Morphological computation
Morphological Computation and Design Concepts for Future High Efficiency Robots
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Buzzwords

amorphous computing  self-assembling robots/materials  morphological computation  biochemical circuits

passive dynamics  molecular recognition systems  cellular computing  biomolecular devices

membrane computing  self-stabilization  autopoeisis  trading space

blob computing  DNA/molecular computing  patterning  genetic regulatory networks

self-organization  self-repair  neuro-morphic computing/engineering  tensegrity
Reservoir computing

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

Basic idea: a physical body as a reservoir

Input stream

Physical body
Temporal integration
Nonlinear combination

Mass points
Fix points

A readout
Linear, static

$y(t)$

$u(t)$

$\ldots$

$\text{states}$

$w_i$

$\sum$

$\ldots$

$\text{readout}$

$w_y$

$x = y$

$F = -kx - k' x' - d \dot{x} - d' \dot{x}' + F_i$

mass-spring system

$F_j(t) = \sum_i w_{ij} y_j(t)$

$P_0(0) = u_{in} : \delta(0)$

$P(t) = \text{fixed}$

$y(t) = \text{readout}$

$u(t) = \text{input stream}$

$w(t)$

$P(t)$

$\text{fix point}$

$\text{mass point}$

$\text{temporal integration}$

$\text{nonlinear combination}$
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
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

Soft to touch

Soft movement

Soft interaction

Expression

surprise  fear

happy  angry
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)
Variants of morphological computation

- **embodied computation, digital result** - need for read-out process (e.g. DNA computing, molecular computing, reservoir computing)

- **fully embodied** (e.g. self-assembling vesicles / molecules, passive dynamic walker, “Cornell Ranger”, “Wanda”, Octopus, “Coffee Ballon Gripper”)

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”

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

The “brainless” robot: walking without control

morphological computation: exploitation of passive dynamics and mechanical feedback
Overall scheme

Information self-structuring

Controller
Central nervous system

Motor commands

Body dynamics/morphology

Mechanical system
Musculoskeletal system

Internal physical stimulation

Movement

Mechanical feedback

Sensory system
Sensory receptors

External physical stimulation

Task-environment
Ecological niche

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?
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.
Previously, nobody would have thought this to be possible.
Overall scheme: self-stabilization in the "Cornell Ranger"

- Information self-structuring
- Controller
  - Central nervous system
- Motor commands
- Body dynamics/morphology
- Mechanical system
  - Musculoskeletal system
- Internal physical stimulation
- Sensory system
  - Sensory receptors
- External physical stimulation
- Task environment
  - Ecological niche

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.
IIT’s “Coman” - Compliant Humanoid Robot

Design and construction: Nikos Tsagarakis, IIT, Genova

morphological computation:
exploitation of passive dynamics
dynamic change of compliance

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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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
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)
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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 stiffness
maneuverability in 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

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 (plutôt 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)

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

re-thinking of “control” (“orchestration”) in terms of morphological computation
Import for manufacturing - the next industrial revolution

beyond traditional manufacturing: new manipulation skills

hard robotics

softbots

Robot Companions

new manufacturing technology

new industrial revolution

OCTOPUS arm prototype

Festo Bionic Handling assistant

ECCE the super-compliant robot

U-Tokyo robot "frog"

Rodney Brooks
New manipulation skills

Foxconn: 1 mio robots within the next three years
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Optic flow and morphological computation

- amazing navigational skills
- fast obstacle avoidance
- learning

Ecological niche of Cataglyphis; salt pan near Maharès in Southern Tunisia.
Different morphologies of insect eyes

housefly

large variation of shapes

honey bee

University of Zurich
Motion parallax and sensor morphology

Non-homogeneous 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.
It can also be shown that there is a dependence of learning speed on morphology (because the environment is sampled differently)
Motion parallax and sensor morphology: summary

- must know embedding of “brain” (neural circuit) in physical organism
- morphology — physical arrangement of facets: part of “computation” — preprocessing
- fast, “free”

field of space-variant vision neuro-morphic engineering

morphological computation

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

pictures and ideas:
courtesy Roy Ritzmann
Case Western Reserve University

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

neural connections
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

angle sensors in joints
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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”

Fully tendon-driven

Anthropomorphic design

→ “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
simulation/real robots
coevolution of
morphology and control
self-organized guided

complementary
components
soft sensing (skin)
soft actuators
energy
materials

societal
desirability
acceptance
legal issues
environment
ethical

Robot
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Companions
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Robot
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Companions

"morph comp"
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

control dominant

informational computation

control and behavior less separable

decreasing relative energy for control

morphological computation

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 → Morphological computation

- Control dominant
  - Increasing dominance of morphology and materials
  - Control and behavior less separable
  - Decreasing relative energy for control

- Morphology and materials dominant
  - Increasing dominance of morphology and materials
  - Control and behavior less separable
  - Decreasing relative energy for control

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) "Trichobutons"
Morphological computation: self-assembly and emergent functionality

“The self-assembled, emergent bicycle”

Design and construction: Shuhei Miyashita (Zurich AI Lab, and CMU)
Morphological computation: self-assembly and emergent functionality

“The self-assembled, emergent bicycle”

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), "Robot Frog" (variable compliance), 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
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Highlights

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

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

The National Centre of Competence in Research (NCCR) Robotics is a nationwide 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 Delta Motion 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 the website, we would like to establish a two-way communication about robotics in Switzerland and aimed at researchers, students, teachers, industry, and the general public.
NCCR - Robotics
12 year perspective

Director:
Prof. Dario Floreano, EPFL

EPFL
University of Zurich
ETH Zurich
World Congress and Exhibition of Robots, Humanoids, Cyborgs and more
9th March 2013 in Zurich

“On the occasion of the 25th anniversary of the Artificial Intelligence Laboratory, University of Zurich”

The aim of the World Congress and Exhibition of Robots, Humanoids, Cyborgs, and more is to present recent advances in artificial intelligence and robotics.
“Better robots — better life!”
“Better robots — better life!”

Thank you for your attention