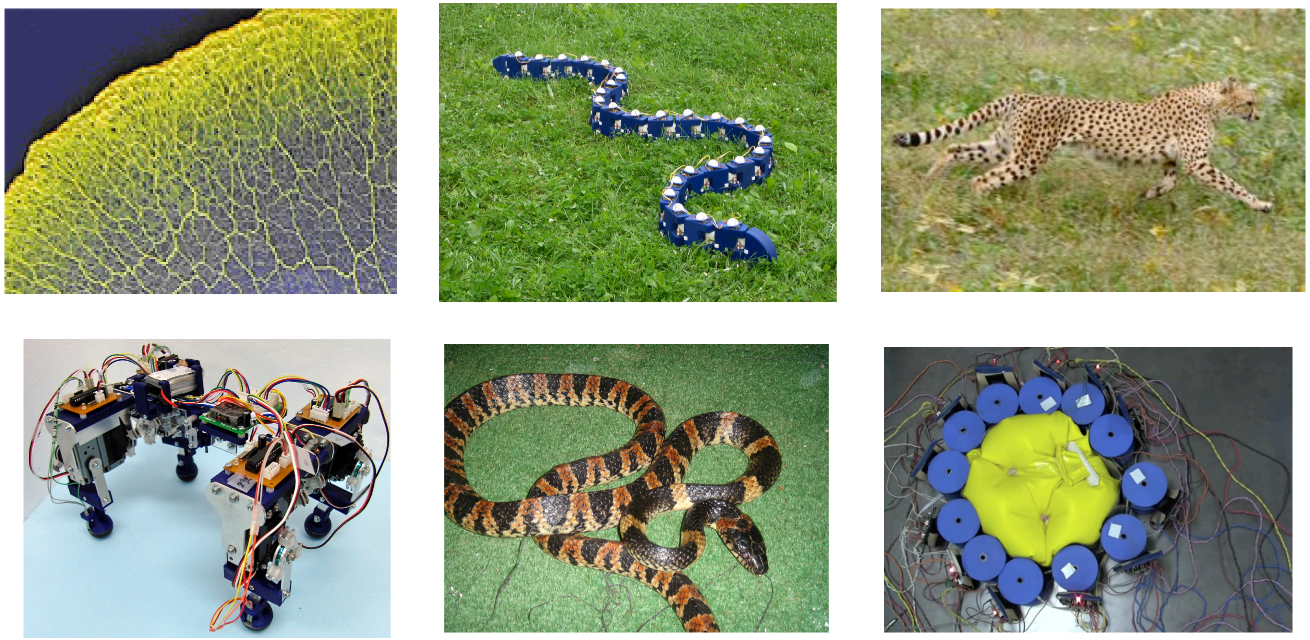
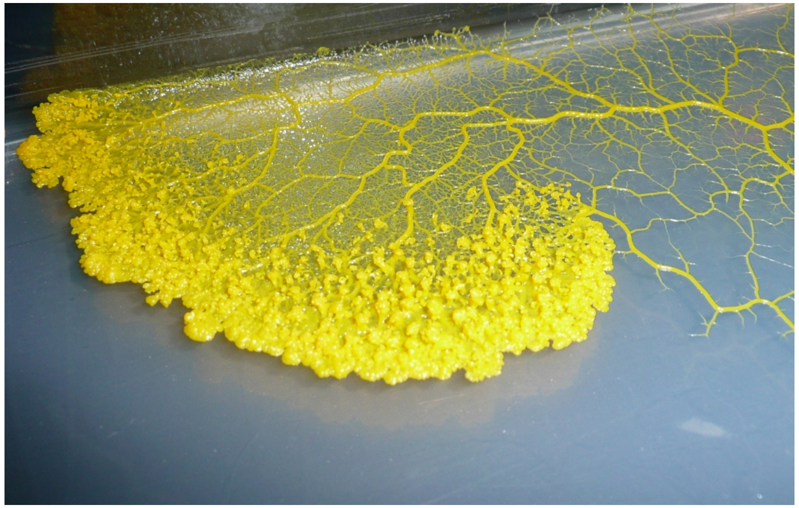
Locomotion of Animals, Robots and Mathematics



R. Kobayashi (Hiroshima Univ.)

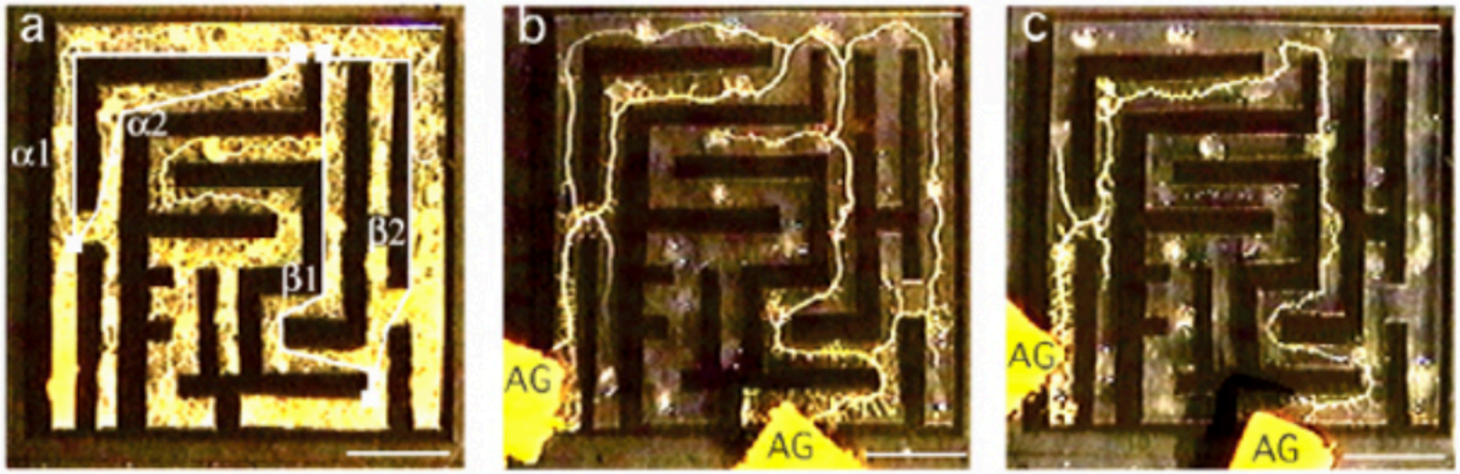
Amazing Creature - True Slime Mold



Physarum Polycepahlum

Large single cell organism with multi nuclei

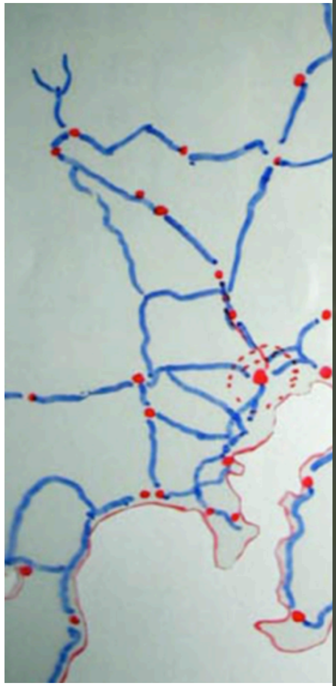
Physarum can solve a maze !



Nakagaki et al., Nature (2000)

Physarum designs networks !

Real Railroad N
in Tokyo ar



Completely Decentralized System

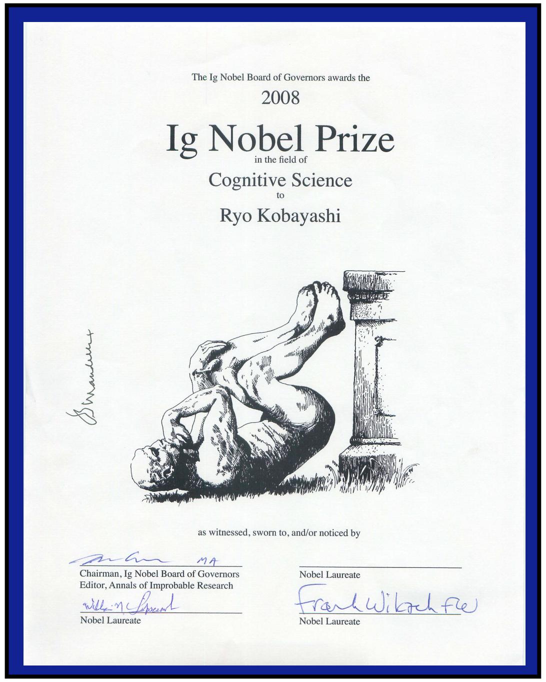
Mathematical Model

A.Tero *et al., Science (2010)*

Ig Nobel Prize

2008 Cognitive Science Prize

2010 Transportation Planning Prize



The Ig Nobel Board of Governors awards the

2008

Ig Nobel Prize

in the field of

Cognitive Science

to

Ryo Kobayashi

as witnessed, sworn to, and/or noticed by

Chairman, Ig Nobel Board of Governors
Editor, Annals of Improbable Research

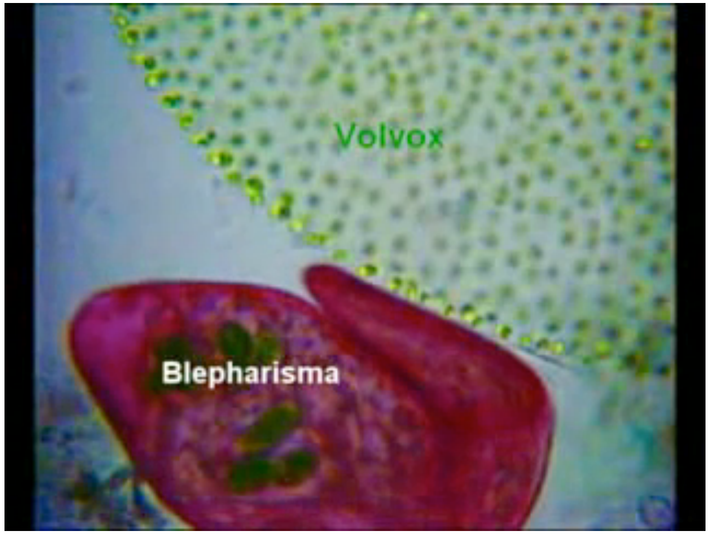
Nobel Laureate

Nobel Laureate

Frank Wilczek
Nobel Laureate

First make people laugh,
and then make them think

Locomotion of Animals

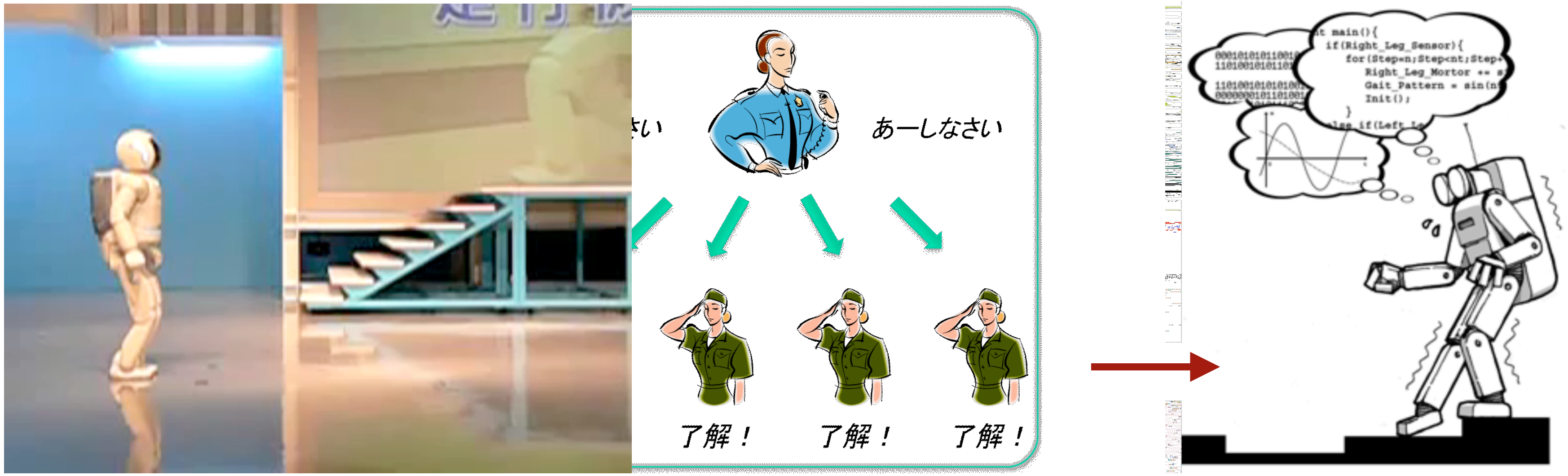


Supple, agile, robust motion

Control very large degrees of freedom

Tough under uncertain surroundings

Locomotion of Robots



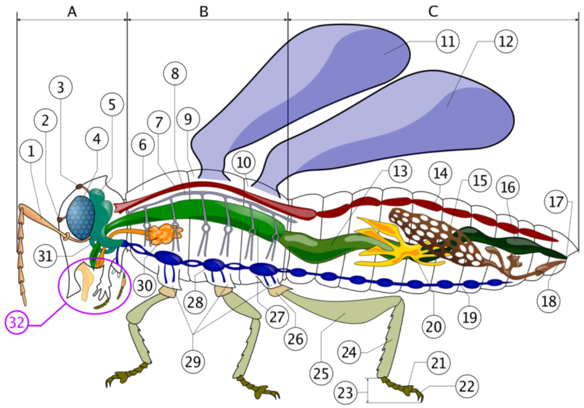
Completely centralized control

Decentralization

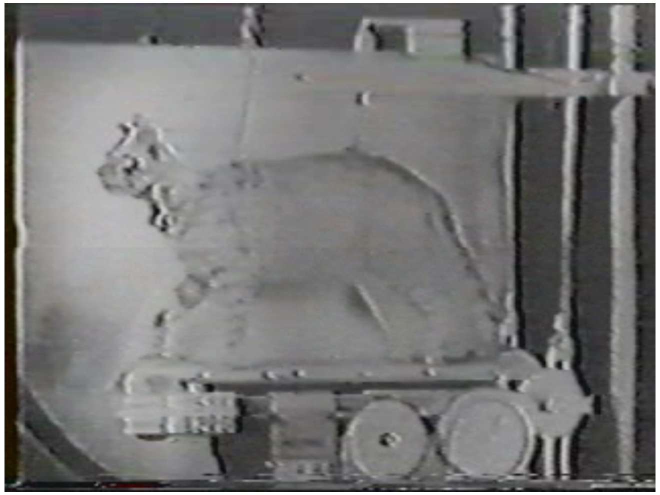
Autonomous Decentralized Control

Control policy which attains useful functions by the interactions between local elements having simple ability of sense, judge and motor output

ADC in Animals



Neural ganglion in each body segment



Gait transition of DC cat on treadmill

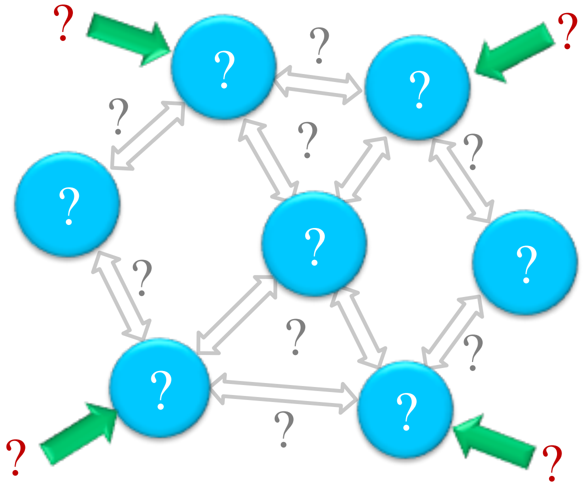
Central Pattern Generator

Neural circuits which generate rhythm

Lamprey, Tadpole ↔ Mammals

Details are still unknown

ADC is OK, but ....



How can we achieve the emergence of function from such systems ?

1. Dynamics of each component
2. Interaction between components
3. Local sensory feedback

ad hoc design for each case example

Still missing a systematic way of designing ADC !

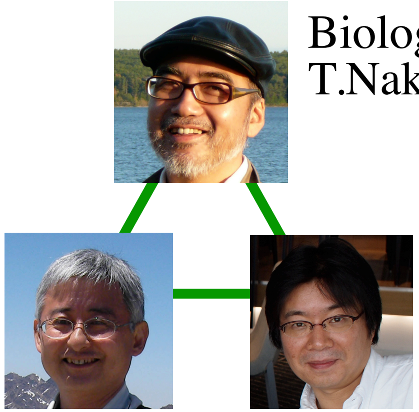
Outline of Our Project

- Goal

  Produce robots which move in supple, agile and robust manner like animals

- Who ?

  Team consists of Biologists, Mathematicians & Roboticists



Biology
T.Nakagaki

Mathematics
R.Kobayashi

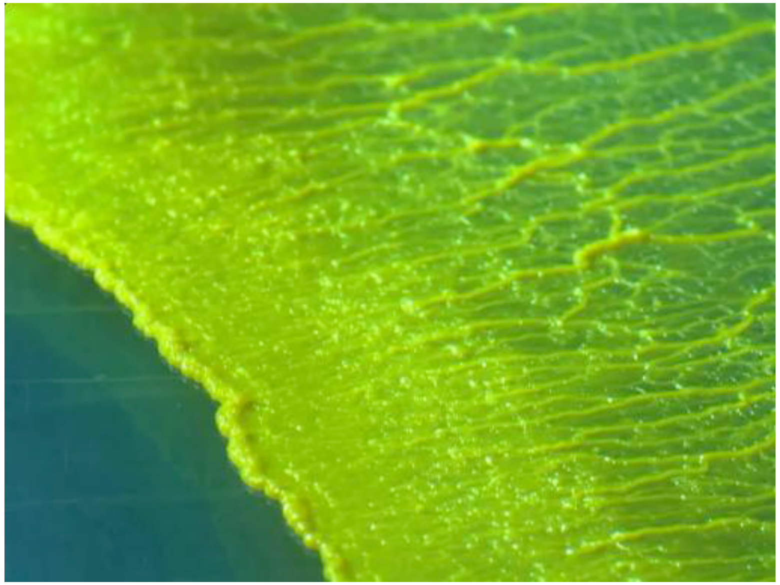
Robotics
A.Ishiguro

- How ?

  Learn from the animals.
  Design robots with large DOF controlled by ADC

Which animal at first ?

Go Back to *Physarum* !



Completely decentralized system

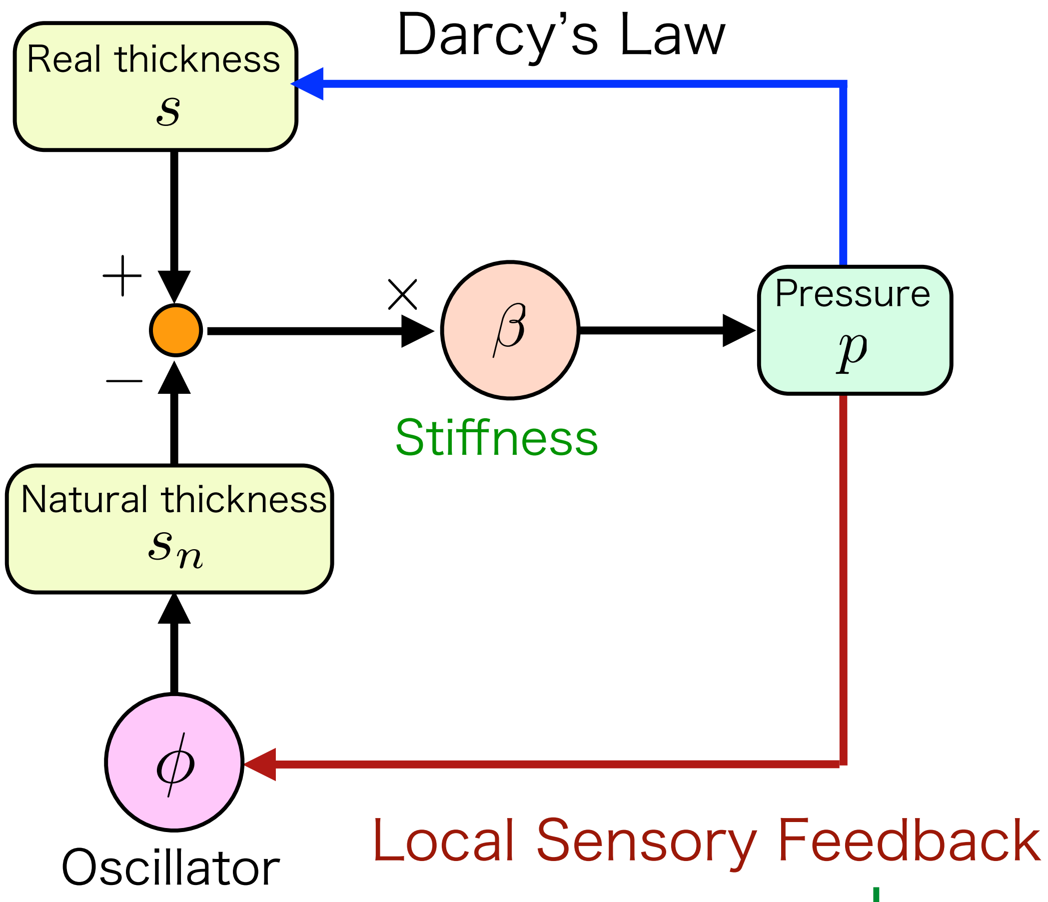
Driven by distributed oscillator system

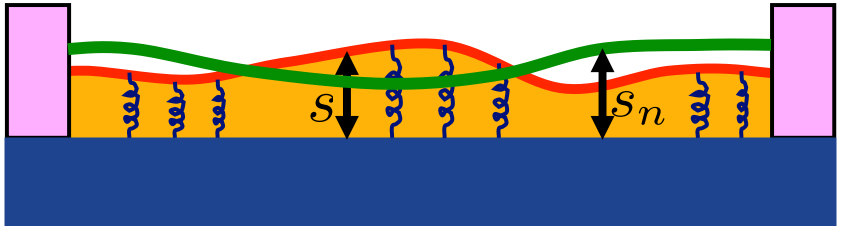
High ability

Solving a maze and designing networks

Physarum Model ver.1

Kobayashi and Nakagaki (2003)
Rediscovered by Ishiguro (2008)





Active spring whose natural length is driven by the phase oscillator ϕ

$$s_n(\phi) = \bar{s}(1 - a\cos\phi)$$

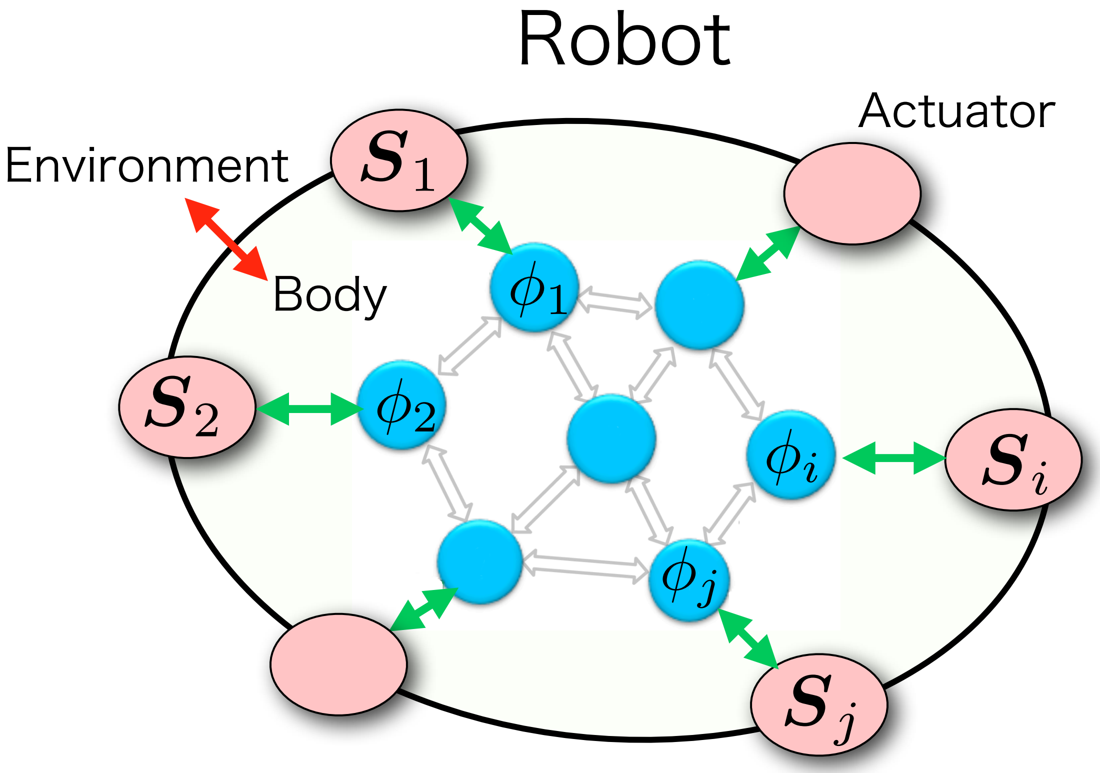
$$p = \beta(s - s_n(\phi))$$

$$\partial_t s = \nabla \cdot (sM\nabla p)$$

$$\partial_t \phi = \omega + \nabla \cdot (D\nabla\phi) \boxed{-\partial_\phi I}$$

$I = \dfrac{\sigma}{2}p^2$: Discrepancy Function

Basic Design Scheme



ϕ_i : the i-th controller (phase oscillator)

$\boldsymbol{S}_i$: State variable of the i-th actuator

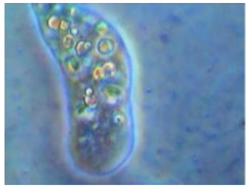
$I_i(\boldsymbol{S}_i, \phi_i)$: Frustration accumulated in the i-th unit

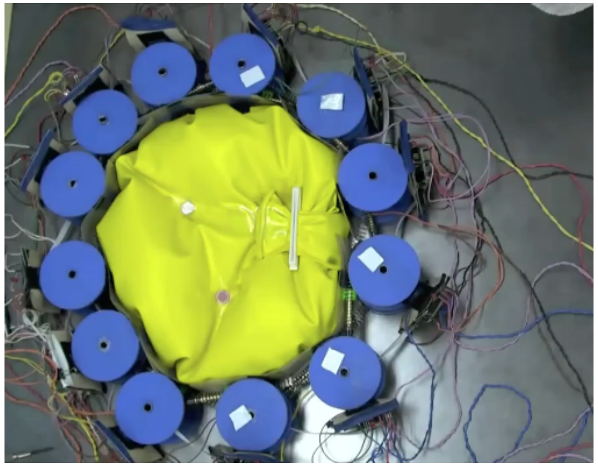
→ Discrepancy Function

$$\partial_t \phi_i = \omega_i + \sum_j g_{ij}(\phi_i, \phi_j) - \partial_{\phi_i} I_i$$

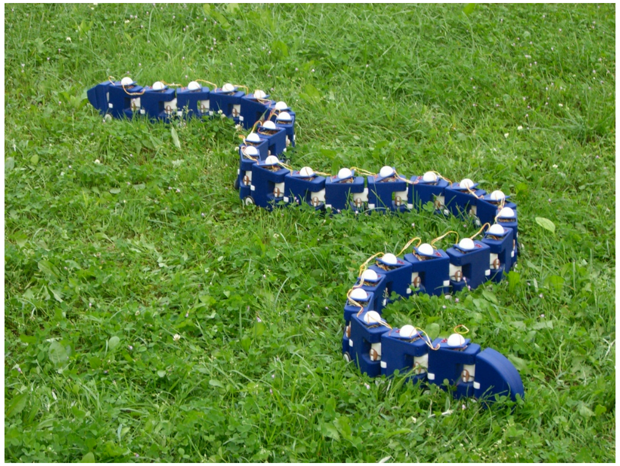
Indirect interaction through the body

Our Robots

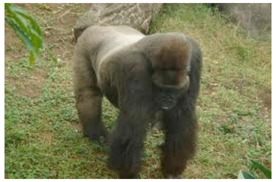


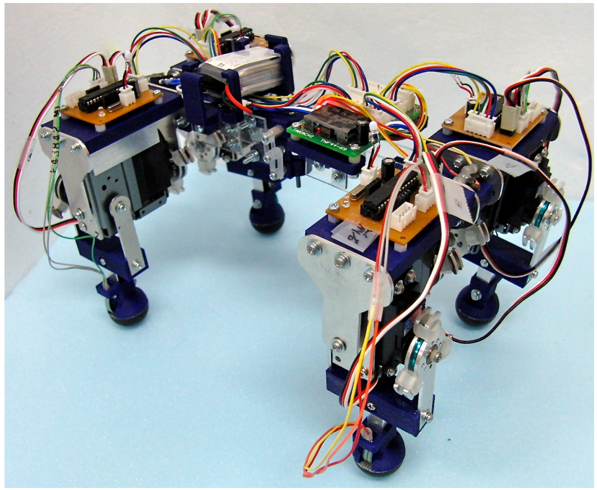


Slimy

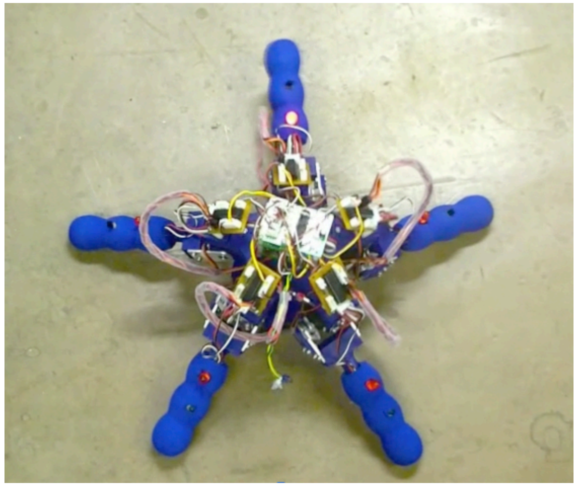


HAUBOT



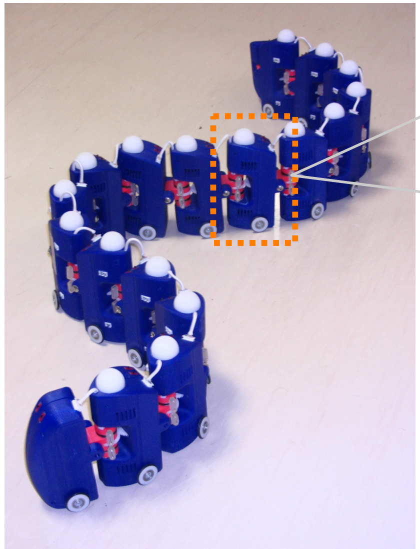


OSCILLEX

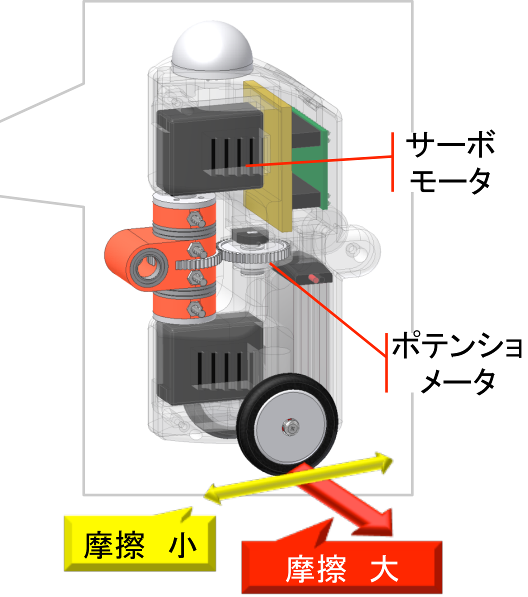


Nameless Now

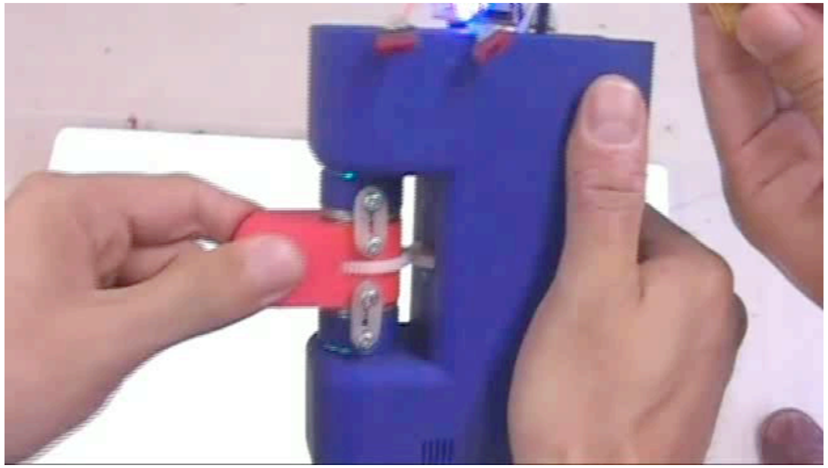
Snake Robot：HAUBOT 2



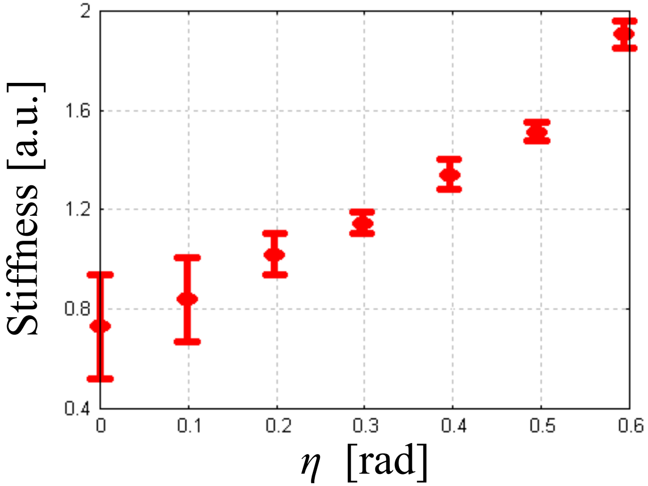
T. Sato (2011)



Joint mechanism



Elastic elements permit discrepancy between the motor angle (target angle)and the actual joint angle

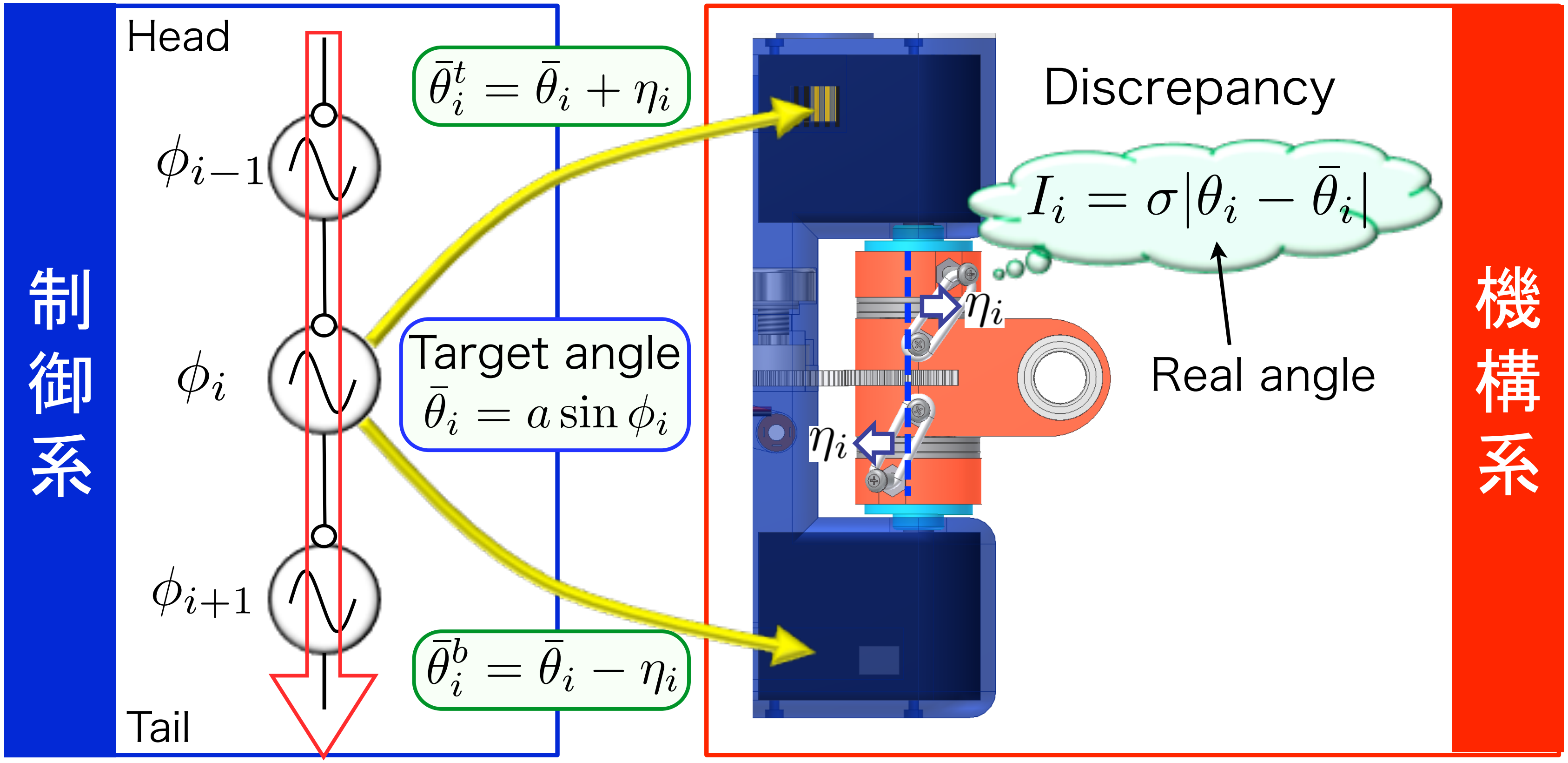


←

Stiffness is also controllable by twisting

Phasic & Tonic Control

- $\partial_t \phi_i = \omega + D(\phi_{i-1} - \phi_i - \Delta\phi) - \partial_{\phi_i} I_i$
- $\partial_t \eta_i = \alpha(\beta I_i - \eta_i)$



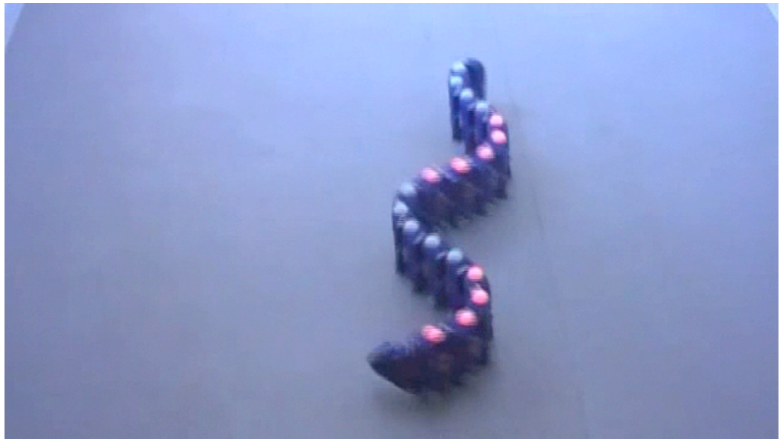
HAUBOT 1 & 2

Phasic Control	Tonic Control
phase adjustment	stiffness adjustment
Energetic efficiency	Powerful motion

HAUBOT 1

Phasic control only

HAUBOT 2

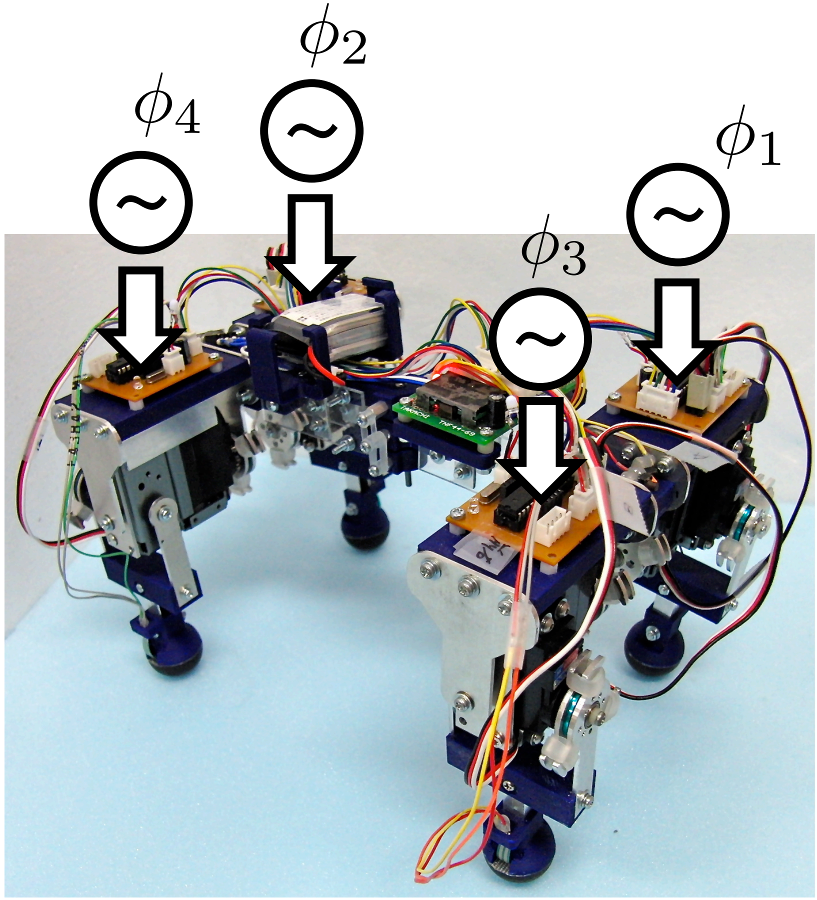


Phasic & Tonic control

NTF Award Finalist for Entertainment Robots and Systems (IROS2011)

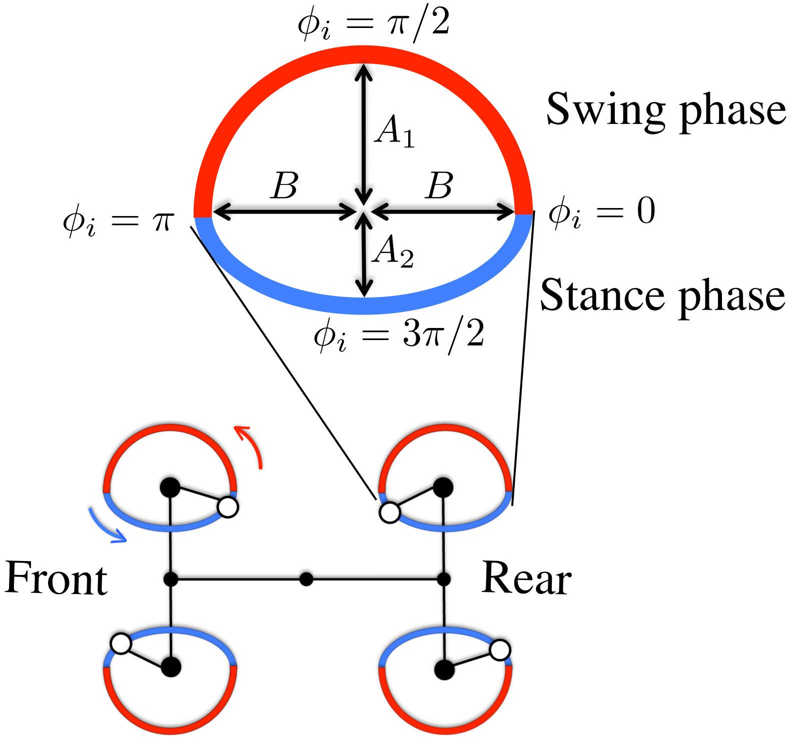
4-legged Robot : OSILLEX

K. Nagasawa, T. Kano et al.



No connections
between controllers

Control of toe position



4-legged Robot : OSILLEX

Discrepancy function
of the i-th unit

$$I_i = \sigma N_i \sin \phi_i$$

N_i : load at the i-th toe

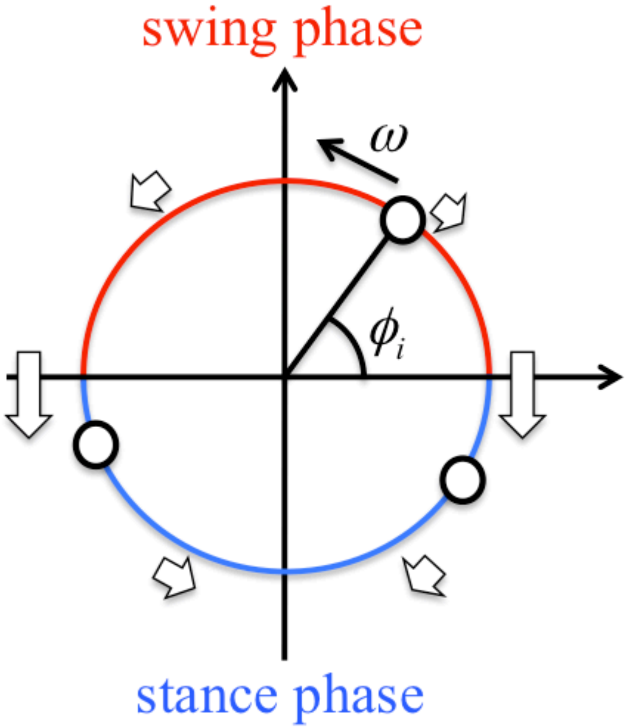
Discrepancy control

$$\partial_t \phi_i = \omega - \partial_{\phi_i} I_i$$

$$\boxed{\partial_t \phi_i = \omega - \sigma N_i \cos \phi_i}$$

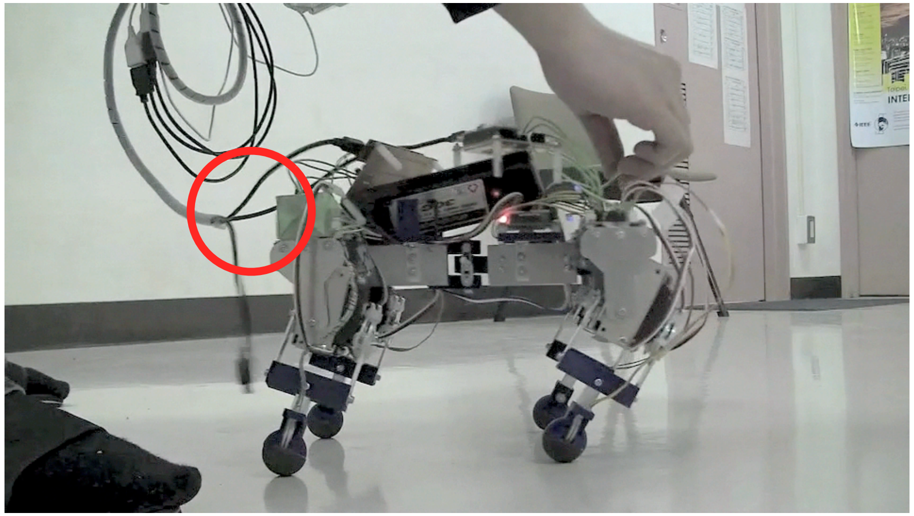
No direct interactions

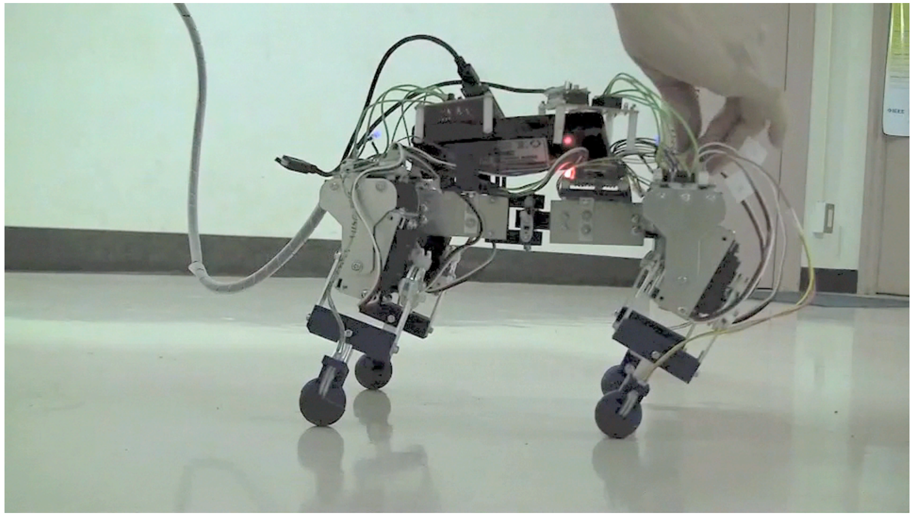
Interaction through the body

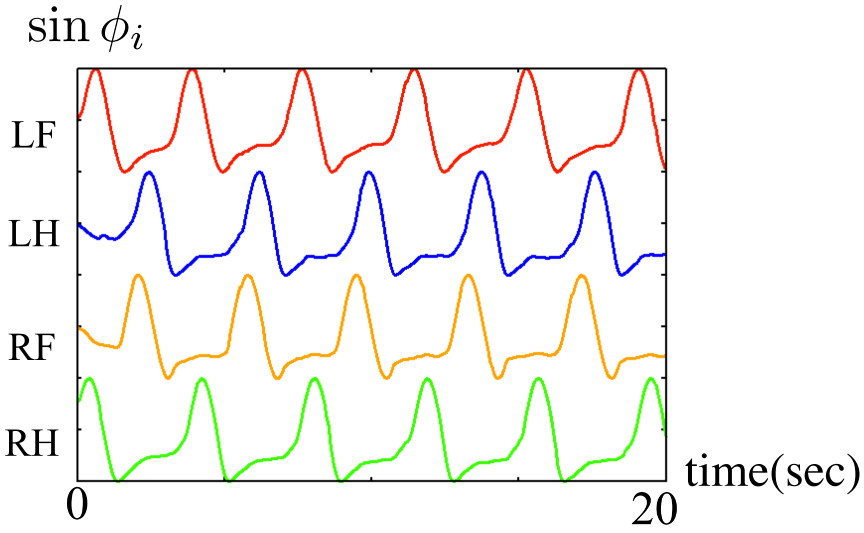


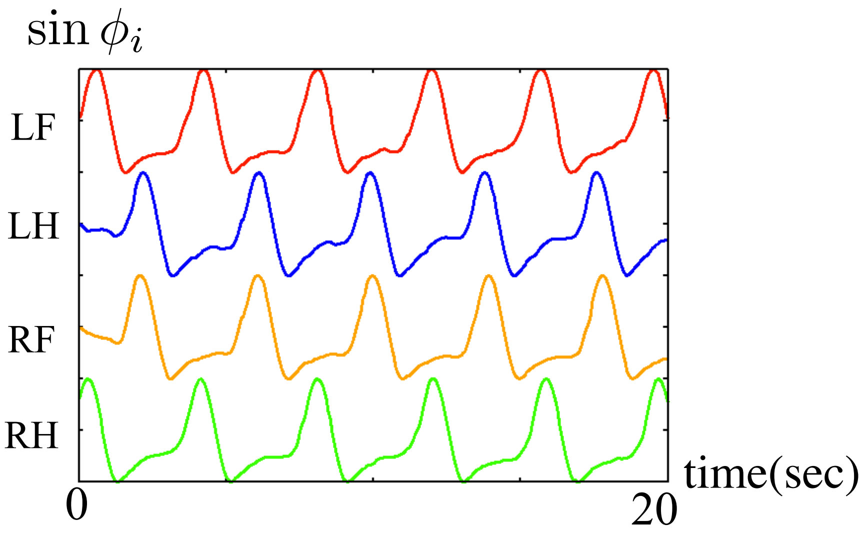
When the leg is loaded,
it tries to stay in a
stance phase.

4-legged Robot : OSILLEX

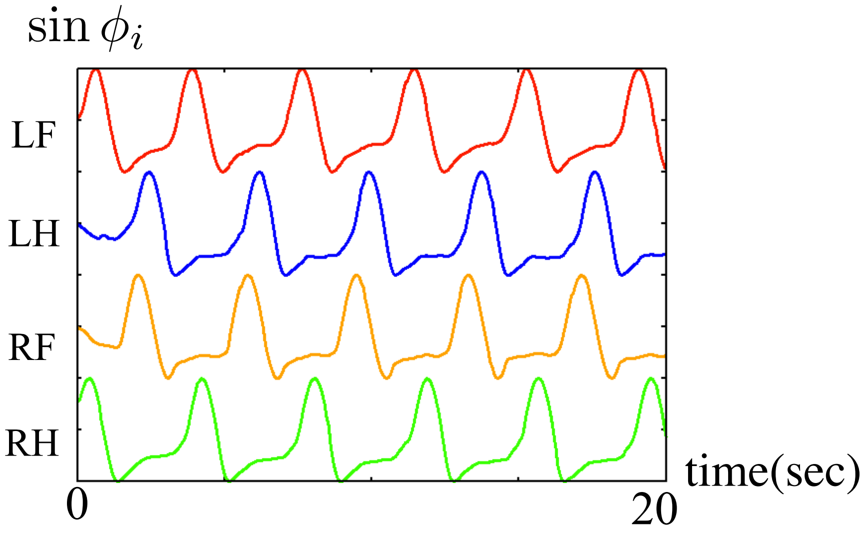


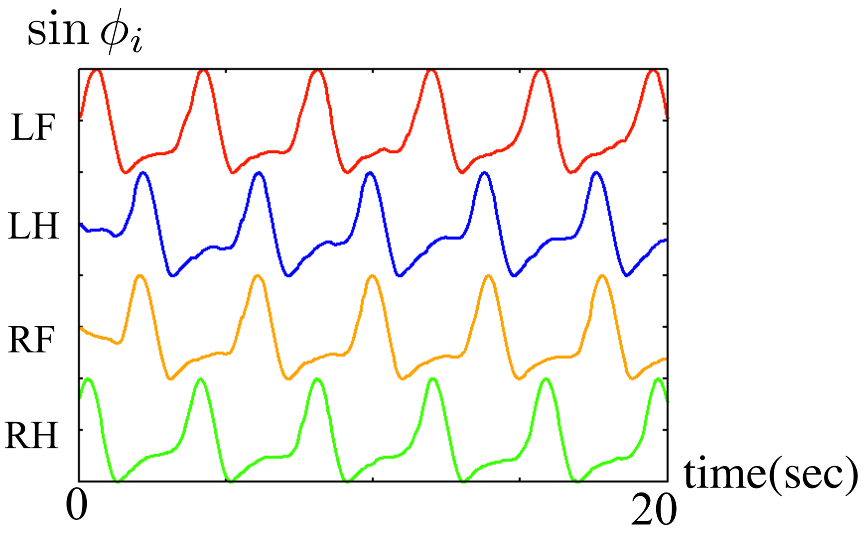






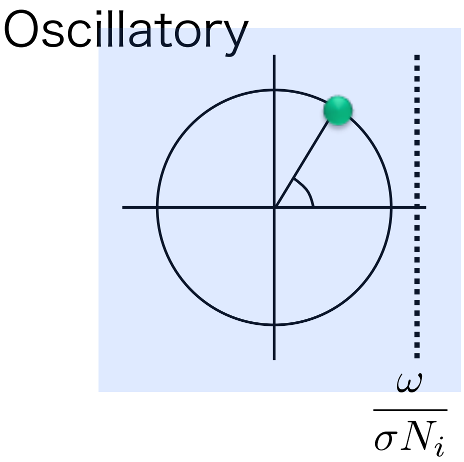
4-legged Robot : OSILLEX

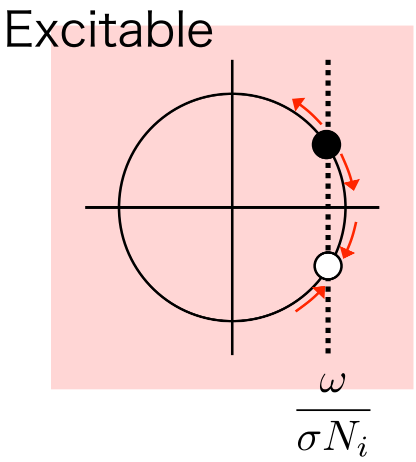


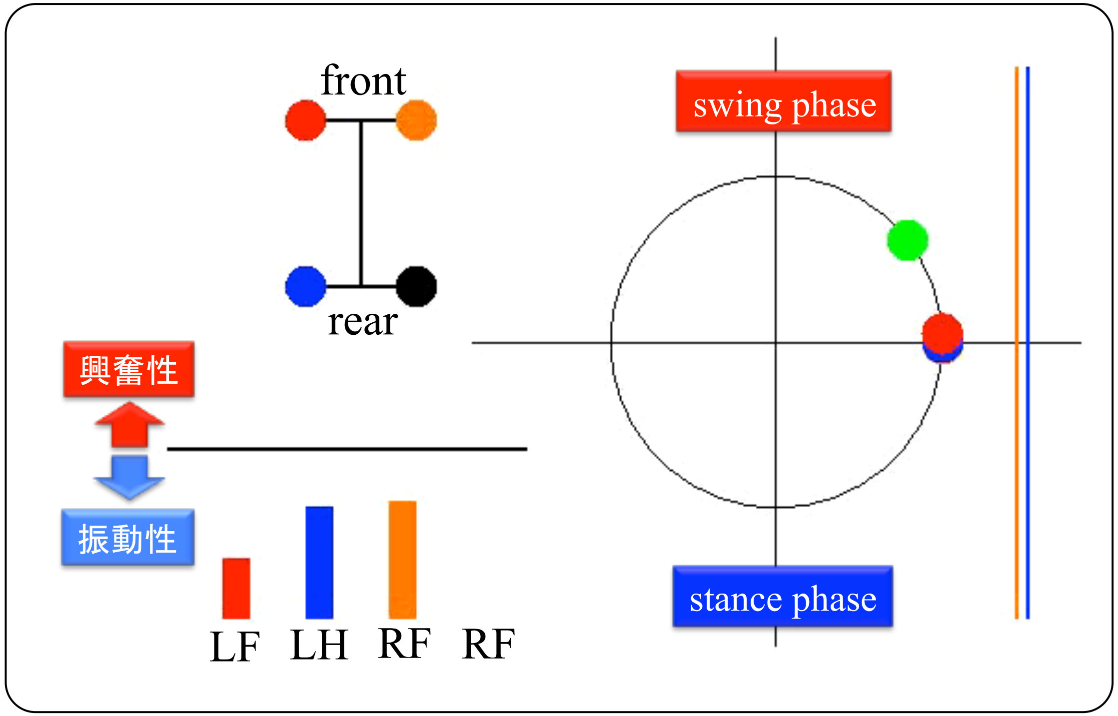


Why OSILLEX ?

$$\partial_t \phi_i = \omega - \sigma N_i \cos \phi_i$$







Go back and force between Oscillatory & Excitable mode

Quick transition to the stationary walking

Summary

- We proposed a design scheme of ADC derived from the model of Physarum, and applied it to our robots.

- Design principle of ADC robots at the present stage
  - Adopt oscillators as local controllers
  - Give a backdrivability to the actuators by combining elastic elements with them
  - Design a discrepancy function appropriately
  - Generate phasic feedback using discrepancy function, and tonic feedback if necessary
  - Not to design the direct interactions between controllers more than needs → Listen to the voice of the body !

Coworkers

Biology Group

T. Nakagaki, S. Takagi, K. Matsumoto, Y. Tanaka

Mathematics Group

K. Ito, T. Kazama, A. Tero, M. Akiyama, M. Iwamoto,

Robotics Group

A. Ishiguro, T. Kano, T. Umedachi, T. Sato,
K. Yaegashi, K. Nagasawa, W. Watanabe,
Y. Watanabe, S. Suzuki

Collaborators

S. Sonobe, Y. Nishigami

Conclusion

Physarum is a great system !

Thank you for your attention.