Morphological Control – Applied Embodied Intelligence in Medicine, Robotics and IT

ML – MEETUP
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• Drinking beer: You walk, because your body computes.
• Chemically embodied intelligence: Much more than robots!
• Evolving self – assembling computers: Some Dos, some Don’t's.
• Spatially structured reaction environments: Synthetizing branched polymers.
• Speculations about the immune system
Embodied Intelligence

Technical Systems
(Robocup 2013)

Biological Systems
Embodied Intelligence

Embodiment: Control outsourced to body morphology.
In general: BLURR DISTINCTION BETWEEN HARD-AND SOFTWARE
Gait Patterns
Gait Patterns

- **Brain** chooses red or green basin of attraction.
- **Body-dynamics** drives system into attractor (and keeps it there).
Gait Patterns: Picture incomplete

- Transient time should be short.
- Fluctuations: Strong damping
- Attractor landscape can be changed.
Aging: Loss of Control over Movements
Good News from MorphControl

We can't rejuvenate your body. But maybe, we can rejuvenate your attractor landscape!
First Steps Towards Support System

Test system for supporting and stabilizing knee dynamics: Not a servo!

A.Dzyakanchuk, Kenneth Hunt, R. Füchslin, R. Luchsinger, M. Muster
• **Feed-forward neural networks** have some but not universal computational power.
• **Mechanical mass-spring systems** can generate time-dependent signals.

**Recent result:** A **properly interfaced hybrid system** (mass-spring + feed forward neural network) can emulate/compute large classes of filters (functions onto functions).

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**References:**


The Hidden Charm of Nature

- Nature is indifferent towards the problems of numerical analysis:
  - Nature doesn't care about the type of ODE to solve.
  - Nature implicitly deals with complicated boundary conditions, e.g. shape of objects.
- Nature is inherently parallel.
- The physics is already there: You haven’t to code it, but you also cannot go beyond it.
- Morphological control is evolvable.
- Temperature delivers random numbers for free.
“Ideal” conventional control: complete abstraction of the control task.
Conventional Control: Real Situation

Real control: minimize the effects of the morphology.

Makes robots stiff (localization in real space) and heavy (localization in momentum space).
Morphological control exploits and optimizes the effects of morphology.
Tendon driven humanoid robot

Soft robots at the lab of G. Whitesides

Soft robots are safe(r) robots! (and cheaper and nicer and …)
Embodied Process Control
Embodied Process Control

Embodied Intelligence in Robotics
Classical Mechanics
= 
Embodied Process Management in Chemistry
Statistical Mechanics

Morphology
= 
Chemistry + supramolecular compounds + membranes + …
Cells: The Network Picture

Cell as a dynamical network of physico-chemical interaction
Multi-Scale Processes: Endocytosis

Receptor-mediated endocytosis:

- Chemical reactions
- Supramolecular self-assembly
- Membrane physics

Endocytosis is an attractor of a non-equilibrium system.

M. Zerial

H. McBride
Lesson learnt: Molecular pathways have to be complemented by multi-scale dynamics.


Visualization: N. Mennes and T. Maeke
Two Types of Diseases

One or several nodes are dysfunctional $\Rightarrow$ network functionality may be affected.

All system components are functional, but system is in wrong basin of attraction.
Darwinian medicine: a case for cancer

Mel Greaves

Abstract | Epidemiological, genetic and molecular biological studies have collectively provided us with a rich source of data that underpins our current understanding of the aetiology and molecular pathogenesis of cancer. But this perspective focuses on proximate mechanisms, and does not provide an adequate explanation for the prevalence of tumours and cancer in animal species or what seems to be the striking vulnerability of Homo sapiens. The central precept of Darwinian medicine is that vulnerability to cancer, and other major diseases, arises at least in part as a consequence of the ‘design’ limitations, compromises and trade-offs that characterize evolutionary processes.

Mice and Elephants
Use of abstract random Boolean networks.
Conundrum: Reaction of cells to irradiation highly non-linear. "The more intensity, the more (long-term) damage" does not hold (Fig. by S. Scheidegger).

Problem: Evolving a 4bit x 4bit Multiplier

Each square represent a logical gate (4 input, one output).

The gates as well as the wiring is evolvable.

- Tangen Uwe.
- Miller, Julian.
Problem: Intelligent Learning

Such arrays of logical gates did not show good evolvability. They never exhibited structure or could generalize results.
Patterned circuits

Many problems are solved by a regular arrangement of simple logical components.

Rationally designed multiplier
Global logic structure of a problem is transferred into the geometry of the arrangement of function generators.
Scalable patterned structures can be obtained from self-assembling logical blocks (SLB).

Function generator

Recognition sites for self-assembly

Morphology = geometry

Self – assembly enables patterned, scalable circuitry.

New genetic algorithm is needed to enforce it.
Co-Evolving Test-Vectors

Each individual carries a construction scheme and a test vector, both evolvable
Tournament by mutual exchange of problems
As soon as the circuit masters 4bit x 4bit („Das kleine Einmaleins“) multiplication, it can be scaled up to arbitrary size ➞ **inductive generalization**.
Size of Test-Vectors

32 runs for each testvector size, quartile box plots.

EITHER successful evolution of multiplier OR stop after 16 million generations.

For test vectors of size 4 or 64, more than three quarters of the runs didn‘t succeed.
Structural Subtask

1. $1101 \times 0000$
   
   0000
   0000
   0000
   0000
   
   00000000

   mult. with zero

2. $0110 \times 0001$
   
   0110
   0000
   0000
   
   0000110

   mult. with one

3. $1010 \times 0100$
   
   0000
   0000
   0100
   0000
   
   00100000

   mult. with $2^n$

4. $1010 \times 1001$
   
   0000
   1001
   0000
   1001
   
   1011010

   carryless addition

5. $1001 \times 1011$
   
   1011
   0000
   0000
   1011
   
   1100011

   full addition
Key Point of Test Vectors

- Information is only **preserved** when **regularly tested**
- "Learning" the solution of a **specific** problem is of limited value; it will be forgotten in the drifting population of test problems
- "Understanding" how to handle a **whole class of problems** can be maintained.
If a circuit „stores“ the result of 13*2, the benefit is temporary, if it implements diagonal shifts for the multiplication with powers of two, a permanent gain results.
Is Self-Assembly Versatile?

- multiplier
- ALU
- binary to Gray-code
- Gray-code to binary
- binary in, add, Gray code out
Evolution and Self-Assembly

- Self assembly **enables** geometrically structured and scalable solutions for circuit design.
- Co-evolving small sets of test problems **enforces** structured solutions → **inductive generalization without exhaustive testing**: A form of understanding!
- **Robustness** against thermodynamic fluctuations.
Synthesizing Branched Molecules by Spatially Structured Reactors

D. Lancet, S. Rasmmussen, J. S. McCaskill, M. Weyland

1. a) Grid - Container
   b) ssDNA

2. a) ssDNA
   b) ssDNA
   c) Container - Container

Evolved (B. Reller)
Golgi Apparatus

Production of oligosaccharides (among other things)


http://jennarever.weebly.com/index.html
Obstacle Avoidance: The Insect's Way

Eye bot

Simple morphology
Complex network

Complex morphology
Simple network

Lukas Lichtensteiger
Question (Roland Scholz, ETHZ): Is there a non–enumerative way to detect non-default states in the states of tissues?
Danger Signals

• Classical view (simplified): The adaptive immune system learn to discriminate between the self and the non-self.
• P. Matzinger developed an alternative view: The immune system is activated by general signs of danger, not (only) by foreignness.
• Among other things, the model explains
  – Why the immune system can respond to tumors
  – Why one needs adjuvants to make vaccines effective.

Detecting Danger by Morphology

Cell with subnetwork

Assume a molecule M with a fold that is evolved to be highly susceptible to chemical conditions.

Default fold

“Something is wrong” fold
Epitope D activates IS
Detecting Danger by Morphology

- Morphology of the molecule is sort of a "checksum".
- We don't claim that the mechanism is present in biological systems, but it may be implemented in artificial evolvable replication systems.

The chemical immune systems know that and what is going wrong.

- The nervous system knows where it is going wrong.
Hypothesis

- Nervous and immune system are coupled.
- Rolf Pfeifer: Find the optimal balance between nervous system and morphological control.
Some Results, Some Claims

• Morpho - computational power of body may be restored by mechanical means.
• The dynamic systems perspective opens a new look on cell dynamics.
• Logic can be transferred into geometry and self-assembly can support induction.
• Spatial organization enables programmable control of chemical reactions by enhancing the probability of specific reaction pathways.
• Morphological control offers a non-enumerative mechanism for protecting replication systems.
• From an engineering perspective, a coupling between nervous and immune system is plausible.
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Hopefully not the End

THANKS for your Attention!