Synergetic Computer and Physical Intelligence

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Topics Today

• Synergetic computer
• What is physical intelligence?
• Links between human, artificial, physical intelligence
• Smart physical systems
Algorithm for pattern recognition based on self-organization principles

Synergetic Computer

Haken (1991) Synergetic computers and cognition, Springer
Michael Bestehorn
Lisa Borland
Andreas Daffertshofer
Thomas Ditzinger
Rudolf Friedrich
Armin Fuchs
Michael Schanz
Jens Starke
…

Prototype patterns

Incomplete initial pattern recognized as prototype

Time

Fuchs, Haken (1988)
Coding: patterns/pictures $\rightarrow$ vectors

Time-dependent state vector $\tilde{q}(t)$

Evolution equation

$$\frac{d}{dt} \tilde{q}(t) = \tilde{N}(\tilde{q}(t), \tilde{v}_A, \tilde{v}_B, \tilde{v}_C, \tilde{v}_D, \tilde{v}_E)$$

$$\xi_j(t) = \tilde{v}_j \cdot \tilde{q}(t) \quad \text{Pattern amplitudes } \rightarrow \text{ order parameters } \xi_j$$

Amplitude equations

$$\frac{d}{dt} \xi_j(t) = \lambda \cdot \xi_j - A \cdot \xi_j^3 - C \cdot \xi_j \sum_{m \neq j} \xi_m^2$$

$\lambda > 0$, $A > 0$, $C > 0$

Winner-takes-all dynamics

Stable fixed points: one amplitude finite, all others zero
Topics Today

• Synergetic computer

• What is physical intelligence?

• Links between human, artificial, physical intelligence

• Smart physical systems
Physical Intelligence

• Human intelligence
  – General ability including various aspects
  – E.g., ability to store knowledge, evaluate & judge

• Artificial intelligence
  – Algorithms mimicking human intelligence
  – E.g., pattern recognition

• Physical intelligence
  – No consensus on general definition
  – Frequently, physical intelligence refers to intelligence
    • produced in non-algorithmic way
    • by systems of in-animate world
    • or by biological systems without brains
Why Physical Intelligence?

• DARPA (US defense agency)
  – New type of computers → dramatic performance increase
  – E.g., DNA computer

• J. Starke
  – Robust against default
  – Intelligence based on self-organization → self-organization process less likely to break down even if parts go default
Are there Intelligent Physical Systems at all?
Lessons from the Synergetic Computer
From the Benard Instability to Artificial Intelligence

Swift-Hohenberg (SH) model

\[ \frac{\partial}{\partial t} c(r,t) = \left( \varepsilon - [B + \Delta]^2 \right) c(r,t) - [c(r,t)]^3 \]

- \( B > 0 \)
- Control parameter \( \varepsilon \)
- Critical value \( \varepsilon = 0 \)

2D \( \rightarrow \) there are several critical modes with \( L = L_c \)

Evolution equation for amplitudes of critical modes

\[ \frac{d}{dt} \xi_j(t) = \lambda \cdot \xi_j - A \cdot \xi_j^3 - C \cdot \xi_j \sum_{m \neq j} \xi_m^2 \]

Amplitude equations of synergetic computer

Haken (1991)
Topics Today

• Synergetic computer
• What is physical intelligence?
• **Links between human, artificial, physical intelligence**
• Smart physical systems
Exploit Links Between HI, AI, PI

Top-down Modeling of Human Intelligent Behavior

- Spatio-temporal modes
  - Spatio-temporal evolution equations
  - Self-organizing multi-stable systems

- Mode amplitudes
  - Problems in fluid dynamics

- Haken's model for pattern formation and recognition
  - Problems in cognition, perception, action & memory

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Perception, Action, Cognition (PAC) & Attention Parameter Spectrum

\[ \frac{d}{dt} \xi_j(t) = \lambda \cdot \xi_j - A \cdot \xi_j^3 - C \cdot \xi_j \sum_{m \neq j} \xi_m^2 \]

- Lyapunov exponents of critical modes \( \lambda \)
- PAC
- \( \rightarrow \) Attention parameters
- \( \rightarrow \) Inhomogeneous

\[ \frac{d}{dt} \xi_j(t) = \lambda_j \cdot \xi_j - \xi_j^3 - g \cdot \xi_j \sum_{m \neq j} \xi_m^2 \]

- Oscillatory perception of ambivalent figures \( \text{Ditzinger, Haken (1989)} \)
- Selective perception \( \text{Fuchs, Haken (1988)} \)
Attention Parameter Spectrum

Stability Analysis

\[ \frac{d}{dt} \xi_k(t) = \lambda_k \cdot \xi_k - \xi_k^3 - g \cdot \xi_k \sum_{m \neq k} \xi_m^2 \]

- Attention parameter \( k \) in stability band \( \rightarrow \) mode \( k \) stable
- Otherwise: unstable

- Mode \( k \) becomes unstable at \( \lambda_k = \lambda(\text{max})/g \)

- Attention parameters are bifurcation parameters

TDF (2009, 2011)
Attention Parameters in Perception and Grasping

Holding candy bars on Halloween can easily be done with 1 hand …

… others thing like first-school-day paper-cones (Germany custom) may better be taken with 2 hands.
Perception & Grasping

Hysteresis

\[ \alpha(\text{crit, asc}) \]

\[ \alpha(\text{crit, desc}) \]
Perception & Grasping

Two modes
j=1: One handed grasp
j=2: Two handed grasp

\[
\frac{d}{dt} \xi_j(t) = \lambda_j \cdot \xi_j - \xi_j^3 - g \cdot \xi_j \sum_{m \neq i} \xi_m^2
\]

- **Object size (bias)**
  \[\lambda_1 = 1 - \alpha\]
  \[\lambda_2 = +\alpha\]

Frank et al. (2009)
Model-based Experimentation
Impact on the Coupling Parameter $g$?

\[
\frac{d}{dt} \xi_j(t) = \lambda_j \cdot \xi_j - \xi_j^3 - g \cdot \xi_j \sum_{m \neq j} \xi_m^2
\]

\[
\lambda_1 = 1 - \alpha
\]

\[
\lambda_2 = +\alpha
\]

Task difficulty: speed & cognitive load

Task difficulty increases mode-mode competition
Attention Parameter Dependency on Maturation

• General idea
• Motor abilities emerge via bifurcations
• Stability band becomes more and more populated during development
• Conditional population dependent on agent-environment relation
Child Development

\[
\frac{d}{dt}\xi_j(t) = \lambda_j \cdot \xi_j - \xi_j^3 - g \cdot \xi_j \sum_{m \neq j} \xi_m^2
\]

Four modes
j=1: One hand grasp
j=2: Two hand grasp
j=3: One hand + crossing
j=4: Two hand + crossing

\[
\lambda_1 = 1 - \alpha \\
\lambda_2 = \alpha \cdot h(\beta; \gamma_2) \\
\lambda_3 = (1 - \alpha) \cdot h(\beta; \gamma_3) \\
\lambda_4 = \alpha \cdot h(\beta; \gamma_4)
\]

Frank/Kamp/Savelsbergh, 2010
Attention Parameters in HI → AI

Three modes
j=1: Letter E
j=2: Letter F
j=3: Letter H

\[
\frac{d}{dt} q(t) = \tilde{N}(\tilde{q}(t), \tilde{v}_E, \tilde{v}_F, \tilde{v}_H)
\]

\[
\frac{d}{dt} \xi_j(t) = \lambda_j \cdot \xi_j - \xi_j^3 - g \cdot \xi_j \sum_{m \neq j} \xi_m^2
\]

Input: incomplete letter pattern
Output: classification

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Pattern Recognition with Adaptive Lyapunov Spectrum

- Goal
  - Improve recognition speed using adaptive Lyapunov spectrum

- Letter recognition
  - Artificial language based on 3 letter alphabet E,F,H

- Update Lyapunov spectrum utilizing a-priori-knowledge about language structure

- Artificial language
  - ‘E’ is followed most frequently by ‘F’
  - Use rule: if ‘E’ is recognized increase Lyapunov exponent of mode ‘F’

<table>
<thead>
<tr>
<th>Fixed</th>
<th>Adaptive</th>
</tr>
</thead>
<tbody>
<tr>
<td>String* #</td>
<td>Recognition time [a.u.]</td>
</tr>
<tr>
<td>1</td>
<td>212.9</td>
</tr>
<tr>
<td>2</td>
<td>211.8</td>
</tr>
<tr>
<td>3</td>
<td>212.8</td>
</tr>
<tr>
<td>4</td>
<td>213.8</td>
</tr>
<tr>
<td>5</td>
<td>212.7</td>
</tr>
</tbody>
</table>

\[
\lambda_E = \lambda_F = \lambda_H = 1 \\
\Rightarrow \lambda_E + \lambda_F + \lambda_H = 3
\]

\[
\lambda_E, \lambda_F, \lambda_H \quad \text{adaptive}
\]

*300 letters
Topics Today

• Synergetic computer
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• Links between human, artificial, physical intelligence
• Smart physical systems
# Smart Physical Systems

**Definition of ‘smart physical systems’**

<table>
<thead>
<tr>
<th>Human intelligence</th>
<th>Artificial intelligence</th>
<th>Physical</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Behavior*</td>
<td>Smart physical systems</td>
</tr>
<tr>
<td></td>
<td>Evolution equations (Amplitude eq.)</td>
<td></td>
</tr>
</tbody>
</table>

* Turing
Intelligent Physical Systems

• Fluid dynamical systems?
• Gas discharge & electronic systems?
Fluid Dynamical PI Systems?

Coding
Pictures $\rightarrow$ Patterns

Input-output interface
Initial picture $\rightarrow$ initial fluid state
Final fluid state $\rightarrow$ recognized picture

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Gas discharge & electronic systems

**U**= voltage between top and bottom of electronic layers

**U**< **U**<sub>crit</sub>: homogeneous current distribution

**U**> **U**<sub>crit</sub>: current distribution akin to localized particle

‘Current particle’ can emerge at any cell position → system is multistable

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Nonlinear (cubic) resistor approximation

\[ U_N(I) = U^* + b \left\{ (I - s)^3 - (I - s) \right\} \]

\[ U^* = b \left( s^3 - s \right) \]
Synergetic Computer – Fundamental Property

- Modes have
  - Activation
  - Cross-inhibition
  - Self-inhibition
- Multistability when

Cross-inhibition > self-inhibition, i.e., $g > 1$

\[
\frac{d}{dt} \xi_j(t) = \lambda_j \cdot \xi_j - \xi_j^3 - g \cdot \xi_j \sum_{m \neq j} \xi_m^2
\]
Evolution equations for cell currents

\[
\begin{align*}
\frac{d}{dt} \tilde{I}_1 &= \tilde{\lambda} - (1 - b) \cdot \tilde{I}_1 - \tilde{I}_2 - G(\tilde{I}_1) \\
\frac{d}{dt} \tilde{I}_2 &= \tilde{\lambda} - (1 - b) \cdot \tilde{I}_2 - \tilde{I}_1 - G(\tilde{I}_2)
\end{align*}
\]

Exhibits fundamental structure of Haken’s multistable networks
(i) Activation, (ii) Weak (lin.) self-inhibition, (iii) Strong cross-inhibition
Stability Analysis

Currents $I_1$ and $I_2$ can be
Low
Medium
High

Stable fixed points of two-cells circuit

Stable co-existence states

Bistable
PI Systems?

THANK YOU

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Appendix
Pattern Formation in the **Animate** and **Inanimate** World

*Atkinson et al. 1996*

Laboratory work: gases heated from below

*Nov 16 2012*

*Helium* | *Argon*
---|---
![Image 1](image1.png) | ![Image 2](image2.png)

*Liu/Ahlers 1996*
Self-Organization

Generalized Reaction-Diffusion Equations Approach

\[ \frac{dc(t)}{dt} = f(c) \]
\[ \frac{\partial}{\partial t} c(x, t) = D \frac{\partial^2}{\partial x^2} c(x, t) \]
\[ \frac{\partial}{\partial t} c(x, t) = f(c) + D \frac{\partial^2}{\partial x^2} c(x, t) \]
\[ \frac{\partial}{\partial t} \tilde{c}(\tilde{x}, t) = N(\tilde{c}, \nabla) \]

Solution method via mode skeleton
\[ \tilde{c}(\tilde{x}, t) = \sum \xi_j(t) \cdot \tilde{w}_j(\tilde{x}) \]

Lyapunov spectrum at bifurcation point
Critical mode \( j \) with \( \lambda_j > 0 \)

Interacting modes
State variables \( c_1, \ldots, c_L \)

Reaction-diffusion equation
Generalized reaction-diffusion equations

Reaction step
Diffusion step
Electronic GDS circuit

Cell 1

Cell n

Ohmic (linear) resistor

Capacitor

Inductor

Nonlinear resistor
Child Development

Age

β

Model

Relative object size α

Frank/Kamp/Savelsbergh 2010

Clinical

Term & Preterm infants

<table>
<thead>
<tr>
<th>Term infants</th>
<th>Preterm infants</th>
<th>Motor skill</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chronological age</td>
<td>Chronological age</td>
<td></td>
</tr>
<tr>
<td>4.5 m</td>
<td>6 m</td>
<td>Rolling over</td>
</tr>
<tr>
<td>7.5 m</td>
<td>11 m</td>
<td>Manages to sit up</td>
</tr>
<tr>
<td>14 m</td>
<td>16 m</td>
<td>Walk (including walking backwards)</td>
</tr>
</tbody>
</table>

Individual life trajectories

TERM

PRE-TERM

Frank 2011