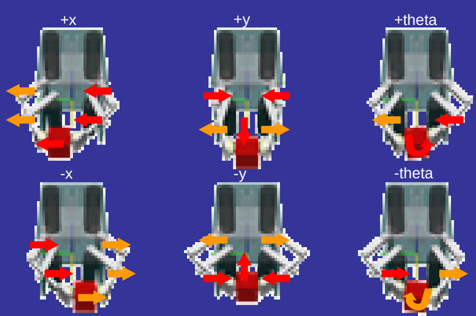
Position and Orientation Control

Simulation of Position and Orientation Control

Experiment of Position and Orientation Control

Yamazaki, Inoue, and Hirai, IEEE ROBIO 2009

Two-Phased Controller



Two-Phased Controller

Virtual Desired Value

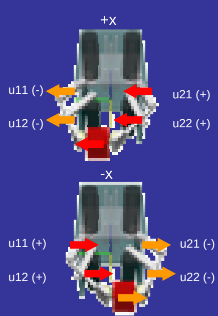
$$x^d = \int (x_{obj} - x^d_{obj})\,dt$$

Right Finger

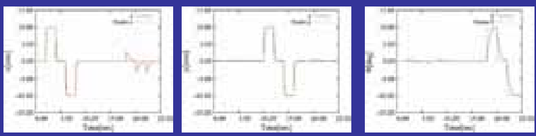
$$u_{11} = -K_{Px1}\{\theta_{11} - \theta_{11(0)} - (\underline{+}K_{Ix1}x^d)\} - K_{Dx1}\dot{\theta}_{11}$$
$$u_{12} = -K_{Px2}\{\theta_{12} - \theta_{12(0)} - (\underline{+}K_{Ix2}x^d)\} - K_{Dx2}\dot{\theta}_{12}$$

Left Finger

$$u_{21} = -K_{Px1}\{\theta_{21} - \theta_{21(0)} - (\underline{-}K_{Ix1}x^d)\} - K_{Dx1}\dot{\theta}_{21}$$
$$u_{22} = -K_{Px2}\{\theta_{22} - \theta_{22(0)} - (\underline{-}K_{Ix2}x^d)\} - K_{Dx2}\dot{\theta}_{22}$$

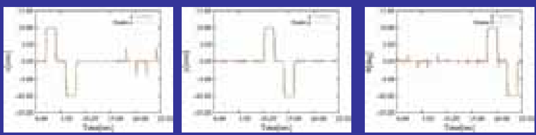


Result



x y theta

Simulation



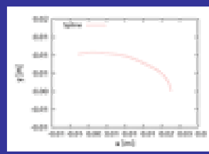
x y theta

Experiment

Anthropomorphic Soft Fingers

representing human fingertip shape by cubic spline

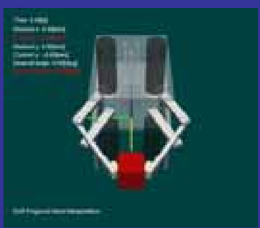
Extraction

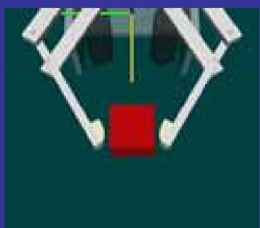


human fingertip

contour of the fingertip

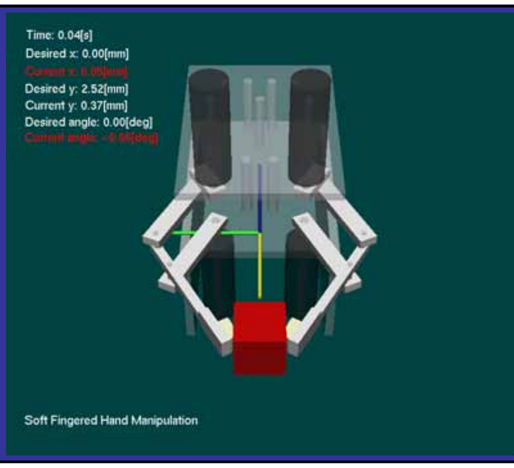
Simulation





Front view

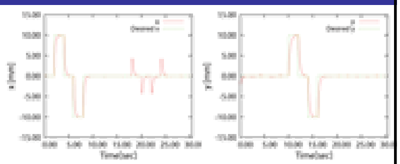
Top view

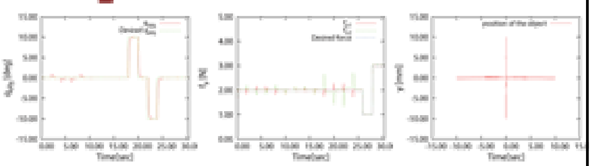


Simulation Result

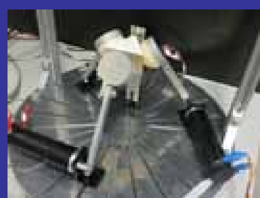
(x, y, θ, f)

4-DOF control





3D Grasping and Manipulation



A triplet of 1-DOF fingers with soft tips
Two-phase controller works well

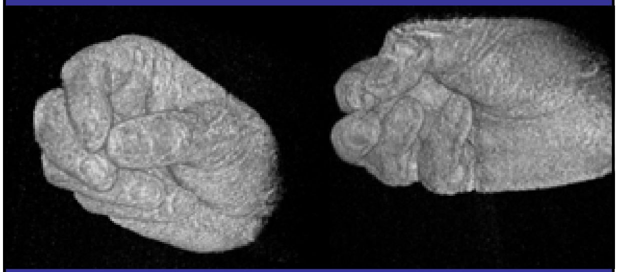
Inoue and Hirai, IEEE ICRA 2009

Fingertip model

Is our theory applicable to human manipulation?

Need to measure inner deformation of fingertips

Measuring human fingertips

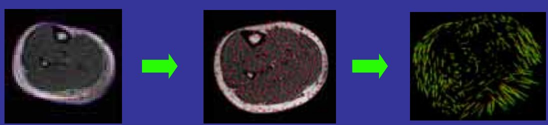


pinch motion **pen grasp**

Inner deformation

Compute deformation field from MR images before and after deformation

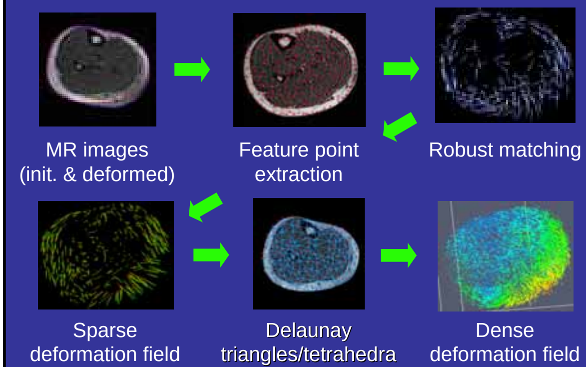
Estimate non-uniform physical parameters from deformation field



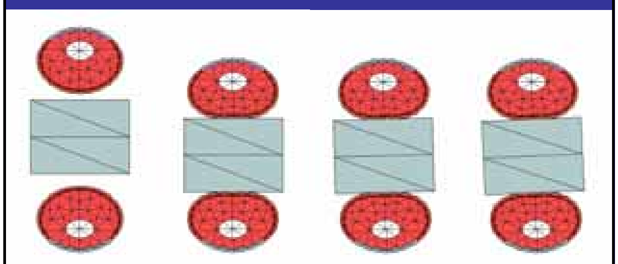
MR images → Image processing → Deformation field

Zhang, Hirai, and Endo, Int. J. ICIC, 2008

Deformation field computation

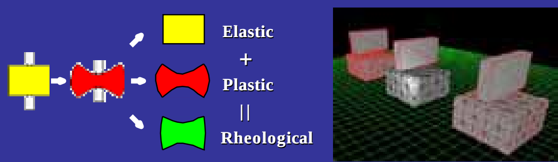


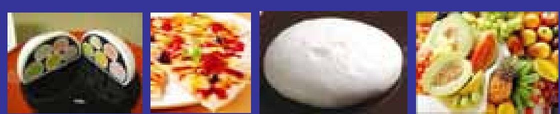
Simulating skin deformation



Namima, Wang, and Hirai, IEEE ROBIO, 2009

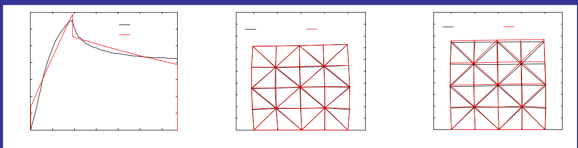
Rheological Deformation



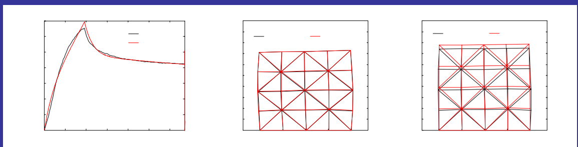


Rheological Deformation

Wang, Namima, and Hirai, TSMBE, 47-1, 2009



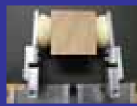
Identification of **three-element** physical model



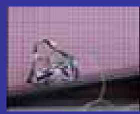
Identification of **four-element** physical model

Researches on Soft Robotics

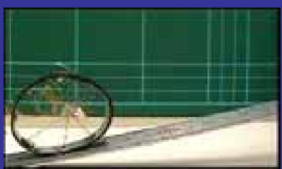
Soft-fingered Manipulation

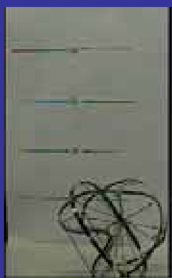


Crawling and Jumping via Deformation



Deformable Soft Robot

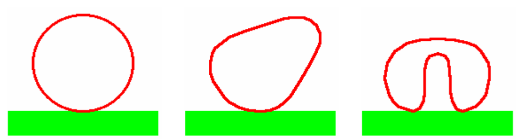




Sugiyama and Hirai, IJRR, Vol.25, No.5-6, 2006

Principle

Charge/Discharge of Potential Energy



Stable | Unstable | Stable with high energy

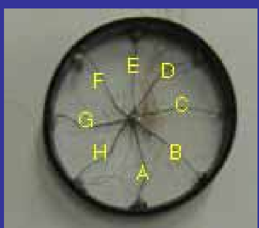
Simulation

2
1
0 10 20 30 40 50 60
Time

0.03
0.02
0.01
0
0 0.02 0.04 0.06 0.08
[m]

Circular Robot (2D motion)

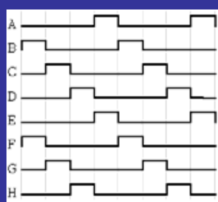
8 SMA coils for crawling
Toki corp. BMX-100



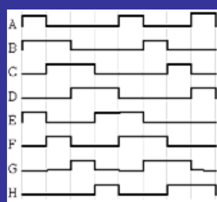
diameter 40mm weight 3g

Control

Open loop PWM control of SMA coils



crawling



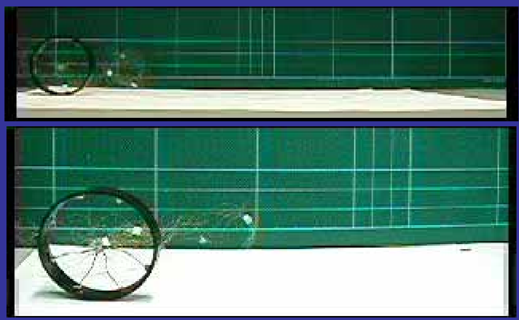
hill-climbing

Simulation

1
0 10 20 30 40 50 60
Time [s]

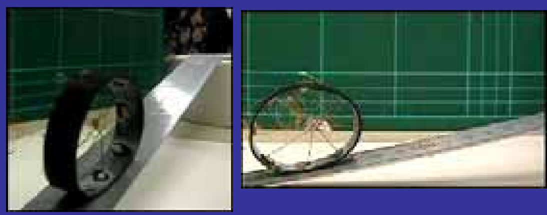
0.01
0
0 0.02 0.04 0.06 0.08
Width [m]

Crawling



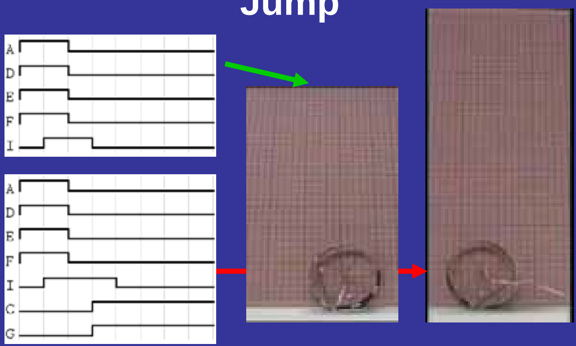
25mm/s (65% of diameter per second)

Slope Climbing



20 degrees

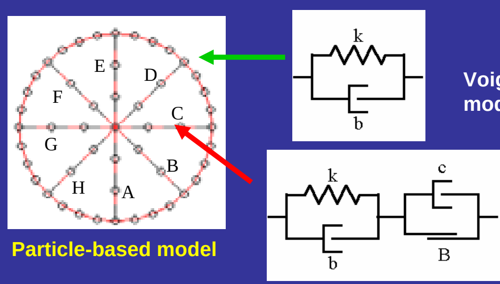
Jump



90mm

300mm
(3 times diameter)

Simulation model

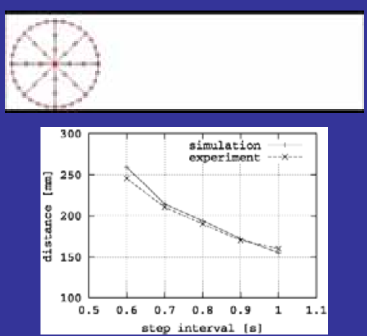


Particle-based model

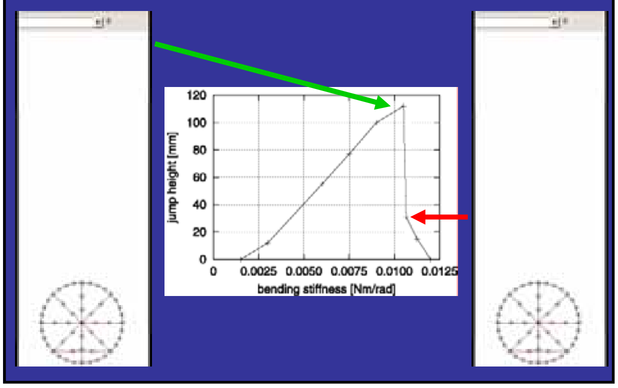
Voigt model

three-element model with slider

Simulation results



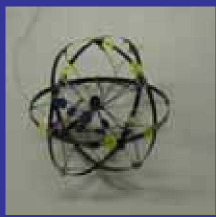
Simulation results



Spherical Robot (3D motion)

22 SMA coils
18 for crawling + 4 for jump

200mm 140g (core 75g)

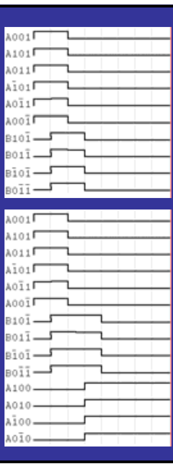


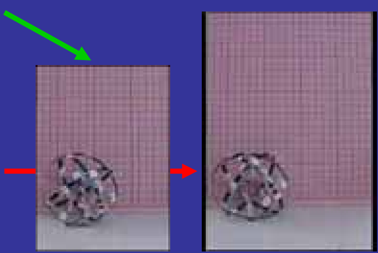
90mm 5g

Slope Climbing

Crawl on slope
of 10 degrees

Jump

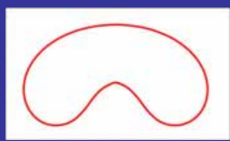




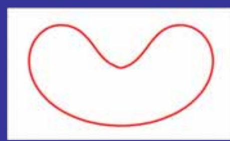
70mm

180mm
(twice diameter)

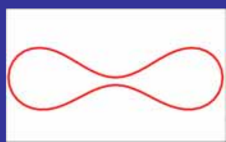
Initial shapes with same energy



(a) Cap shape



(b) Cup shape

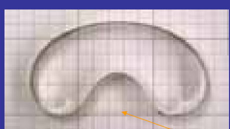


(c) Peanut shape

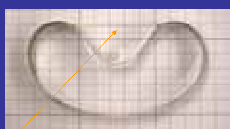
(d) Dish shape

$16.0 \times 10^{-2}\mathrm{Nm}$

Initial shapes with same energy

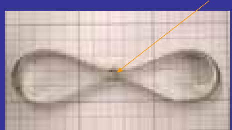


(a) Cap shape



(b) Cup shape

thread

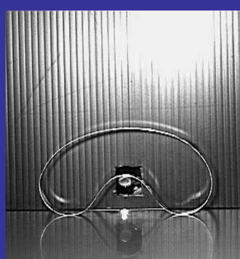


(c) Peanut shape

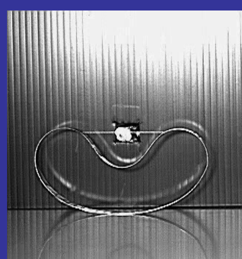
(d) Dish shape

$16.0 \times 10^{-2}\mathrm{Nm}$

Experiments (1/2)



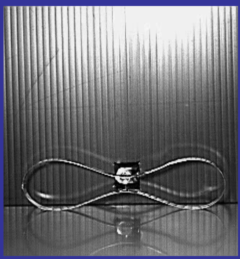
(a) Cap shape



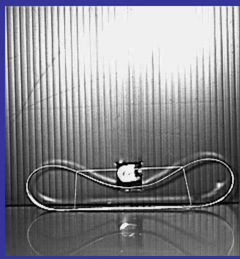
(b) Cup shape

frame rate: 1 KHz

Experiments (2/2)



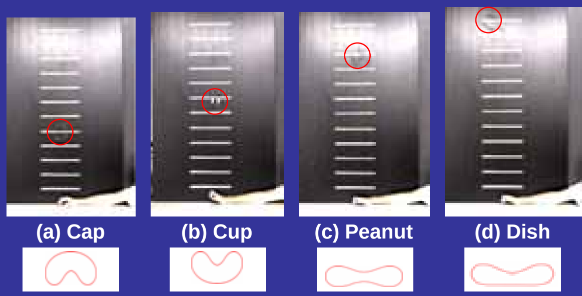
(c) Peanut shape



(d) Dish shape

frame rate: 1 KHz

Effect of initial shapes



Matsuyama and Hirai, IEEE ICRA, 2007

Simulation

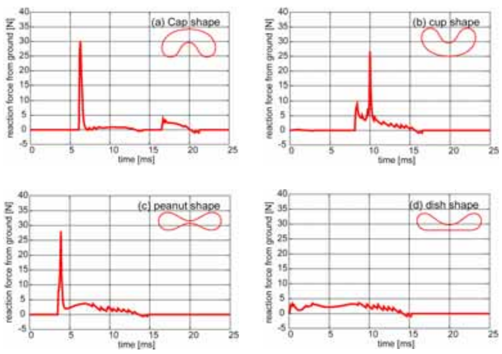
(b) Cup shape

(d) Dish shape

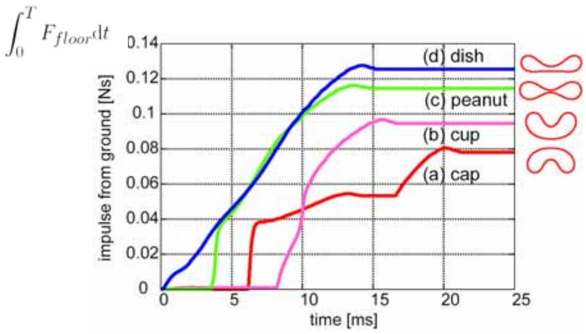
Jumping heights

	experiment [mm]	simulation[mm]
(a) cap	480	457
(b) cup	670	669
(c) peanut	970	980
(d) dish	1180	1171

Reaction force



Impulse



Impulse

High jumper vs long jumper

High jumper keeps contact between foot and the ground longer

One inch punch

Kung fu technique

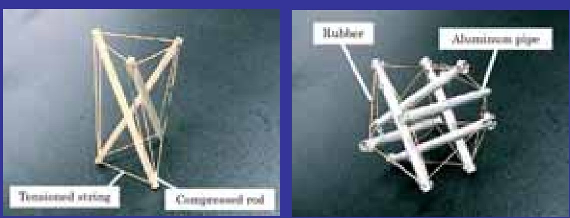
Became popular by Bruce Lee

Keeps contact between hand and target longer

Summary

- Proposal of locomotion by deformation
- 2D motion by circular robot
  - crawling : 65% of diameter / second
  - climbing : 20 degrees
  - jump : three times its diameter
- Simulation
  - particle-based modeling works well
- 3D motion by spherical robot
  - crawling : 9% of diameter / second
  - climbing : 10 degrees
  - jump : twice its diameter

Tensegrity robots



Consists of rigid rods and extensible strings
Can select body size and body stiffness independently

Shibata, Saijyo, and Hirai, IEEE ICRA, 2009

Rolling of tensegrity robot

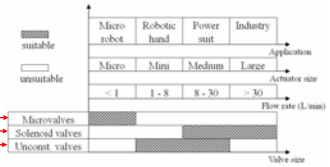
Can roll by reducing distance between two rods

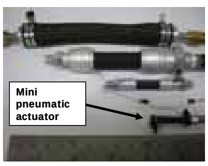
Pneumatic Valves: State-of-the-art

MEMS microvalves
- Low flow rate / pressure

Commercially available valves
Solenoid valves
Piezo valves
- On-going miniaturization
- Complexity in assembly

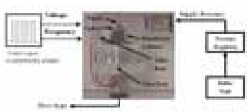
Unconstrained valves
- Ease of assembly
- Alleviate heat distortion problem
- Piezoelectric actuation

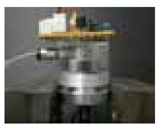


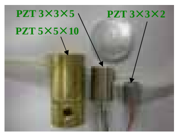


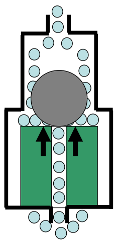
集積機械知能研究室

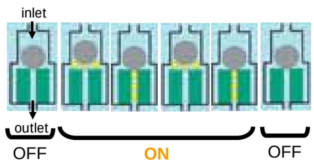
Vibration-driven Unconstrained Valves











集積機械知能研究室

Vibration-driven Unconstrained Valves

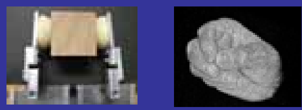
- Pressure control for PAM @ 1 Hz (0.1~0.4 MPa)

Sumadi, Hirai, and Honda, IEEE/ASME Trans. Mechatronics, 14-5, 2009

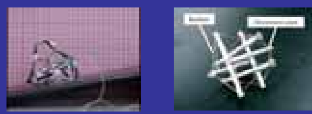
集積機械知能研究室

What learned from researches on Soft Robotics

Soft-fingered Manipulation



Crawling and Jumping via Deformation



What learned from researches on Soft Robotics

Soft-fingered Manipulation

natural stability in grasping and manipulation, which originates from local minimum of potential energy

Crawling and Jumping via Deformation

store and release of potential energy, working as a mechanical capacitor

Contributors

Dr. Takahiro Inoue (Okayama Pref. Univ.)
soft-fingered manipulation

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inner deformation measurement

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Mr. Zhongkui Wang (graduated from HIT)
anthropomorphic soft fingers
skin deformation

Mr. Y. Sugiyama, Mr. Y. Matsuyama
soft robot locomotion

Dr. Mizuho Shibata (Ritsumeikan Univ.)
tensegrity robots

課題

自分で"ソフトロボット"を考案し，

その実現可能性について技術的に考察せよ．

（将来的にどのような技術が必要か）

http://www.ritsumei.ac.jp/se/~hirai/

［講義］ ［2010年度］ ［特殊講義Ｉ］