Locomotion of Animals, Design of Robots and Mathematics

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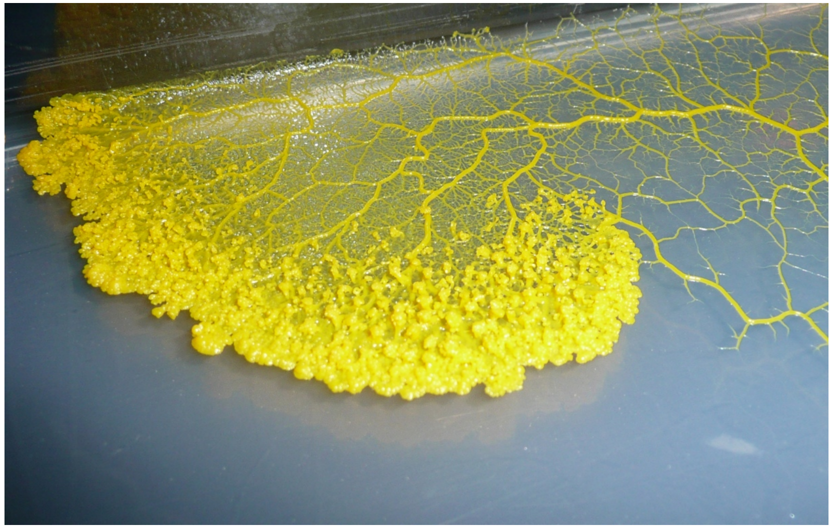
Amazing Creature - True Slime Mold



Physarum Polycepahlum

（和名：モジホコリ）

Large single cell organism
with multi nuclei

Tubular structure

Physarum can solve a maze !

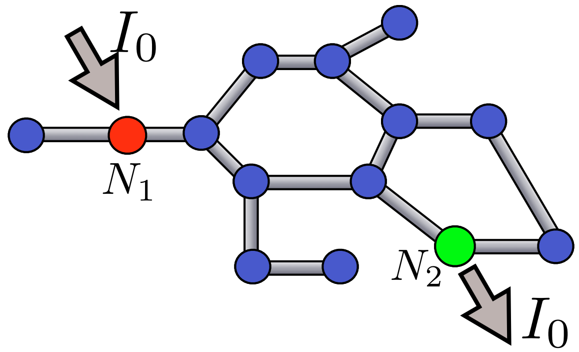
Nakagaki et al., Nature (2000)

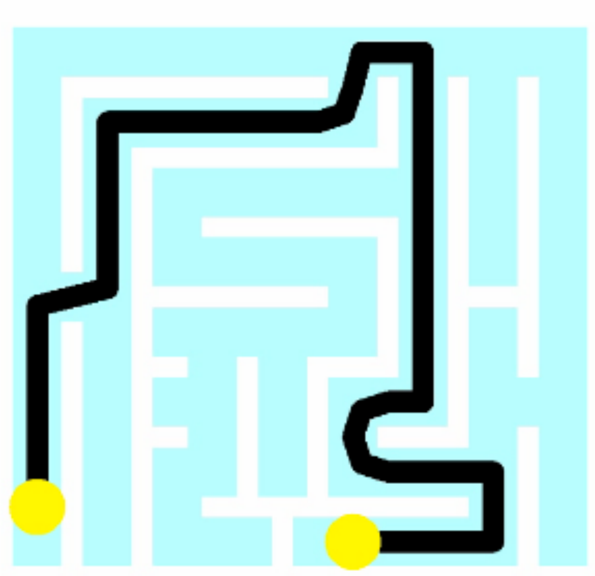
Physarum Solver

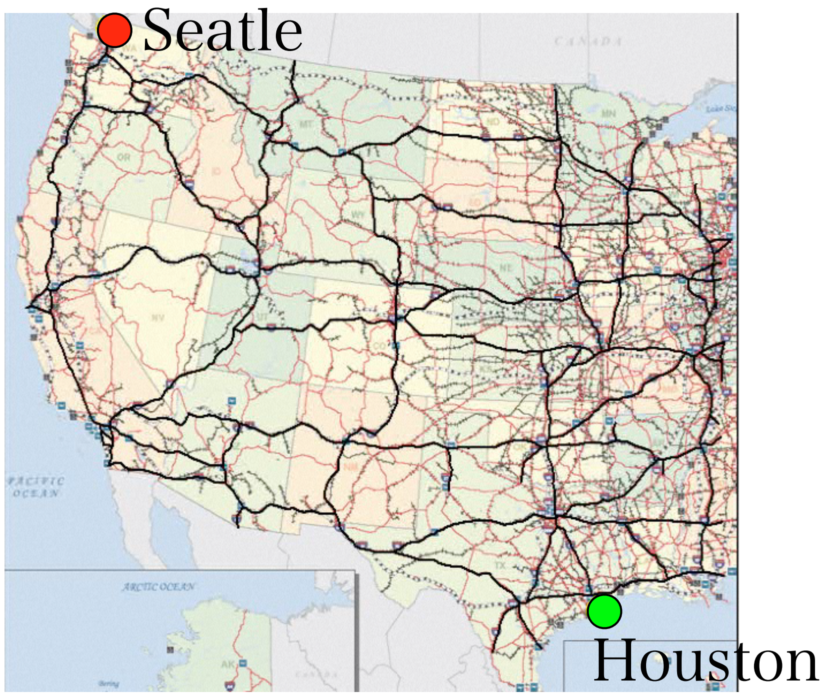
Shortest path finding model on the graph

$$\sum_i \frac{D_{ij}}{L_{ij}}(p_i - p_j) = \begin{cases} -I_0 & \text{for } j = 1, \\ I_0 & \text{for } j = 2, \\ 0 & \text{otherwise.} \end{cases}$$

$$\frac{d}{dt}D_{ij} = f(|Q_{ij}|) - D_{ij} \qquad Q_{ij} = \frac{D_{ij}}{L_{ij}}(p_i - p_j)$$



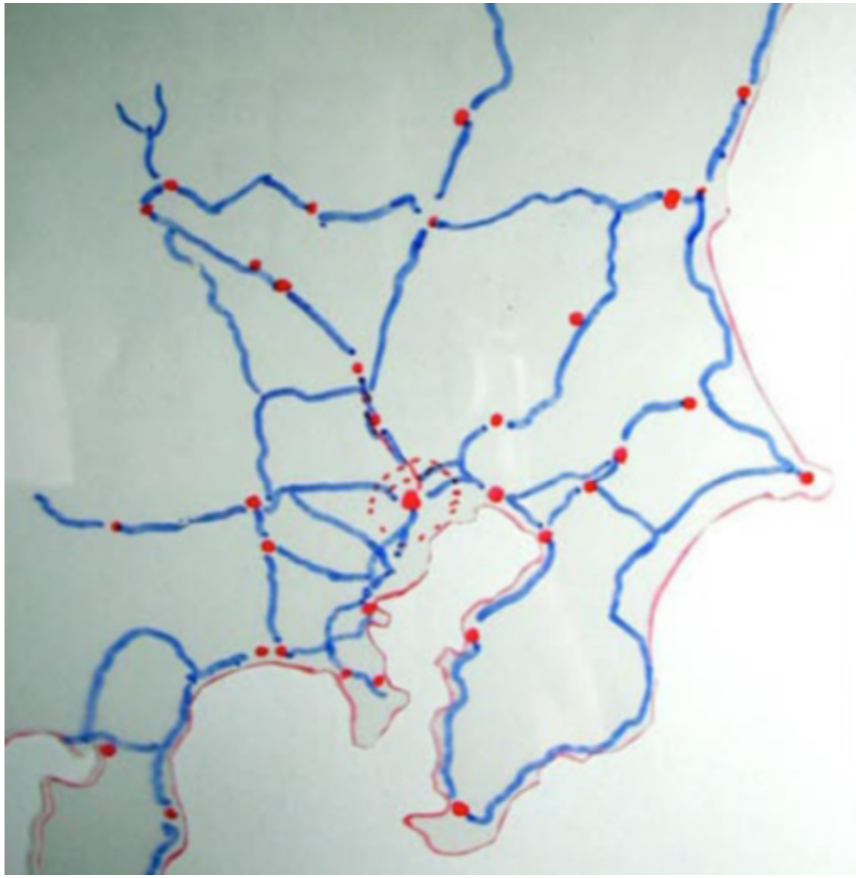




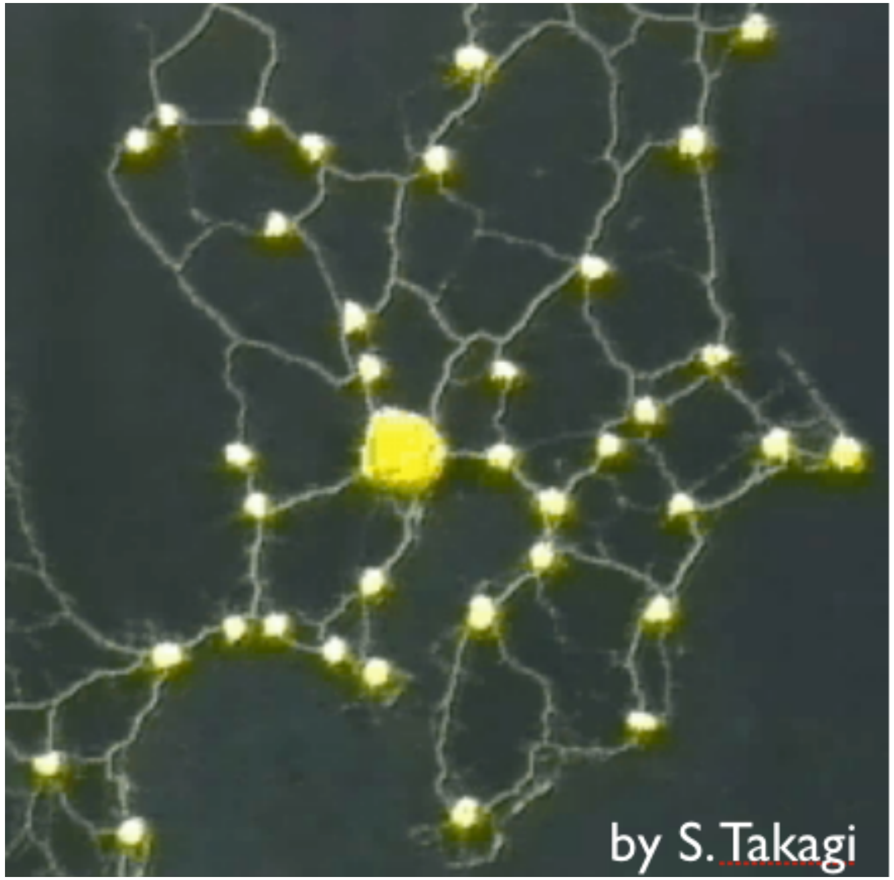
Tero, Kobayashi, Nakagaki, J. Theor. Bio. (2007)

Physarum designs networks !

Real Railroad Network
in Tokyo area



Network produced
by *Physarum*



Tero et al., Science(2010)

Efficiency ↔ Cost ↔ Fault tolerance

Extended Physarum Solver

Cost

Efficiency, Fault tolerance

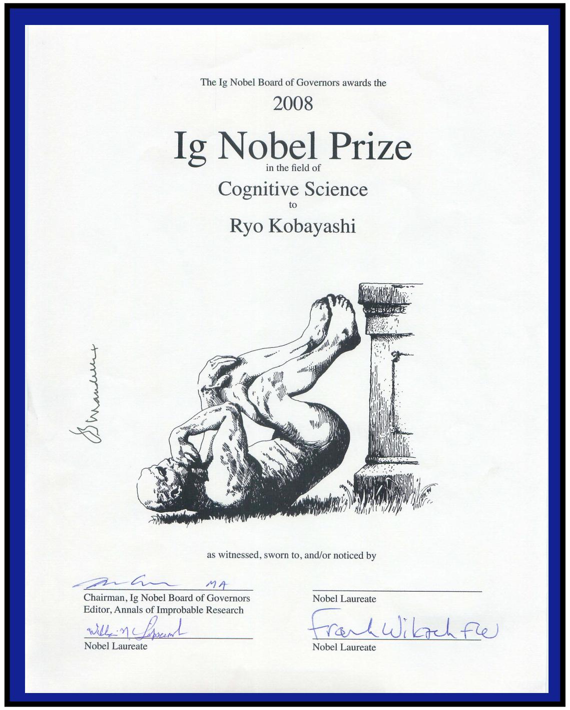
by A.Tero

Physarum is completely decentralized system !

Ig Nobel Prize

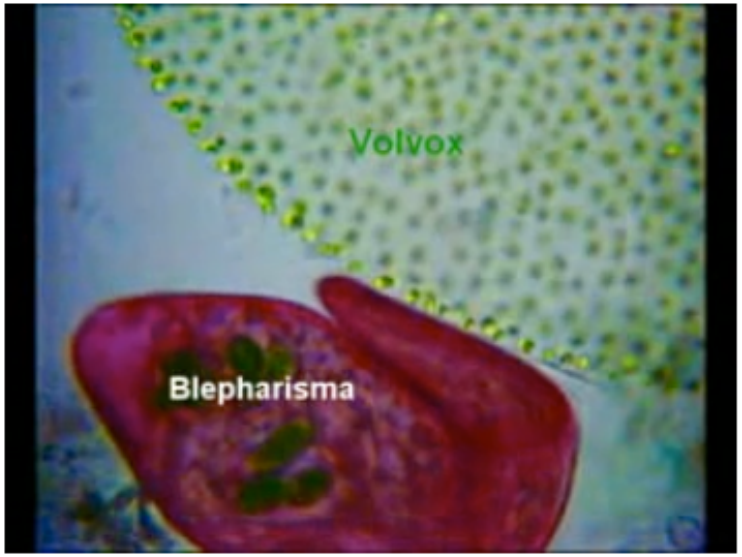
2008 Cognitive Science Prize

2010 Transportation Planning Prize



First make people laugh,
and then make them think

Locomotion of Animals

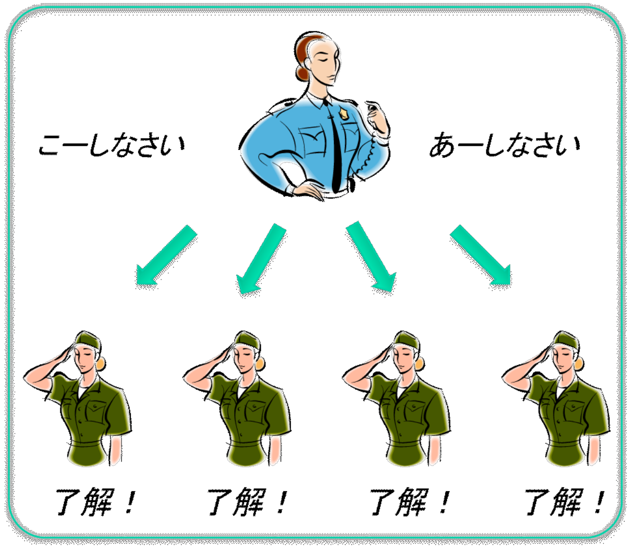


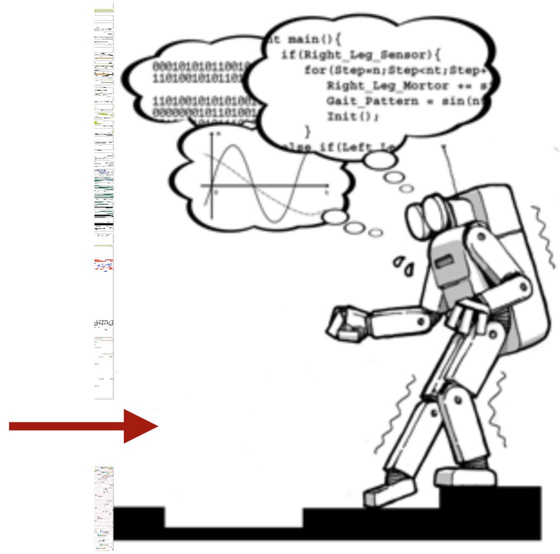
Supple, agile, robust motion

Control very large degrees of freedom

Tough under uncertain surroundings

Locomotion of Robots





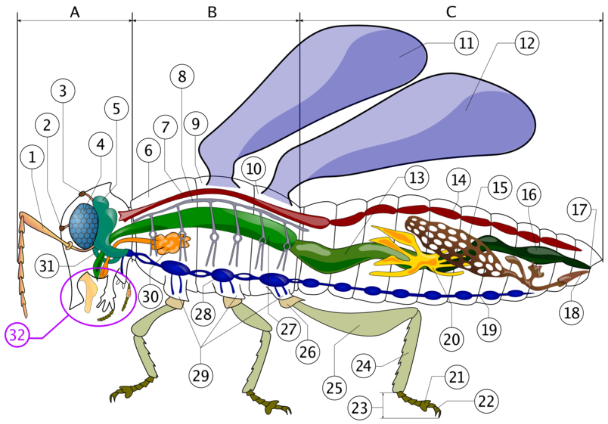
Completely centralized control

Decentralization

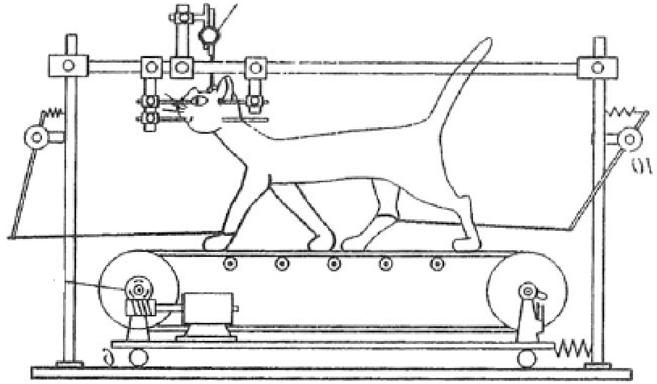
Autonomous Decentralized Control

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

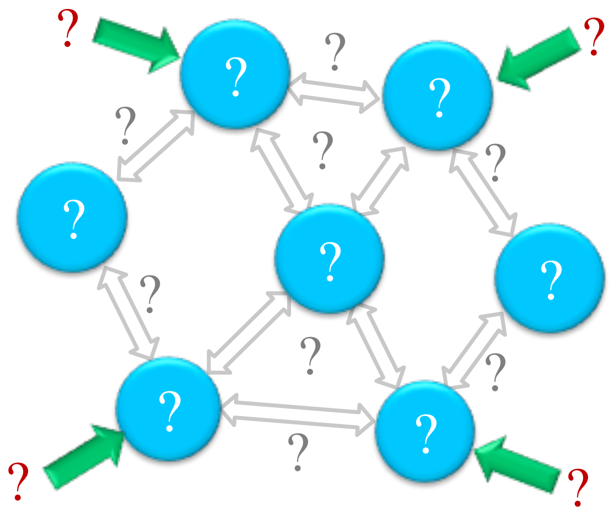
Central Pattern Generator

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

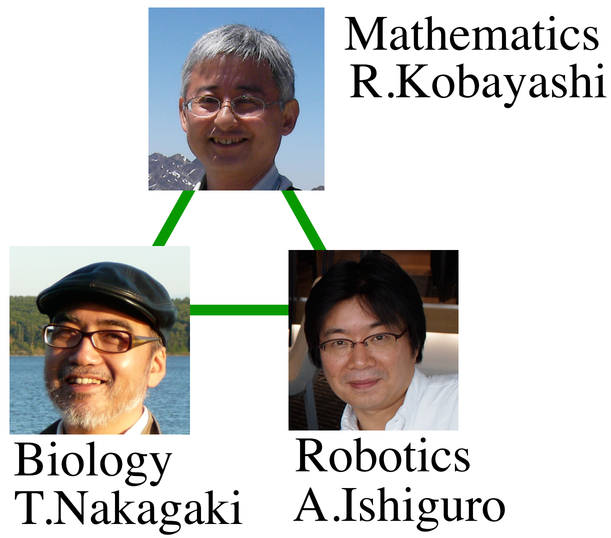
- Goal

  Understand the animal's locomotion from the view point of mechanics and control

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

- Who ?

  Team consists of Biologists, Mathematicians & Roboticists



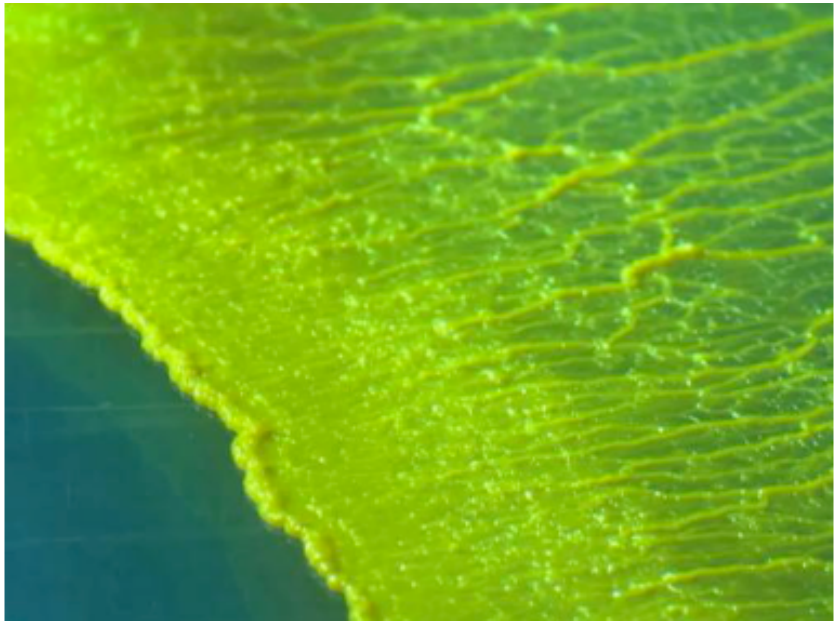
- How ?

  Learn from the animals

  Design robots with large DOF controlled by ADC

Which animal at first ?

Go Back to *Physarum* !

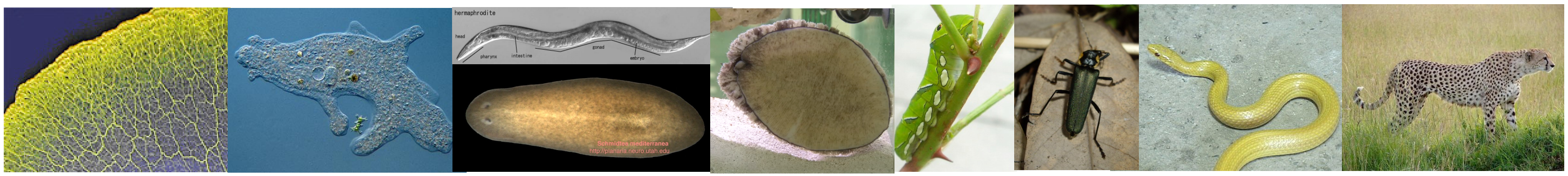


Completely decentralized system

Driven by distributed oscillator system

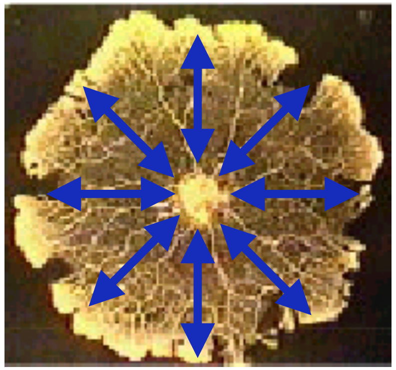
High ability

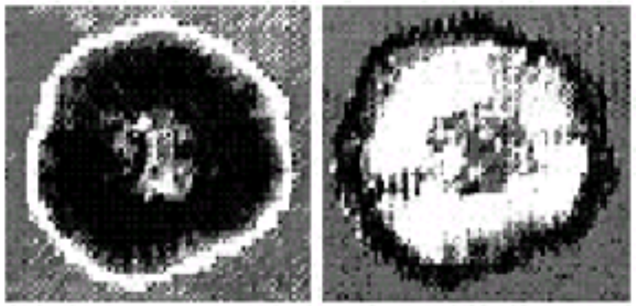
Solving a maze and designing networks



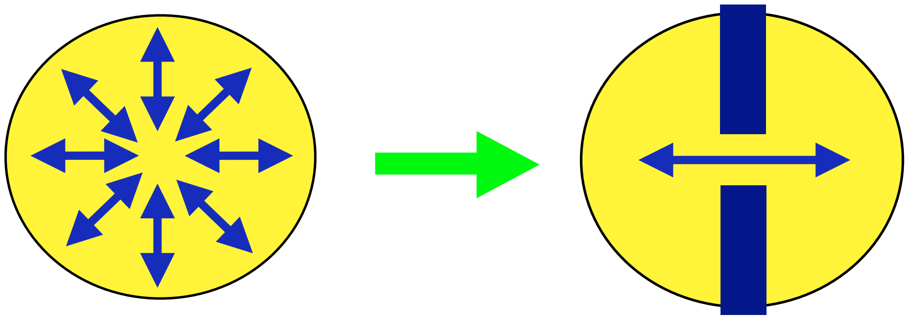
Anti-phase Oscillations

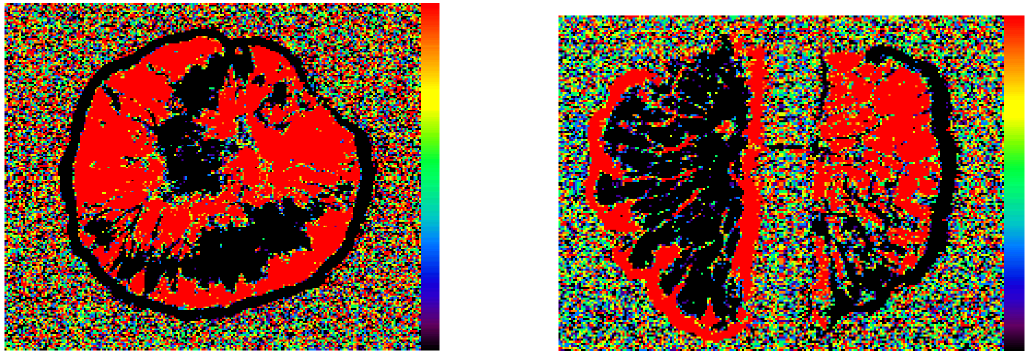
Peripheral Phase Inversion



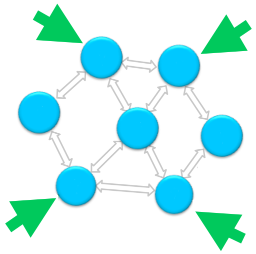


Bottleneck Phase Inversion



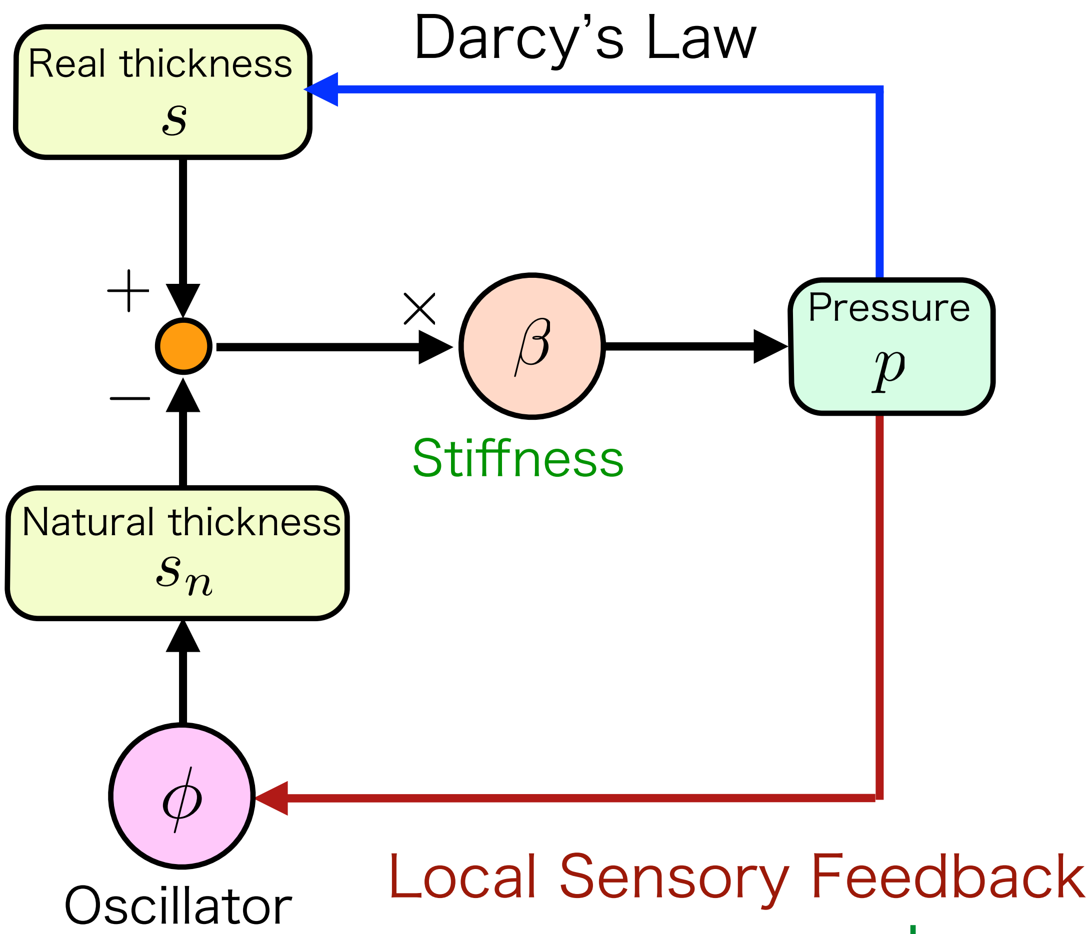


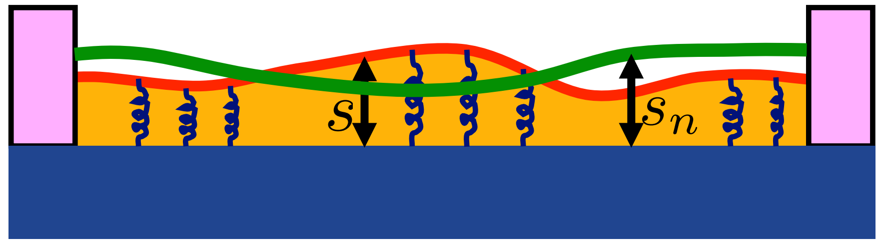
Body → Phase of oscillators



Physarum Model ver.1

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





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

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

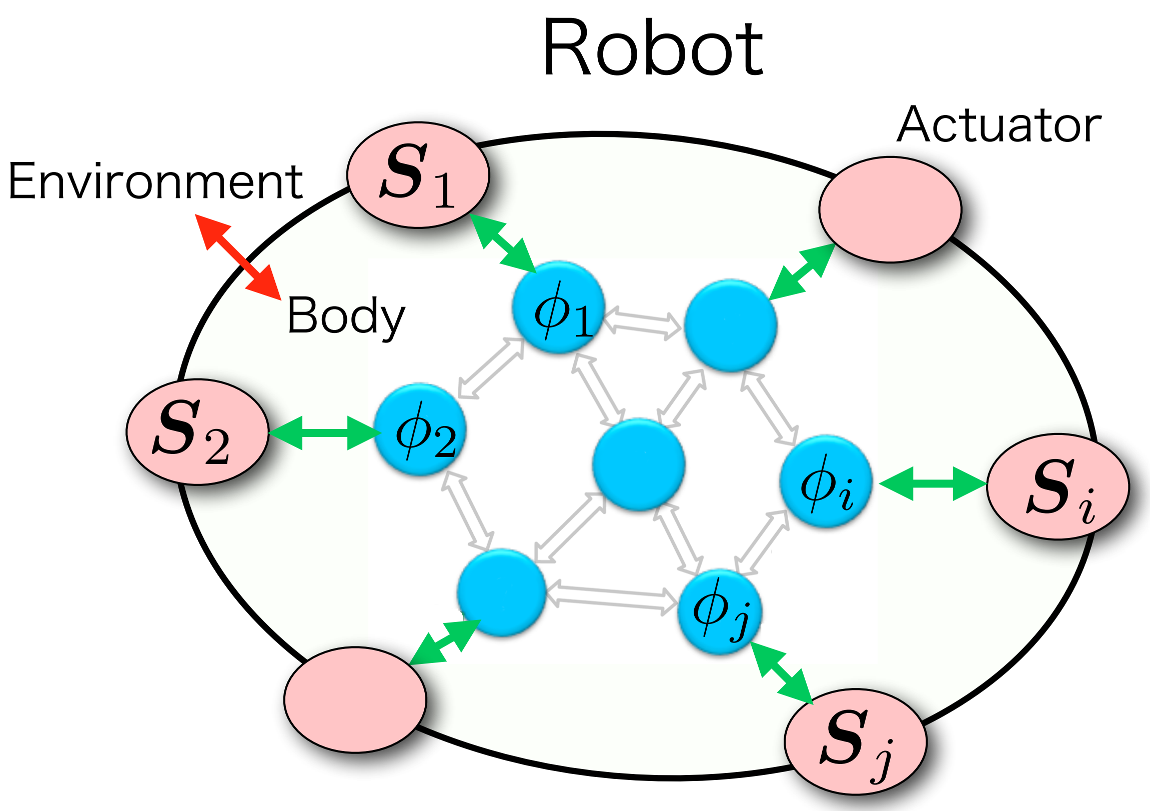
$$p = \beta(s - s_n(\phi))$$

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

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

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

Basic Design Scheme



ϕ_i : the i-th controller (phase oscillator)

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

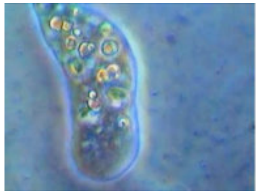
$I_i(\boldsymbol{S}_i, \phi_i)$: Frustration accumulated in the i-th unit

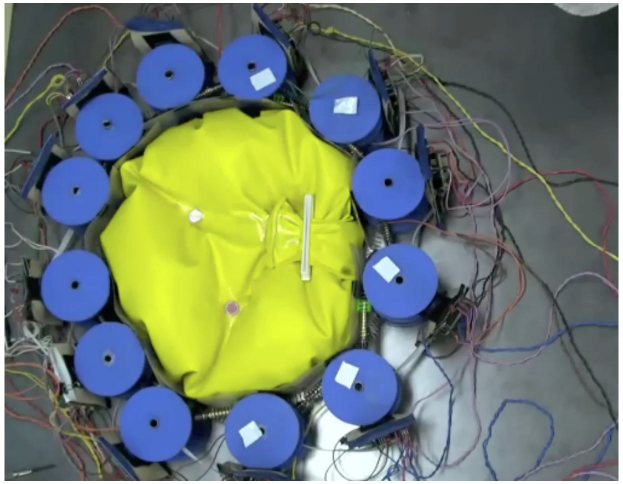
→ Discrepancy Function

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

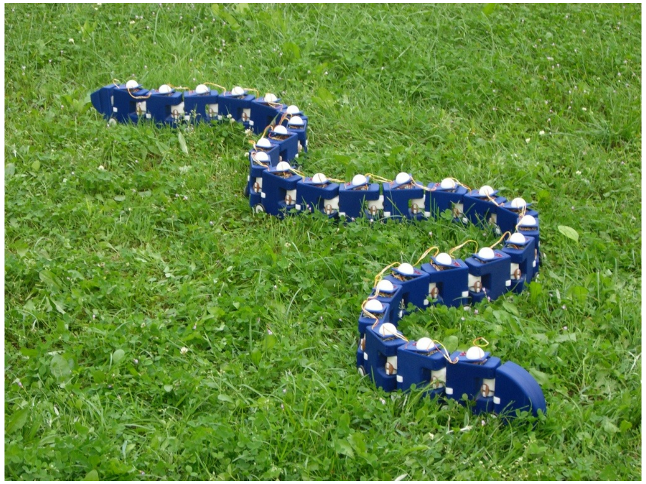
Indirect interaction through the body

Our Robots

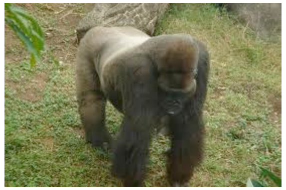


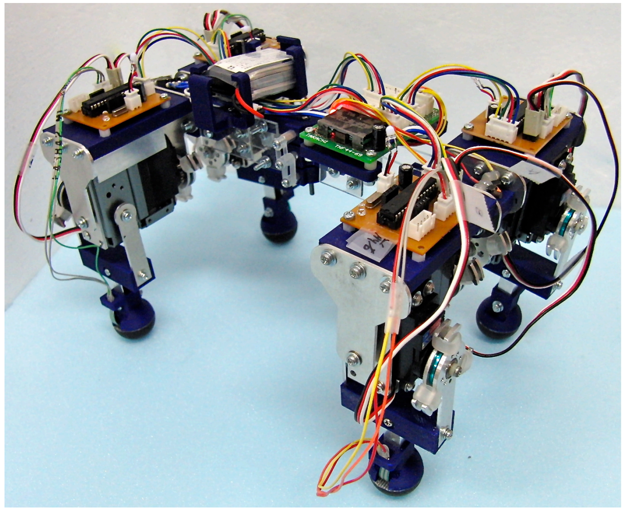


Slimy

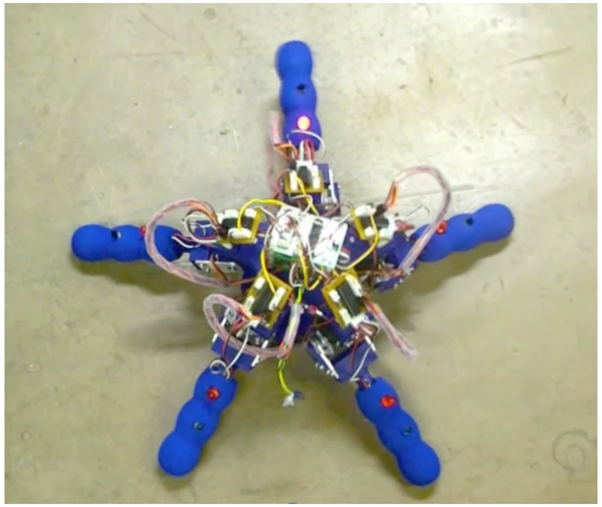


HAUBOT



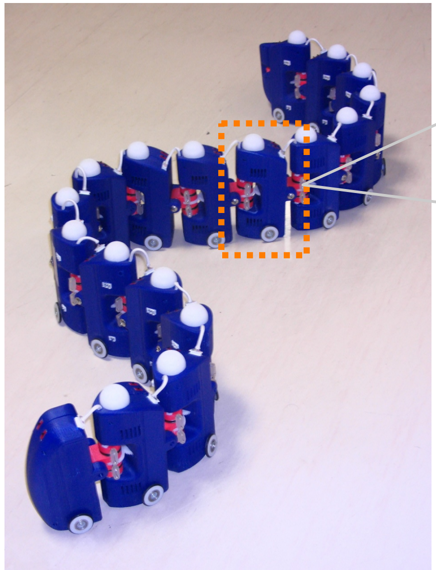


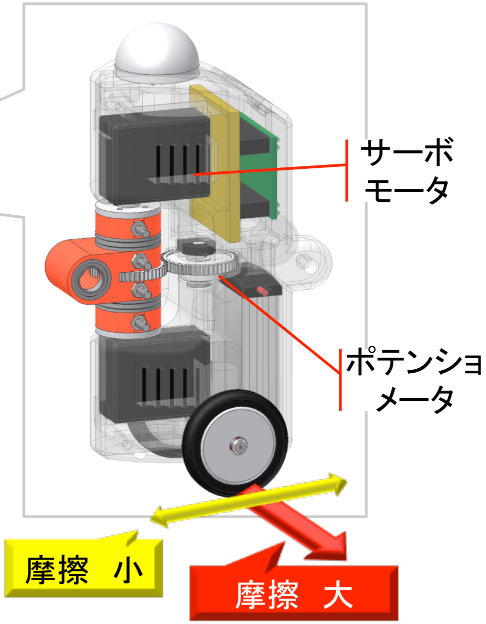
OSCILLEX



PENTABOT

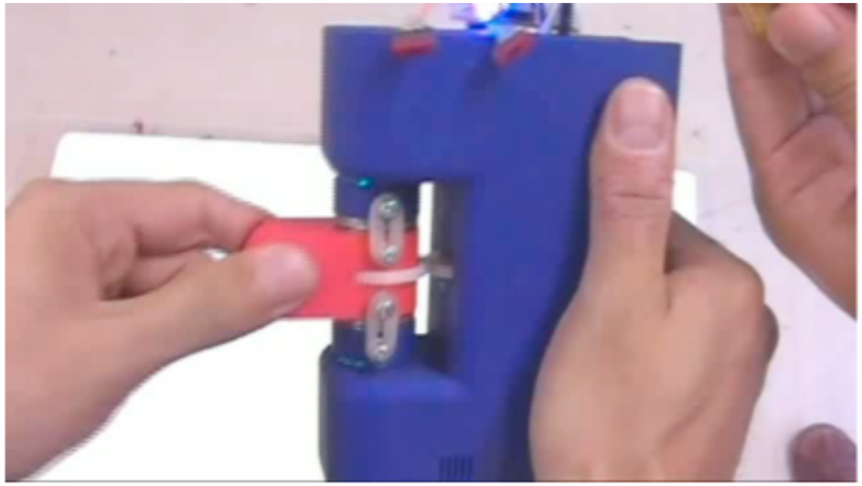
Snake Robot : HAUBOT 2



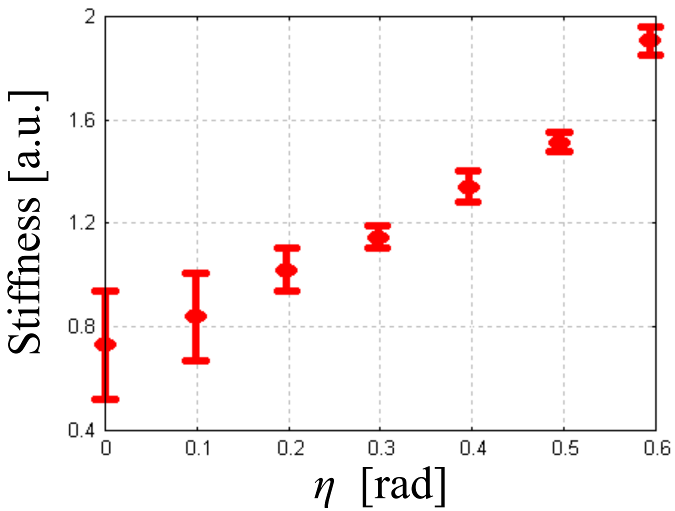


T. Sato (2011)

Joint mechanism



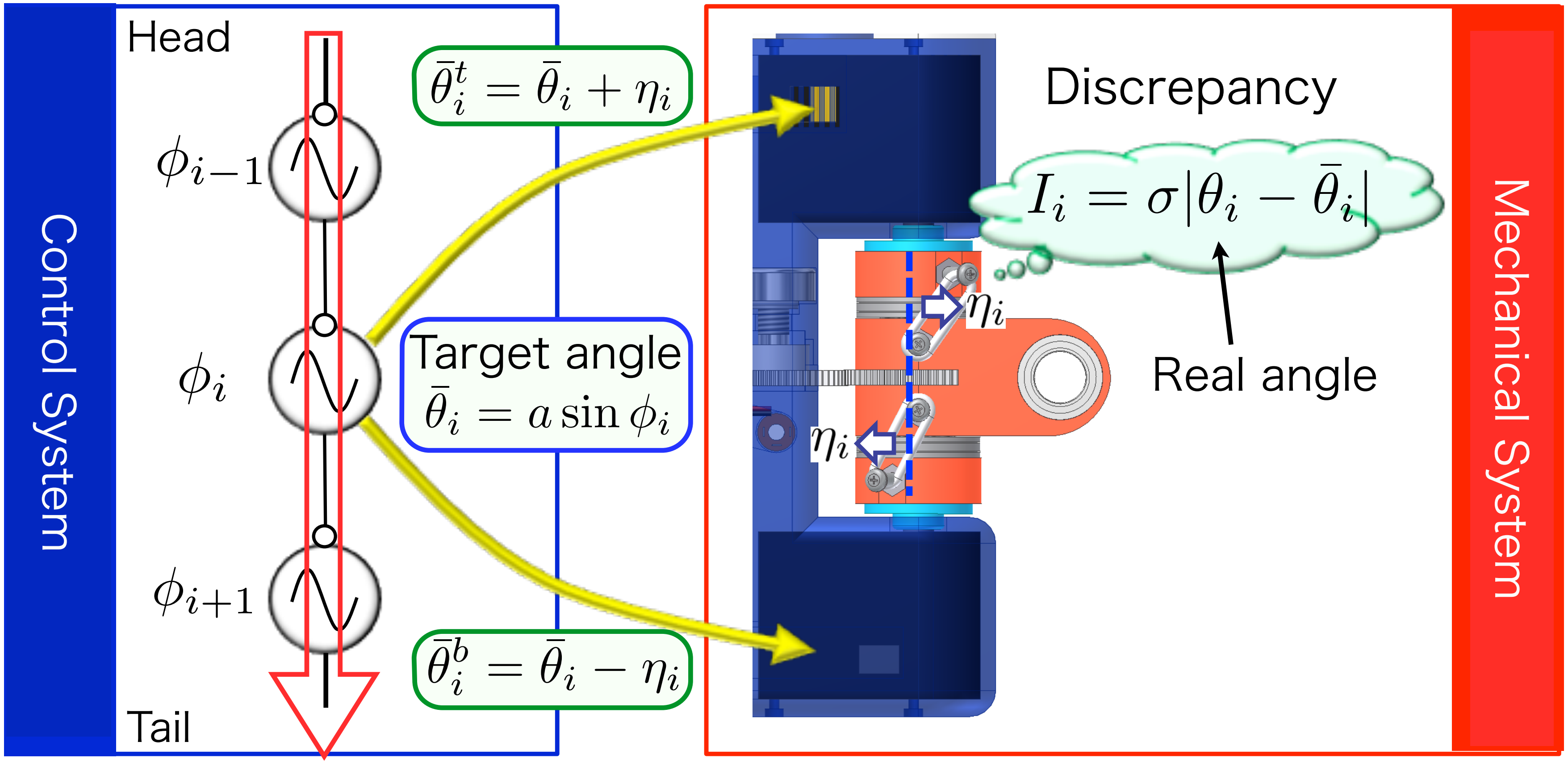
Elastic elements permit discrepancy between the motor angle (target angle)and the actual joint angle



← 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

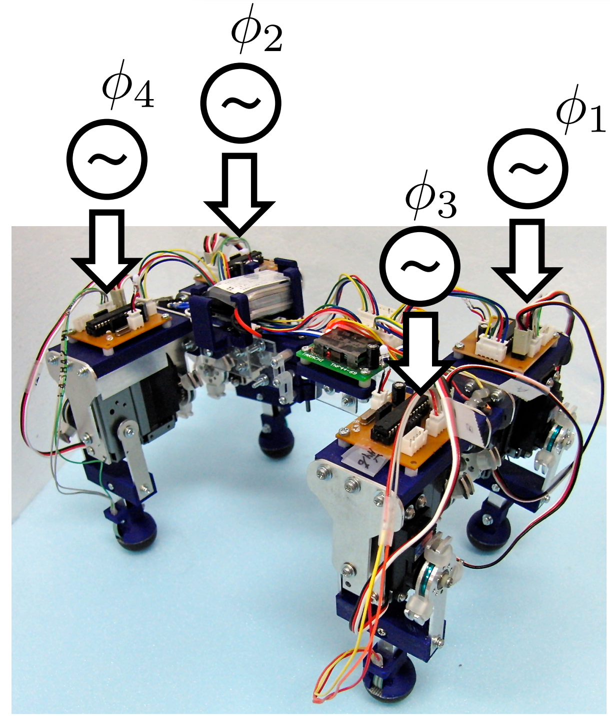
Phasic control only

HAUBOT 2

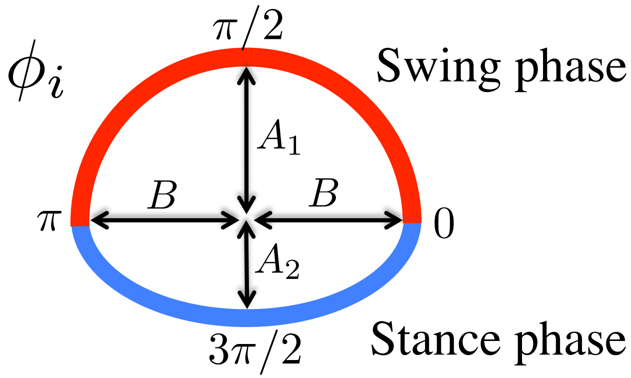
Phasic & Tonic control

NTF Award Finalist for Entertainment Robots and Systems (IROS2011)

OSCILLEX series



脚先位置の制御



Control rule

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

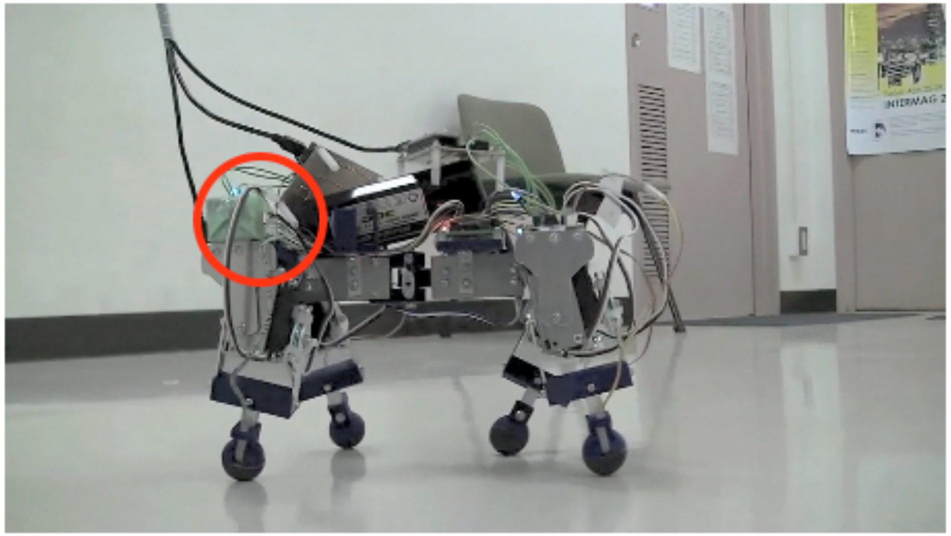
Control parameter from the center

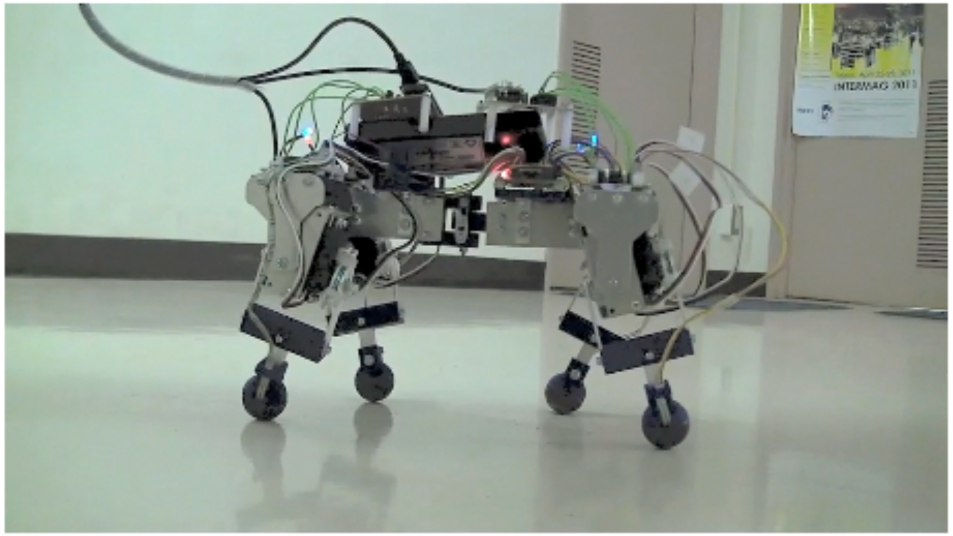
Load at the toe

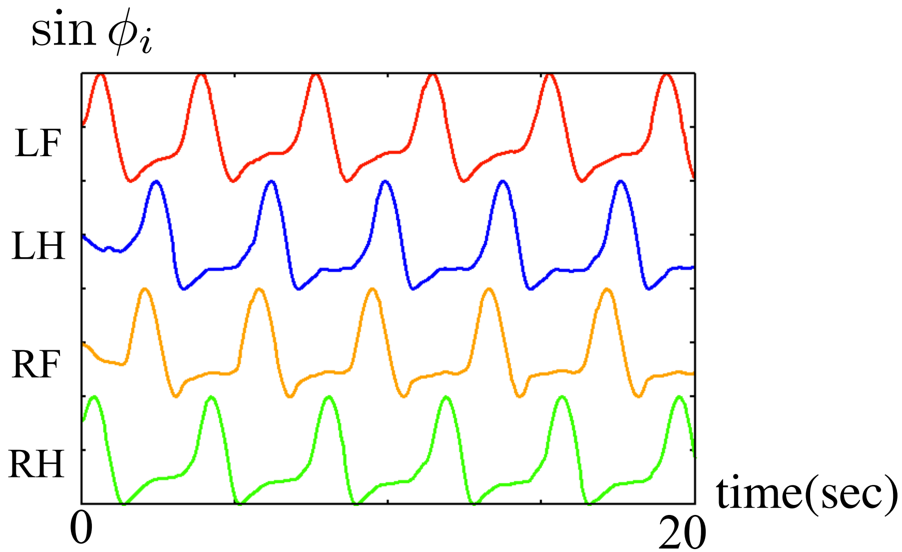
No direct interaction between controllers, but indirect interaction through the body

Try to keep the leg in stance phase if loaded

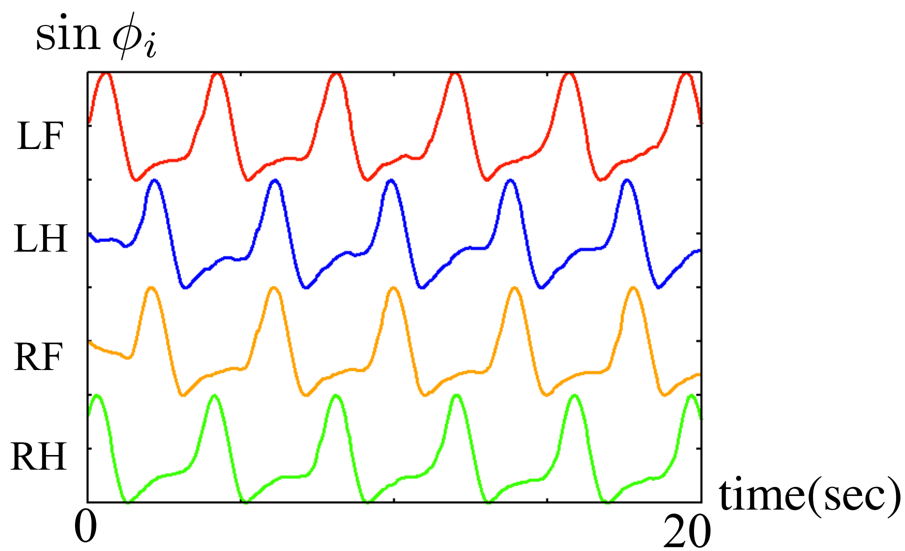
OSILLEX 1







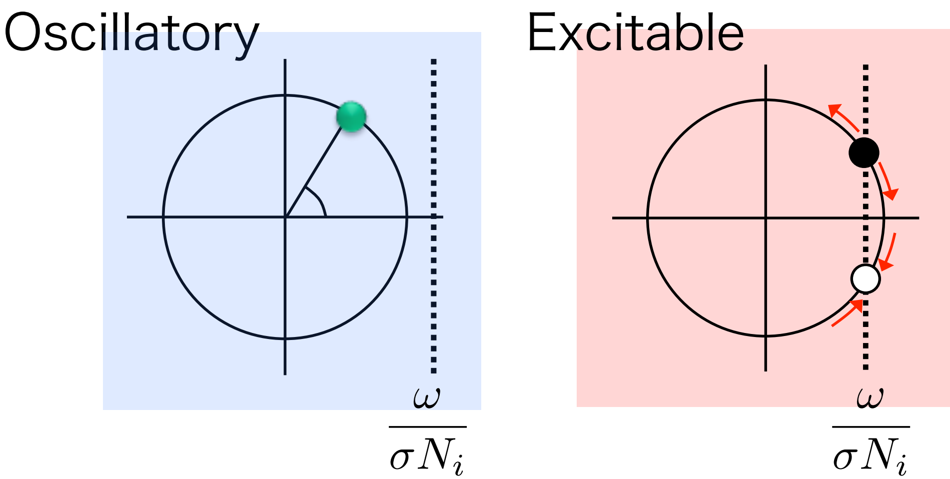
$\sin \phi_i$
LF
LH
RF
RH
0
20
time(sec)

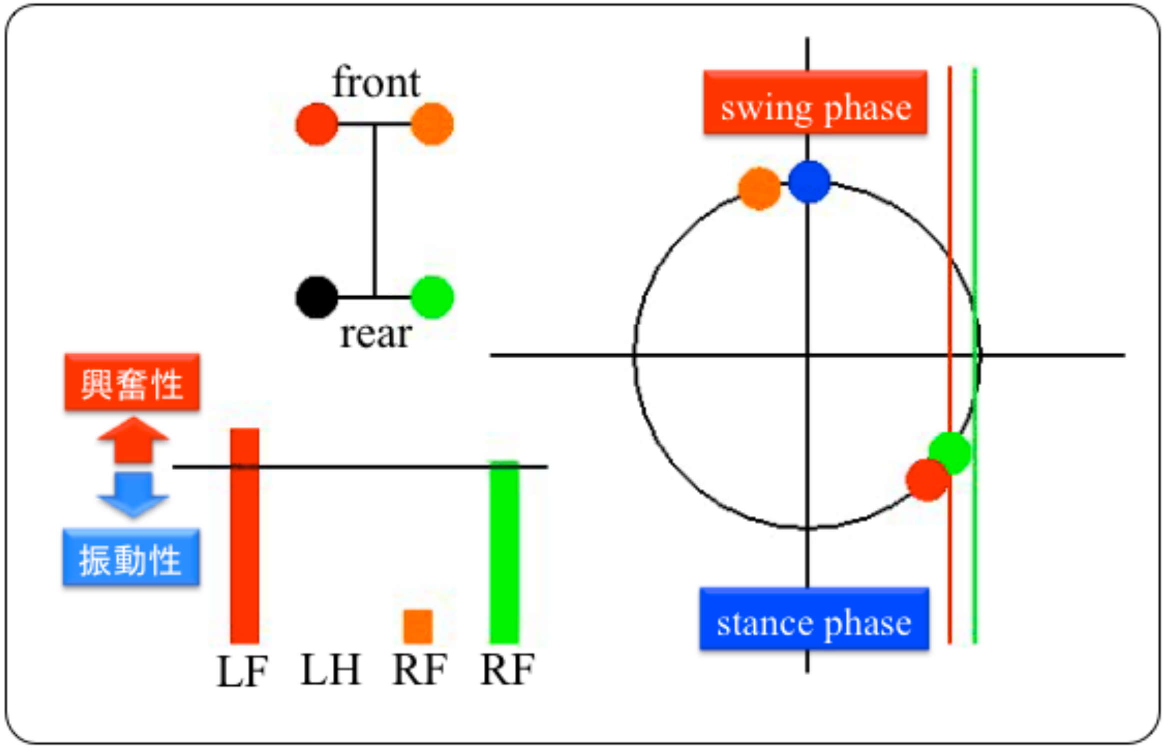


$\sin \phi_i$
LF
LH
RF
RH
0
20
time(sec)

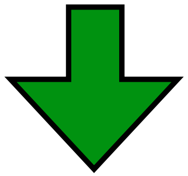
Why we call it OSILLEX ?

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



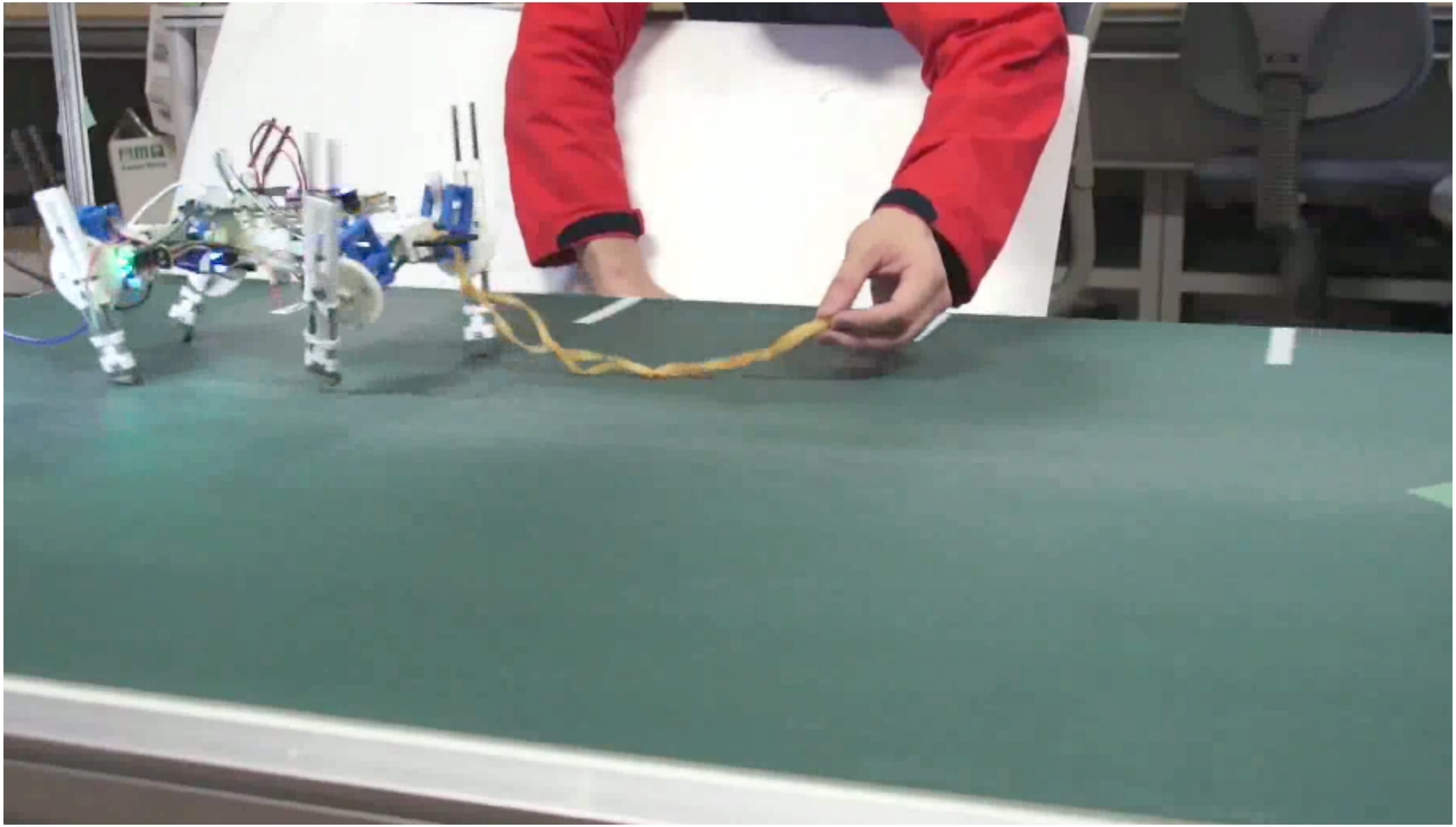


Go back and force between Oscillatory & Excitable mode



Quick transition to the stationary walking

OSCILLEX 3.1



Significance of OSCILLEX

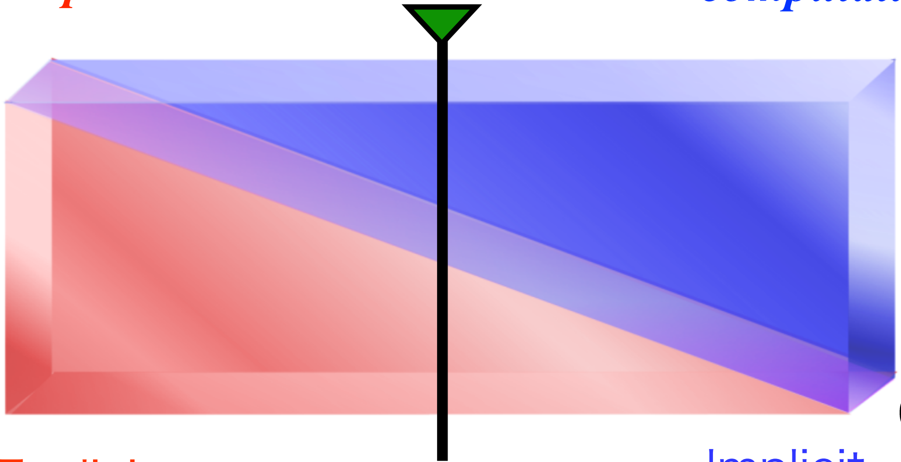
$$\partial_t \phi_i = \omega - \sigma N_i \cos \phi_i$$

Control System

Completely Explicit Control

Brain computation

Morphological computation



Explicit Control

Implicit Control

Body System

Completely Implicit Control

Manmals ←?→ Insects

Successful example of attaining Adaptive Behavior by the balance of Explicit Control and Implicit Control

Summary

- We extracted the concept of discrepancy function from the model of Physarum.

- The design scheme of ADC using discrepancy function was implemented to our robots, and it worked very well.

- Do not design the complicated explicit control rule.

  → Listen to the voice of the body !