特殊講義 I　2012/06/01

ソフトロボティクス
Soft Robotics

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Motivation to Soft Robotics

Robots
  rigid materials
  rigid actuators

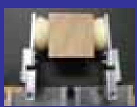
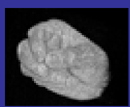
Creatures
  soft materials
  soft muscles

Challenge: Soft Robots?

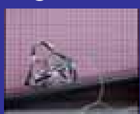
Does softness yield advantages?

Researches on Soft Robotics

Soft-fingered Manipulation

Crawling and Jumping via Deformation




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

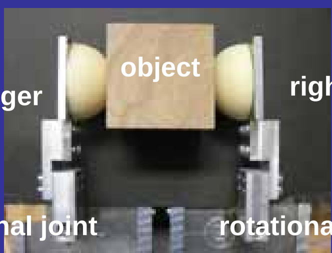
rigid fingertips

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)

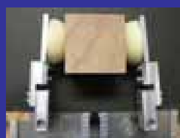
Observations (1/3)

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



Observations (2/3)

move two fingertips inward

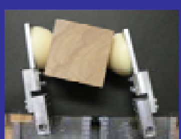
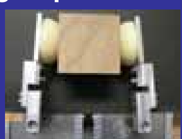
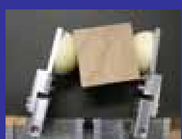




small deformation (grasping force) → large deformation (grasping force)

Can control grasping force

Observations (3/3)

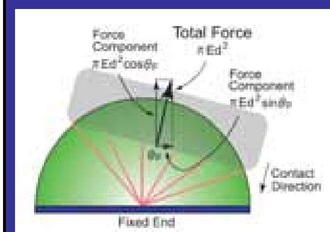
rotate two fingertips in the same direction

Can control object orientation

Modeling (1/3)

Old model: Radially distributed model



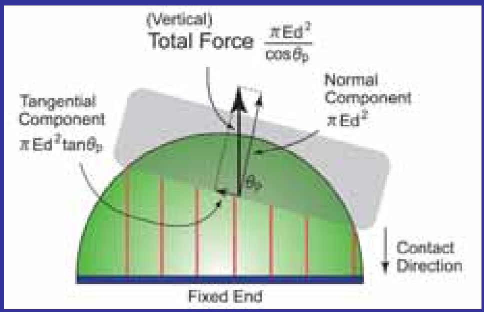
Contact force passes the center of hemisphere

Two fingertips cause non-zero moment around the object

The 3rd DOF to cancel out the moment

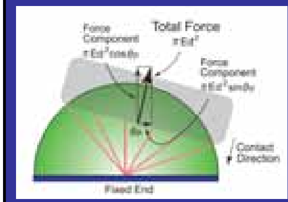
Modeling (2/3)

Our model: Parallel distributed model

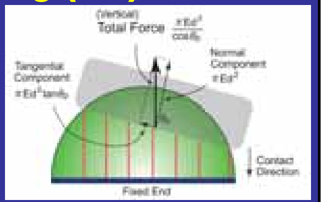


Inoue and Hirai, IEEE TRO, 22-6, 2006

Modeling (3/3)



radial



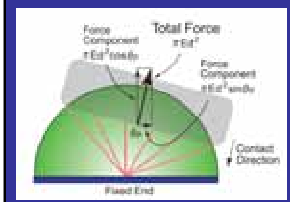
parallel

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

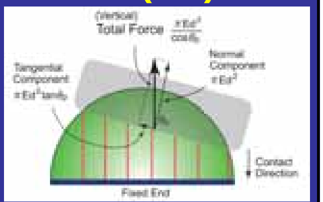
$$F_{\mathrm{perp}} = \frac{\pi E d^2}{\cos\theta_{\mathrm{p}}}$$

Force depends on object orientation

Model verification (1/2)



radial



parallel

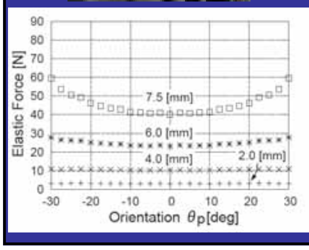
$$F_{\mathrm{radial}} = \pi E d^2$$

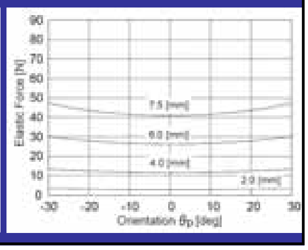
$$F_{\mathrm{perp}} = \frac{\pi E d^2}{\cos\theta_{\mathrm{p}}}$$

Examine if force depends on orientation

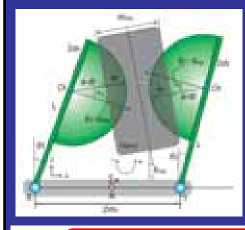
Model verification (2/2)

parallel model





Simulation (1/3)



Inoue and Hirai, Experimental Robotics X, Springer, 2008

dynamic simulation based on Lagrange formulation

object

left fingertip right fingertip

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

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

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

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

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

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

fingers

$$\frac{\mathrm{d}}{\mathrm{d}t}\frac{\partial\mathcal{L}}{\partial\dot{\theta}_1} - \frac{\partial\mathcal{L}}{\partial \theta_1} = \frac{\partial}{\partial\dot{\theta}_1}\{\lambda_1^{\mathrm{N}} C_1^{\mathrm{N}} + \lambda_2^{\mathrm{N}} C_2^{\mathrm{N}}\},$$

$$\frac{\mathrm{d}}{\mathrm{d}t}\frac{\partial\mathcal{L}}{\partial\dot{\theta}_2} - \frac{\partial\mathcal{L}}{\partial \theta_2} = \frac{\partial}{\partial\dot{\theta}_2}\{\lambda_1^{\mathrm{N}} C_1^{\mathrm{N}} + \lambda_2^{\mathrm{N}} C_2^{\mathrm{N}}\},$$

fingertips

normal

$$\frac{\mathrm{d}}{\mathrm{d}t}\frac{\partial\mathcal{L}}{\partial\dot{d}_{\mathrm{n}1}} - \frac{\partial\mathcal{L}}{\partial d_{\mathrm{n}1}} = \frac{\partial}{\partial\dot{d}_{\mathrm{n}1}}\{\lambda_1^{\mathrm{N}} C_1^{\mathrm{N}} + \lambda_2^{\mathrm{N}} C_2^{\mathrm{N}}\},$$

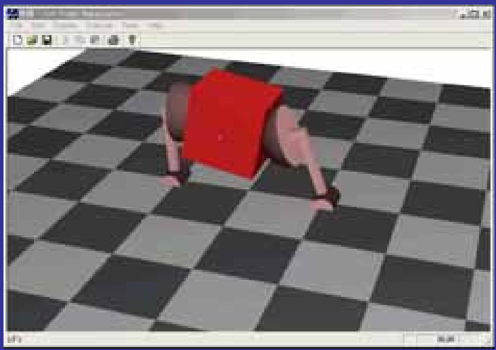
$$\frac{\mathrm{d}}{\mathrm{d}t}\frac{\partial\mathcal{L}}{\partial\dot{d}_{\mathrm{n}2}} - \frac{\partial\mathcal{L}}{\partial d_{\mathrm{n}2}} = \frac{\partial}{\partial\dot{d}_{\mathrm{n}2}}\{\lambda_1^{\mathrm{N}} C_1^{\mathrm{N}} + \lambda_2^{\mathrm{N}} C_2^{\mathrm{N}}\},$$

tangential

$$\frac{\mathrm{d}}{\mathrm{d}t}\frac{\partial\mathcal{L}}{\partial\dot{d}_{\mathrm{t}1}} - \frac{\partial\mathcal{L}}{\partial d_{\mathrm{t}1}} = \frac{\partial}{\partial\dot{d}_{\mathrm{t}1}}\{\lambda_1^{\mathrm{N}} C_1^{\mathrm{N}} + \lambda_2^{\mathrm{N}} C_2^{\mathrm{N}}\},$$

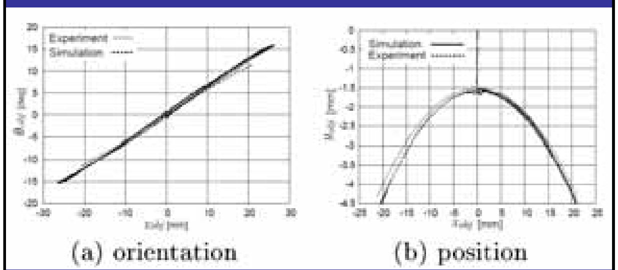
$$\frac{\mathrm{d}}{\mathrm{d}t}\frac{\partial\mathcal{L}}{\partial\dot{d}_{\mathrm{t}2}} - \frac{\partial\mathcal{L}}{\partial d_{\mathrm{t}2}} = \frac{\partial}{\partial\dot{d}_{\mathrm{t}2}}\{\lambda_1^{\mathrm{N}} C_1^{\mathrm{N}} + \lambda_2^{\mathrm{N}} C_2^{\mathrm{N}}\}$$

Simulation (3/3)



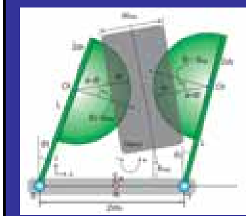
Experiment

Comparison



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

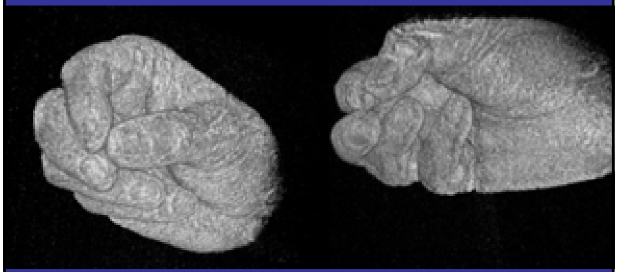
Springer-Verlag 978-1-84800-980-6

Human fingertip model

Is our theory applicable to human manipulation?

Need to measure inner deformation of fingertips

Measuring human fingertips

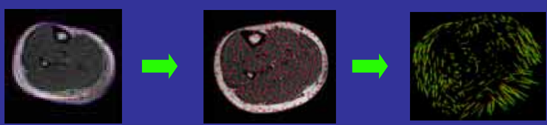


pinch motion **pen grasp**

Inner deformation

Compute deformation field from MR images before and after deformation

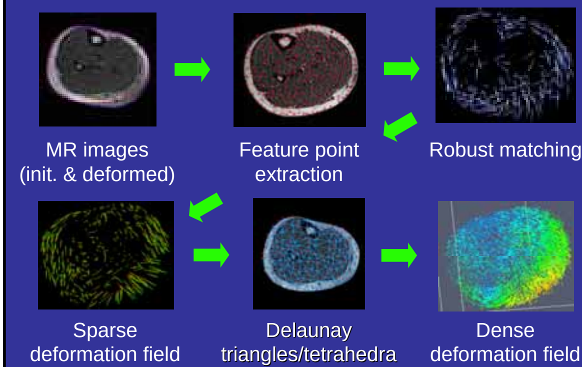
Estimate non-uniform physical parameters from deformation field



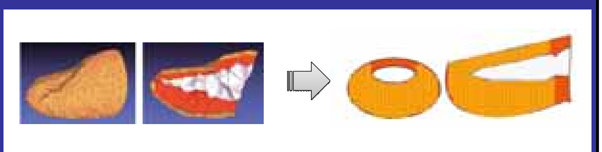
MR images → Image processing → Deformation field

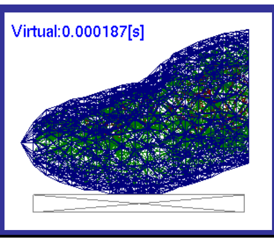
Zhang, Hirai, and Endo, Int. J. ICIC, 2008

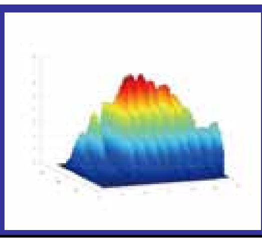
Deformation field computation



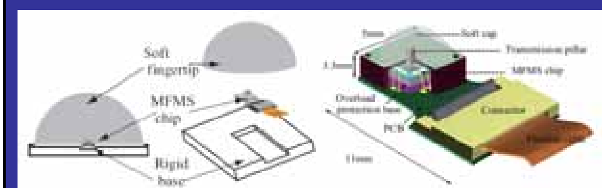
Simulating skin deformation







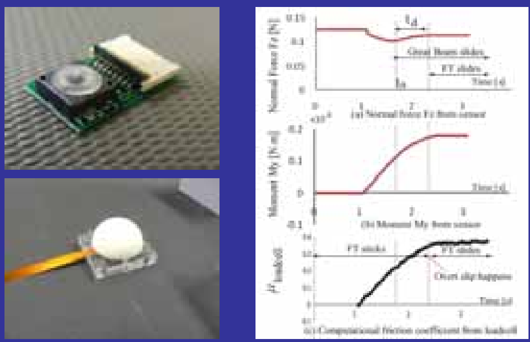
Micro force sensor



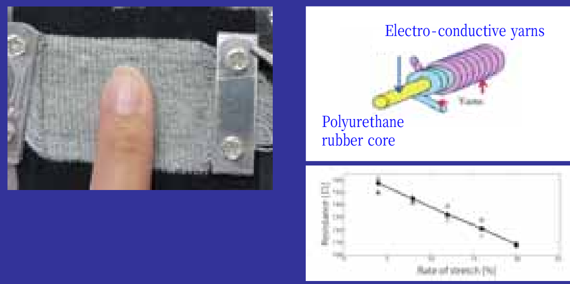
components Fz, Mx, My

Ho, Dao, Sugiyama, and Hirai,
IEEE Trans. on Robotics, 27-3, 2011

Micro force sensor

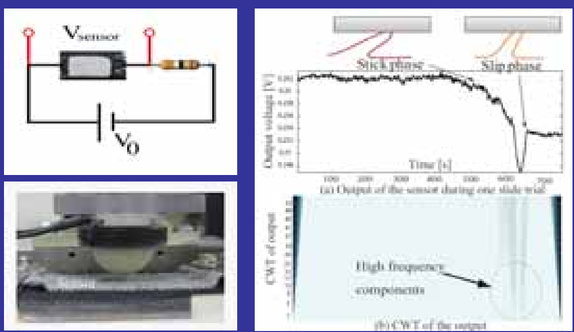


Slippage sensor

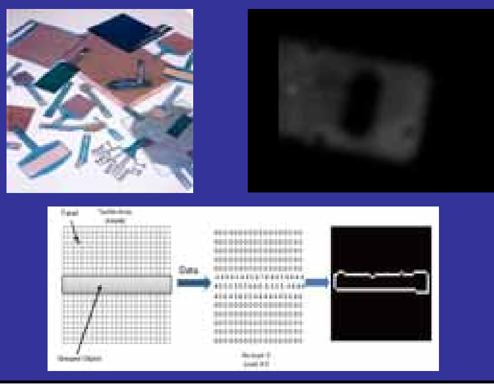


Ho, Kondo, Okada, Araki, Fujita, Makikawa, and Hirai, IEEE IROS, 2011

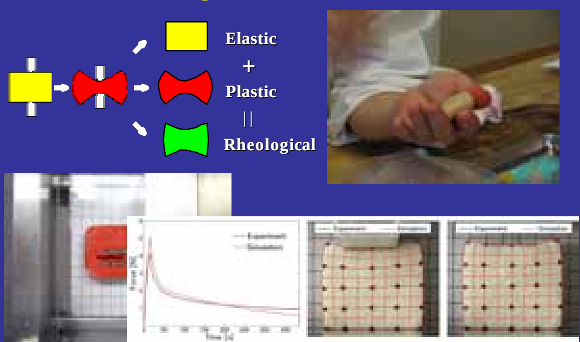
Slippage sensor



Tactile image processing

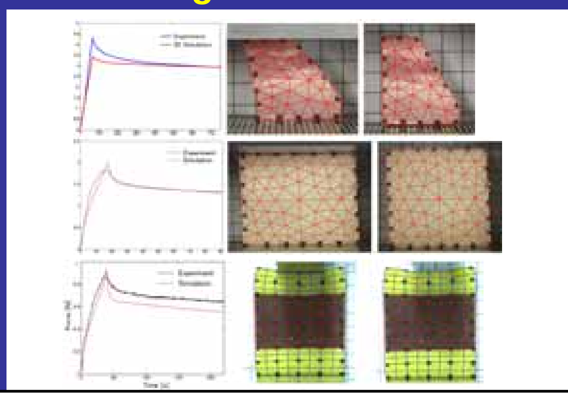


Rheological Deformation



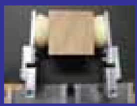
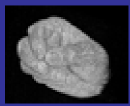
Wang and Hirai, J. of Food Research, Vol.1, No.1, 2012

Rheological Deformation

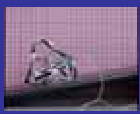


Researches on Soft Robotics

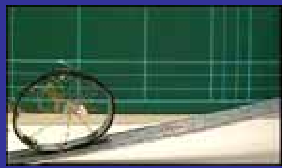
Soft-fingered Manipulation

Crawling and Jumping via Deformation



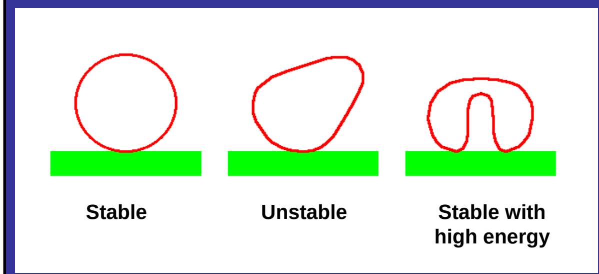

Deformable Soft Robot




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

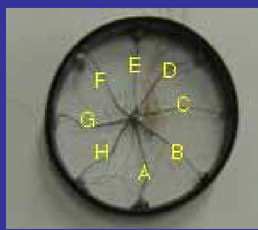
Principle

Charge/Discharge of Potential Energy



Circular Robot

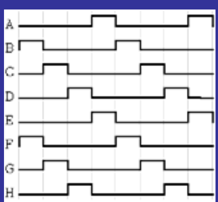
8 SMA coils for crawling
Toki corp. BMX-100



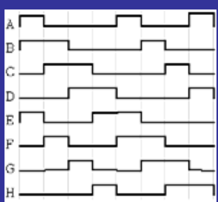
diameter 40mm weight 3g


Control

Open loop PWM control of SMA coils

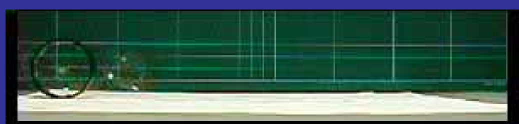
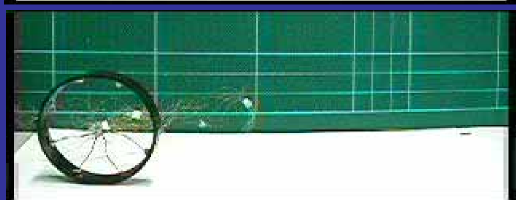


crawling



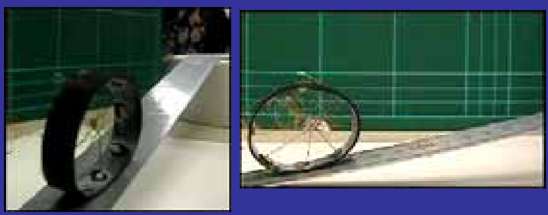
slope-climbing

Crawling

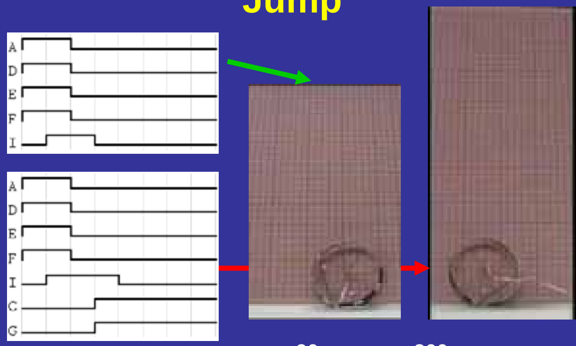
25mm/s (65% of diameter per second)

Slope Climbing



20 degrees

Jump

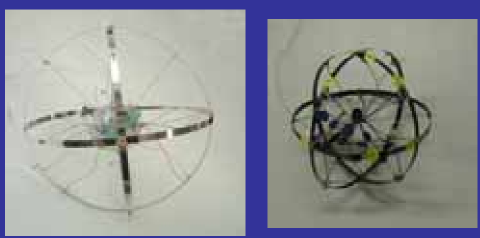


90mm

300mm
(3 times diameter)

Spherical Robot

22 SMA coils
18 for crawling + 4 for jump



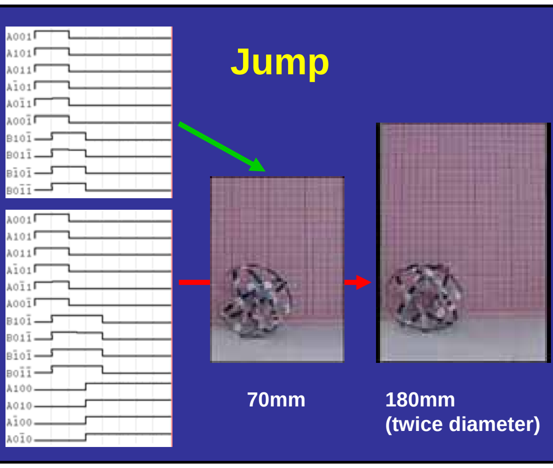
200mm 140g (core 75g)

90mm 5g

Slope Climbing

Crawl on slope
of 10 degrees

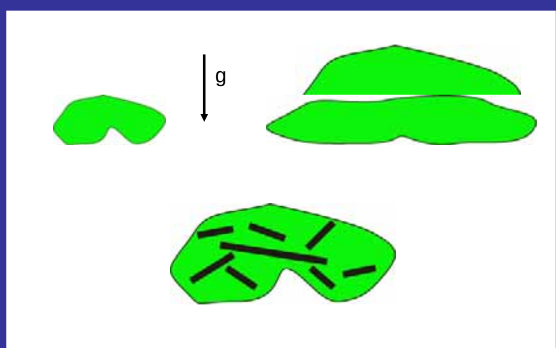
Jump



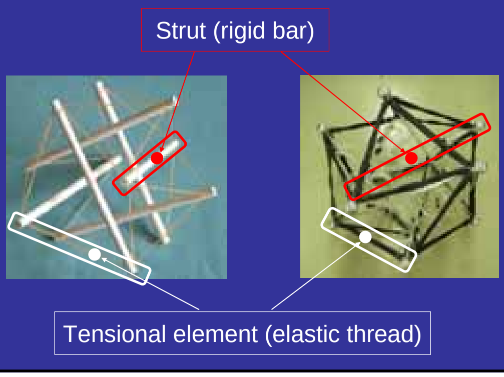
70mm

180mm
(twice diameter)

Size problem



Tensegrity



Tensegrity

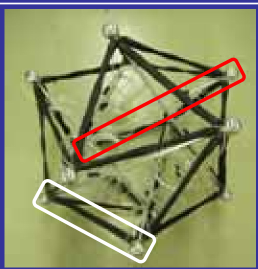
Easy to deform

Shock absorbing

Tensegrity robots

Struts: pipes made of aluminum

Tensional elements: pneumatic McKibben actuators



6 struts
24 tensional elms.

strut: 570mm

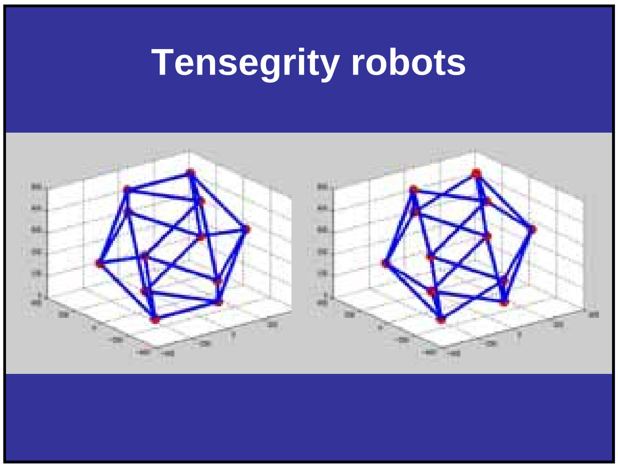
height: 590mm
width : 780mm
weight: 3.3 kg

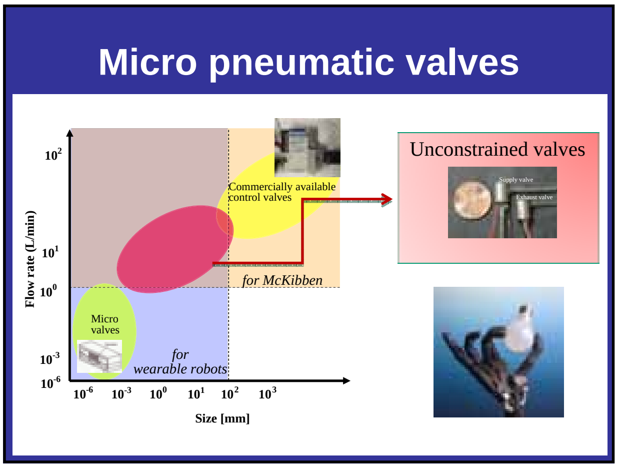
Koizumi, Shibata, and Hirai, IEEE ICRA, 2012

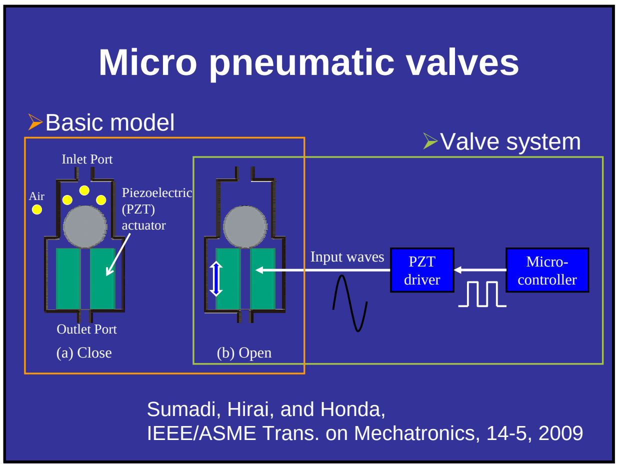
Tensegrity robots

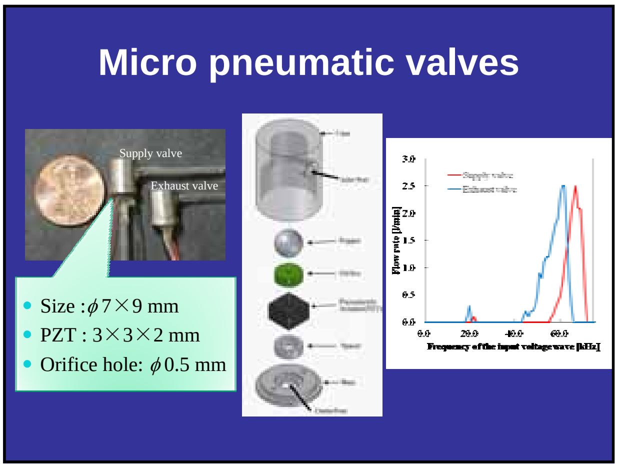
Tensegrity robots

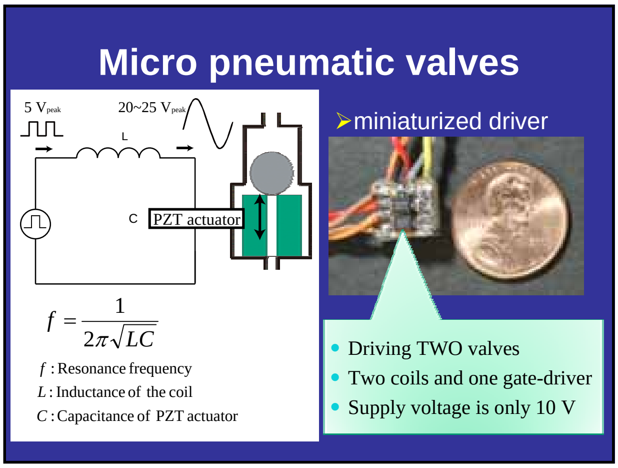
Tensegrity robots

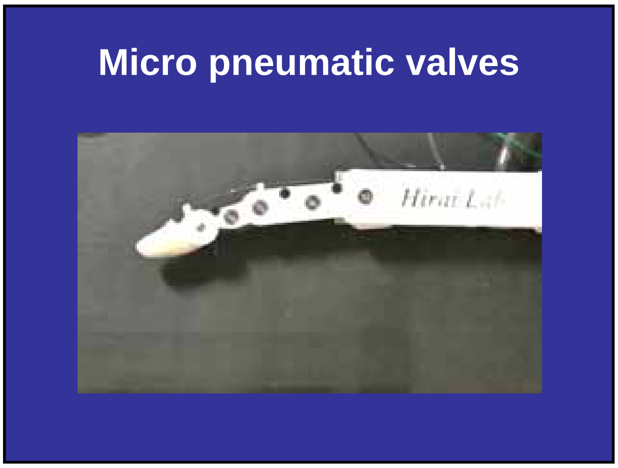

Tensegrity robots


Micro pneumatic valves
Unconstrained valves
Commercially available control valves
for McKibben
Micro valves
for wearable robots
Flow rate (L/min)
Size [mm]


Micro pneumatic valves
Basic model
Valve system
Inlet Port
Air
Piezoelectric (PZT) actuator
Outlet Port
(a) Close
(b) Open
Input waves
PZT driver
Micro-controller
Sumadi, Hirai, and Honda,
IEEE/ASME Trans. on Mechatronics, 14-5, 2009


Micro pneumatic valves
Supply valve
Exhaust valve
Size : φ7×9 mm
PZT : 3×3×2 mm
Orifice hole: φ0.5 mm


Micro pneumatic valves
5 V peak
20~25 V peak
L
C
PZT actuator
f = 1 / 2π√LC
f : Resonance frequency
L : Inductance of the coil
C : Capacitance of PZT actuator
miniaturized driver
Driving TWO valves
Two coils and one gate-driver
Supply voltage is only 10 V


Micro pneumatic valves

What learnt from soft robotics

Soft-fingered Manipulation

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

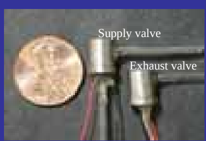
Crawling and Jumping via Deformation

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

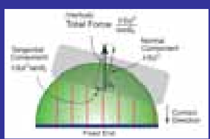
平井研究室

発想の基


転倒しても動く移動ロボット



これまでと違う構造の弁



現象を説明できるモデル

平井研究室

ポストドクトラルフェロー	2名
博士後期課程	4名
博士前期課程	16名
学部生	8名

平井研究室

2012年

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J. Food Research

System Design & Dynamics

2011年度

論文 3　**国際会議** 13　**国内発表** 13

IEEE Trans. Robotics

Advanced Robotics

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］［2012年度］［特殊講義 I］