Morphogenetic Self-Reconfiguration of Modular Robots

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Outline

● Motivation / Introduction
● Background
● Applications
● Evaluation
● Conclusion
Modular Robotic Systems

- Robots with variable morphology
  - Reorganizing the connectivity of modules
  - Perform new tasks, adapt to new environments, recover from damage
- Consists of independent units: connect/disconnect

Potentially more robust and more adaptive under dynamic environments
Modular Robotic Systems – Classification

Chain-based:

- **Pro**: scalable, easy motion planning
- **Con**: can't build complex 3D patterns

Modular Robotic Systems – Classification (cont.)

Lattice-based:

- **Pro**: easy build of complex 3D patterns
- **Con**: complicated control and motion planning

https://upload.wikimedia.org/wikipedia/commons/thumb/5/5c/The_Distributed_Flight_Array.jpg/800px-The_Distributed_Flight_Array.jpg
Hybrid approaches:

- Integrates advantages of chain and lattice based classes
- M-TRAN II + III, SUPERBOT, SMORES
Morphogenesis

Morphogenesis = "biological pattern formation"

https://mcb.berkeley.edu/labs/bilder/images/Morphogenesis/Picture5.jpg

http://www.livescience.com/images/i/000/037/153/original/zebra.jpg
Gene Regulatory Networks (GRNs)

Cell 1

Gene 1  Gene 2

Protein 1  Protein 2

Diffused from cell 2

+  -  -  +

diffusion

Cell 2

Gene 1  Gene 2

Protein 1  Protein 2

Diffused from cell 2

[1]
What is Morphogenetic Robotics?

Developmental Robotics

Epigenetic Robotics
(Cognitive and mental development)

Morphogenetic Robotics
(Physical, including morphological and neural development)

Environment

[1]
Cross-Ball
Cross-Ball: Hierarchical Morphogenetic Model

Layer 1
Chemical pattern formation
Generate target pattern

Layer 2
Physical pattern realization
Generate reconfiguration plan

Layer 3
Motion controlling
Support module movement process
Layer 1: Chemical pattern formation

[Diagram showing chemical pattern formation with labels: Neighboring Position, Module, Virtual Cell, Inter-Cell Interaction, Cell-Environment Interaction]
Layer 1: Chemical pattern formation (cont.)

Change of v-cell density in grid $i$:

$$\frac{dn_i}{dt} = r \cdot n_i (N - n_i) - d \cdot K_i \cdot M_i - a \cdot \frac{\rho_i}{n_i + \rho_i} + \sum_k n_k^{rec}$$

$$K_i = [k_i^{up}, k_i^{down}, k_i^{left}, k_i^{right}, k_i^{forward}, k_i^{backward}]^T$$

$$M_i = [m_i^{up}, m_i^{down}, m_i^{left}, m_i^{right}, m_i^{forward}, m_i^{backward}]^T$$

$N$: maximum number of v-cells in the grid

$K_i$: dispersal control vector

$M_i$: density gradient vector

$\rho_i$: ECM-value (environmental constraint)

$r,d,a$: predefined constants

[3]
Layer 1: Chemical pattern formation (cont.)

Change of ECM value in grid i:

\[
\frac{d \rho_i}{dt} = -b \cdot \frac{n_i}{n_i + \rho_i} + e \cdot \sum_j f_{ji}(n_j)
\]

\(f_{ji}(n_j)\): function rules depend on desired pattern (e.g. vehicle pattern)

\(b, e\): predefined constants

Morphogen level of grid i = \(\Delta(n_i, \rho_i)\)
Layer 2: Physical pattern realization

- Target pattern known
- **State transitions** controlled by a GRN model:
  - Attracting gene-protein pair \((g_A, p_A)\)
  - Repelling gene-protein pair \((g_P, p_P)\)

- Modules with a **higher morphogen level** are more likely to **attract** other modules
- Modules with a **lower morphogen level** are more likely to be **repelled**
Layer 3: Motion controlling

- Evaluate self-reconfiguration plan generated from layer 2 controller
- Hardware-specific controller
- Introducing **skeleton modules** and allow modules to work in groups

Reducing complexity of searching process on the module movement plan
https://www.youtube.com/watch?v=z9yemQJtyQg
M-TRAN III

Modular Transformer III:

- Developed by AIST and Tokyo-Tech (since 1998)
- Hybrid design


https://unit.aist.go.jp/is/frrg/dsysd/mtran3/mtran123.jpg
Module Control:
- Centralized or distributed
- Communication via bus
  → Controller Area Network (CAN)
https://www.youtube.com/watch?v=4oSavAHf0dg
## Comparison of Cross-Ball and M-TRAN III

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<thead>
<tr>
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<th>Cross-Ball</th>
<th>M-TRAN III</th>
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<tbody>
<tr>
<td><strong>Design</strong></td>
<td>- Hybrid design</td>
<td>- Hybrid design</td>
</tr>
<tr>
<td><strong>Experiments</strong></td>
<td>- Embodied simulation environment</td>
<td>+ Physical prototype</td>
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<td><strong>Controlling</strong></td>
<td>- Bio-inspired approach using the theory of morphogenesis with GRNs</td>
<td>- Distributed controller and global communication using a network bus</td>
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<td>+ Completely independent modules</td>
<td>- Mostly independent modules</td>
</tr>
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<td><strong>Autonomy</strong></td>
<td>+ Fully autonomous self-reconfiguration (target pattern dependent on predefined function).</td>
<td>- No autonomous self-reconfiguration.</td>
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<td><strong>Scalability</strong></td>
<td>- Successful simulation using 27 modules</td>
<td>- Successful experiments using 24 modules</td>
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<td>+ Theoretically no limitations</td>
<td>- Limited by global bus and ID numbering (max. 50 modules)</td>
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Conclusion

Advantages

- Modularity reduces cost of design, manufacturing, maintenance
- Easy adaptation to changes in the environment
- Robust to system failures, malfunctions
- Ability for self-repairing
- Hierarchical framework almost completely generic

Future work

- Build and evaluate physical design
- Simplify controllers to further reduce complexity and computational costs
Questions?

Thank you for your attention!
Literature


