Neural Networks
25 May 2012

Morphological computation

FET Flagships: a new and ambitious European initiative
Rise of Sentient Machines? Robot Companions for Citizens

Enabling technology for sustainable welfare

Robot Companions for Citizens

Coordination Action for the design and description of the FET Flagship candidate

Morphological Computation and Design Concepts for Future High Efficiency Robots

Bern, 22 May 2012

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Buzzwords

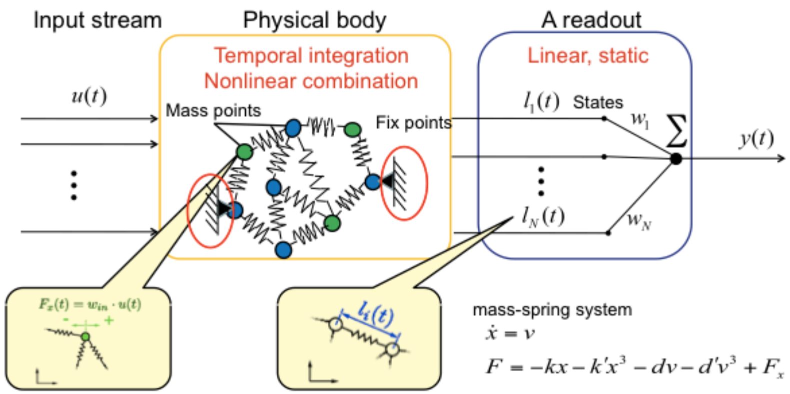
- amorphous computing
- self-assembling robots/materials
- morphological computation
- biochemical circuits
- passive dynamics
- molecular recognition systems
- cellular computing
- biomolecular devices
- autopoeisis
- membrane computing
- self-stabilization
- trading space
- tensegrity
- genetic regulatory networks
- blob computing
- DNA/molecular computing
- patterning
- neuromorphic computing/ engineering
- self-repair
- self-organization
- ...

Reservoir computing

Adaptive Modular Architectures for Rich Motor Skills

T3.1.1 Theoretical Foundation for Morphological Computation (TUG+UniZu) – proposed model 1

Basic idea: a physical body as a reservoir



$$\dot{x} = v$$

$$F = -kx - k'x^3 - dv - d'v^3 + F_x$$

Goals

- power of concept "morphological computation"
- research technological challenges
- create "mind set" for design

Contents

- background and introduction
- morphological computation: examples and case studies
- the "power of materials"
- exploiting sensory morphology
- information structure through sensory-motor coordination
- research challenges
- the Swiss perspective

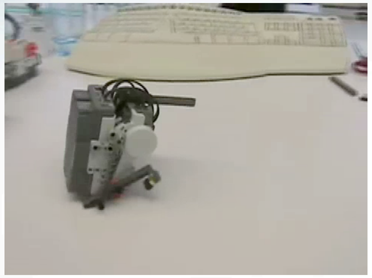
Embodiment, "soft robotics", and morphological computation

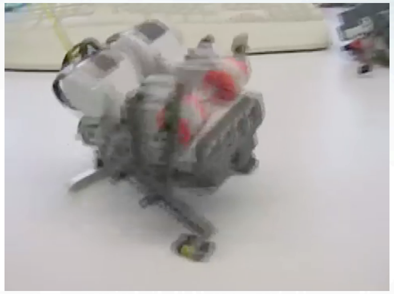
Hypothesis: **The next generation of robots - the Robot Companions - will be of the "soft" kind. Advances in "soft technology" will lead to a quantum leap in intelligent robotics.**

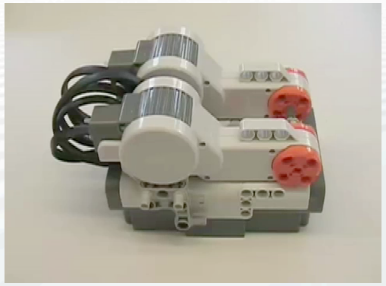
Theoretical underpinnings: **The key to "soft robotics" will be an understanding of embodiment, which in turn, requires an understanding of morphological computation.**

"Soft":
- varying degrees of softness
- changeable material characteristics
- multifunctionality

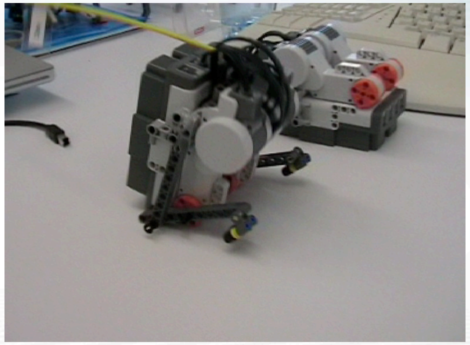
Getting into the “spirit” of embodiment





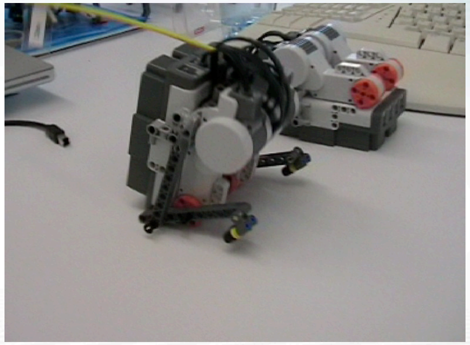


“Crazy Bird” - morphology and control



loosely hanging feet
rubber/plastic

"Crazy Bird" - morphology and control



loosely hanging feet
rubber/plastic

behavior of "Crazy Bird": emergent

Principle 1: Physical embedding

Studying brain (or control) not sufficient:

Understanding of

- embedding of brain into organism

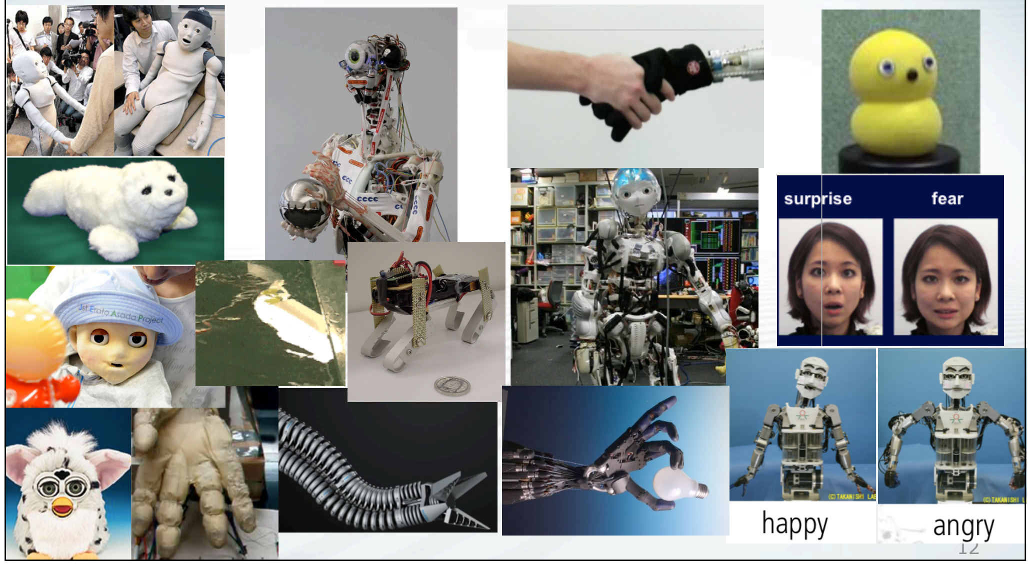
- organism's morphological and material properties

- environment

required

“Soft robotics”

Soft to touch | **Soft movement** | **Soft interaction** | **Expression**



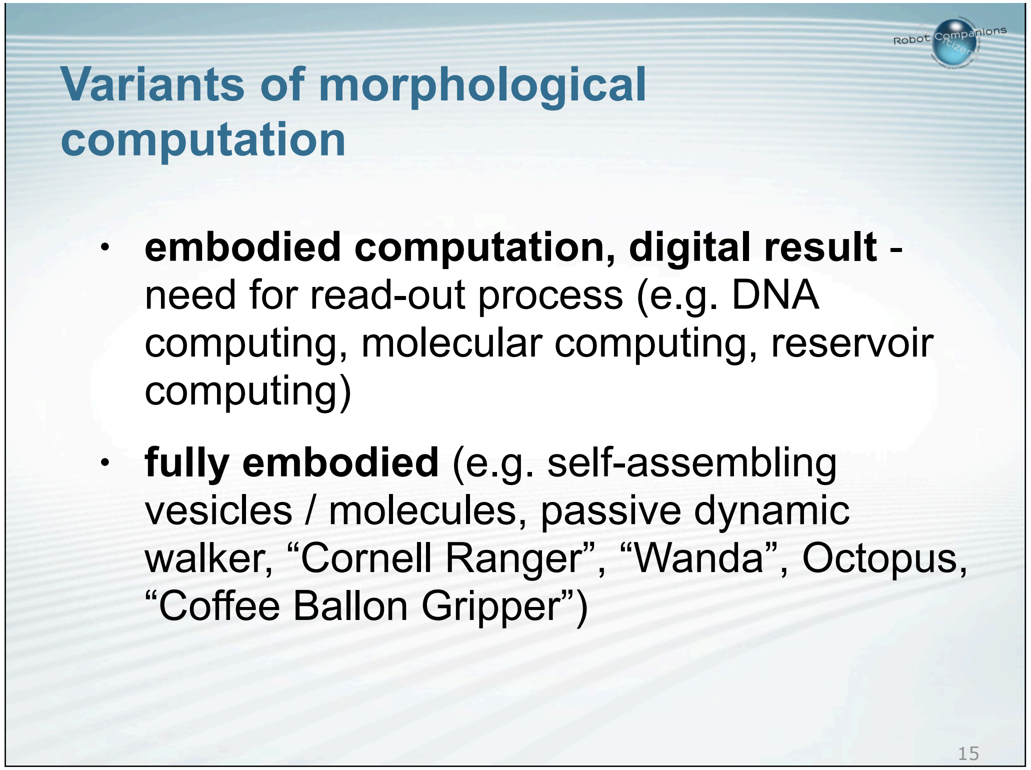
Morphological computation: “Definition”

Morphological computation designates the idea that part of the computation required for particular behaviors can be performed by the body, incorporated into the morphological and material characteristics of the agent. The brain itself, as part of the body, also applies morphological design principles to achieve its computational tasks.

Morphological computation: requirements (Norman Packard)

- **need I/O**
- **need programmability**
- **need teleological embedding (functionality, purpose, goal)**

(from "International Conference on Morphological Computation" 2007 summary of discussion)



Fully embodied: here the desired functionality is the behavior of the system itself, irrespective of whether we consider the body as computing or not. However, the “computation” of the body can be exploited (e.g. to produce certain information about the environment, for example, the steepness of the terrain in “Puppy”).

There has to be a readout process that can be viewed as the translation of the physical state of the system back to its digital interpretation in terms of the original – digital – problem. The standard computational problems – unusual (physical) computational process.

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Examples and case studies of morphological computation

- the "Passive Dynamic Walker"
- the "Cornell Ranger"
- the compliant humanoid "Coman"
- the dancing robot "Stumpy"
- the robot fish "Wanda"
- the artificial "Octopus"
- the "coffee-balloon gripper"
- the "Tribolons"

Walking: Classical control

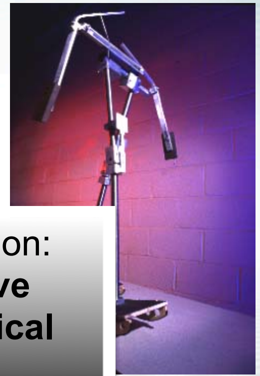
Sony Qrio:
high stiffness
centralized control
computationally intensive

“Passive Dynamic Walker”

Design and construction:
Ruina, Wisse, Collins: Cornell University
Ithaca, New York

The “brainless” robot”: walking without control

“Passive Dynamic Walker”

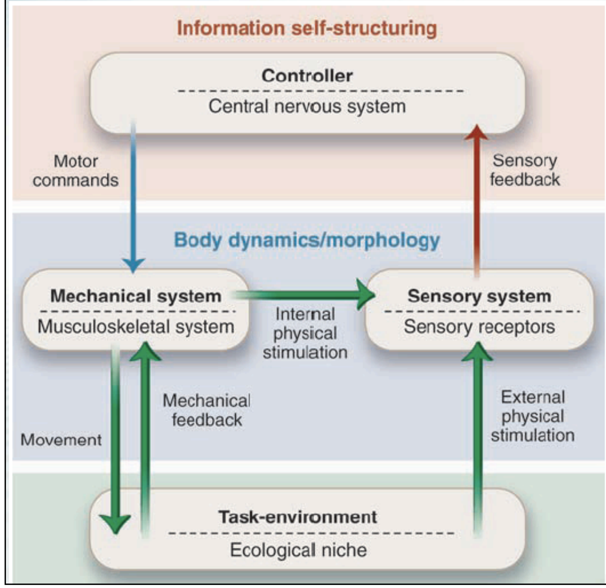


morphological computation:
exploitation of passive dynamics and mechanical feedback

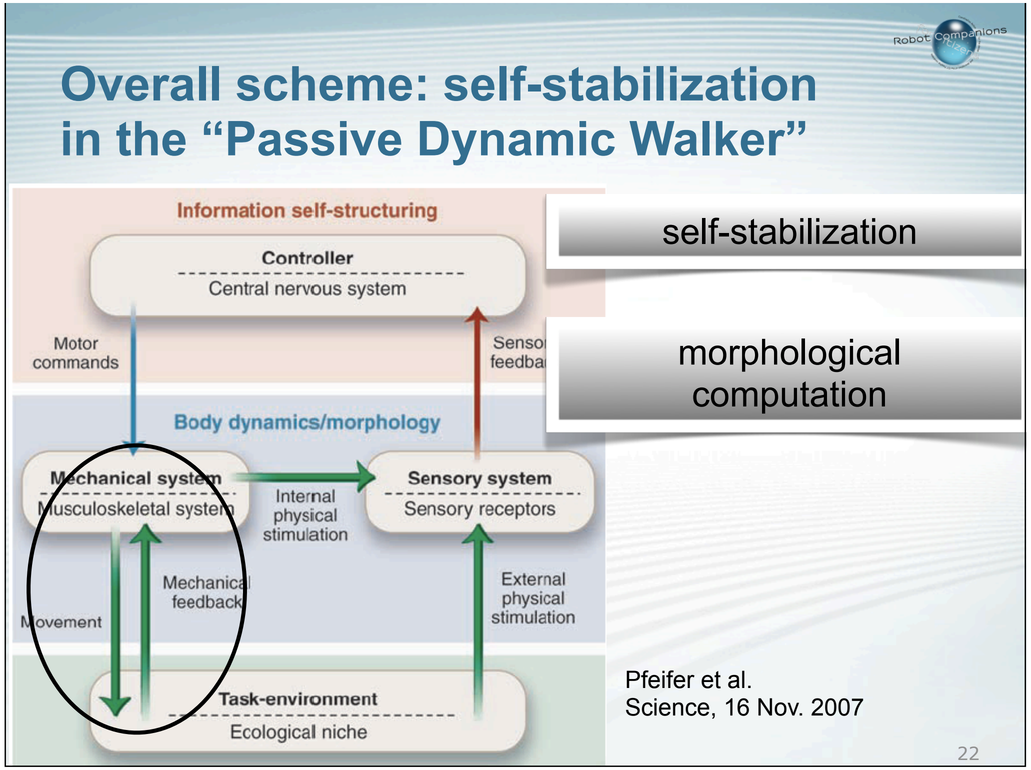
Design and construction:
Ruina, Wisse, Collins: C
Ithaca, New York

The “brainless” robot”: walking without control

Overall scheme



Pfeifer et al.,
Science, 16 Nov. 2007

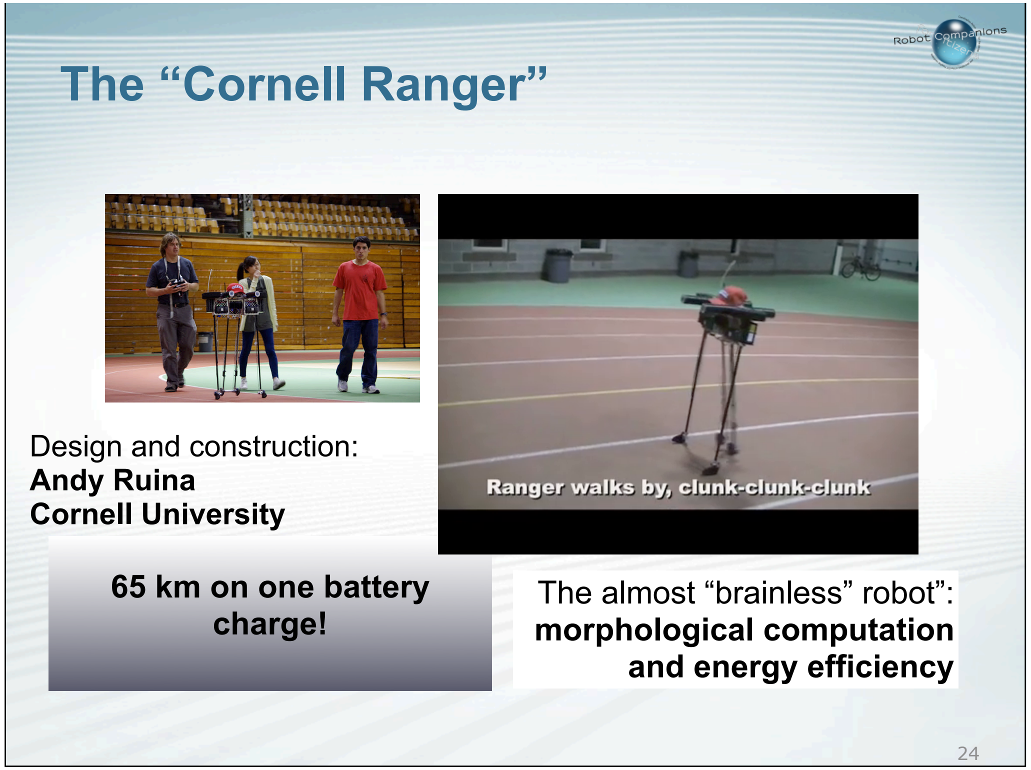


Exploitation of passive dynamics: is an instance of self-organization.

These principles apply also to human walking — dynamic change of muscle tension depending on phase within walking cycle.

Short question

memory for walking?



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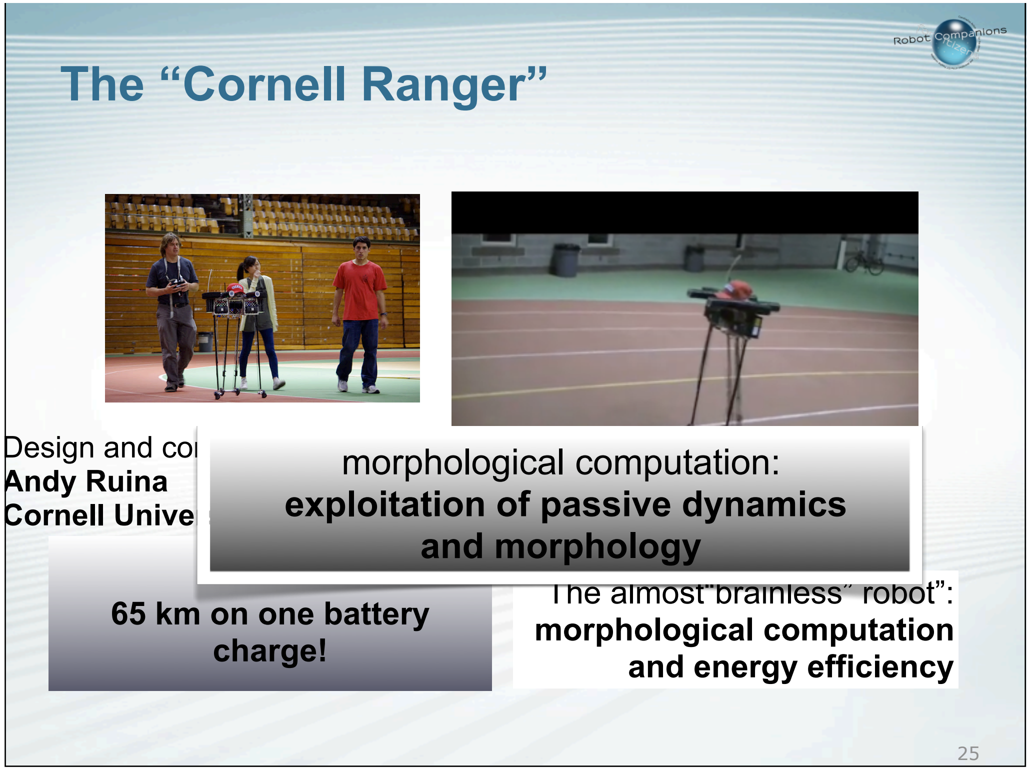
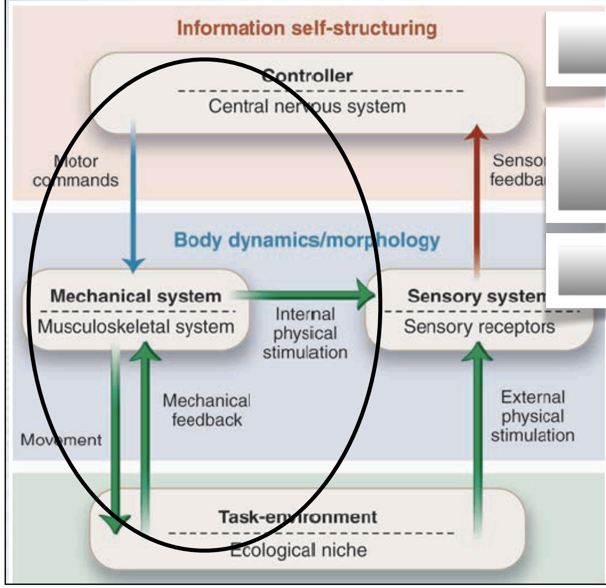


Previously, nobody would have thought this to be possible.

Overall scheme: self-stabilization int he “Cornell Ranger”

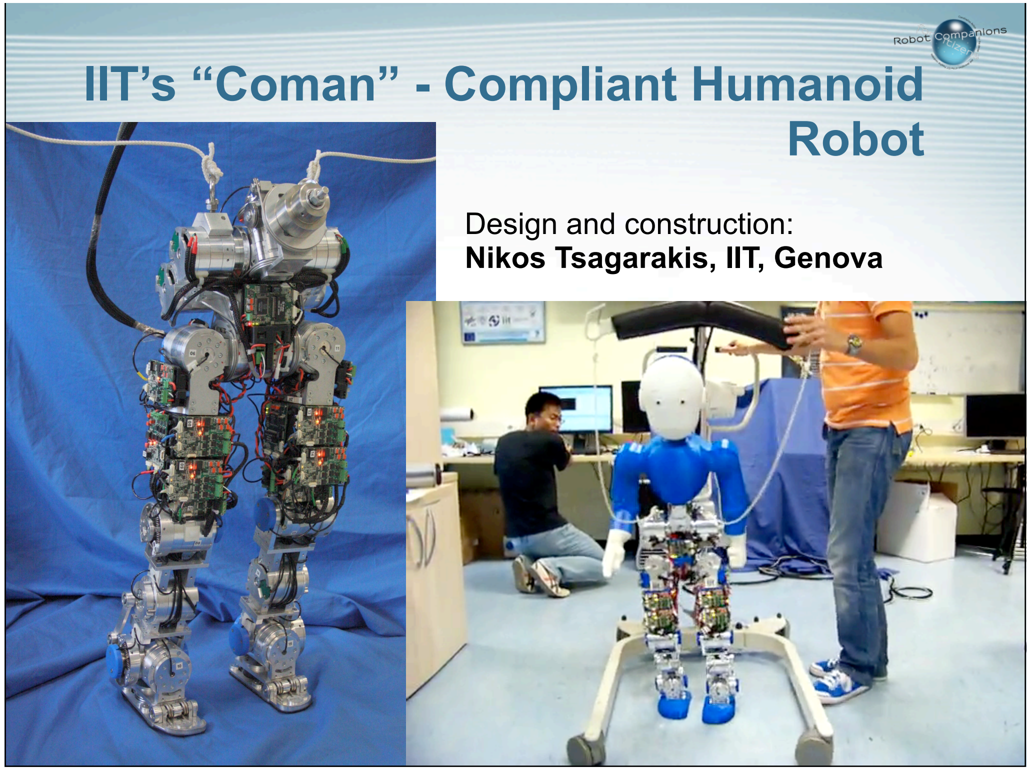


- self-stabilization
- morphological computation
- self-organization

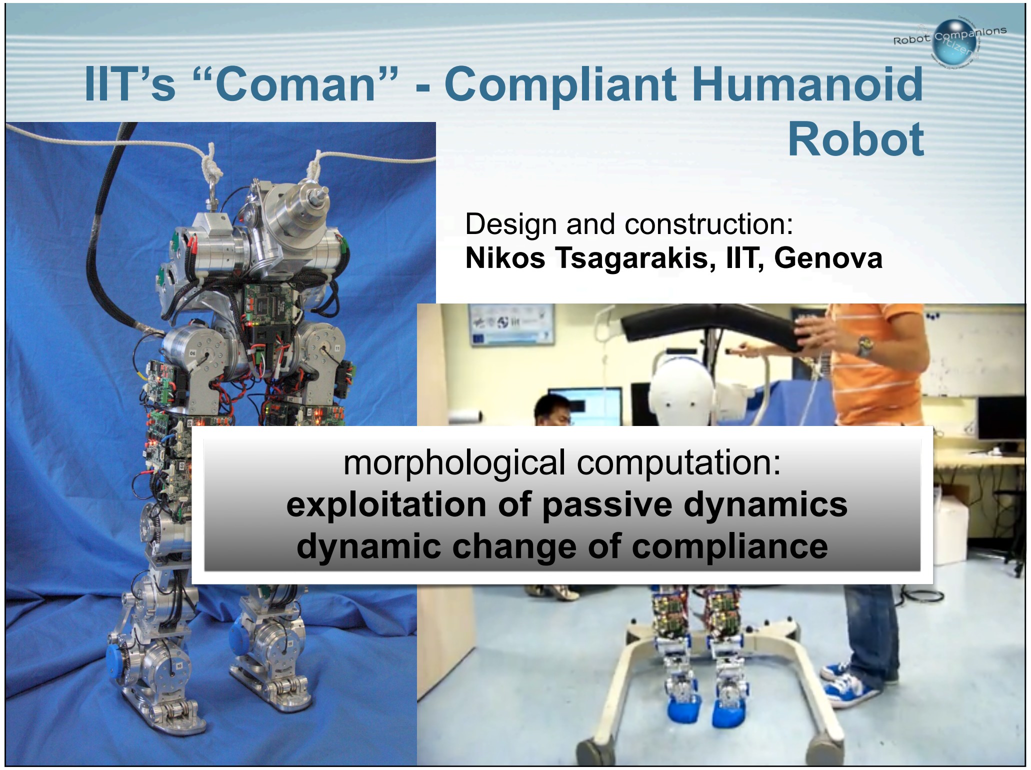
Pfeifer et al.
Science, 16 Nov. 2007

Human walking

- dynamical change of stiffness of muscles
- exploitation of passive swing forward
- high stiffness on impact
- coping with unevenness of ground
- “outsourcing” of functionality



variable-compliance: can dynamically change stiffness of joints; springs at joints —> coping with unevenness in the ground.



operates with on less than 200W
application to human walking

Principle 2: Task distribution

Task distribution between brain (control), body (morphology, materials), and environment

no clear separation between control and hardware ("soft robotics" - compliant legs)

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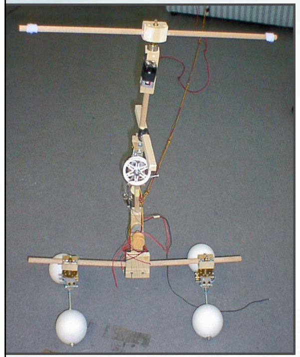
re-thinking of "control"
("orchestration")
in terms of morphological computation

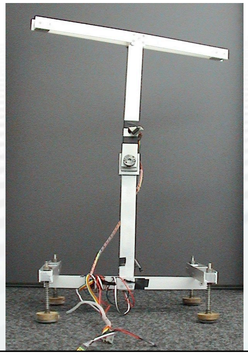
- exploitation of passive dynamics
- exploitation of - changeable - material properties

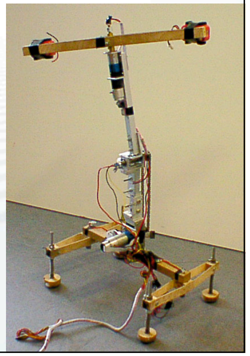
The dancing robot "Stumpy"



almost brainless: 2 actuated joints
springy materials
surface properties of feet

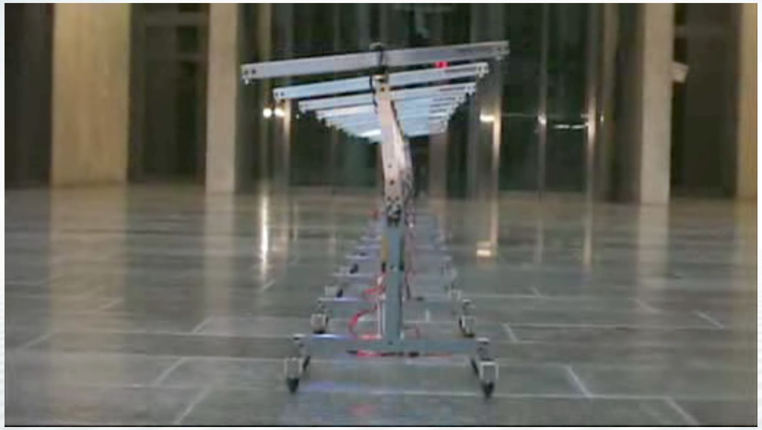
Design and construction: **Raja Dravid, Chandana Paul, Fumiya Iida**





—> many different gait patterns with only 2 joints

Choreography with “Stumpy”



Movie:
Dynamic Devices and AILab, Zurich

(with Louis-Philippe Demers, Nanyang Technological University, Singapore)

Contents

The "robot frog" driven by pneumatic actuators (UTokyo)

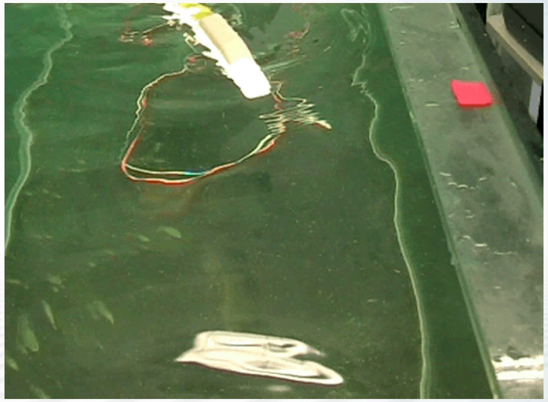
Design and construction:
Ryuma Niiyama and Yasuo Kuniyoshi University of Tokyo

pneumatic actuators:
compliant materials

The damped oscillatory movement after impact is not controlled but the result of the morphological and material characteristics (pneumatic actuators).

The power of materials: The robot fish “Wanda”

design and construction:
Marc Ziegler, AI Lab, UZH

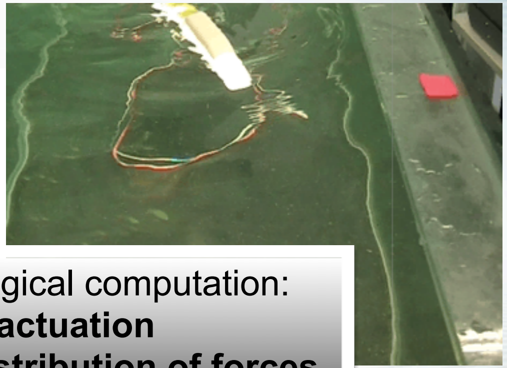


materials

changeable stiffness

maneuverability in 3D space

The power of materials: The robot fish "Wanda"



design and construction:
Marc Ziegler, AI Lab, UZH

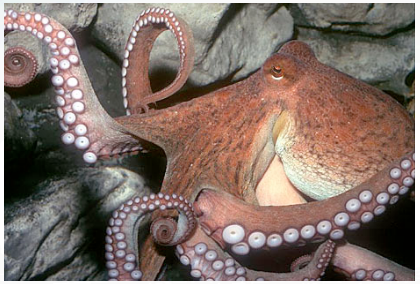
materials

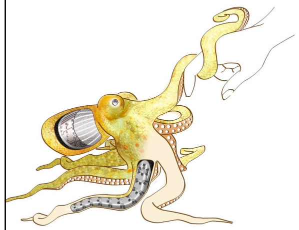
changeable st

maneuverabili
3D space

morphological computation:
actuation
optimal distribution of forces along tail fin

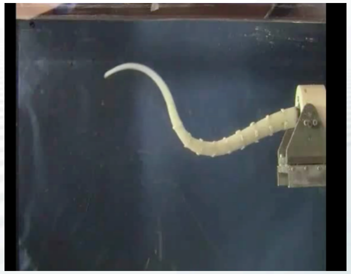
The power of materials:
The robot octopus (Cecilia Laschi)



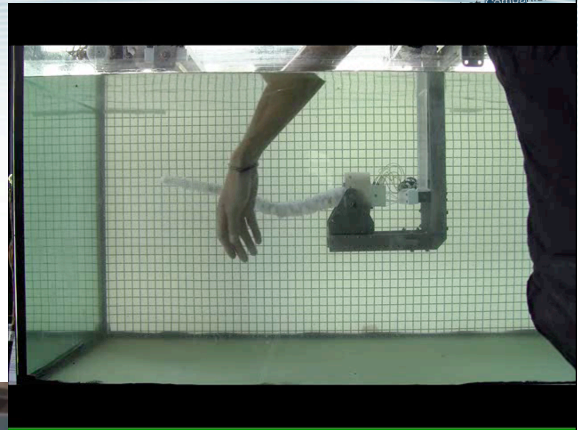


Octopus arm
design and construction:

Matteo Cianchetti (SSSA)
Cecilia Laschi (SSSA)
Tao Li (UZH)
Naveen Kuppuswami (UZH)

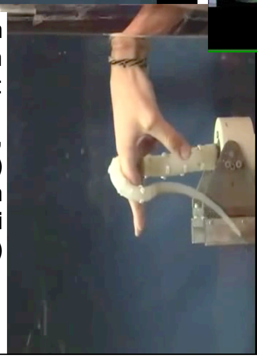


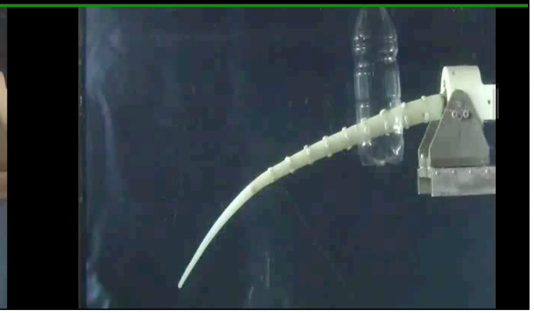
Movements of octopus arm

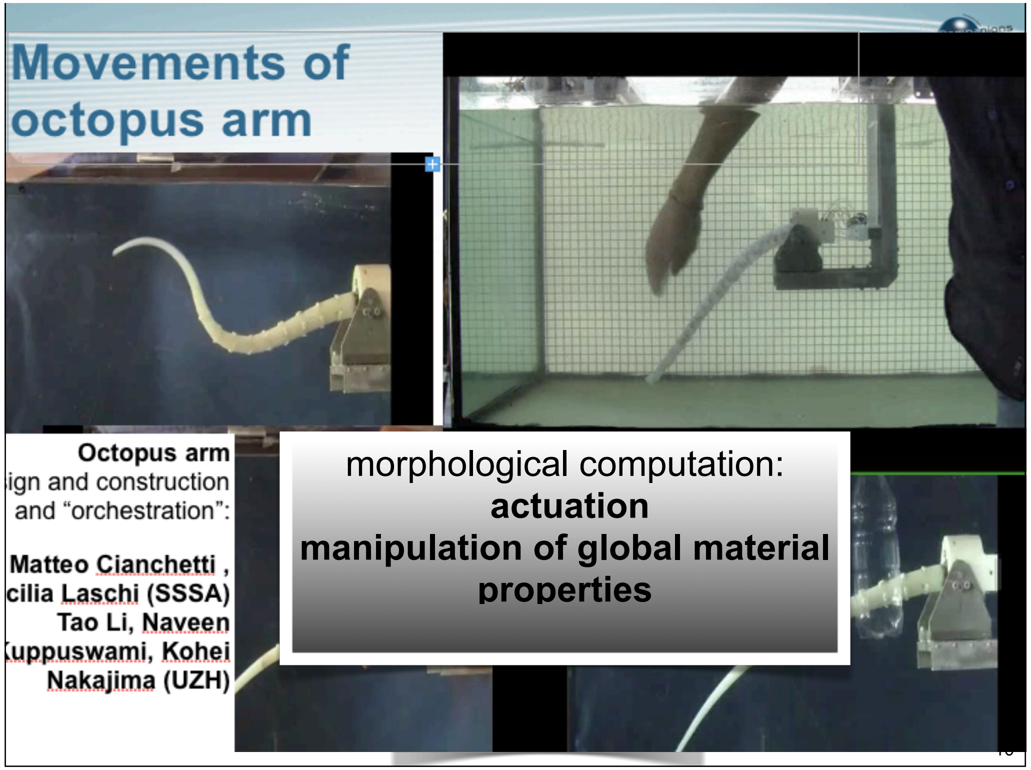


Octopus arm
design and construction and "orchestration":

Matteo Cianchetti , Cecilia Laschi (SSSA) Tao Li, Naveen Kuppuswami, Kohei Nakajima (UZH)







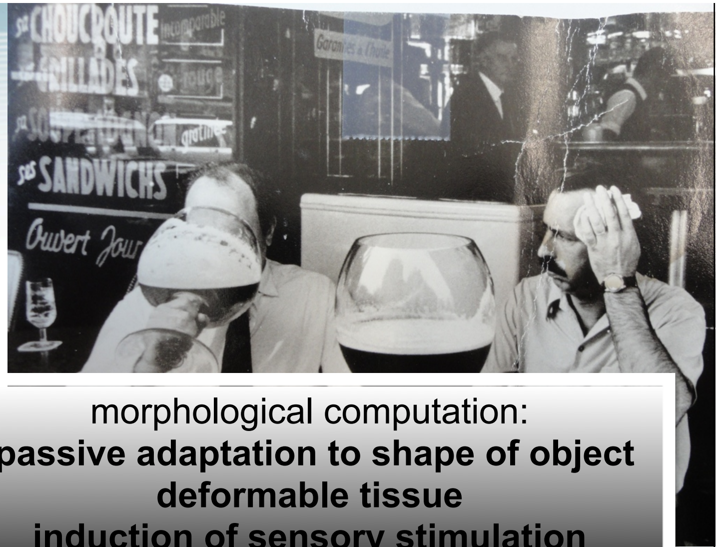
mouvements d’un prototype
actionnement de la base du bras - le reste est passif
plusieurs conceptions: cables attachés à positions divers à l’intérieur du bras;
propagation d’une onde de rigidité (plustôt que controller des segments individuels)

Orchestration of grasping

stably grasping hard object

other manipulation tasks

Orchestration of grasping

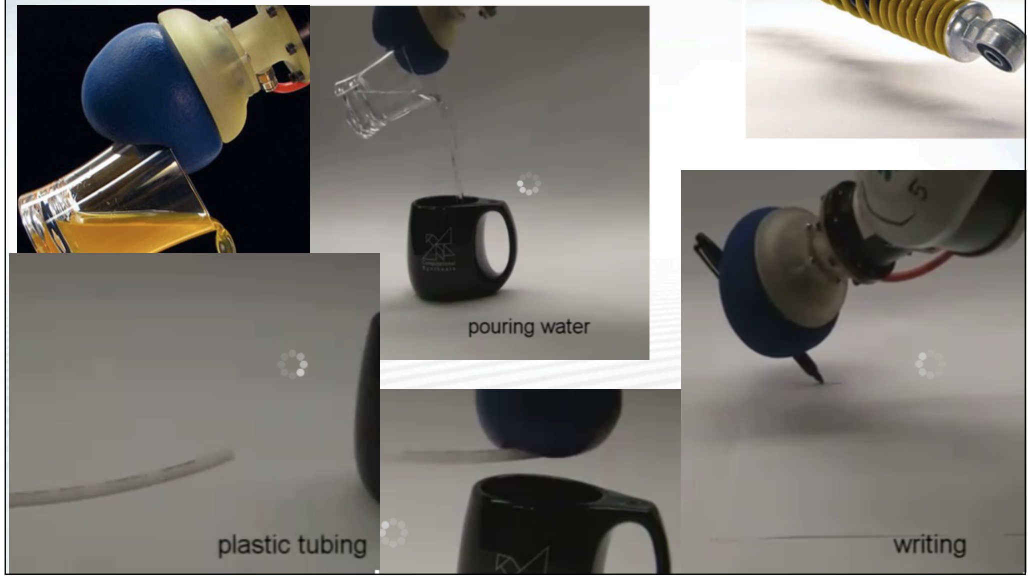


morphological computation:
passive adaptation to shape of object
deformable tissue
induction of sensory stimulation

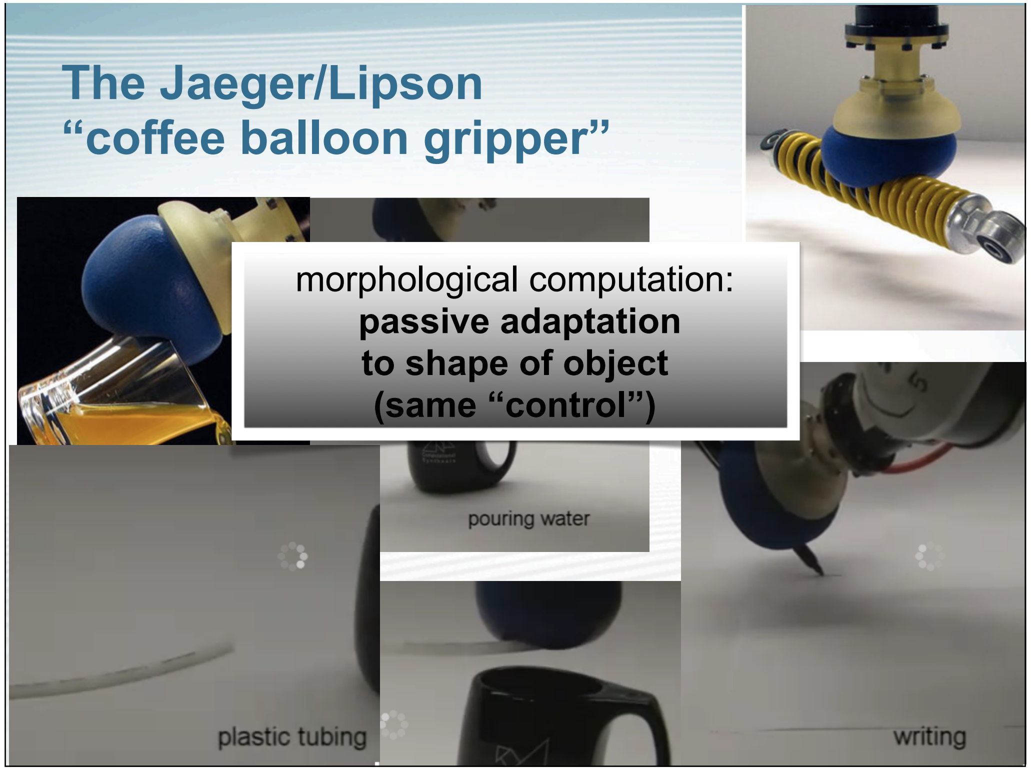
stably grasping hard object

other manipulation tasks

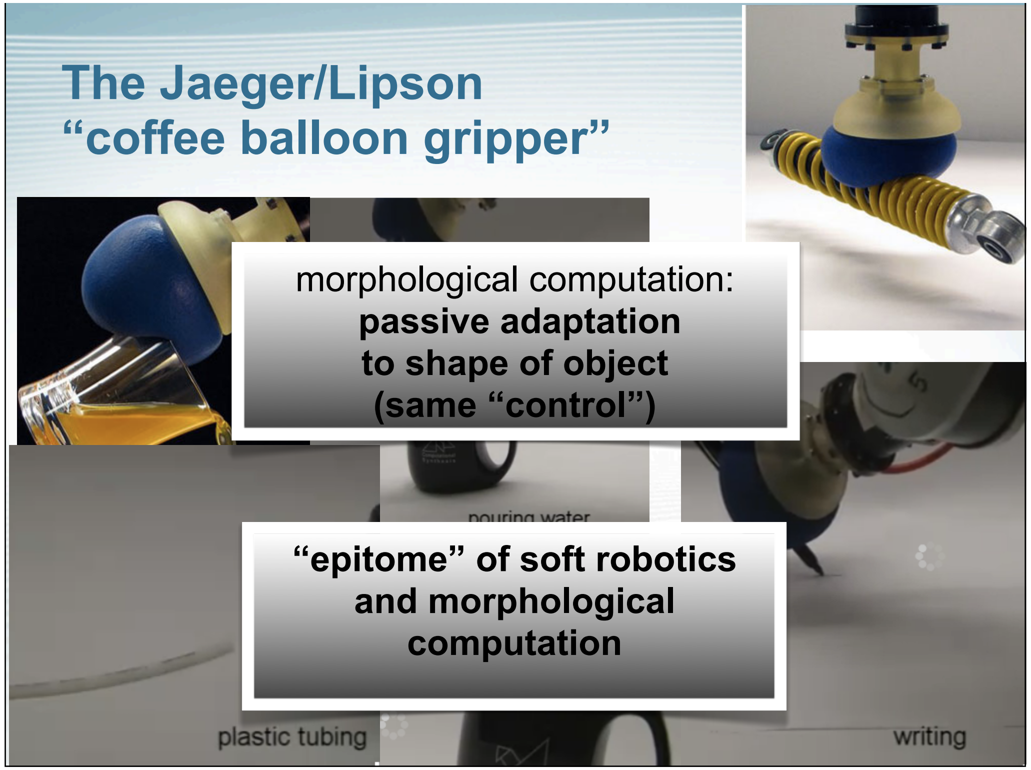
The Jaeger/Lipson “coffee balloon gripper”



The Jaeger/Lipson "coffee balloon gripper"


The Jaeger/Lipson
“coffee balloon gripper”
morphological computation:
passive adaptation
to shape of object
(same “control”)
pouring water
plastic tubing
writing

The Jaeger/Lipson "coffee balloon gripper"



morphological computation:
passive adaptation to shape of object (same "control")

"epitome" of soft robotics and morphological computation

Principle 2: Task distribution

Task distribution between brain (control), body (morphology, materials), and environment

no clear separation between control and hardware ("soft robotics" - compliant legs)

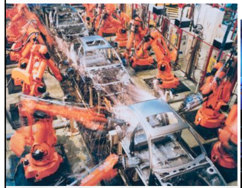
re-thinking of "control"
("orchestration")
in terms of morphological computation

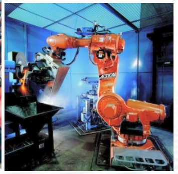
- exploitation of passive dynamics
- **exploitation of - changeable - material properties**

Import for manufacturing - the next industrial revolution

beyond traditional manufacturing: new manipulation skills

hard robotics





softbots
Robot Companions

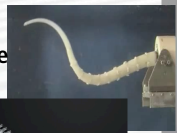
new manufacturing technology

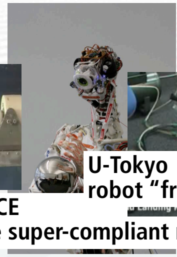
new industrial revolution

HEARTLAND ROBOTICS

Rodney Brooks

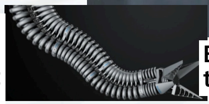
OCTOPUS
arm prototype





U-Tokyo
robot "frog"

Festo Bionic
Handling assistant



ECCE
the super-compliant robot

adept
YOUR INTELLIGENT ROBOTICS PARTNER

Foxconn: 1 mio robots within the next three years

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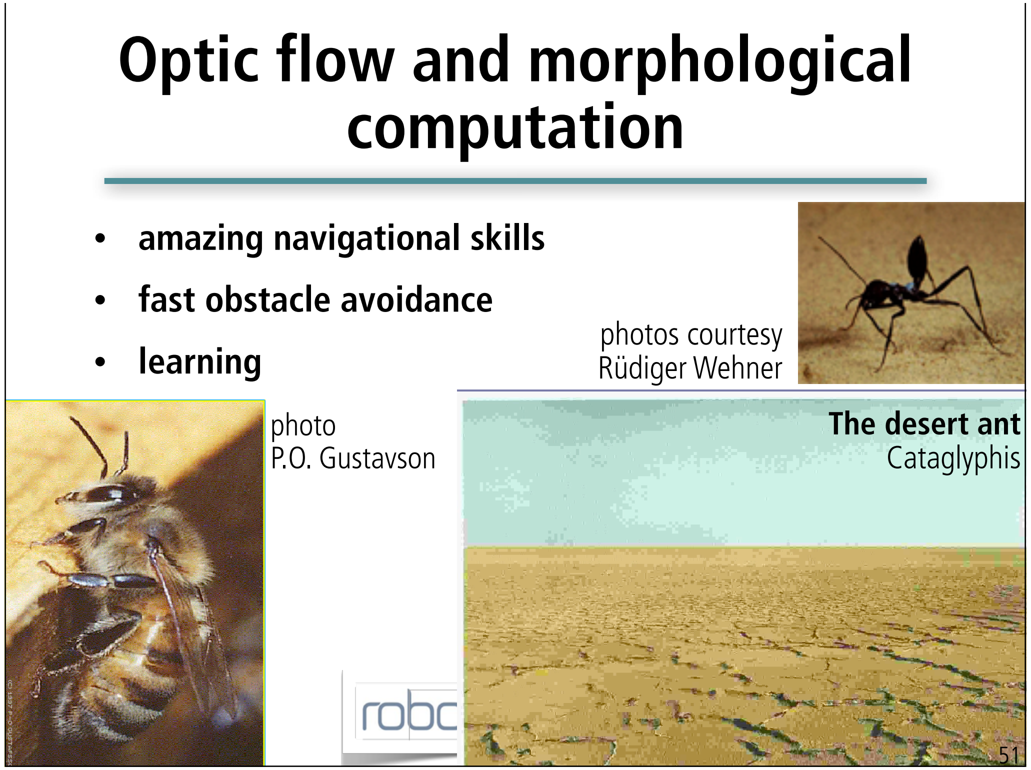
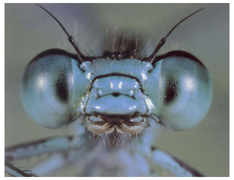


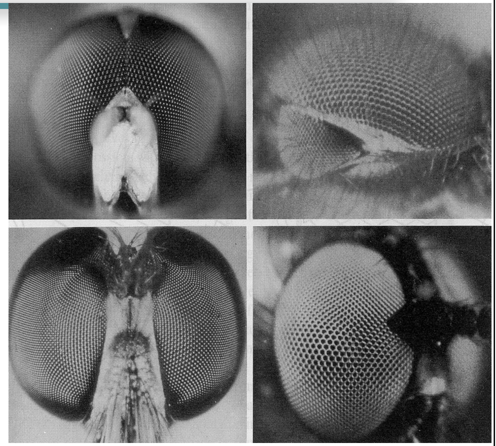
Ecological niche of Cataglyphis; salt pan near Maharès in Southern Tunisia.

Different morphologies of insect eyes

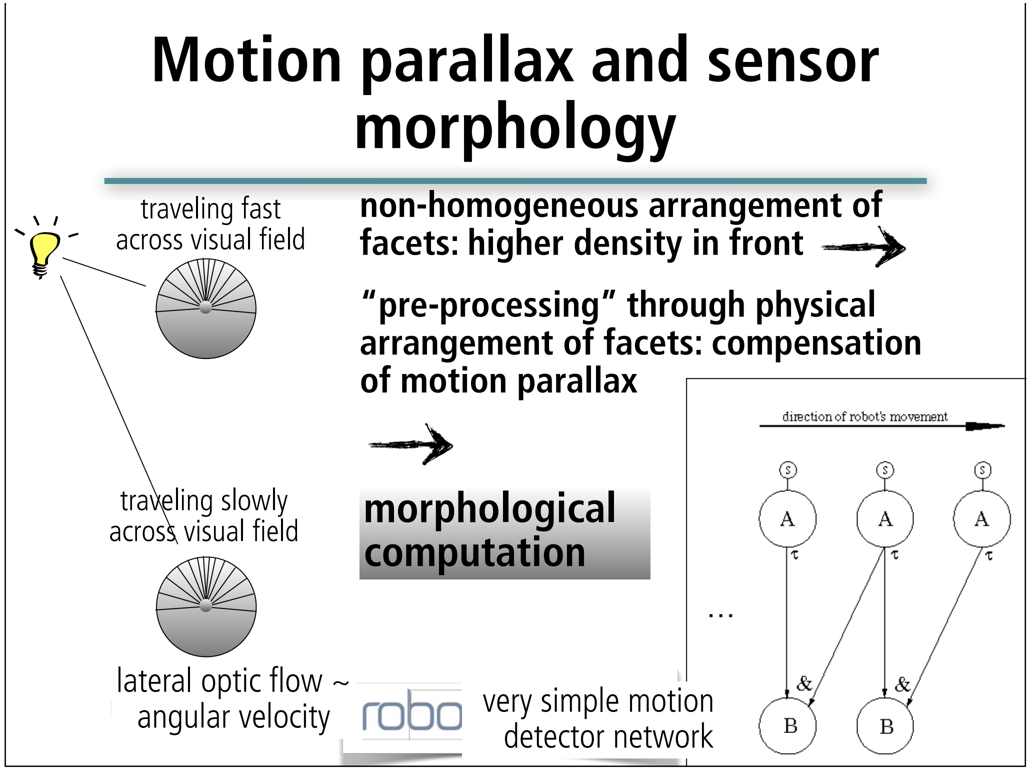
housefly



large variation of shapes



honey bee

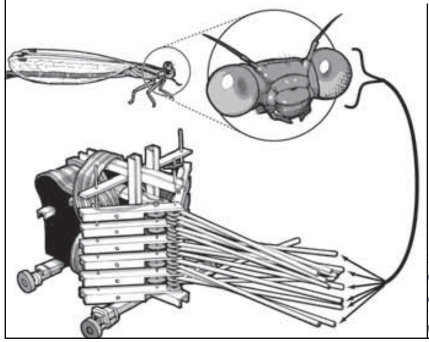


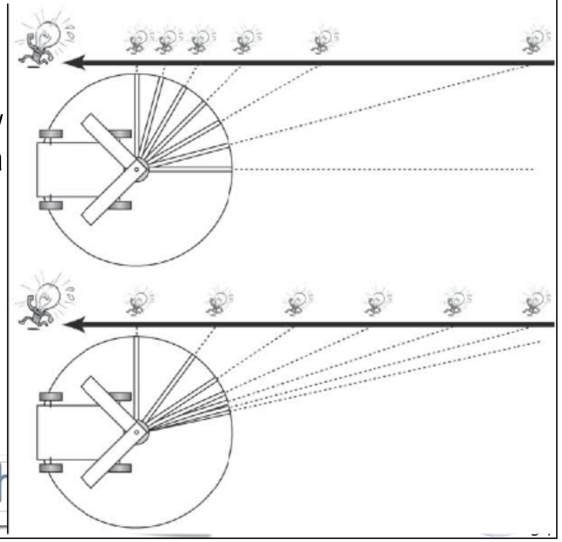
Non-homogenious arrangement of facets --> compensates motion parallaxe.

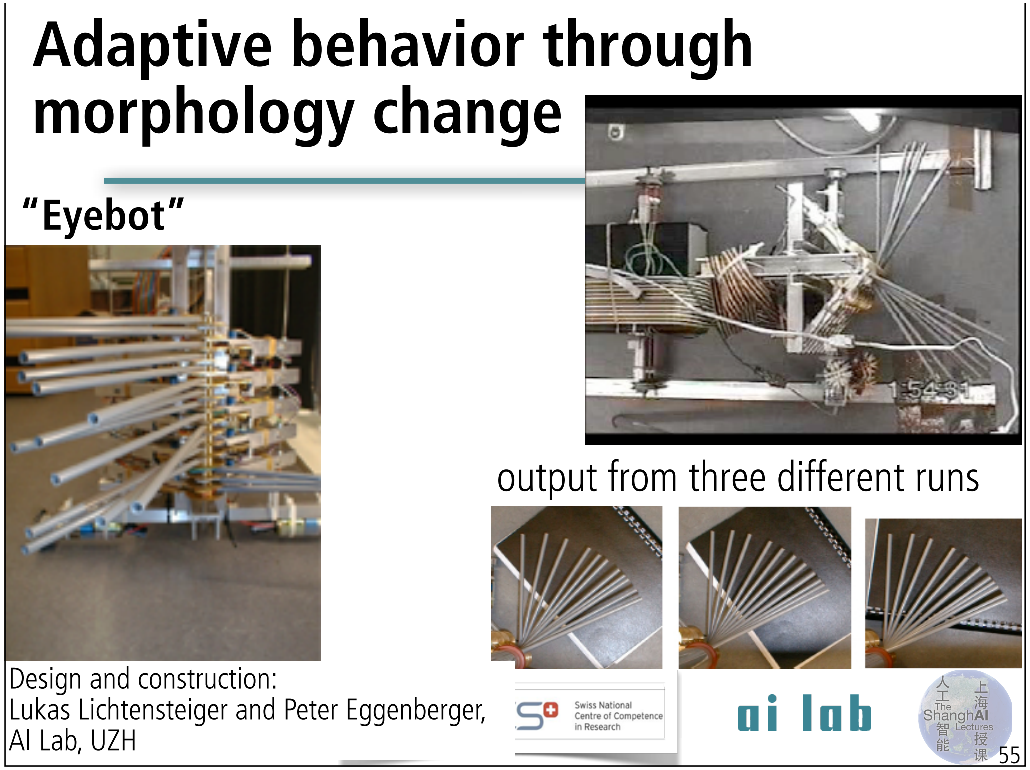
The “Eyebot” and motion parallax

read details in:
“How the body…” p. 131

Cartoons by
Shun Iwasawa







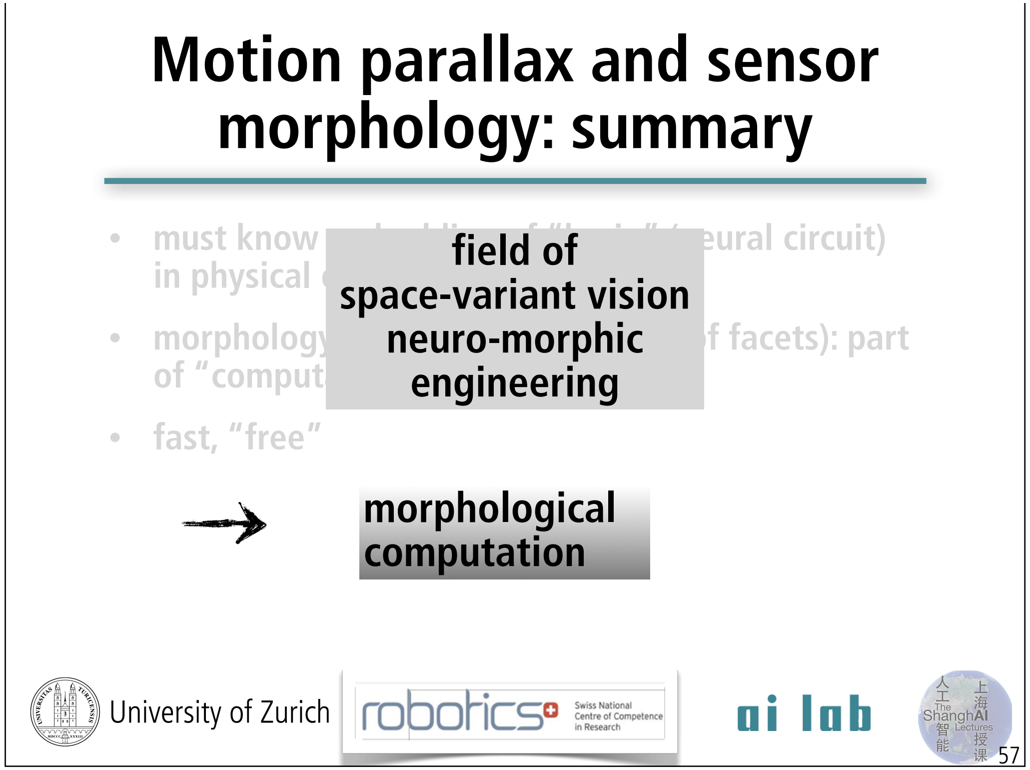
The "facets" which are tubes with a light-sensitive cell at the end, can be moved individually. The task of the robot was to maintain a fixed lateral distance to a light source. An evolutionary algorithm (see lecture 6) was run that modified the angular positions of the "facets". The "brain" of the robot, i.e. the controller in the form of a neural network was not changed; the robot had to solve the problem by changing its morphology. If the robot managed to solve the task, nothing was changed, if not, the angular positions of the "facets" were changed ("mutation"). Because of motion parallax, this is a hard problem. The output from three different runs shows that the resulting arrangements are all non-homogeneous, with densities higher in the front.

Motion parallax and sensor morphology: summary

- **must know embedding of "brain" (neural circuit) in physical organism**
- **morphology (physical arrangement of facets): part of "computation" (pre-processing)**
- **fast, "free"**

→ **morphological computation**

It can also be shown that there is a dependence of learning speed on morphology (because the environment is sampled differently)



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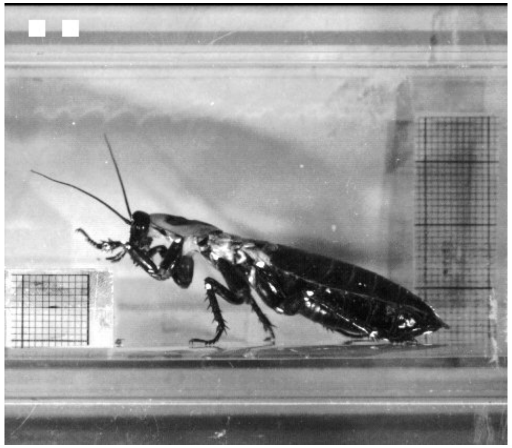
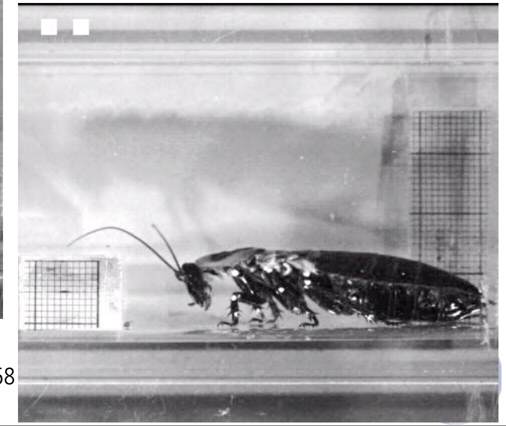
Exploiting morphology: managing complex bodies

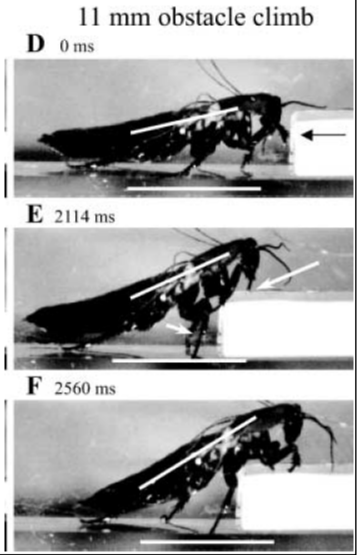


pictures and ideas:
courtesy Roy Ritzmann
Case Western Reserve University



"Outsourcing" functionality: exploiting morphology

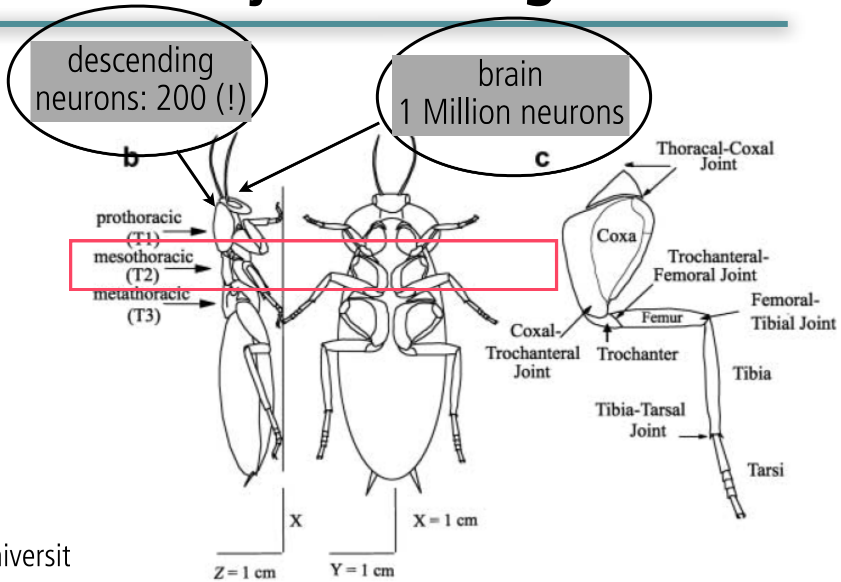
- **brain: 1 Million neurons (rough estimate)**
- **descending neurons: 200 (!)**
- brain:
  - cooperation with local circuits
  - morphological changes (shoulder joint)



- **Watson, Ritzmann, Zill & Pollack, 2002, J Comp Physiol A**

The following considerations are highly speculative but they make, hopefully, a good story about morphological computation.

Effects of morphology change shoulder joint configuration



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rather than recalculating the joint trajectories: changing the mechanical configuration of the mesothoracic shoulder joint (morphological - global - parameter)

Climbing over obstacles

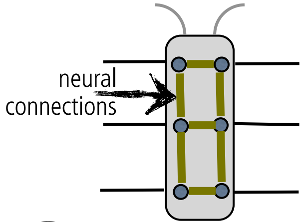
- CPG on flat ground
- get hight estimate from antenna
- change configuration of shoulder joint
- CPG continue to function as before (don't "know" about climbing)
- brain-body cooperation

because the mechanical configuration of the shoulder joint is changed, even though the local CPGs continue doing the same thing, the effect on behavior will be different

Insect walking: Information transmission through interaction

Holk Cruse, German biologist

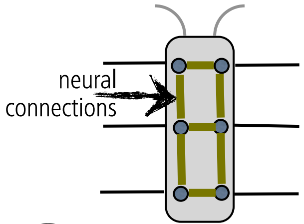
- **no central control for leg-coordination**
- **only communication between neighboring legs**



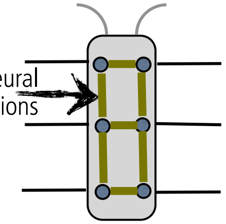
Insect walking

Holk Cruse, German biologist

- **no central control for leg-coordination**
- **only communication between neighboring legs**
- **global communication:**



Insect walking



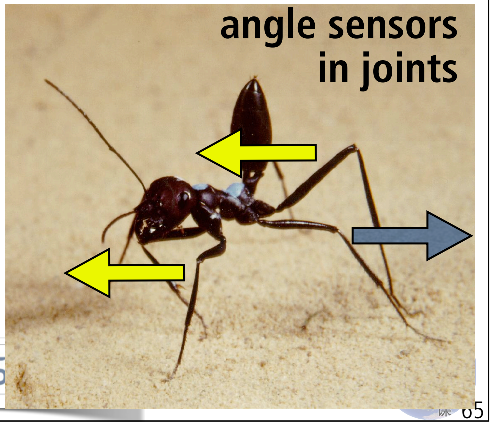
Holk Cruse, German biologist

- **no central control for leg-coordination**
- **only communication between neighboring legs**
- **global communication: through interaction with environment**

Communication through interaction with environment

- exploitation of interaction with environment
  → simpler neural circuits

morphological computation

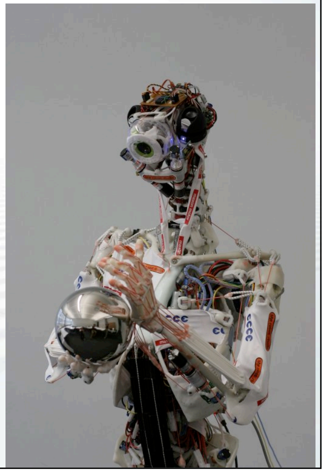


Contents

Induction of “information structure”: the soft, super-compliant humanoid “ECCE”

Generation of sensory stimulation through action

- knowledge about environment: **pressure, haptic, acceleration, vision, ...**
- knowledge about own body: **angle, torque, force, vestibular, …**



(**ECCE:** Embodied Cognition in a Compliantly Engineered Robot EU-FP7, Cognitive Systems)

Principle 3: Physical dynamics and information structure

Induction of patterns of sensory stimulation through physical interaction with environment

—>

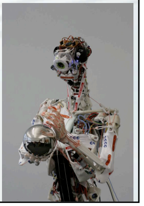
raw material for information processing of brain (control)

—>

induction of correlations (information structure)

—>

predictions/expectation



Induction of information structure through interaction with world

morphological computation:

patterns of sensory stimulation:

dependence on

- morphology

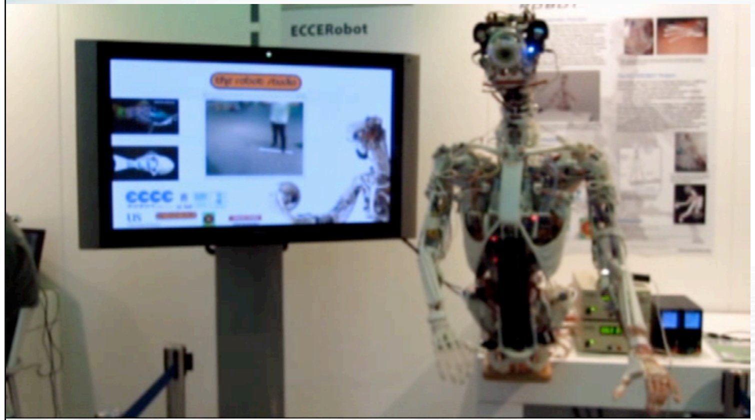
- materials

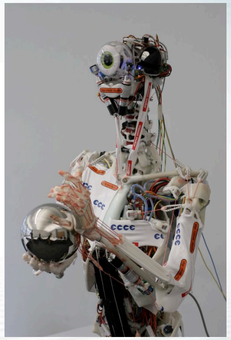
- action

- environment

induction of information structure

Induction of “information structure”: the soft, super-compliant humanoid “ECCE”





Anthropomorphic design

fully tendon-driven

—> “Bernstein’s problem”

Bernstein's problem: coping with very many degrees of freedom

programming? —> complexity barrier

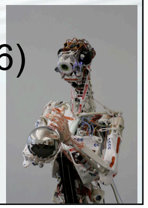
—> developmental approach - learning methods required

- "motor babbling"

- induction of information structure through physical interaction with real world

(nice illustration of morphological computation)

Nikolai Bernstein, Russian Physiologist, 1896 - 1966)



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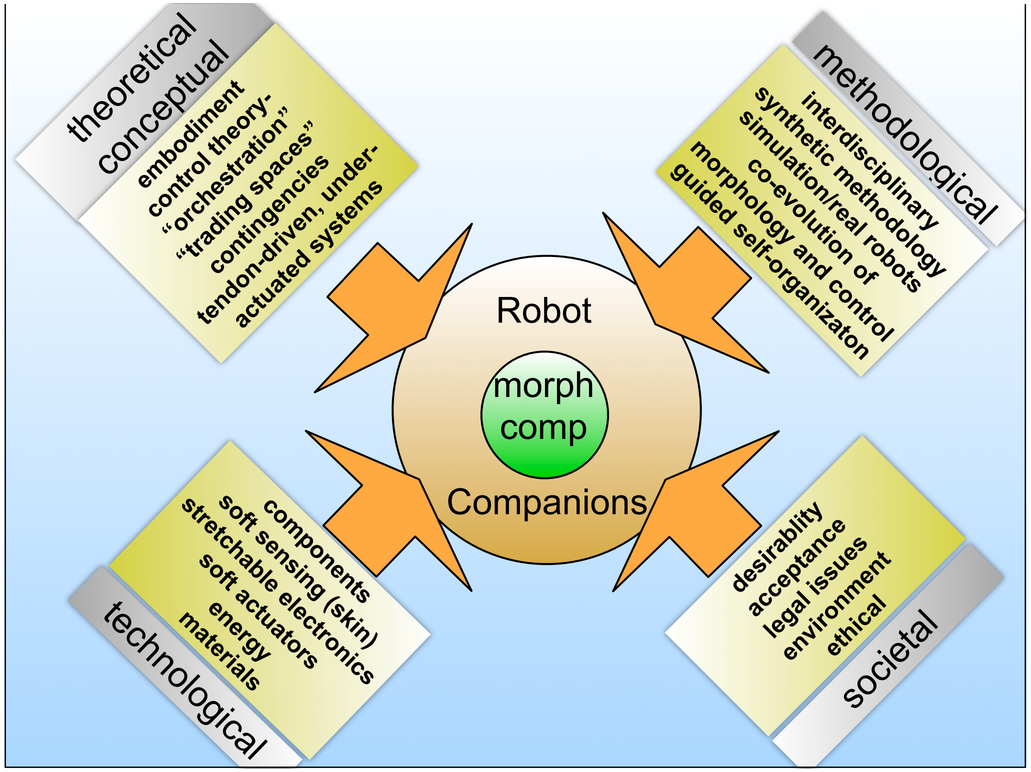

theoretical
conceptual
embodiment
control theory-
"orchestration"
"trading spaces"
contingencies
tendon-driven, under-
actuated systems
methodological
interdisciplinary
synthetic methodology
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Robot
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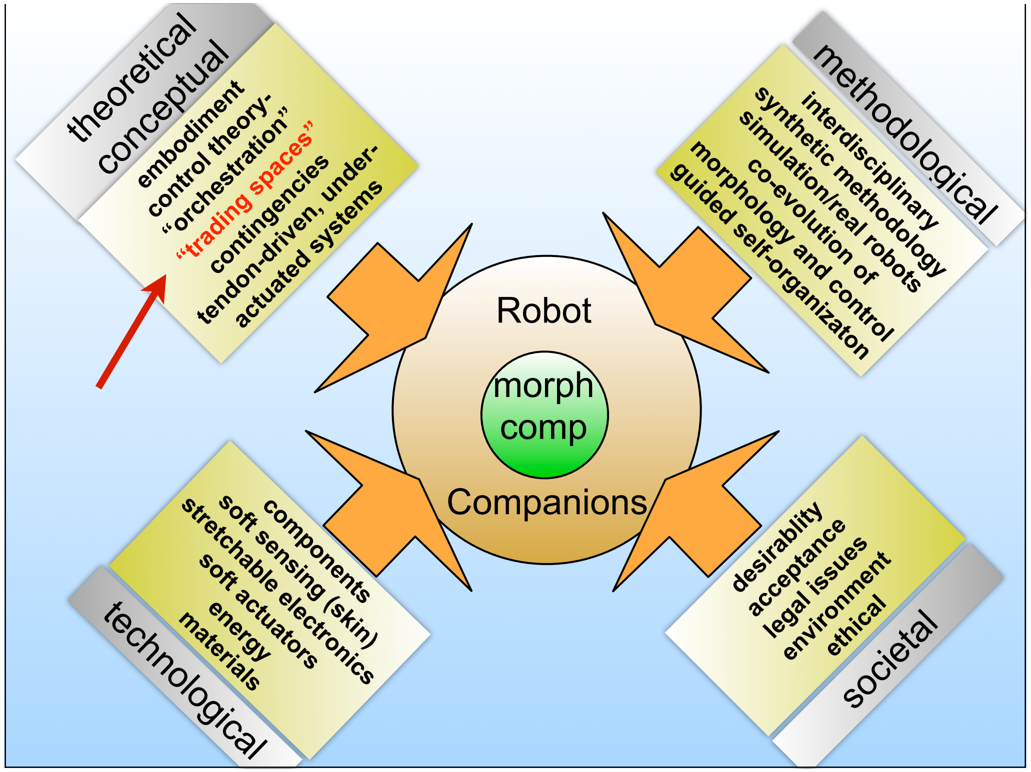
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Expansion of design space: trading spaces and trade-offs

- morphologies (physical structure, distribution of sensors, actuators)

- many materials, functionalities

- changeable characteristics (e.g. stiffness, length, shape, sensor distribution)

- trade-offs: morphology/materials - flexibility (but changeable properties)

- must understand “trading space”: morphology - computation/control

- “orchestration of movement” (partly contained in morphology and materials)

Morphology and computation: “trading spaces”

increasing dominance of morphology and materials

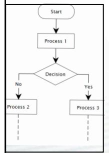
informational computation

control and behavior less separable
decreasing relative energy for control

morphological computation

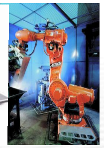
control dominant

morphology and materials dominant



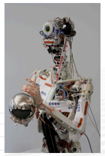
pure algorithm

computer (running algorithm)

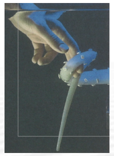


industrial robot (centralized control

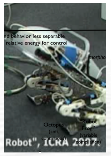
Asimo (and similar robots)



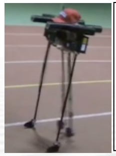
ECCE (compliant, tendon-driven)



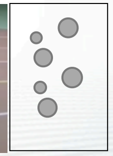
Octopus (soft, continuous)



“Robot Frog” (variable compliance)



Cornell Ranger (exploiting morphology)



cells molecules “Tribolons”

Morphology and computation: "trading spaces"

increasing dominance of morphology and materials

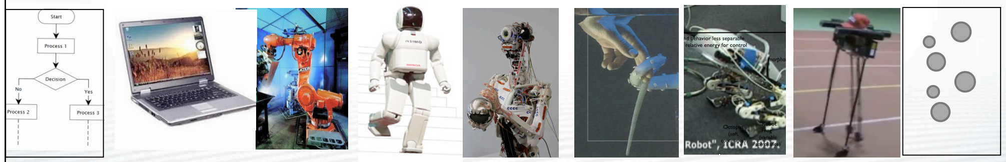
informational computation

control and behavior less separable
decreasing relative energy for control

morphological computation

control dominant

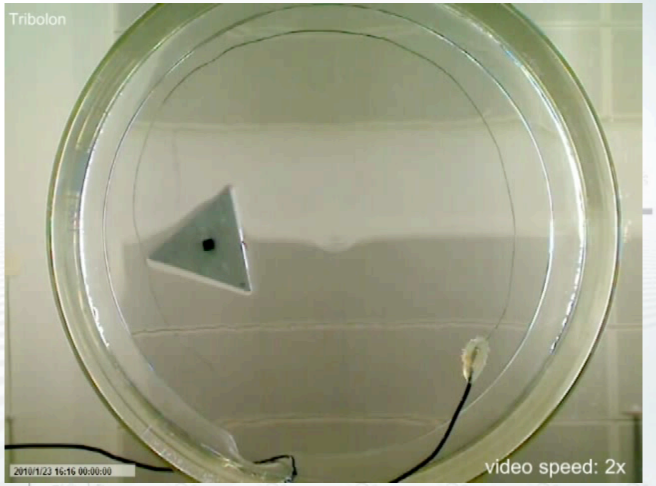
morphology and materials dominant



pure algorithm	computer (running algorithm)	industrial robot (centralized control	Asimo (and similar robots)	ECCE (compliant, tendon-driven)	Octopus (soft, continuous)	"Robot Frog" (variable compliance)	Cornell Ranger (exploiting morphology)	cells molecules "Tribolons"

Morphological computation: self-assembly and emergent functionality

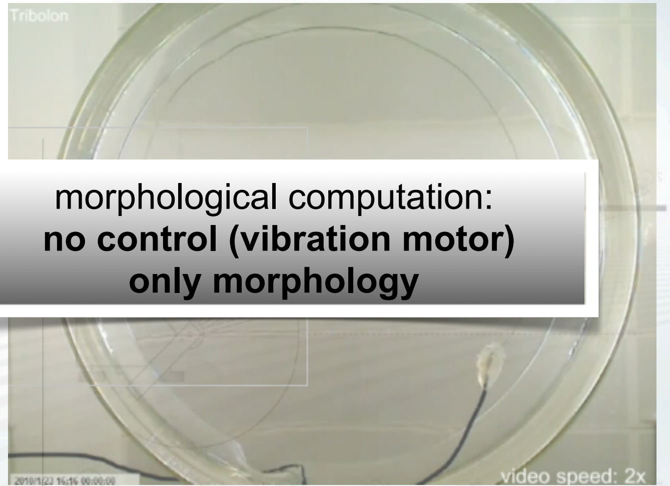
"The self-assembled, emergent bicylce"



Design and construction:
Shuhei Miyashita
(Zurich AI Lab, and CMU)

Morphological computation: self-assembly and emergent functionality

“The self-assembled, emergent bicylce”



morphological computation:
no control (vibration motor)
only morphology

Design and construction:
Shuhei Miyashita
(Zurich AI Lab, and CMU)

Morphology and computation: “trading spaces”

increasing dominance of morphology and materials

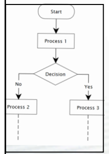
informational computation

control and behavior less separable
decreasing relative energy for control

morphological computation

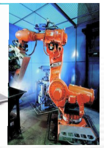
control dominant

morphology and materials dominant



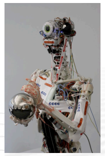
pure algorithm

computer (running algorithm)

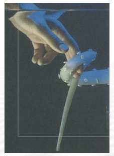


industrial robot (centralized control

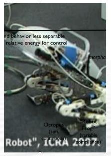
Asimo (and similar robots)



ECCE (compliant, tendon-driven)



Octopus (soft, continuous)



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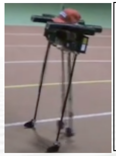
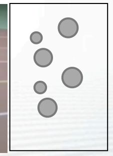


Cornell Ranger (exploiting morphology)



cells molecules “Tribolons”

Mind set: “Design for emergence”

given a set of desired behaviors, design a robot/device:

- morphology (shape, sensor distribution, materials [possibly changeable], actuation)

- neural system (“control”, “orchestration”)

such that its behavior emerges from morphology, materials, and “control”/ “orchestration”

(always with soft machines)

Summary of morphological computation principles

must understand:

- physical embedding and information processing (principle 1)

- task distribution (morphology, materials, control, environment) and embedding (principle 2)

- induction of information structure through interaction with real world (principle 3)

—> exploitation of embodiment

Contents

- background and introduction
- morphological computation: examples and case studies
- the “power of materials”
- exploiting sensory morphology
- information structure through sensory-motor coordination
- research challenges
- **the Swiss perspective**

robotics

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Intelligent robots for improving the quality of life

Version Française

The National Centre of Competence in Research (NCCR) Robotics is a nation-wide center, launched by the Swiss National Science Foundation, with the common objective of developing new, human-oriented robotic technology for improving our quality of life.

This center gathers leading robotic experts in Switzerland from cutting-edge research institutions: EPFL as the home institution, ETH Zurich, University of Zurich and Dalle Molle Institute for Artificial Intelligence. Launched on 1 December 2010, the NCCR Robotics will run for up to twelve years.

The NCCR Robotics brings together Swiss robotic research and aims to generate long-term benefits to society as a whole. Through this website, we would like to establish two-way communication about robotics in Switzerland and abroad with researchers, students, teachers, industries, and the general public.

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Highlights

Robots in Daily life -
NCCR Robotics 1st Symposium
16 June 2011, ETH Zurich
Registration is now closed. We will re-open the registration again if any seats become available.

Europe shortlisted Robotics Flagship
Project *Robot Companions for Citizens* has been chosen among six other *grand challenges* by European Commission in Budapest. This project aims at developing *sentient machines* whose applications include helping elderly people or rescuing people in natural disasters.

Summer School - Dynamic Walking and Running with Robots
11-15 July 2011, ETH Zurich

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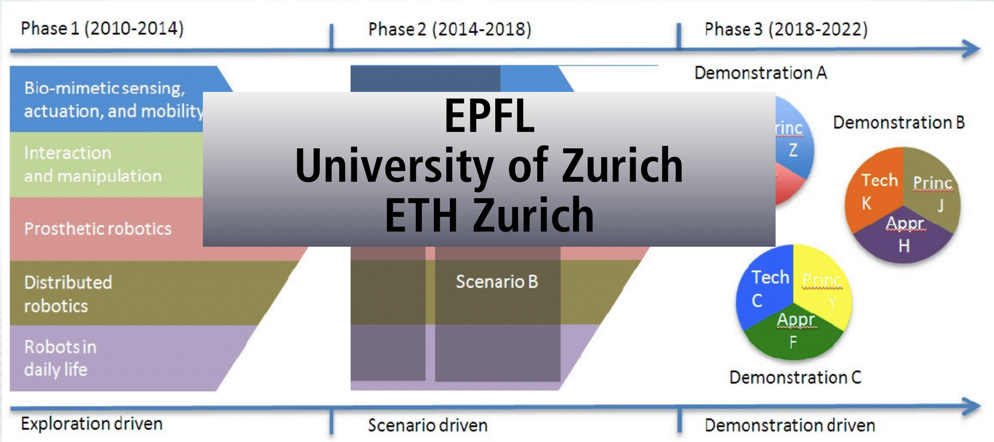
NCCR - Robotics
12 year perspective

Director:
Prof. Dario Floreano, EPFL



Exhibition
Public
Debate
Panels

“Better robots — better life!”

“Better robots — better life!”

Thank you for your attention