Co-development of morphology and cognitive skills

RobotCub
First Open Day
14 July 2005
Genova

Rolf Pfeifer
Artificial Intelligence Laboratory, Department of Informatics
University of Zurich, Switzerland

World Expo Aichi Receptionist

Goal of presentation

- implications of “embodiment” → surprising insights
- brain at center stage
- however: much can be achieved with very little control by exploiting embodiment (morphology and materials)

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- much about movement, sensory-motor skills

Question: ***“relation to intelligence/cognition?”***

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Question: ***“relation to intelligence/cognition?”***

“Why do plants not have brains? The answer is actually quite simple: they don’t have to move.”

Daniel Wolpert

Contents

- Introduction
  - embodiment, synthetic methodology
- „Morphological computation“: Case studies
  - actuators, interaction with environment
- Information self-structuring – sensory-motor coordination
- A note on development
- Summary and conclusions

Artificial Intelligence

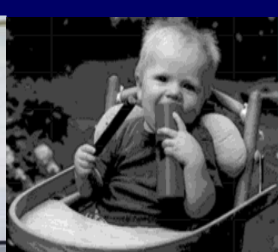
higher level intelligence/ cognition

goals

understanding biological systems

principles of intelligent systems

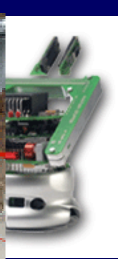
useful artifacts applications


abstract

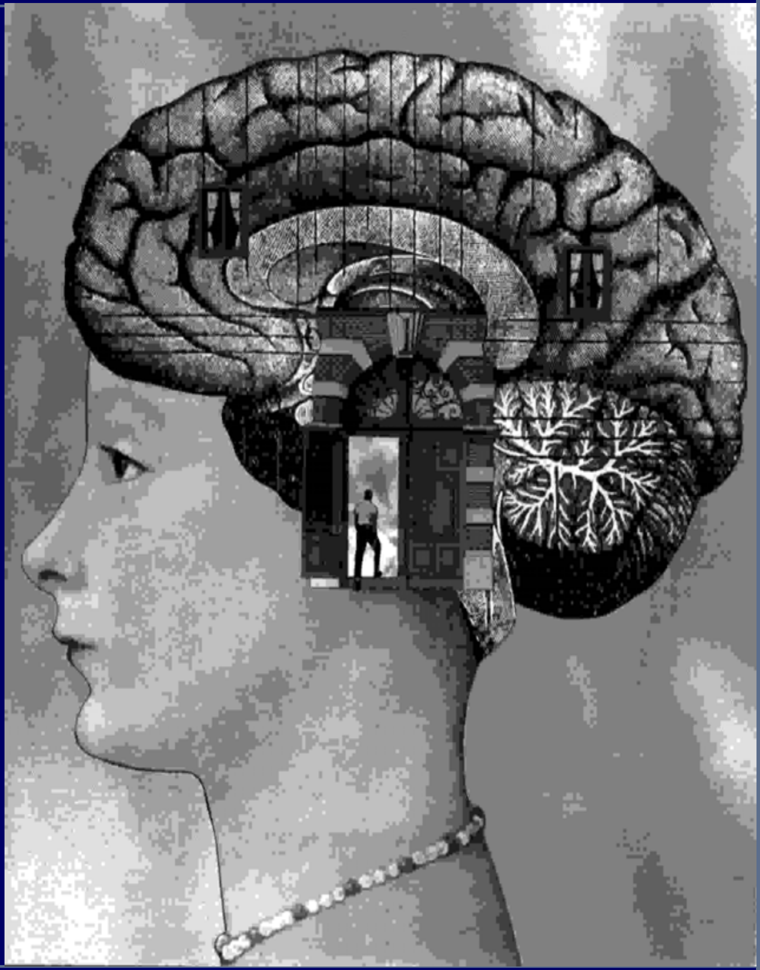
theory





Embodiment

- classical (dis-embodied): "cognition as computation"
- many successes, many failures



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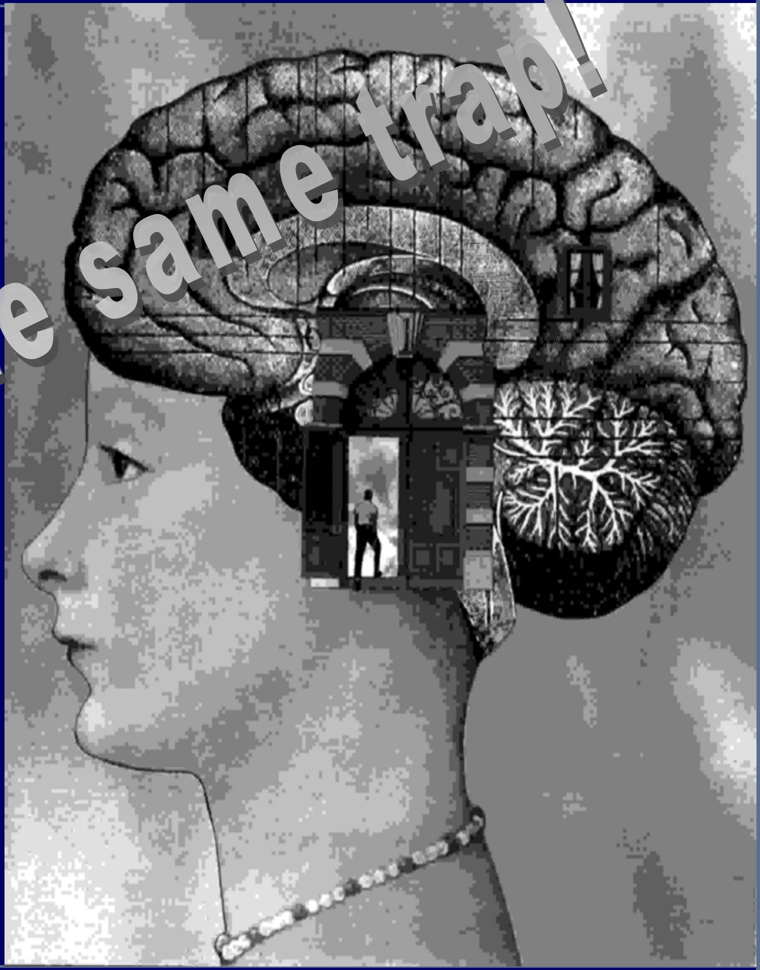

let's not fall into the same trap!

Embodiment

- *trivial meaning:*
  “intelligence requires a body”

Embodiment

- *trivial meaning:*
  "intelligence requires a body"
- *non-trivial meaning:*

  interplay
  - brain (neural processing)
  - morphology
  - materials
  - environment

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--> not only physical but "information theoretic" implications

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--> not only physical but
“information theoretic” implications

“morphological computation”

Synthetic methodology

“Understanding by building”

- modeling behavior of interest (movement, locomotion, sensory-motor coordination)
- abstracting principles

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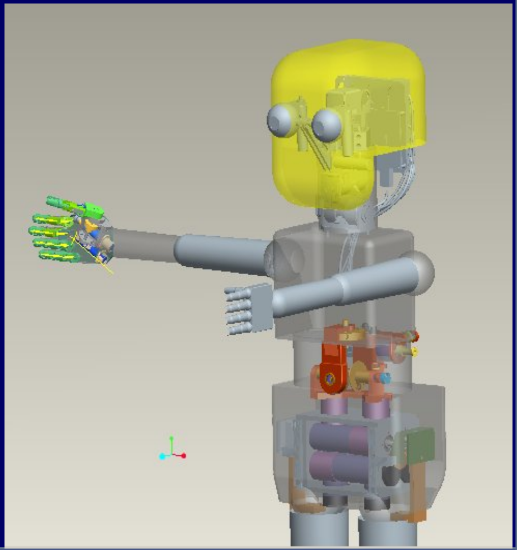
→ building robots for exploration

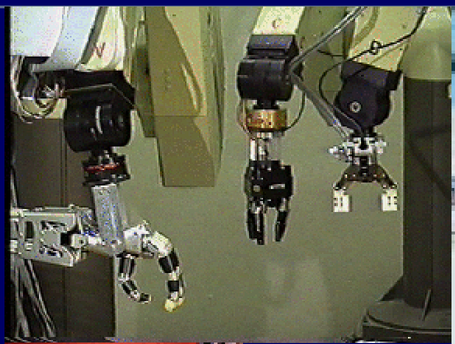


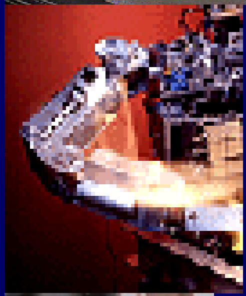
Contents

Illustrations

- morphology, materials, and actuation
- interaction with the environment
- generation of sensory stimulation through interaction with environment („sensory-motor coordination")
- (sensors)

Control from materials (“computational properties of materials”)





traditional robot arms:
- hard materials
- electrical motors

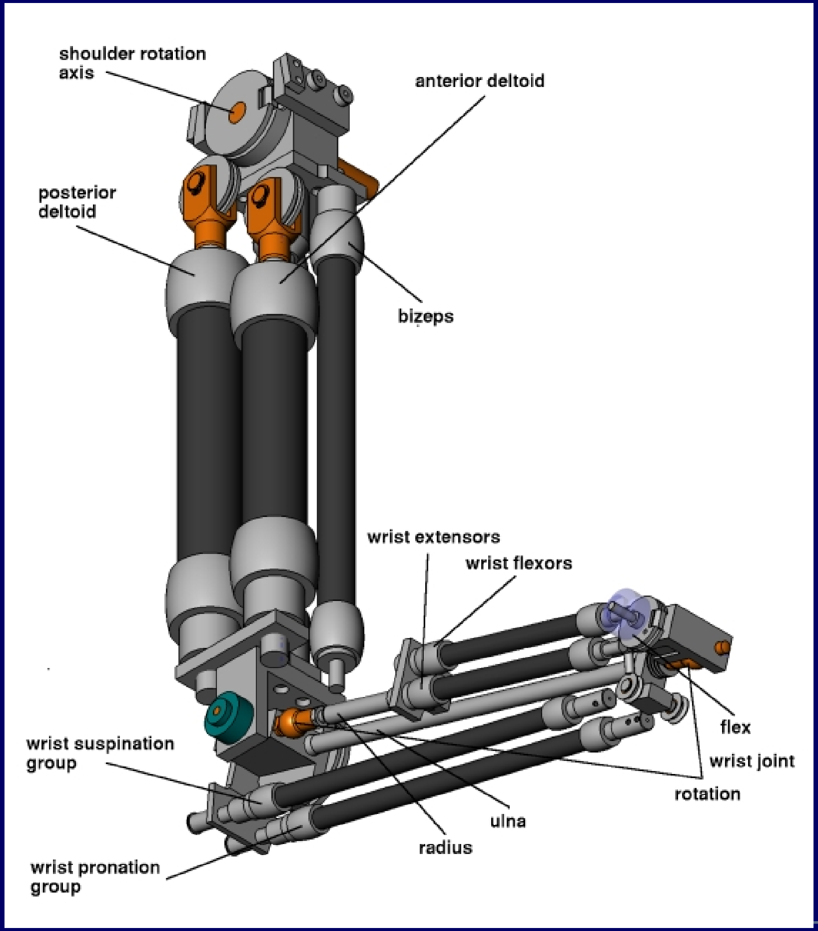
human muscle-tendon system:
- elasticity
- stiffness
- damping

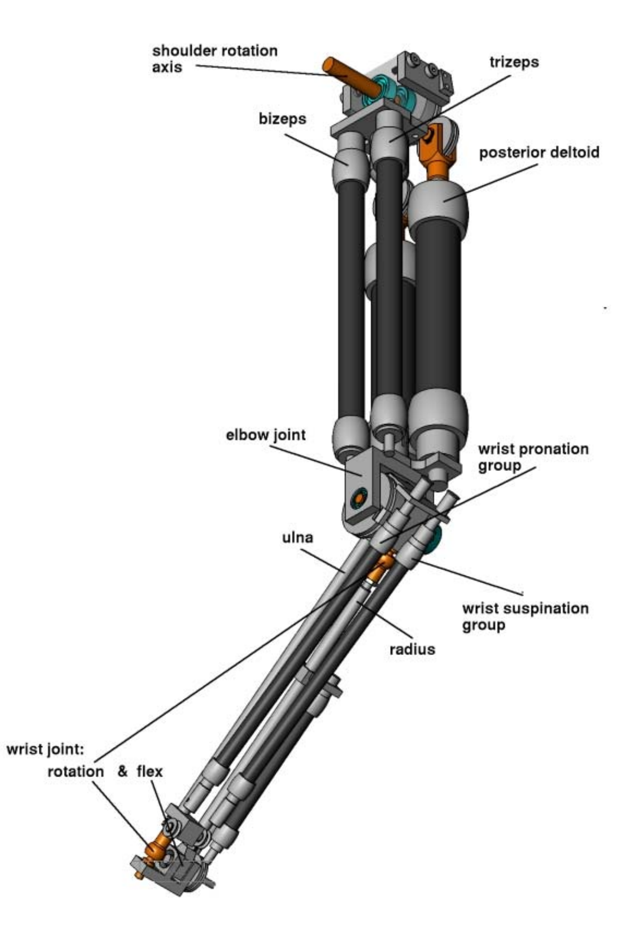
Control properties of muscle-tendon system

- grasping of object
- winding a spring
  → effort, energy expenditure
- release
  → back to normal position without control
- is exploited by brain

"good" control
- decentralized – no central resources required
- "free" – exploitation of physical properties

Anthropmorphic arm with artificial muscles (pneumatic actuators)





design and construction: Raja Dravid

Anthropomorphic arm with pneumatic actuators

turning the wrist

lifting entire arm

passive compliance

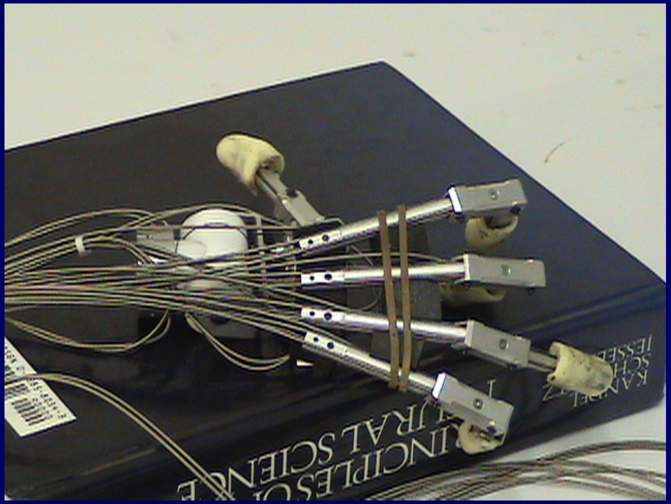
Pneumatic actuators

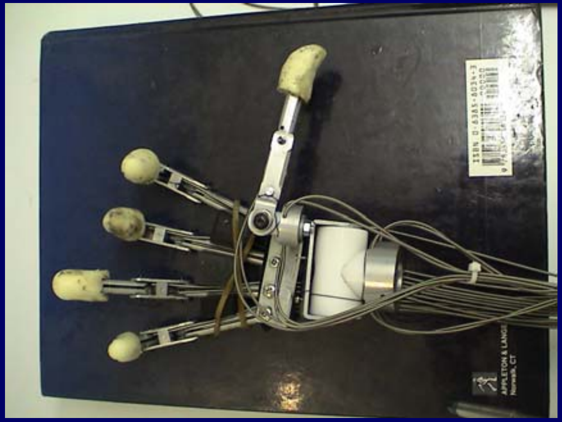
- intrinsic dynamics
- passive compliance for free
- muscle-like modules → anthropomorphic design
- constraints from morphology and materials
  → preferred trajectories (requiring little control)

Pneumatic actuators

- intrinsic dynamics
- passive compliance for free
- muscle-like modules → antrhopomorphic design
- constraints from morphology and materials
  → preferred trajectories (requiring little control)
- difficult to make mathematical model
- highly non-linear
- valve-control hard

The "Yokoi hand": morphology and materials





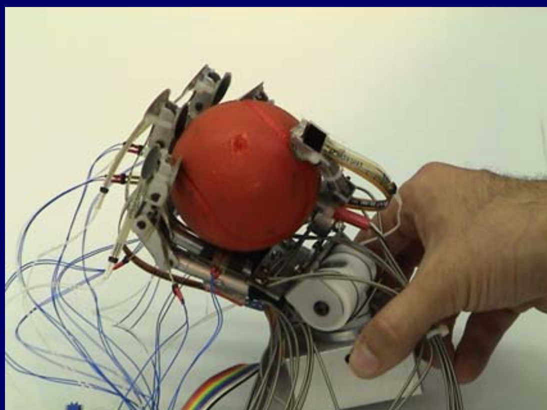
robot hand:
- anthropomorphic design
- elastic tendons
- soft, deformable materials

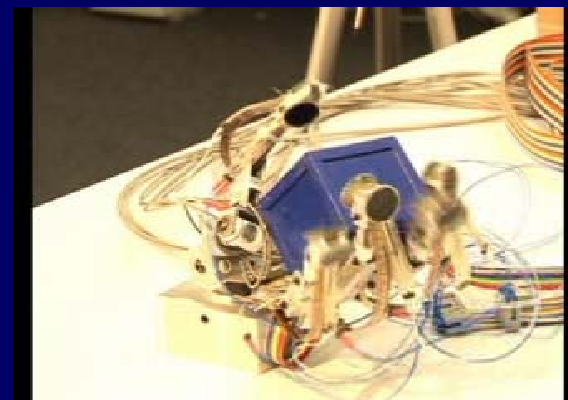
design and construction:
Hiroshi Yokoi, Alejandro Hernandez
Univ. of Tokyo and AI Lab, Univ. of Zurich

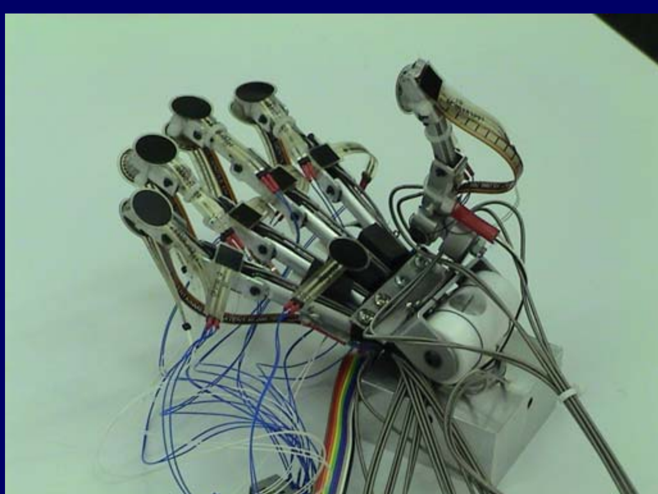
The “Yokoi hand”
shaking a robot hand

Hiroshi Yokoi
Univ. of Tokyo

The "Yokoi hand"
grasping: "morphological computation"







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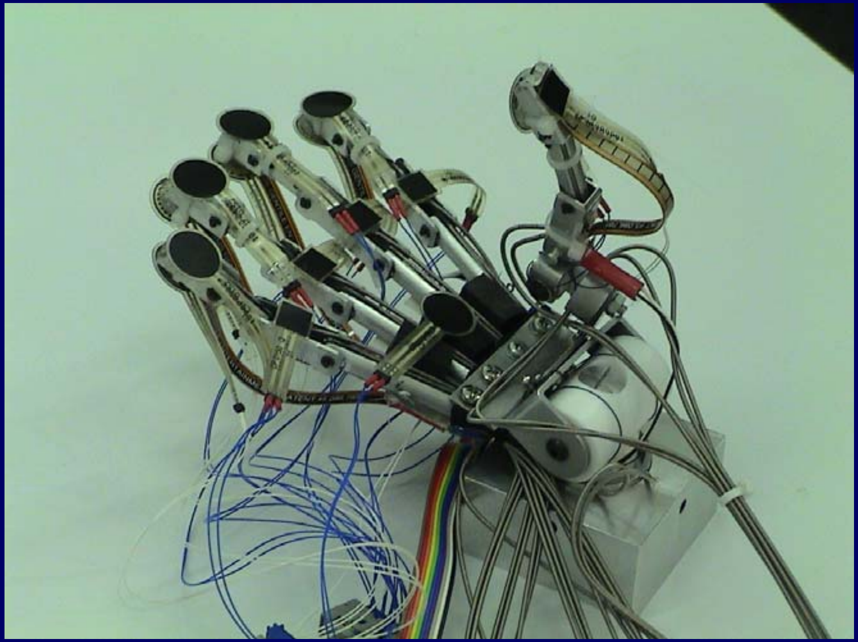
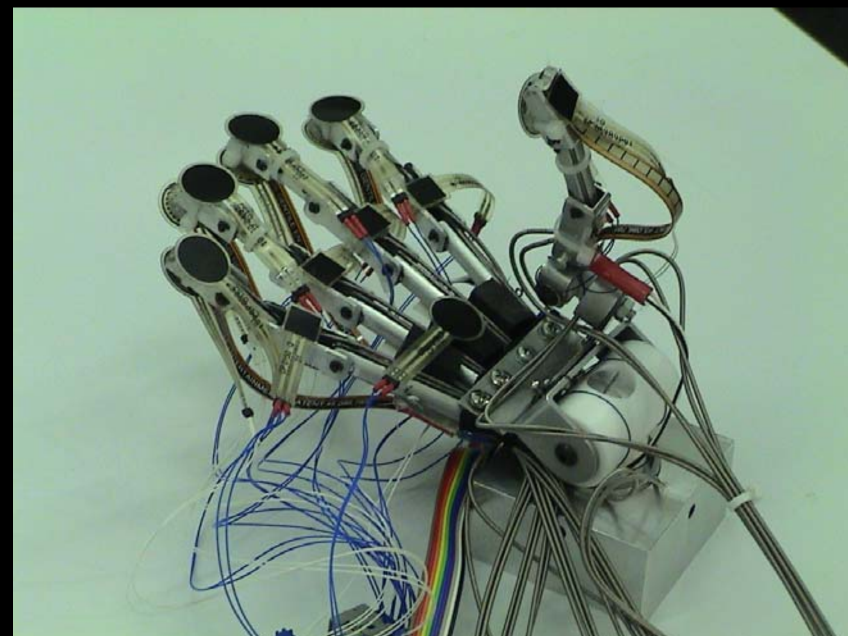
Grasping: “morphological computation”



elastic tendons and soft deformable materials

control of grasping:
- simple “close”
- details performed by morphology and materials

Grasping: “morphological computation”



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Grasping: Yokoi hand

- can grasp any shape
- “knows” nothing about shapes
- self-regulation
- easy to control (prosthetics – EMG-signals)

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exploitation of morphology and materials

Testing on patients

Alexandro Hernandez
University of Tokyo
and Artificial
Intelligence Laboratory
University of Zurich

Grasping: Yokoi hand

- can grasp any shape
- “knows” nothing about shapes
- self-regulation
- easy to control (prosthetics – EMG-signals)

exploitation of morphology and materials

Aichi Receptionist

facial expression:

exploitation ofmaterial properties

"Passive Dynamic Walker" – the brainless robot

Design and construction:
Ruina/Wisse/Collins, Cornell University (1)

walking without control

Morphology:
- wide feet
- elastic heels
- counterswing of arms
- friction on bottom of feet

passive swing of leg

"Passive Dynamic Walker" – the brainless robot

Design and construction:
Ruina/Wisse/Collins, Cornell University (2)

walking without control

Morphology:
- wide feet
- elastic heels
- counterswing of arms
- friction on bottom of feet

Extending the "Passive Dynamic Walker" – the almost brainless robot

Design and construction:
Ruina/Wisse/Collins, Cornell/Delft University

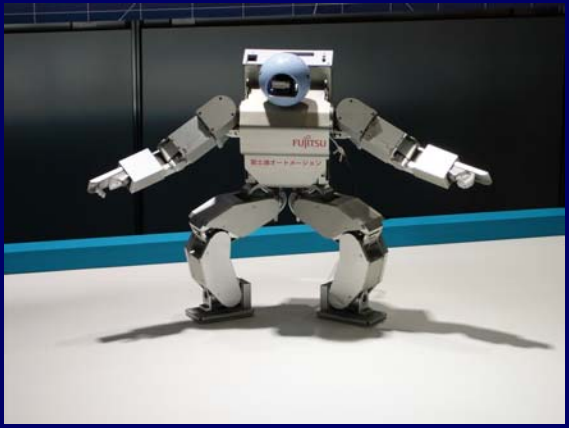
walking with little control

Morphology:
- wide feet
- elastic heels
- counterswing of arms
- friction on bottom of feet

Humanoid robots

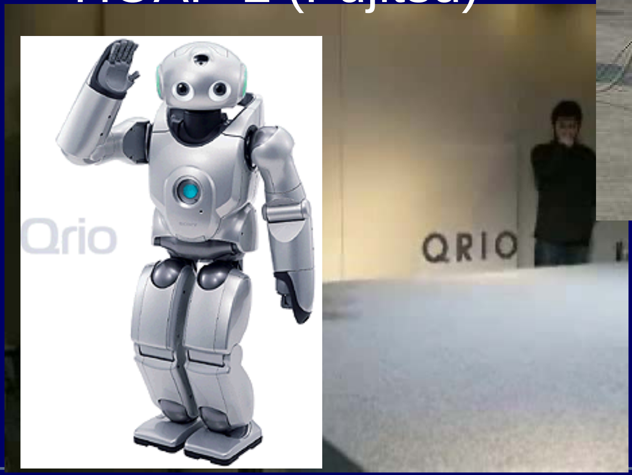
Asimo
(Honda)

HRP-2
(Kawada)



HOAP-2 (Fujitsu)

H7
Univ. of Tokyo



Qrio
(Sony)

Rapid locomotion

- hard problem

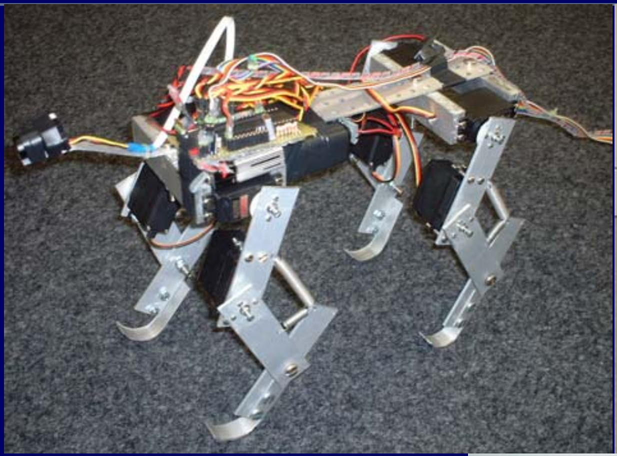
Rapid locomotion

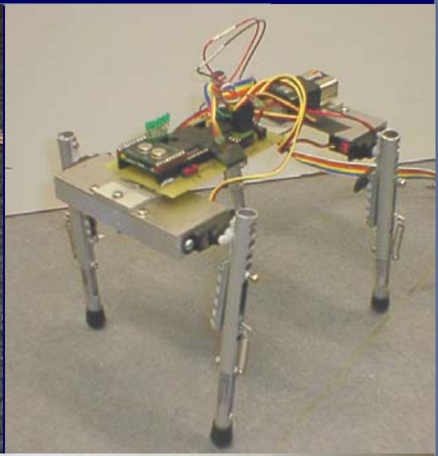
- hard problem

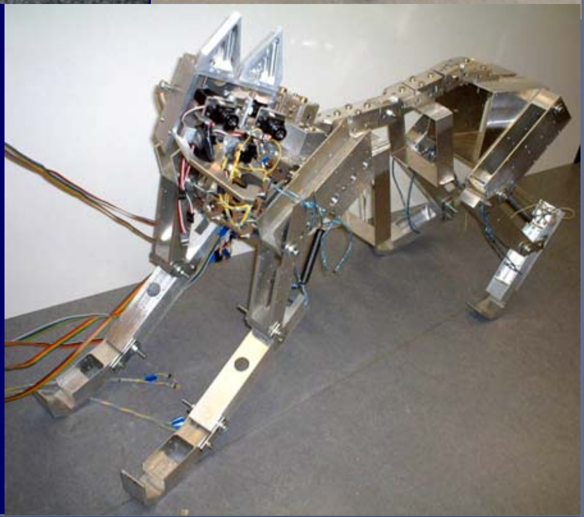
  where is the bottleneck?

Rapid locomotion
the quadruped “Puppy”

rapid locomotion
in biological systems



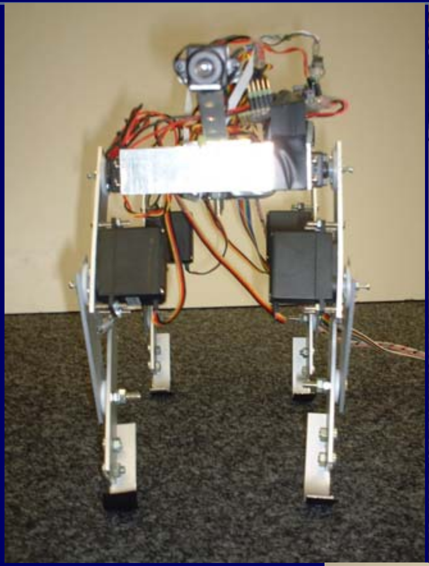


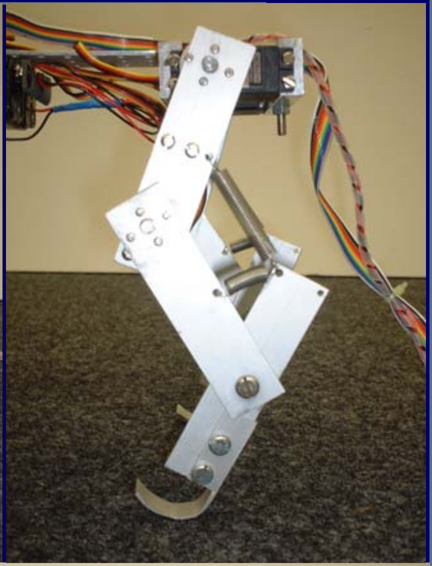


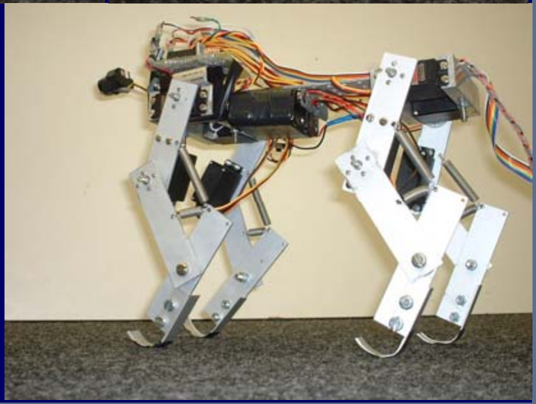
Design and construction:
Fumiya Iida

The quadruped "Puppy"

slow motion



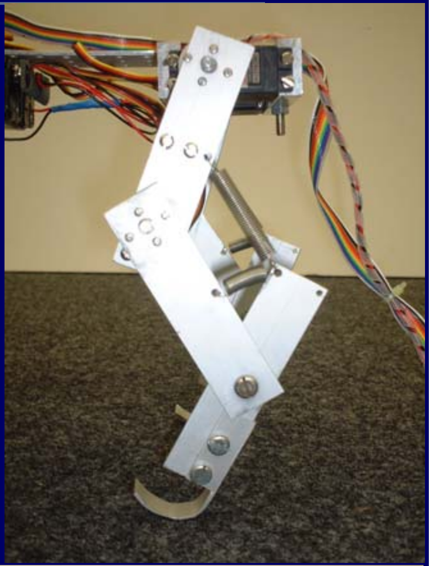


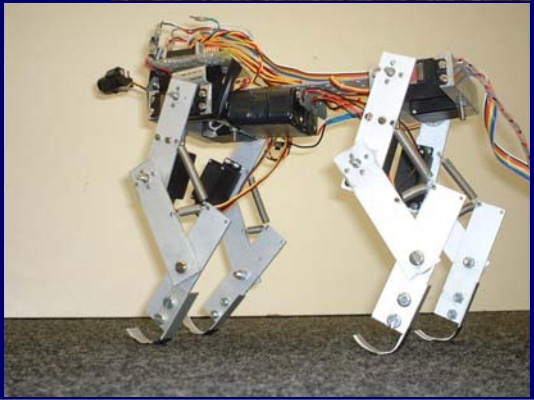


Design and construction:
Fumiya Iida

The quadruped “Puppy”: summary

- simple control (!)
- spring-like material properties
- exploitation of dynamics
  in interaction with environment
- self-stabilization





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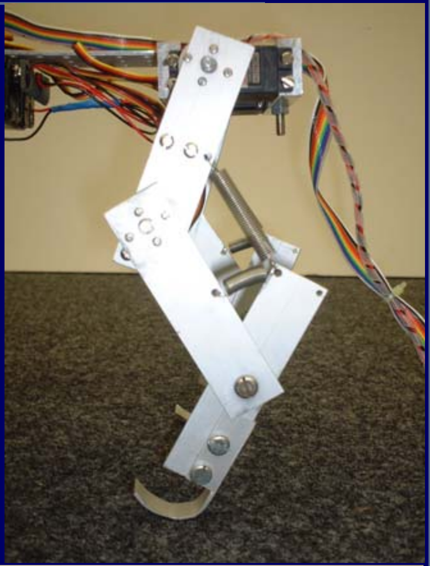
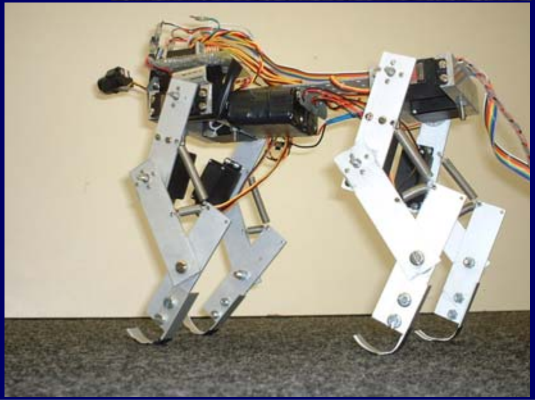


"cheap design"



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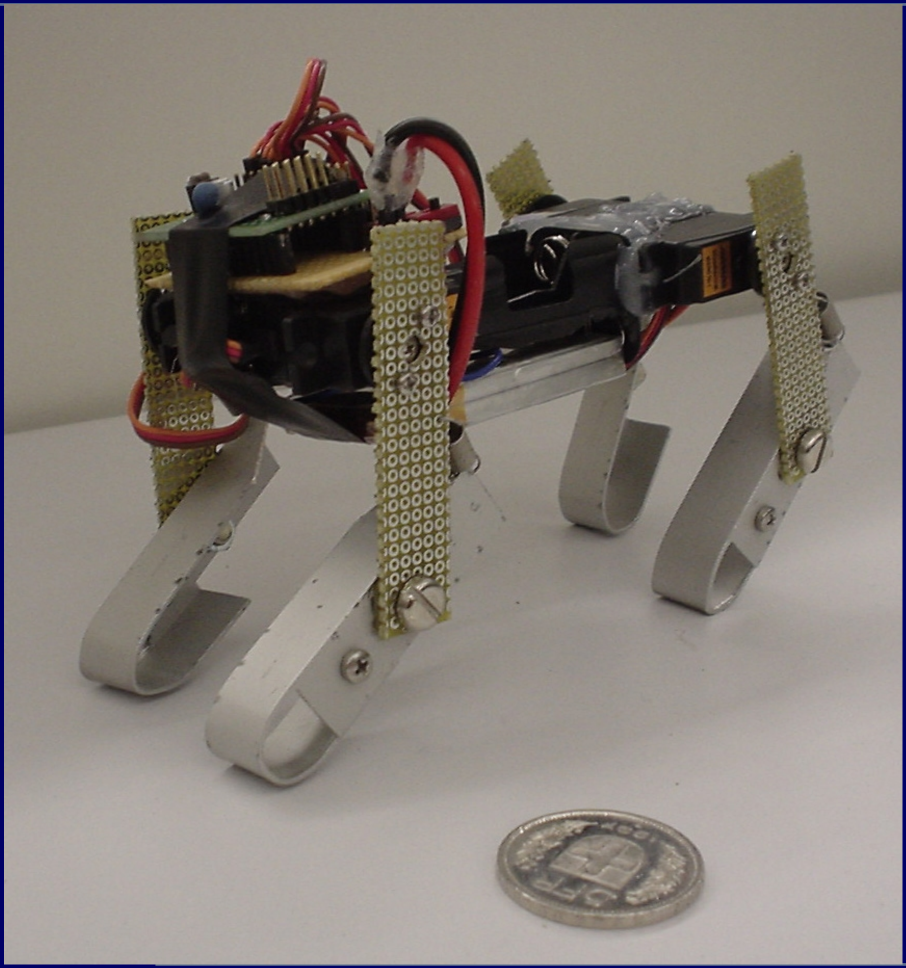
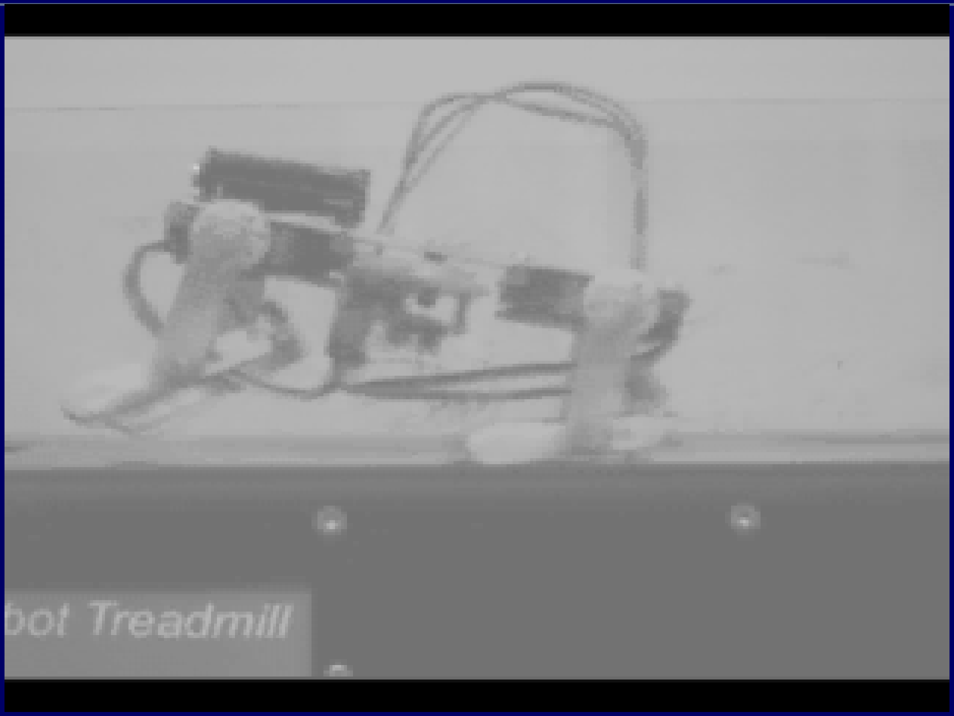
The “mini dog” by Fumiya Iida



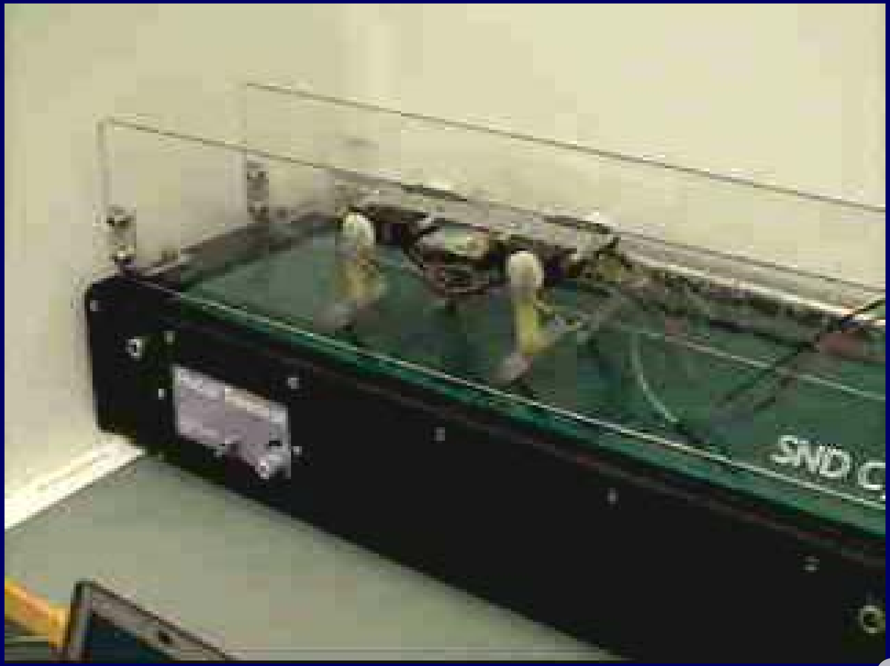
Artificial Intelligence Laboratory
Dept. of Information Technology
University of Zurich

Self-stabilization: “Puppy” on the treadmill

Video from high-speed camera



"Puppy" on the treadmill

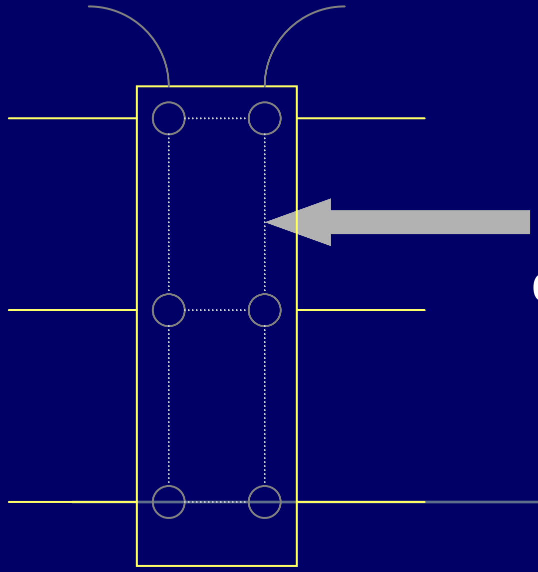


World Expo in Aichi

Insect walking

Holk Cruse

- no central controller for leg-coordination
- only local communication



neuronal connections

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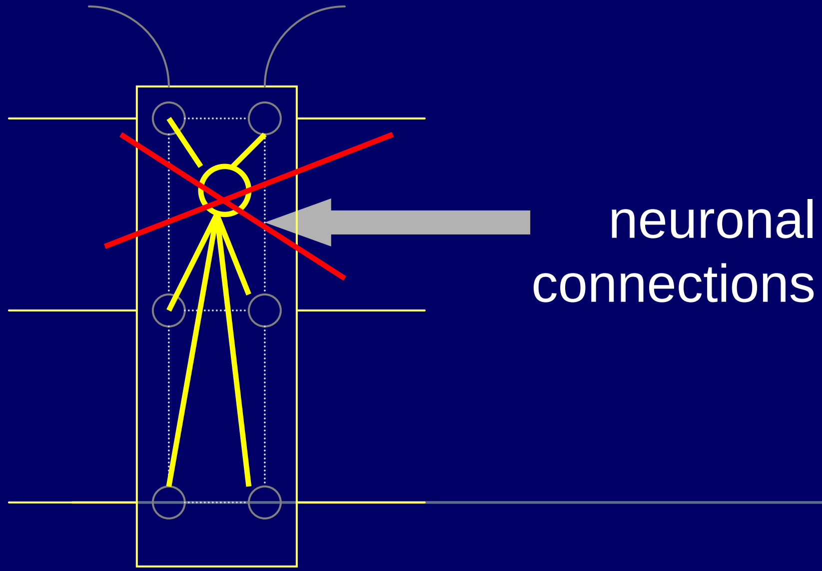

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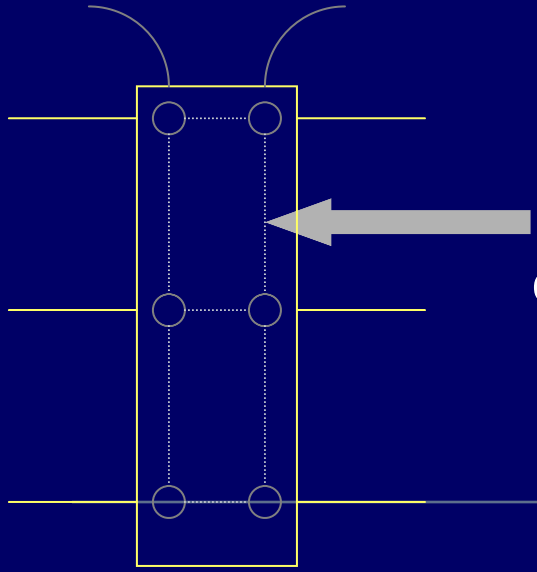
- only local communication
- global communication through interaction with environment



neuronal connections

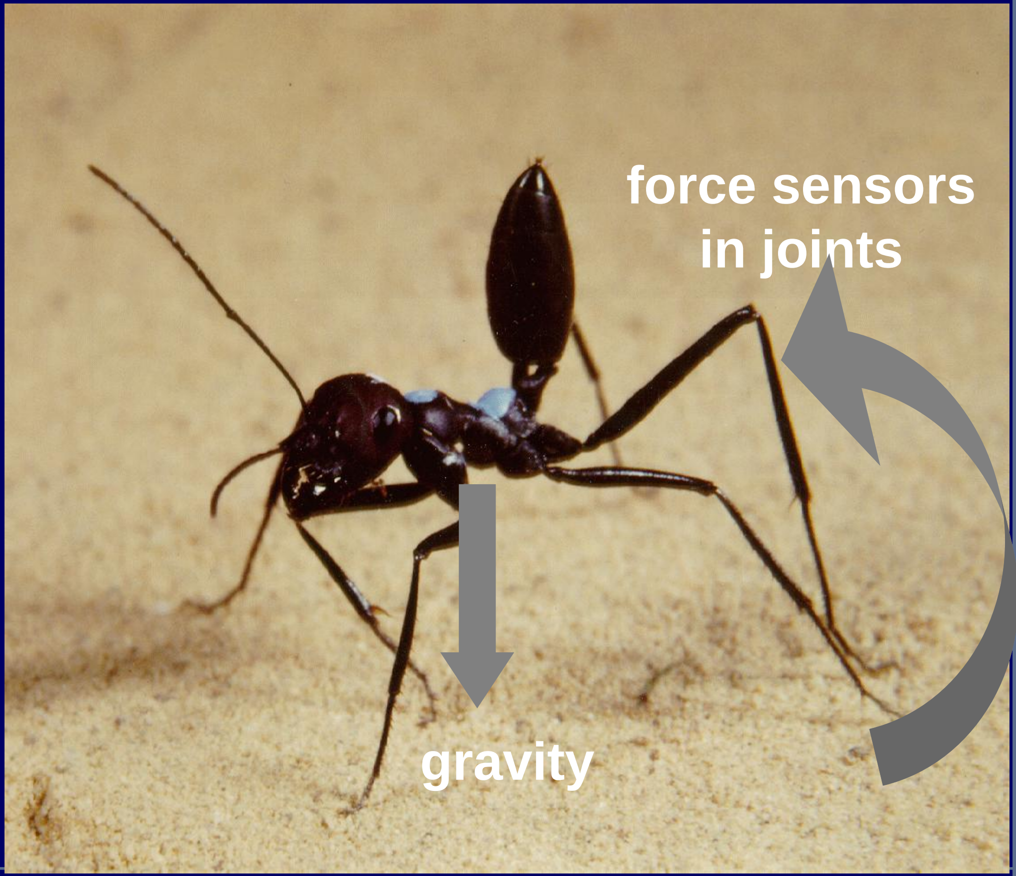
Global communication through interaction with environment

- exploitation of interaction with environment

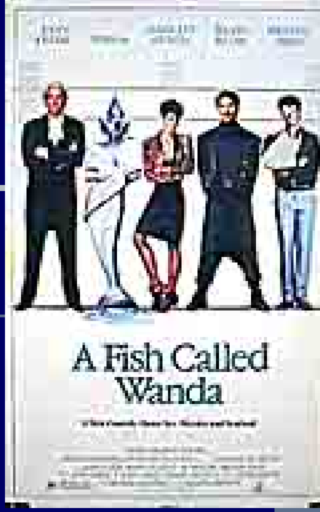
→ simpler neuronal circuits

→ "cheap design"

→ ***„morphological computation"***



A fish called “Wanda”: exploitation of morphology and system-environment interaction



1 DOF actuation

controlling:

- up-down
- left-right
- speed
- reaching any point in x, y, z-space

Design and construction:
Horishi Yokoi
Fumiya Iida
Mark Ziegler

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“morphological computation”

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Generation of sensory stimulation through interaction with environment

- constraints from morphology and materials
- generation of correlations in sensors through physical process

–> „good“ raw material for neural processing

(example: baby grasping object)

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- generation of correlations in sensors through physical process

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The principle of sensory-motor coordination

- self-structuring of sensory data through – physical – interaction with environment
- reduction of complexity – induction of correlations
- *physical process – not „computational“*

  → ***„morphological computation“***

The principle of sensory-motor coordination

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prerequisite for learning

inspiration
— John Dewey, 1896 (!)
— Edelman, Sporns, and co-workers
— developmental studies; Thelen and Smith

The principle of sensory-motor coordination

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→ ***„morphological computation"***

information theoretic analysis:
Lungarella, Sporns, te Boekhorst, Gomez, Pfeifer

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— Edelman, Sporns, and co-workers
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The principle of sensory-motor coordination

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  → ***„morphological computation"***

  prerequisite for learning

importance hard to over-estimate

inspiration
— John Dewey, 1896 (!)
— Edelman, Sporns, and co-workers
— developmental studies; Thelen and Smith

An interesting quote

“Instead of trying to produce a programme to simulate the adult mind, why not rather try to produce one which simulates the child’s? If this were then subjected to an appropriate education one would obtain the adult brain... Our hope is that there is little mechanism in the child brain that something like it can be easily programmed. The amount of work in the education we can assume as a first approximation, to be much the same as for a human child.”

“Instead of trying to produce a programme to simulate the adult mind, why not rather try to produce one which simulates the child’s? If this were then subjected to an appropriate education one would obtain the adult brain... Our hope is that there is little mechanism in the child brain that something like it can be easily programmed. The amount of work in the education we can assume as a first approximation, to be much the same as for a human child.”

from *Computing machinery and intelligence*

by Alan Turing (1950)

→ research program in developmental robotics

→ development of cognition continuous and incremental

→ not digital property, but “more or less”

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Robots vs. biological agents

stating the obvious:

Robots: build hardware, then add “intelligence”

Biological agents: Co-development of morphology and cognition

“Development – more than learning”

- learning: focus on neural processes
- development: growth/morphological change (see progress report – yesterday)

→ more adaptive neural system: extension with neuromodulators (ligand-receptor concept)

→ morphological change “in the service of learning”

Inspiration

Newborns, young infants:

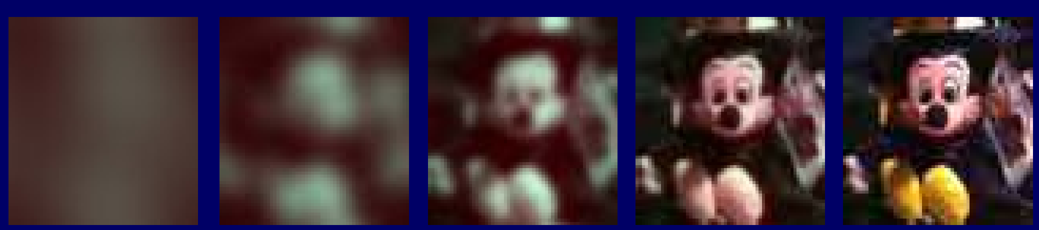
morphological (sensory, motor)

and **neural** limitations

Inspiration

Sensory system

- fixed accommodative system and low acuity
  → world is “fuzzy”
- low contrast sensitivity
- limited color perception
- fixed distance focus



20 cm 30 cm any distance

newborn 1 month 2 months 3 months 6 months

Inspiration

Motor system

- lack of control and coordination
- limited postural control of trunk
- head and arms → inefficient and jerky movements

Neural system

- restricted working memory
- attention span
- reduced predictive abilities

Limitations: Adaptive role in development?

sensory

- reduction of amount of information

motor

- reduction of complexity of motor learning: approach to „degrees-of-freedom problem“ (Bernstein, 1967)
- reduction of space of possible movements
- enables acquisition of early motor skills through exploratory activity

neural

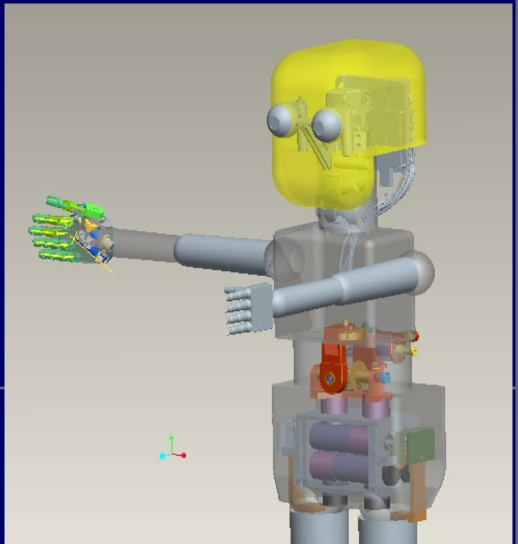
- processing limitations beneficial for learning (Elman, 1993)

Robots: no growth (currently)

mimicking growth/development:

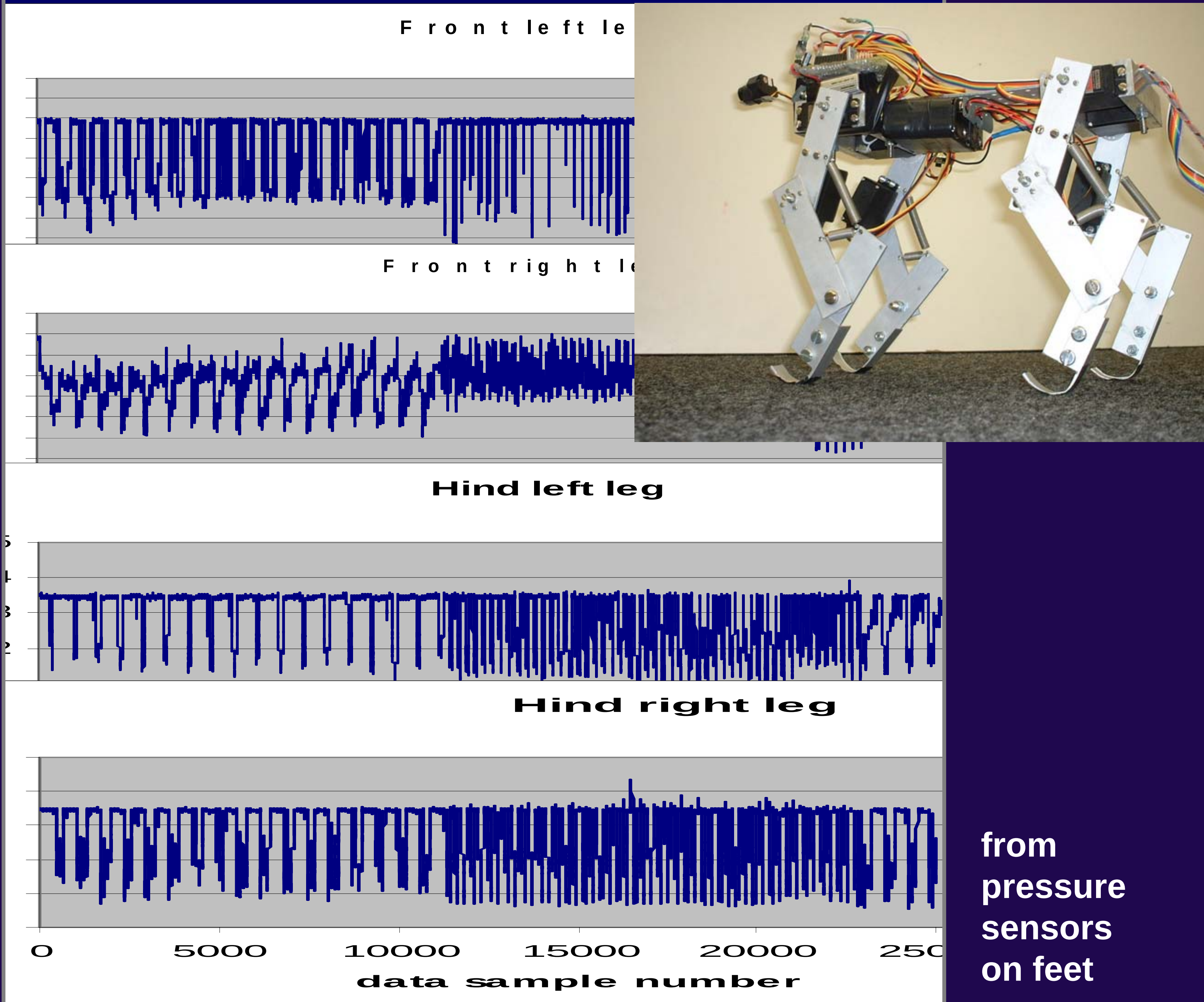
- high-DOF, high-resolution system
- freezing DOFs
- low-resolution in software, successive increase
- low complexity of neural system, successive increase

→ iCub as testbed

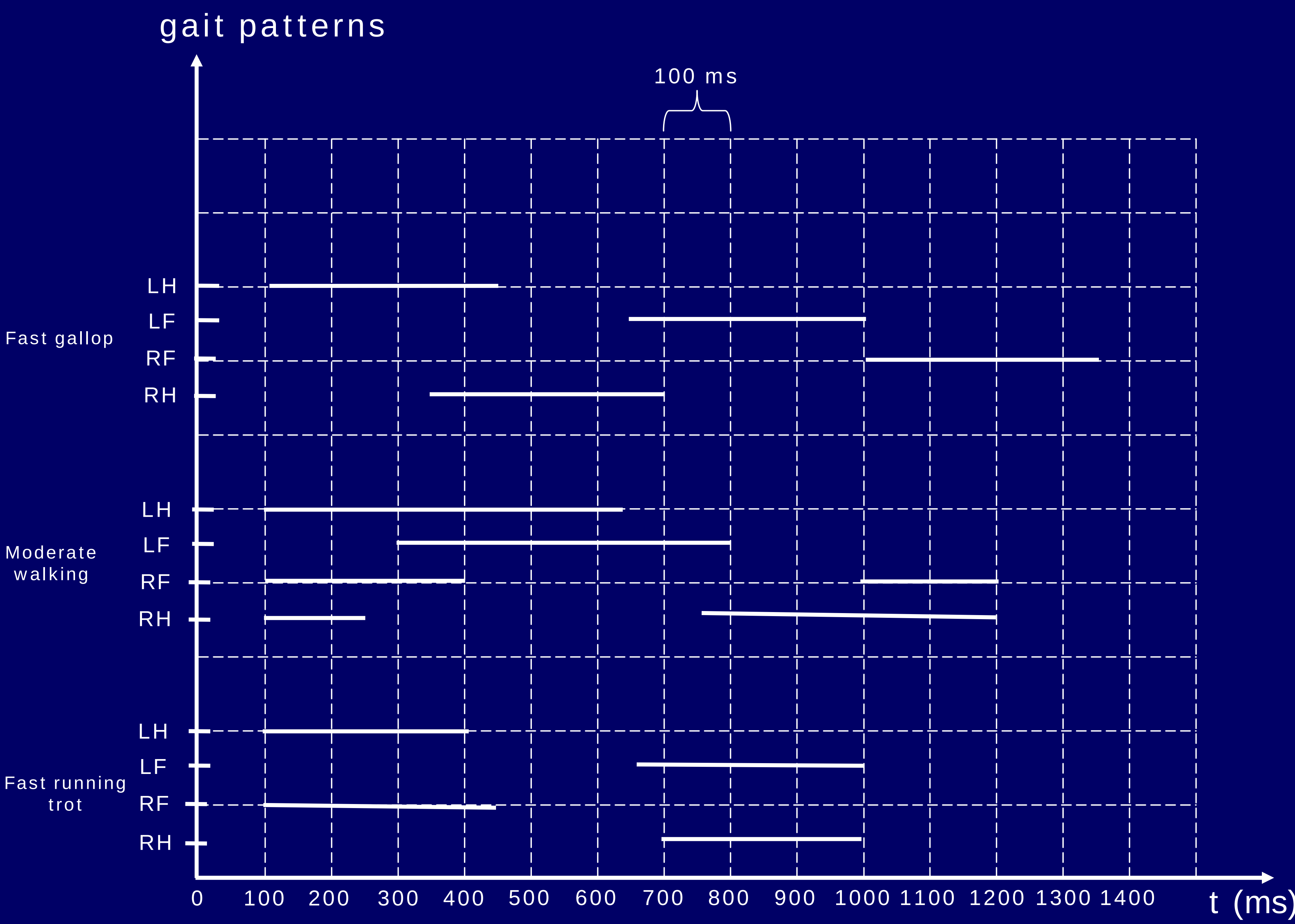


Some speculation on „symbol grounding“

- “from locomotion to cognition”
- grounding cognition in sensory-motor patterns
- building a body image bottom-up



from pressure sensors on feet


gait patterns
100 ms
LH
LF
RF
RH
Fast gallop
LH
LF
RF
RH
Moderate walking
LH
LF
RF
RH
Fast running trot
0
100
200
300
400
500
600
700
800
900
1000
1100
1200
1300
1400
t (ms)

Gait patterns as attractor states

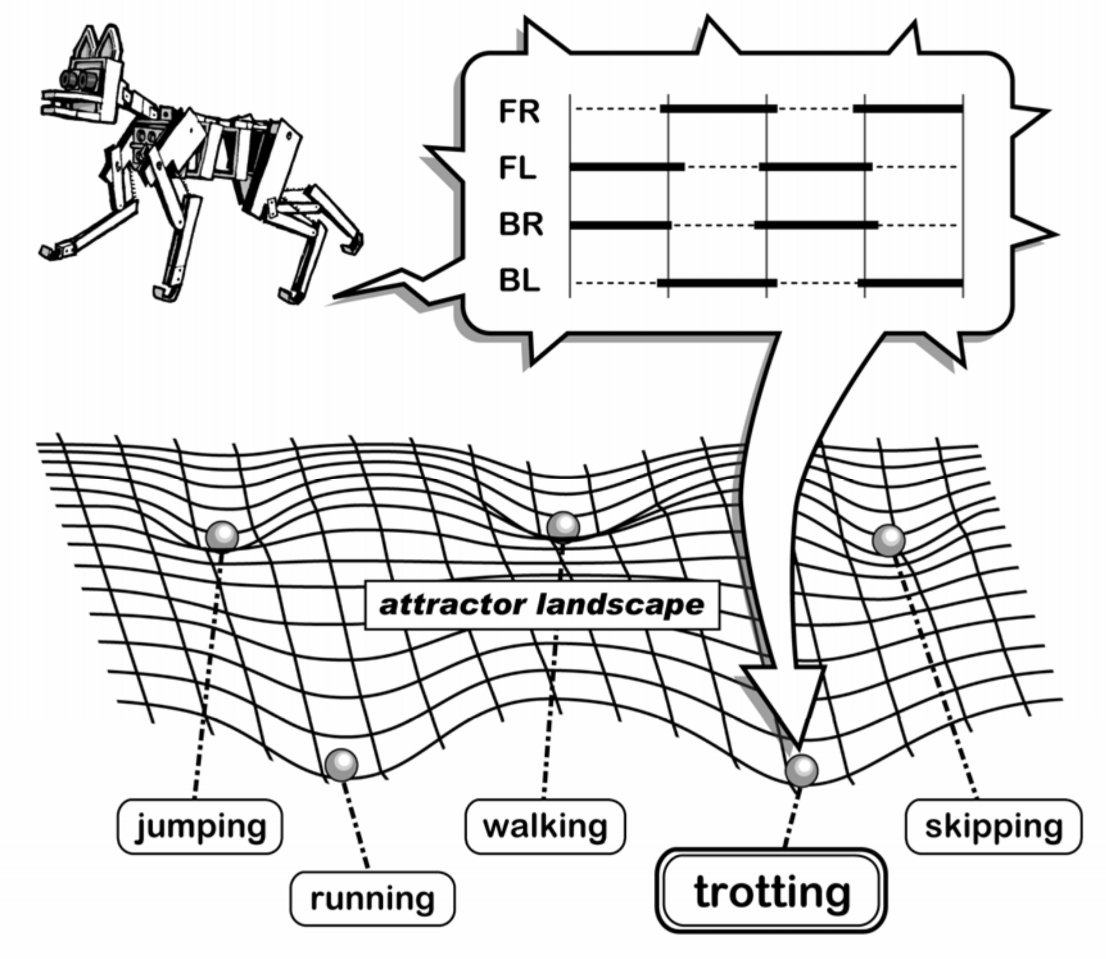
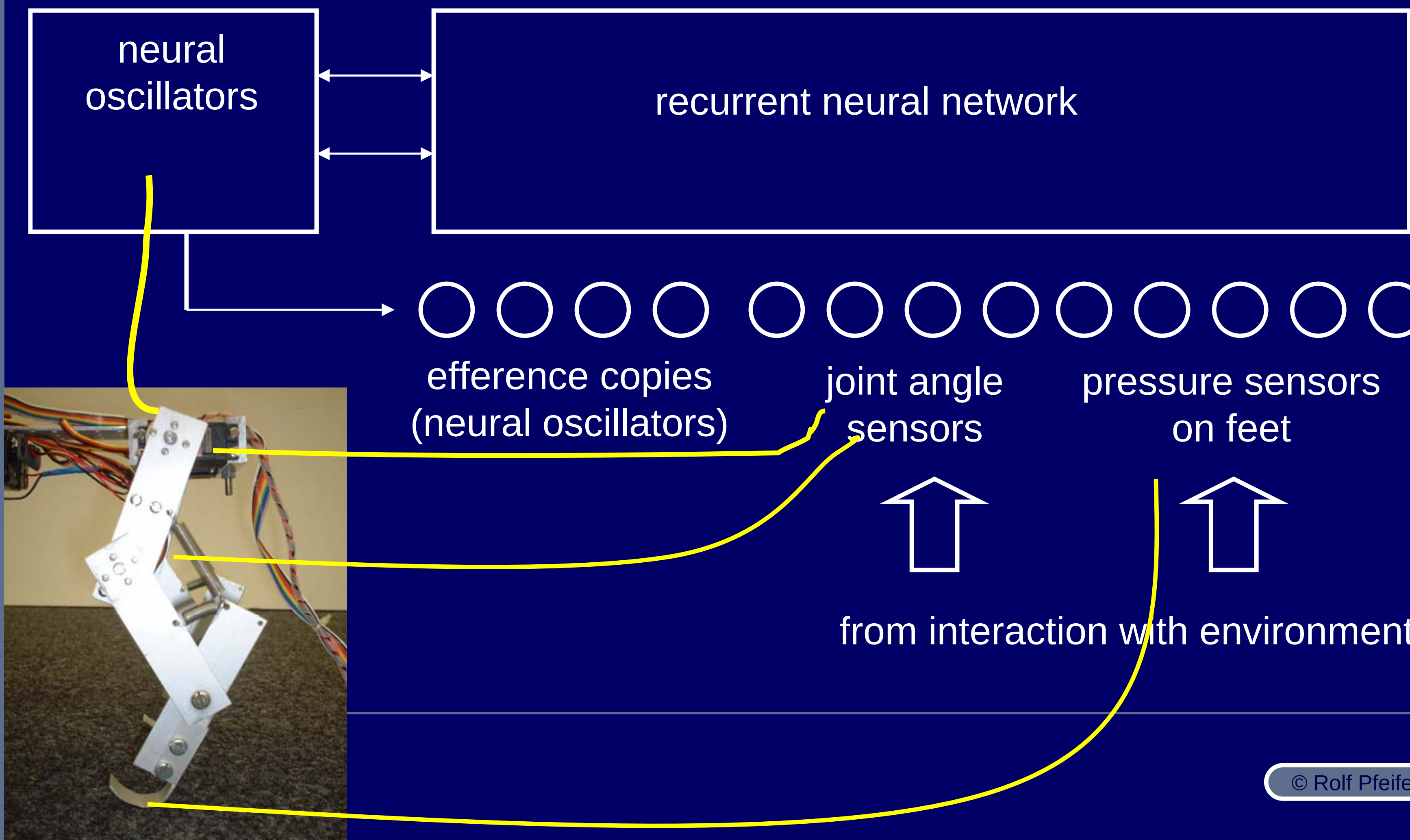
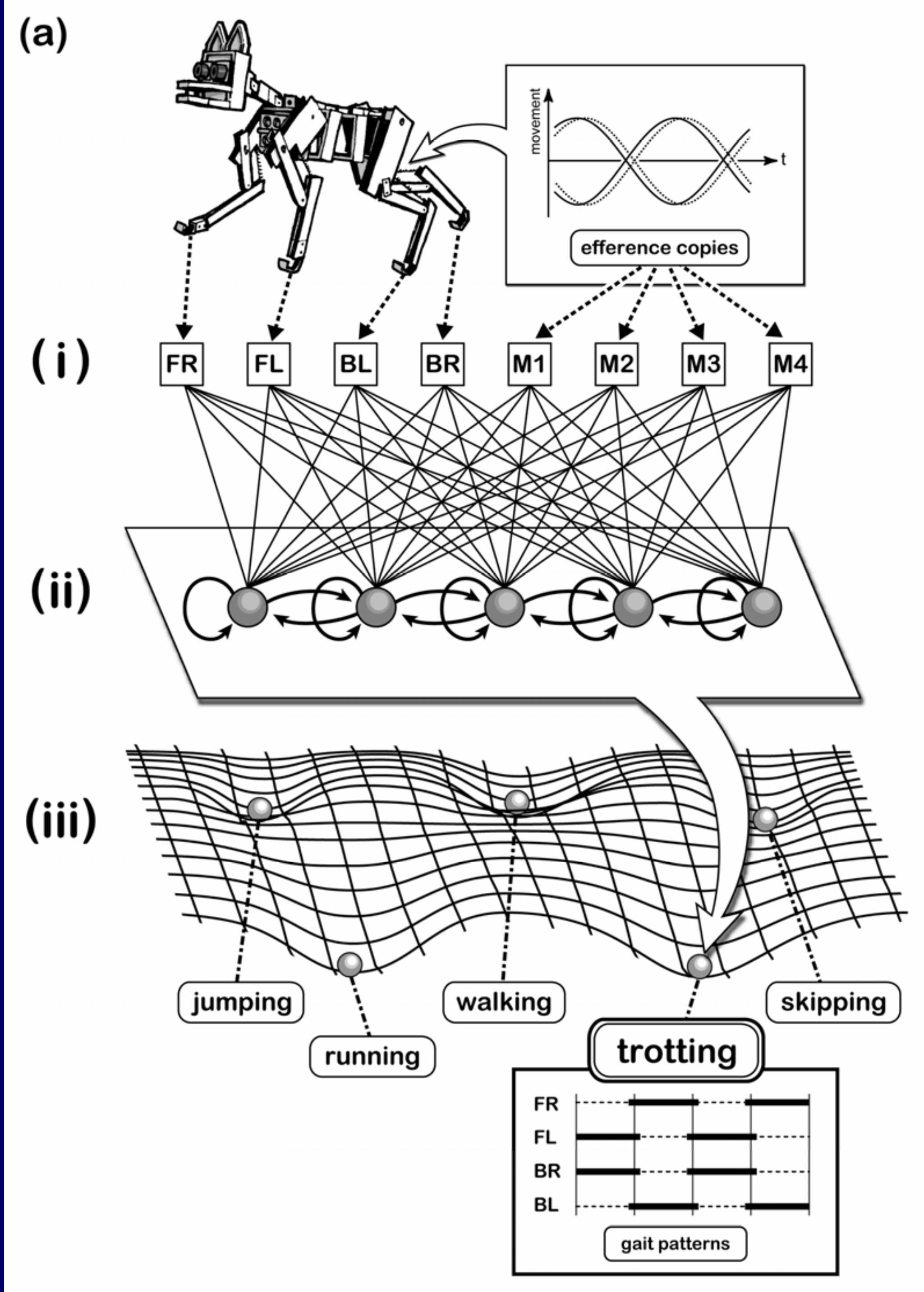


Illustration by Shun Iwasawa

Body image: capturing the causal structure





Building up a body image

Illustration by Shun Iwasawa

Symbol grounding

- basic symbols: attractor states of joint physical-neural system
- symbol processing: attractor dynamics (transitions)
- building body image “bottom-up” (ontogenetic development)

Cognition: a “joint dynamics”

- Cognition: interplay
  - neural processing („brain dynamics“)
  - morphology and materials („body dynamics“)
  - system-environment interaction („behavioral dynamics“)
- co-ordinated by interaction with environment -- sensory-motor coordination

Contents

- Introduction
  - embodiment, synthetic methodology
- „Morphological computation“: Case studies
  - actuators, interaction with environment
- Information self-structuring – sensory-motor coordination
- A note on development
- Summary and conclusions

Artificial Intelligence

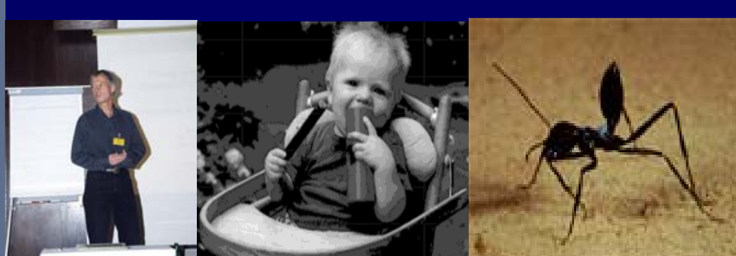
higher level intelligence/ cognition

goals

understanding biological systems

principles of intelligent systems

useful artifacts applications



abstract

theory

Artificial Intelligence

higher level intelligence

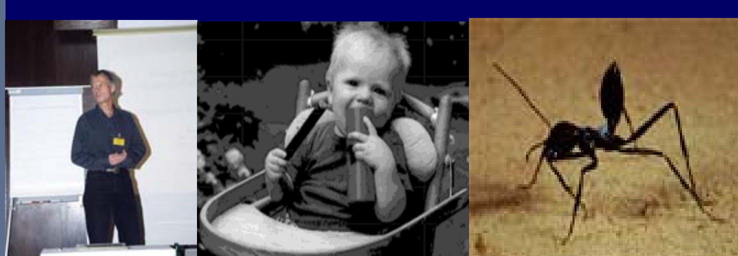
goals

successive development of cognition from sensory-motor activities

understanding biological systems

principles of intelligent systems

useful artifacts applications



abstract theory

Bootstrapping „high-level cognition“ (grand goal)

→ sensory-motor coordination

→ cross-modal associations

→ basic categorization behavior

→ gradual decoupling from sensory-motor level

→ same neural structures involved (cf . mirror neurons)

→ new types of mechanisms?

Abstract thought

George Lakoff and Rafael Nunez

“Where mathematics comes from”

“Take-home message”

- intelligence not (exclusively) in the brain:
  “morphological computation”
- task distribution between
  morphology, materials, control (brain), and environment

or between

“brain, body, and environment”

- development as an approach to hard problems
- “proto symbols” as attractor states of the joint neural/physical system

Like to know more?

New Book

“How the body shapes the way we think – A new view of intelligence”

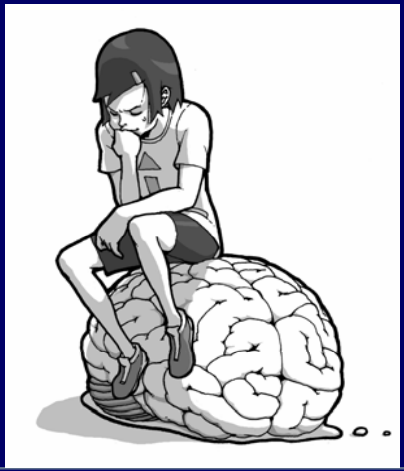
Rolf Pfeifer and Josh Bongard

Illustrations by Shun Iwasawa

Foreword by Rodney Brooks

MIT Press, 2006

(popular science style)



two views of intelligence

Thank you for your kind attention!

Situatedness: the world from the agent's perspective

- relation to outside world through sensory and motor systems → obvious
- but: ***only*** means to connect to outside world
- "understanding" from agent's perspective

→ agent-based view of the world

Frame-of-reference
Designer-based ontologies vs. situatedness

- ontologies – designer-based categories: “gait pattern”, “obstacle”, “obstacle avoidance”, “water”, “up”, “down”
- sensory-motor setup of agent: ***grounding***

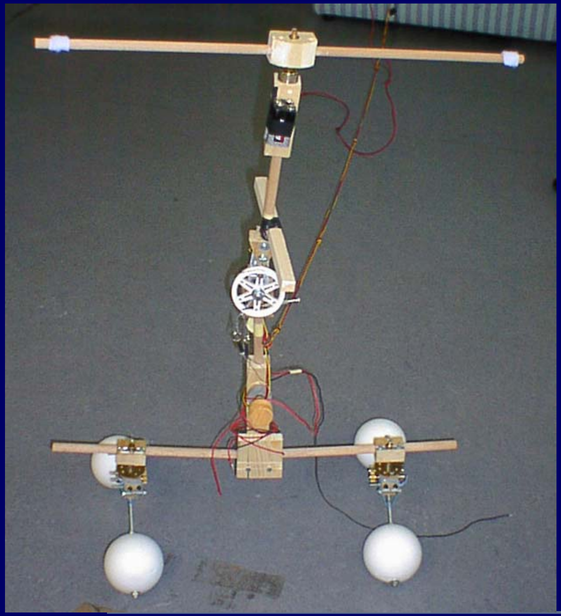
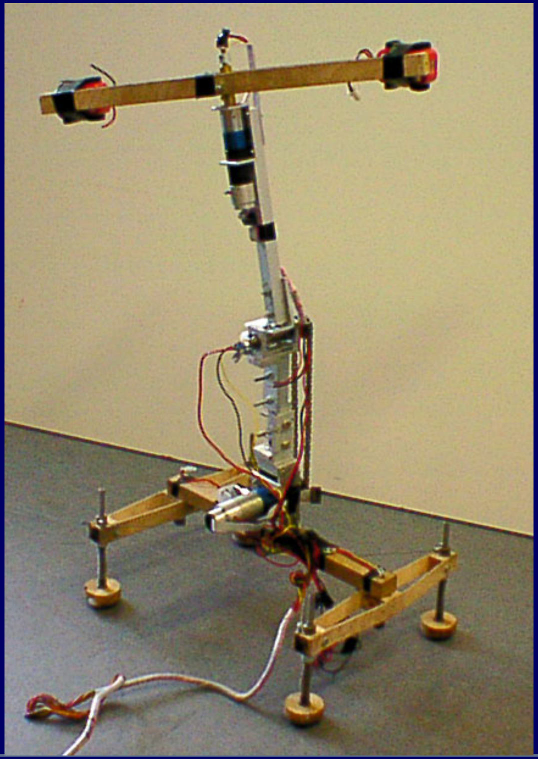
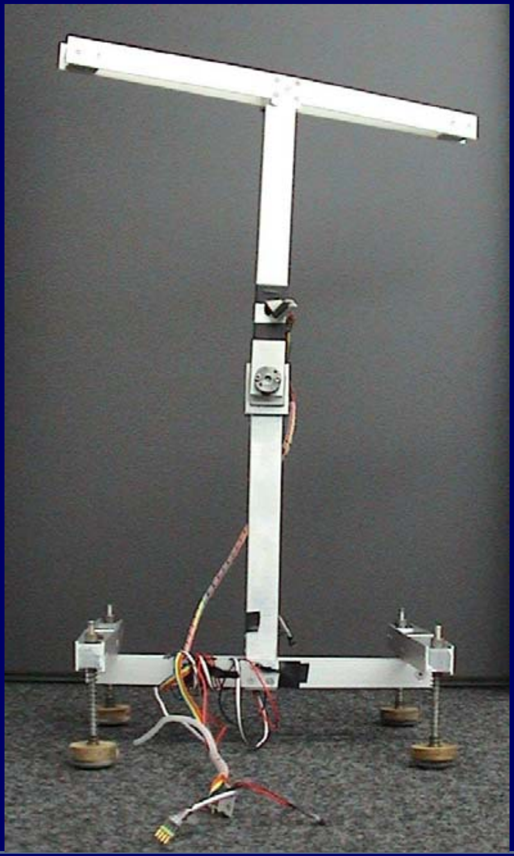
→ be aware of McFarland’s slogan

(“anthropomorphization, the incurable disease”)

artificial agents:
completely different “understanding” of world

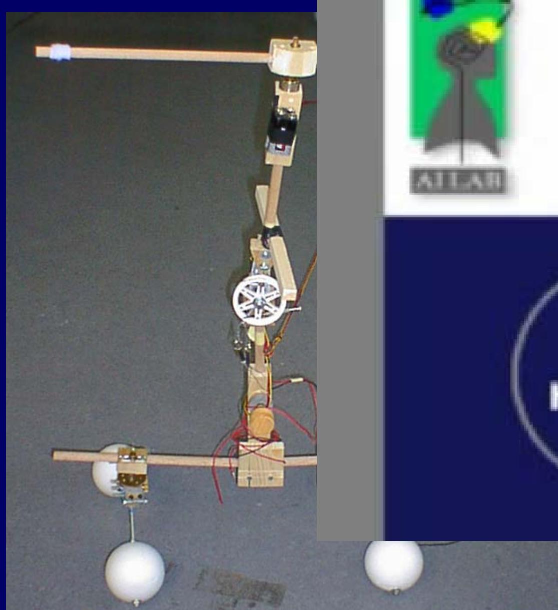
Farewell dance by “Stumpy”

design and construction:
Raja Dravid, Fumiya Iida and Chandana Paul

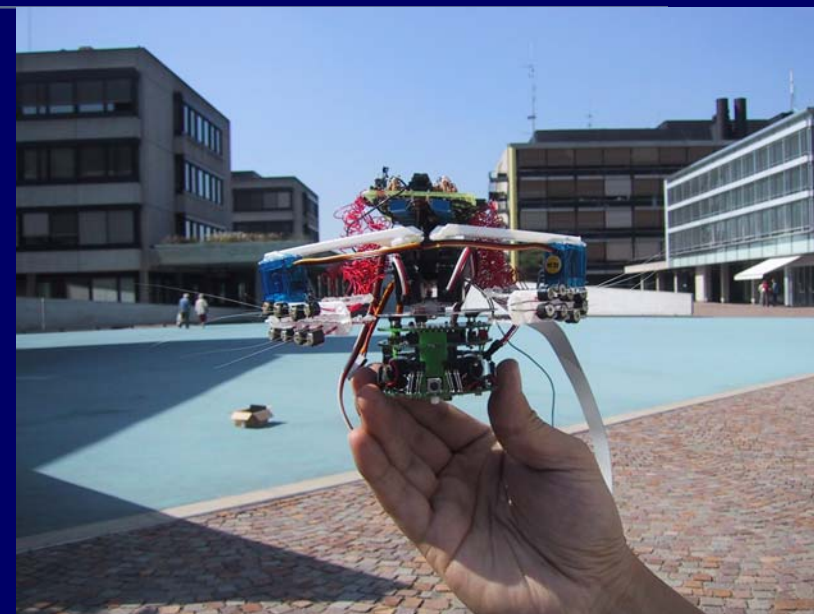
Farewell dance by “Stumpy”

design and cons
Raja Dravid, Fu



Thank you for your kind attention!

Function of whiskers in rats

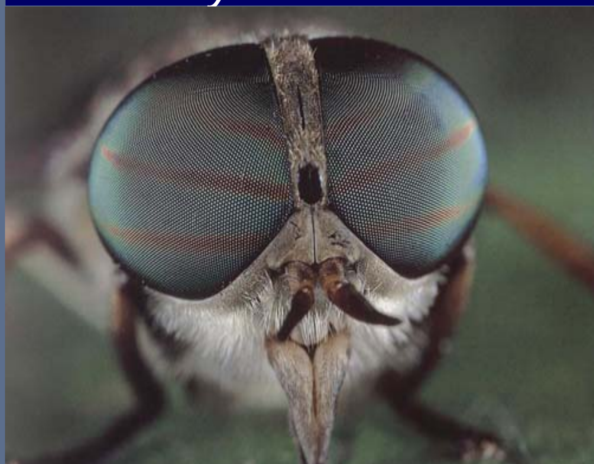


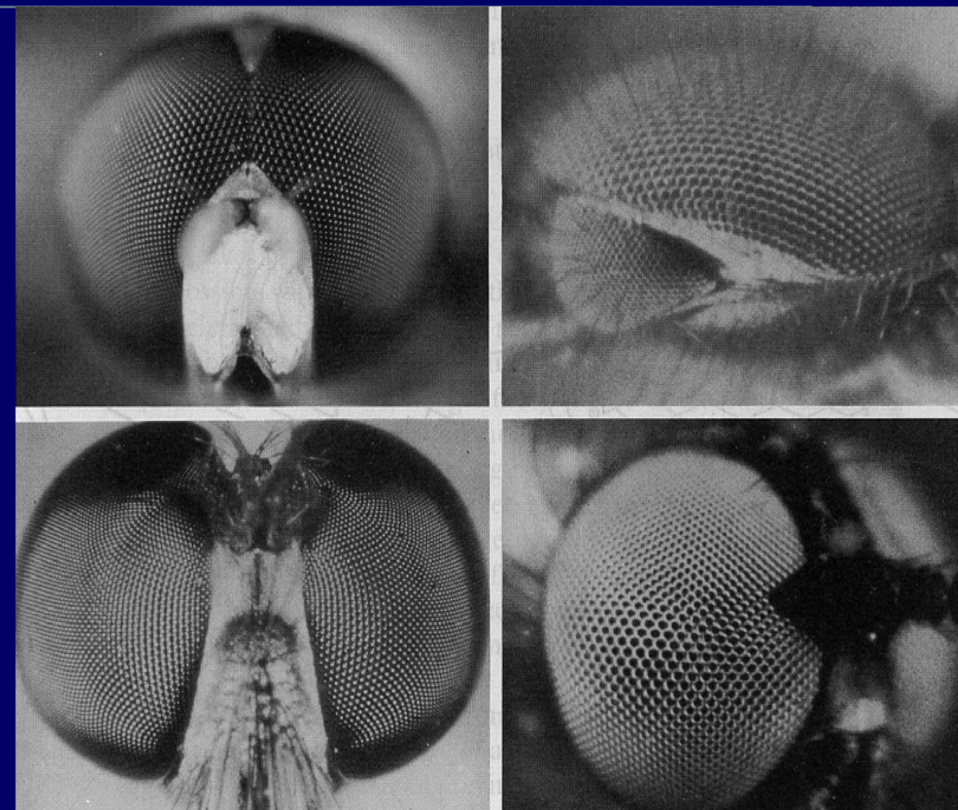
Design and construction:
Verena Hafner, Miriam Fend
Simon Bovet, and Hiroshi Yokoi

A-Mouse, the Artificial Mouse

Morphology of insect eyes

horsefly

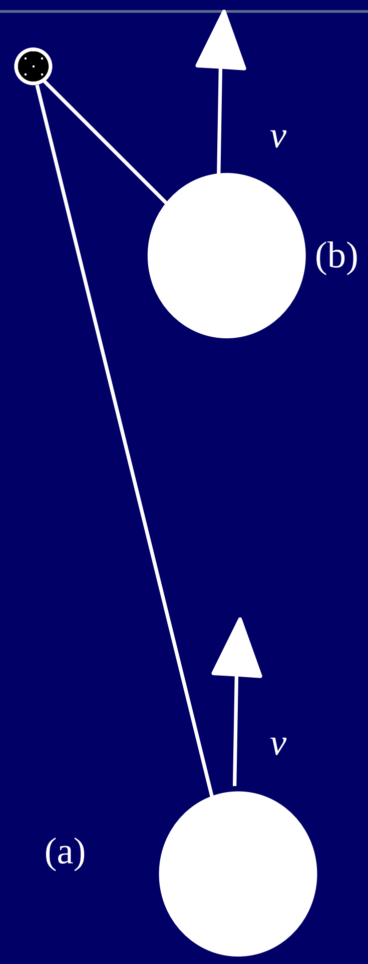




honeybee

large variation of shapes and characteristics

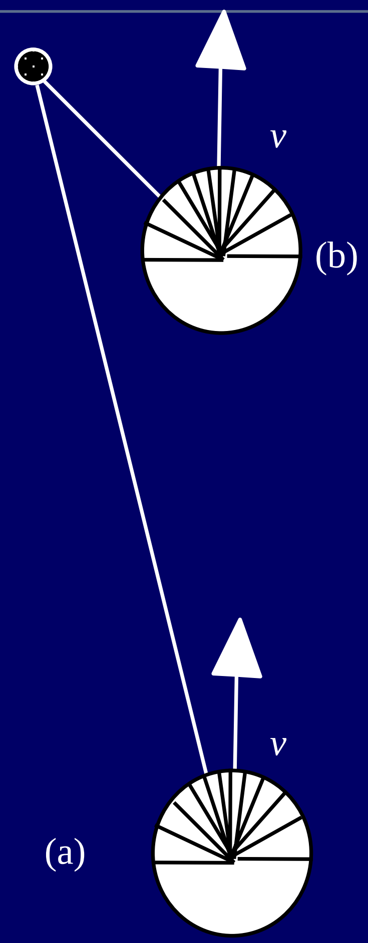
Motion parallax and sensor morphology



high angular velocity

low angular velocity

Motion parallax and sensor morphology



high angular velocity

Insects

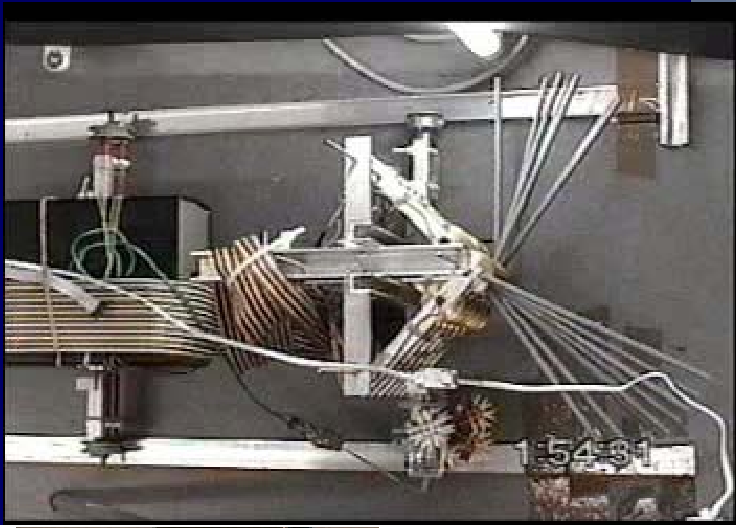
non-homogeneous distribution of facettes (Franceschini et al.)

EMDs (elementary motion detectors)

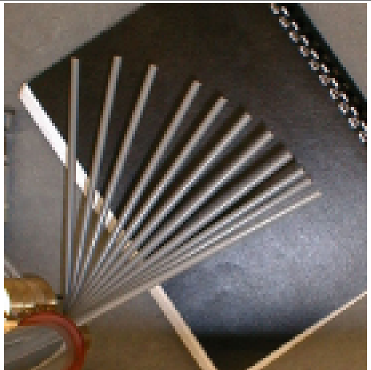
low angular velocity

The "Eyebot": adaptive behavior through changing morphology

Evolution evolution of morphology of insect eye on real robot



Design and construction:
Lukas Lichtensteiger
and
Peter Eggenberger



Motion parallax and sensor morphology: Summary

- “brain” (artificial neural network):

  must be viewed in relation to embodiment and specific interaction with environment
- morphology performs part of the “computation” (pre-processing) -> fast, “free”

→ ***“morphological computation”***

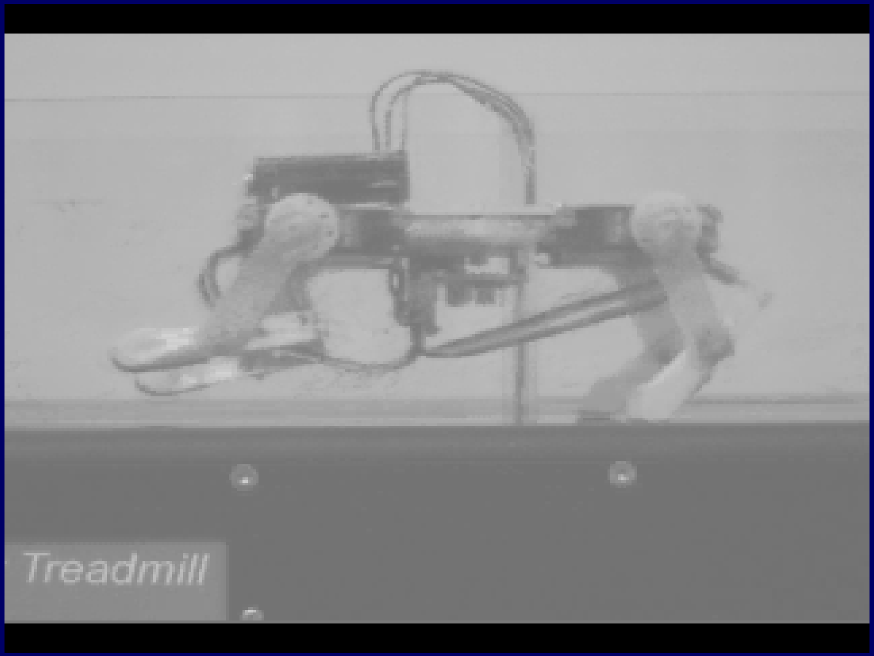
Principle of “ecological balance”

balance / task distribution between

- morphology
- neuronal processing (nervous system)
- materials
- environment

→ ***“morphological computation”***

Video from high-speed camera



Embodiment

- *trivial meaning:*
  "intelligence requires a body"

Embodiment

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- *non-trivial meaning:*

  interplay
  - brain (neural processing)
  - morphology
  - materials
  - environment

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--> not only physical but "information theoretic" implications

Embodiment

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--> not only physical but
“information theoretic” implications

“morphological computation”

Synthetic methodology

"Understanding by building"

- modeling behavior of interest
- abstracting principles

Synthetic methodology

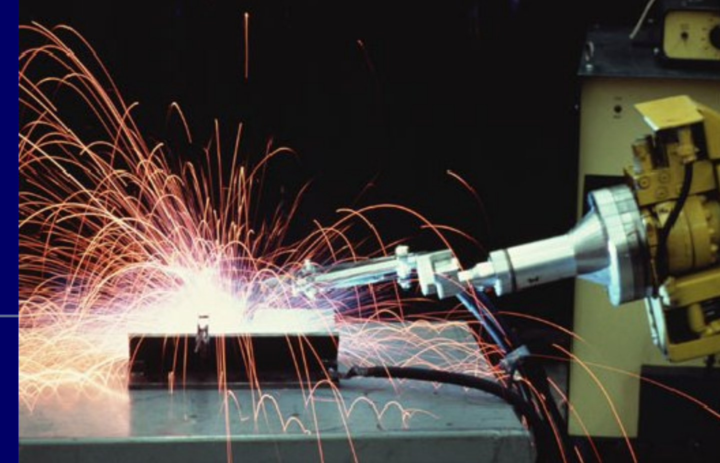
“Understanding by building”

- modeling behavior of interest
- abstracting principles

→ *build robots / artifacts*

Industrial robots

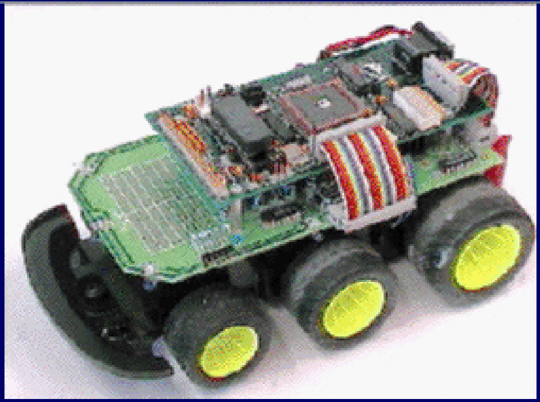
welding robots



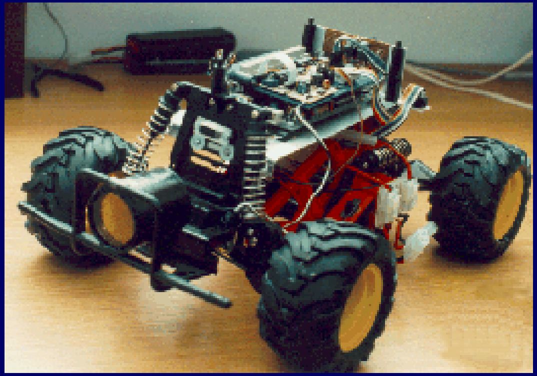
programmable
“do exactly as told”

automobile industry

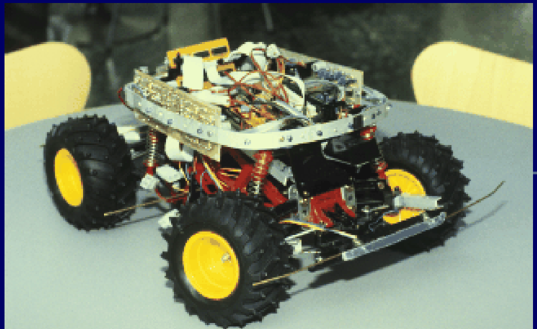
Zurich AI Lab robots



Didabot

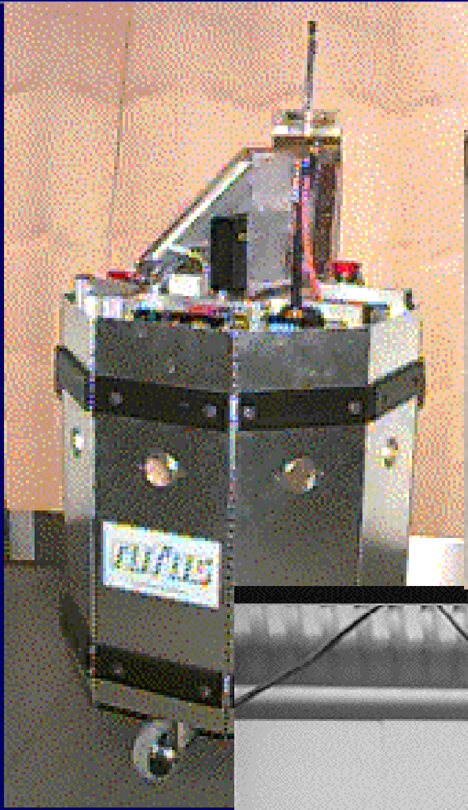


Famez

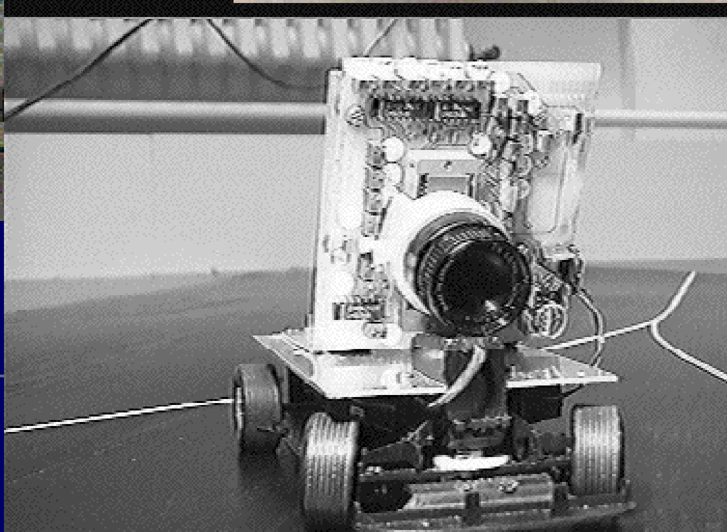


Sita

Rufus T. Firefly

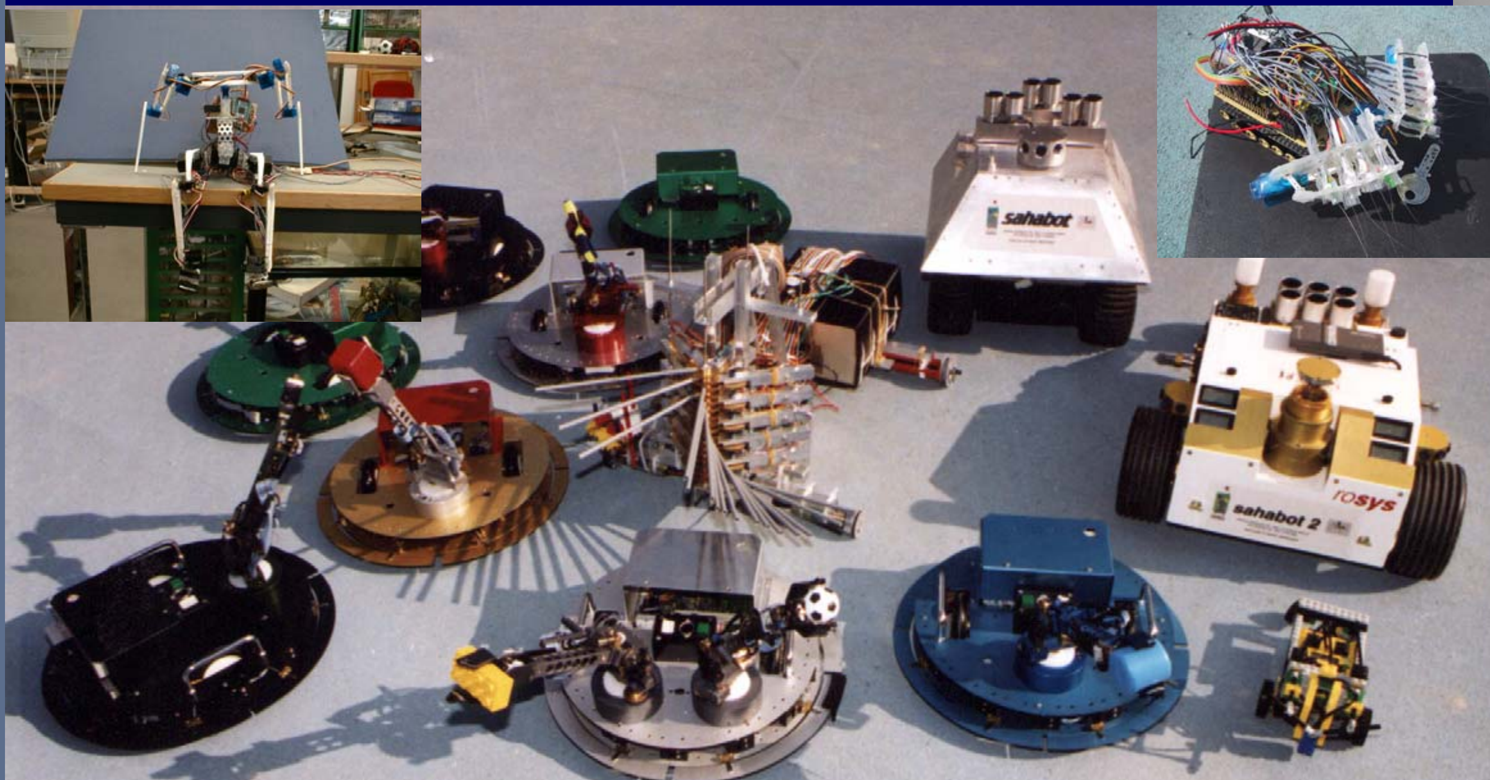


Ms. Gloria Teasdale

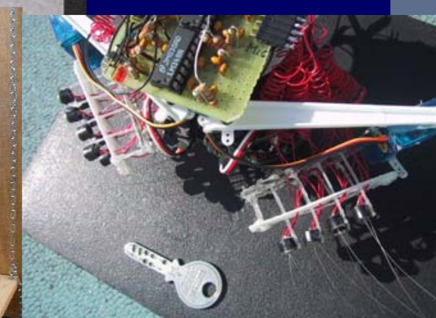


Morpho

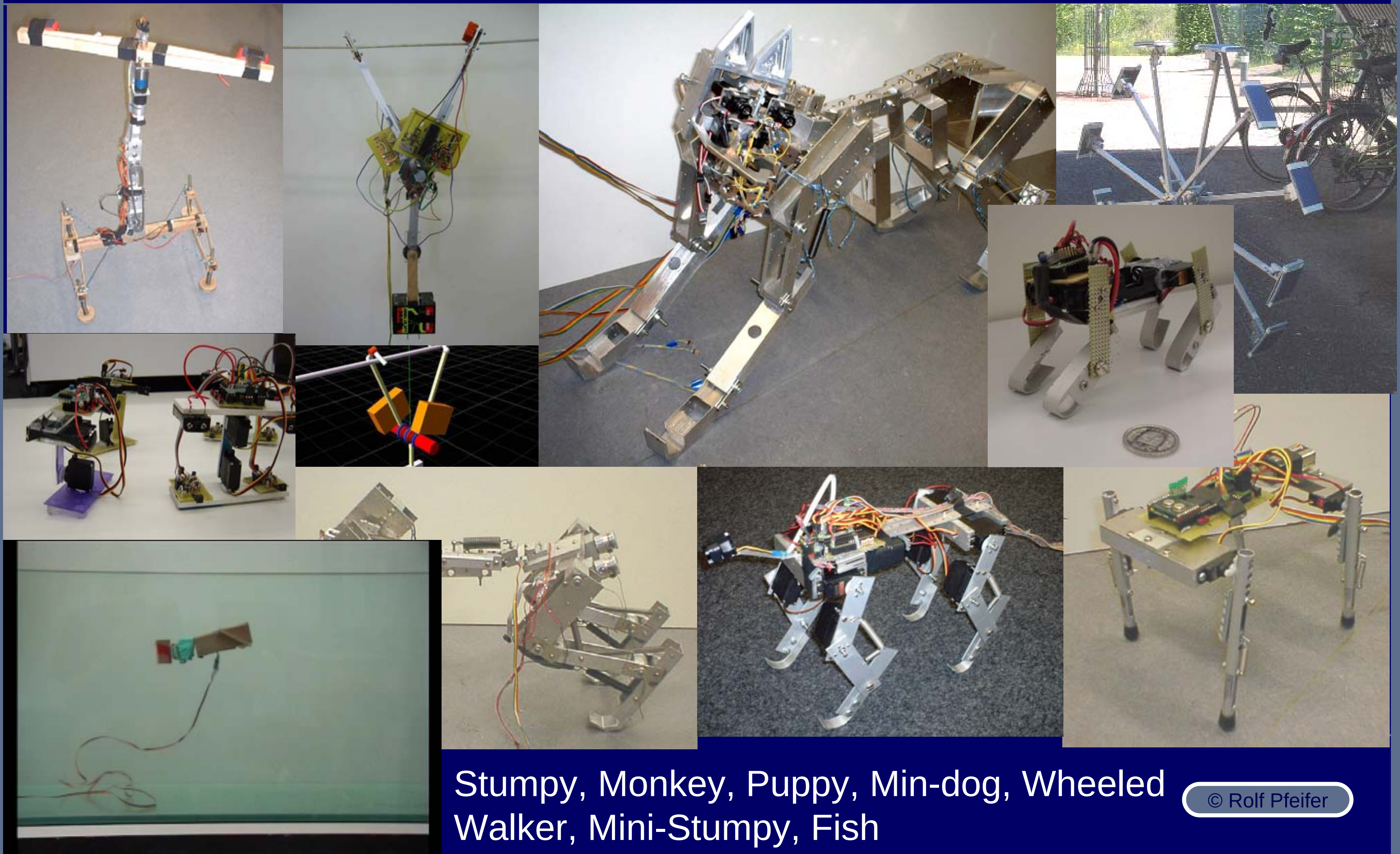
Zurich AI Lab robots



Amouse
Sahabots
Melissa
Tripp
Samurai
Analogrob
Dexterolator
Stumpy
Eyebot
Mindstorms
Kheperas
Mitsubishi
Forkleg



Zurich AI Lab robots (locomotion)



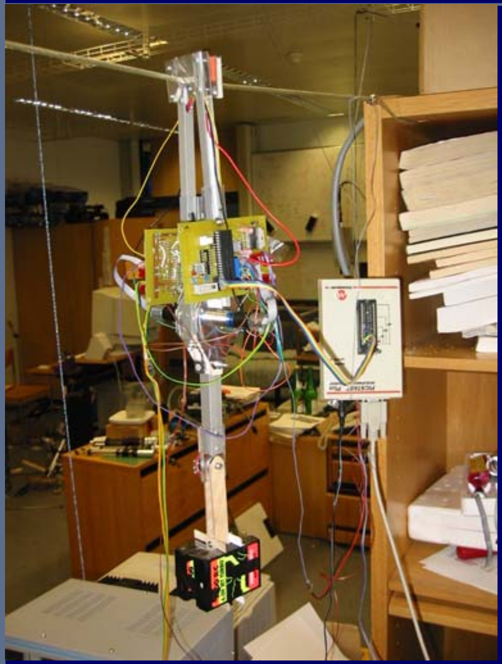
Stumpy, Monkey, Puppy, Min-dog, Wheeled Walker, Mini-Stumpy, Fish

Rapid locomotion

- hard problem
- where is the bottleneck?
- electronics?
- more rapid that biological circuitry
- biological agents move faster
- cannot be the problem!

→ "ecological balance": exploitation of "computational power" morphology and materials in interaction with environment

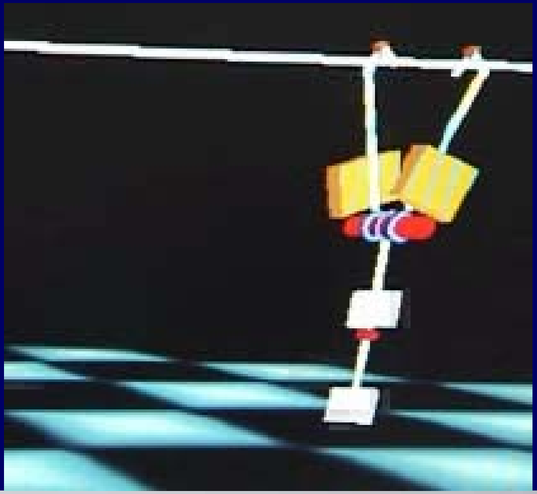
Dynamics of brachiation

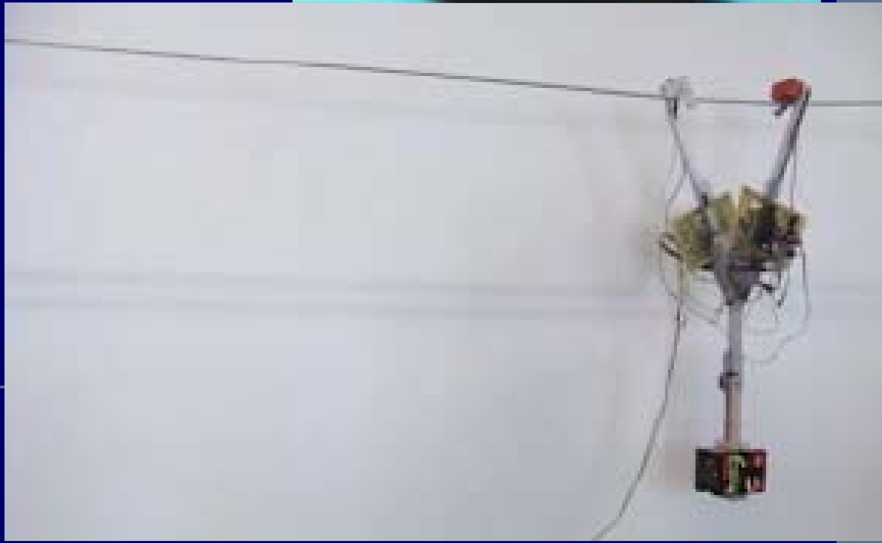


the “Monkey robot”

Design and construction:
Dominique Frutiger

simulation

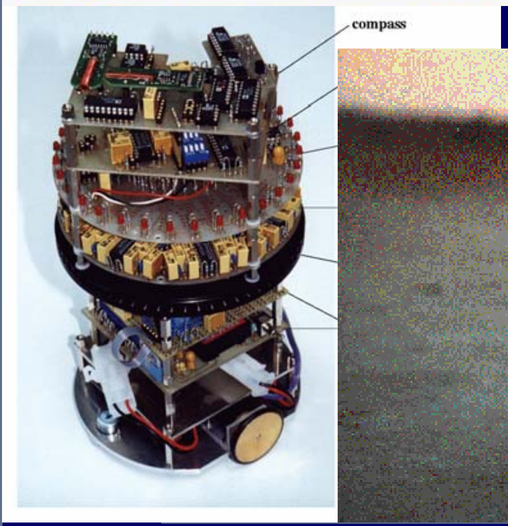


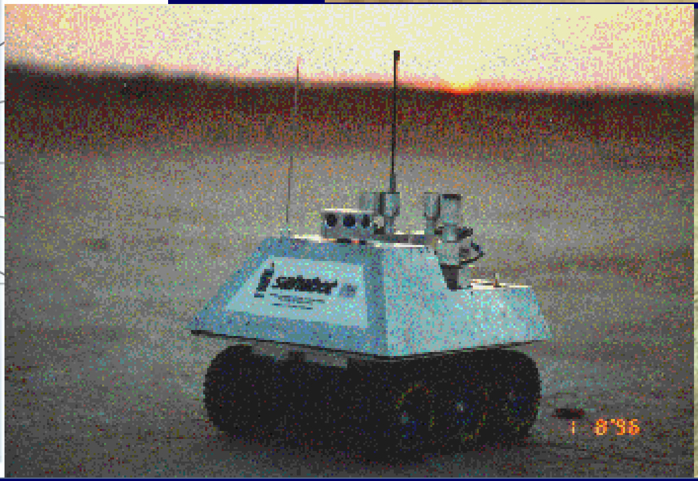


robot

Synthetic methodology: examples

Navigation behavior of desert ants

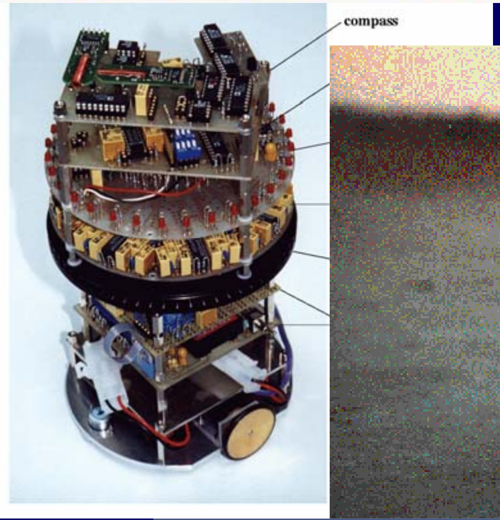


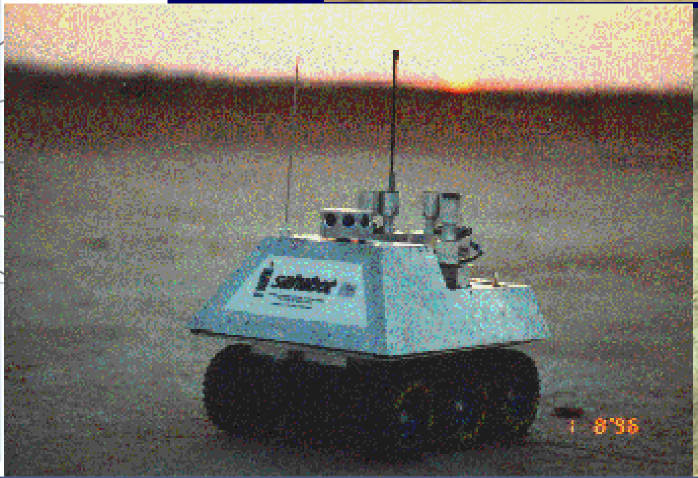


Design and construction:
Hiroshi Kobayashi, Dimitri Lambrinos, Ralf Möller, Marinus Maris

Navigation behavior of desert ants

Importance of morphology





Design and construction:
Hiroshi Kobayashi, Dimitri Lambrinos, Ralf Möller, Marinus Maris

Evolution of insect eye morphology

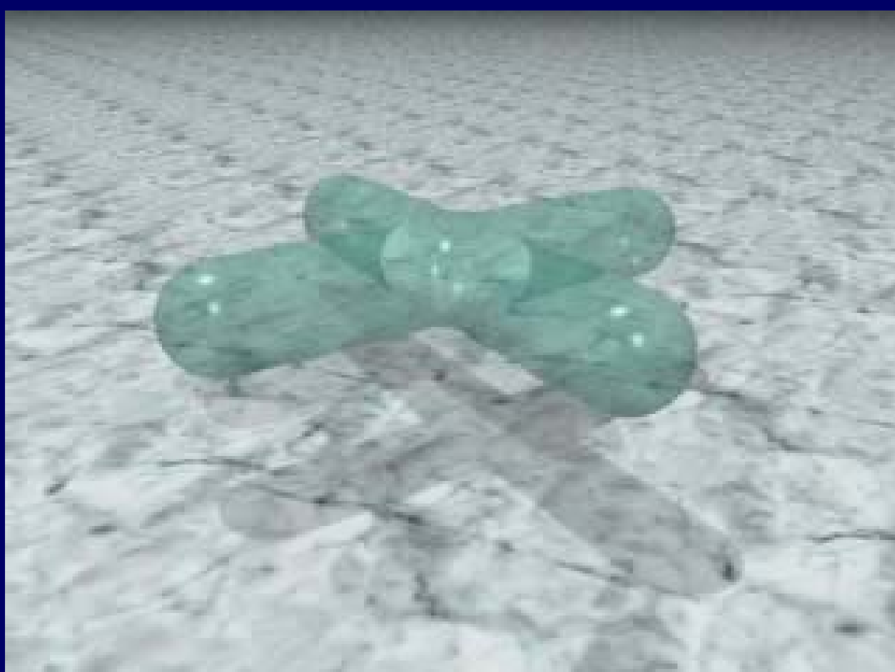
Design and construction:
Lukas Lichtensteiger and
Peter Eggenberger

The “Eyebot”:
Adaptive behavior through
changing
morphology

more later

"Elastic Life"
Locomotion with elastic, deformable materials

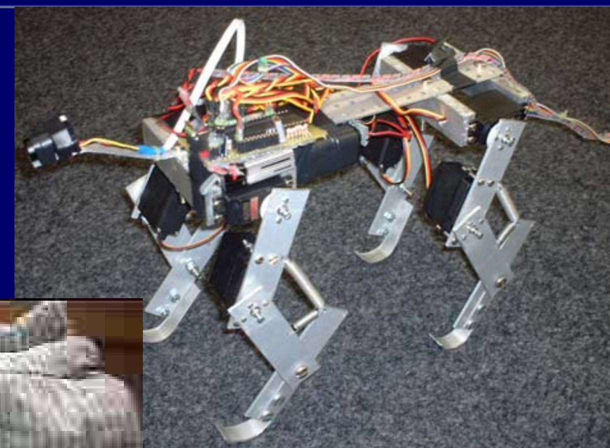
Design and construction:
Dale Thomas

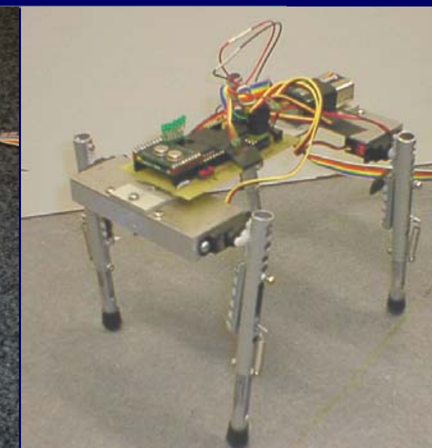


relation of deformable elastic materials using artificial evolution and morphogenesis

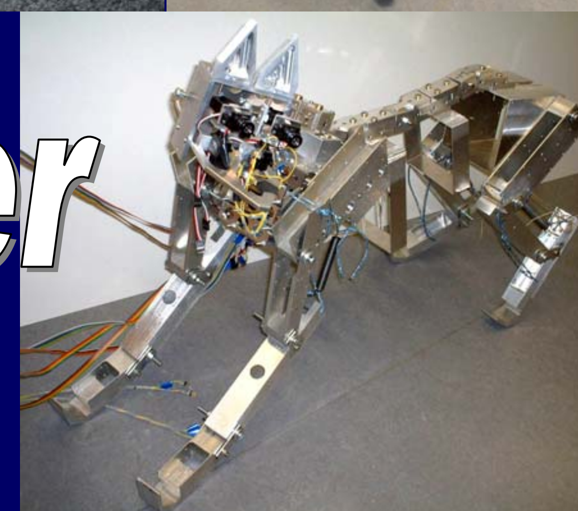
Rapid locomotion

the quadruped “puppy”





more later



Design and construction:
Fumiya Iida

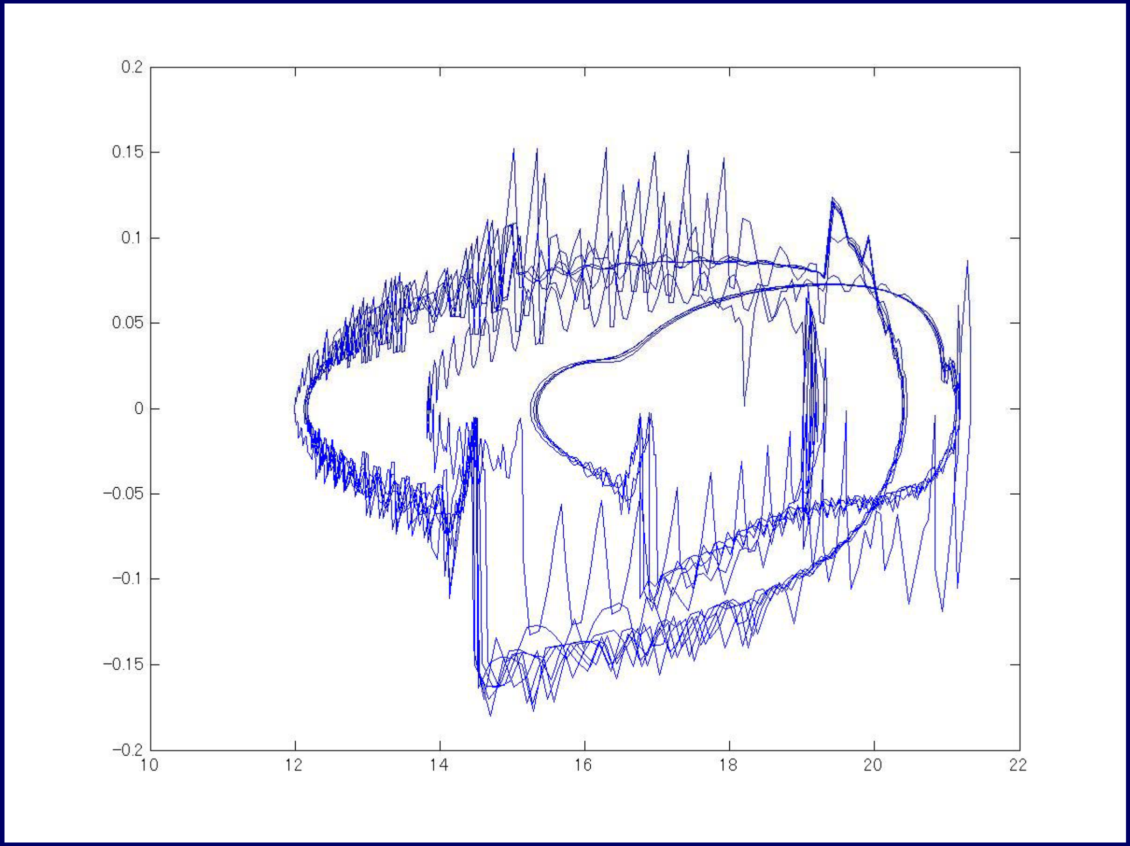
Artificial Fish: Exploitation of morphology and system-environment interaction

more later

Design and construction:
Horishi Yokoi
Fumiya Iida
Mark Ziegler

Transition: slow – fast
joint angle of passive joint on “Puppy”

phase
plot



small shape:
slow movement

output from a computer simulation by Fumiya Iida

Like to know more?

visit our laboratory in Zurich

or read

Morphological change in the service of learning

- freezing and freeing DOFs → approach to Bernstein's problem
- coupling of fingers in the hand, then releasing
- initial low resolution vision: successive increase
- coarse control → more fine-grained control

→ development necessary for highly complex organism

Mimicking morphological change in robots

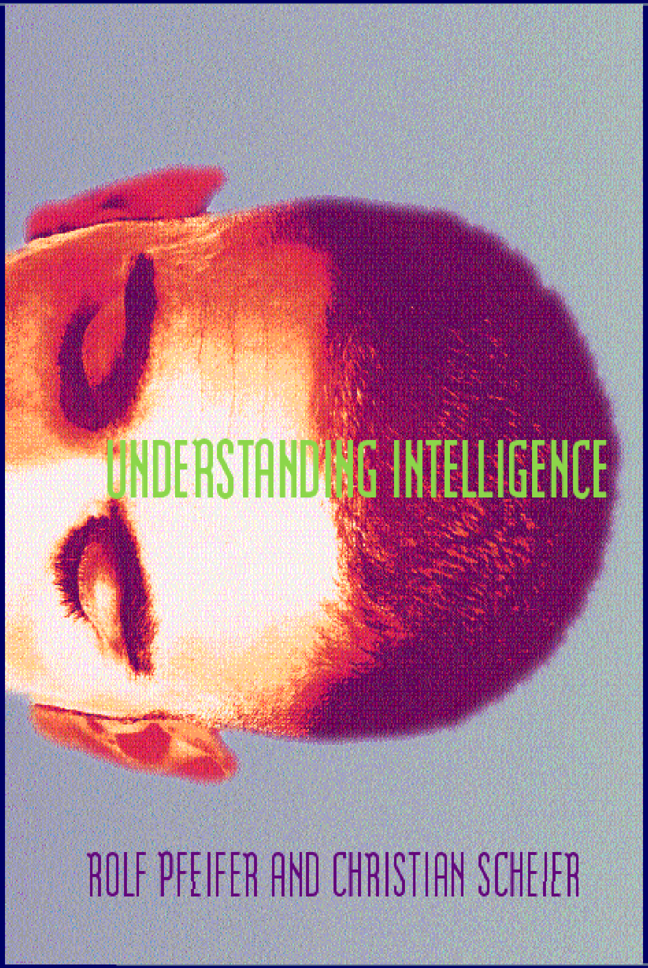
starting with:

- low-resolution sensory system
- low-precision motor system
- low complexity of neural structure

→ faster learning

(demonstrations, see previous progress report)

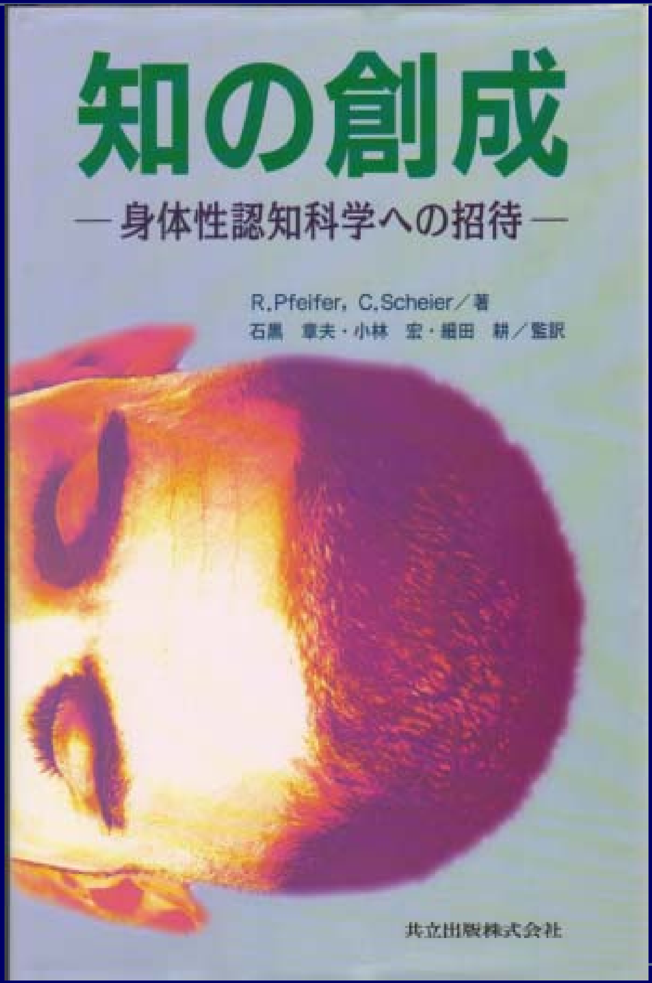
“Understanding Intelligence”

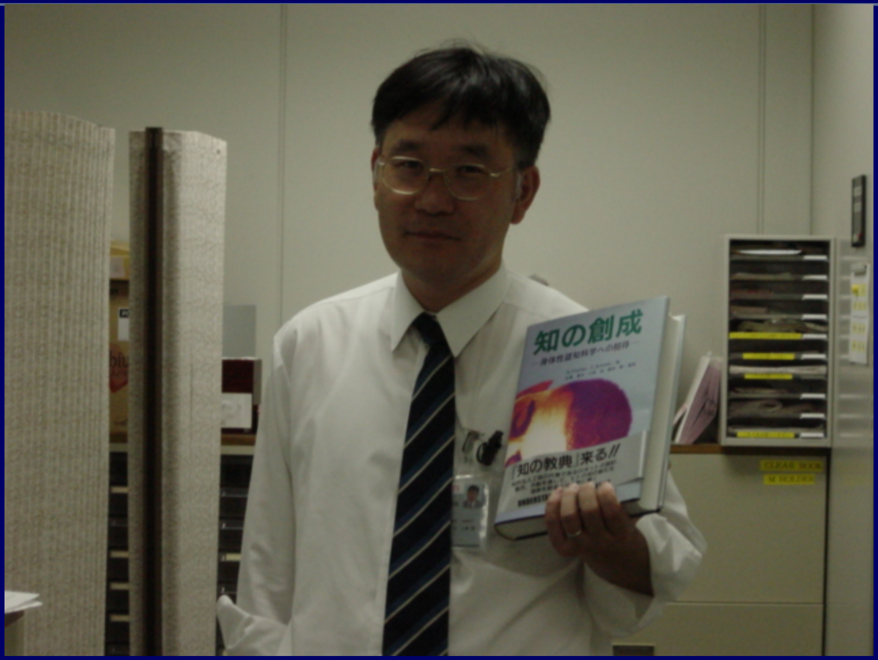


MIT Press
November 1999
(2nd printing 2000, paperback edition)

“*Understanding Intelligence* is a comprehensive and highly readable introduction to embodied cognitive science.”
– **Arthur B. Markman**, *Science*

in Japanese





translated by Koh Hosoda. Akio Ishiguro
and Hiroshi Kobayashi
with a preface by Minoru Asada