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HYDRA: From Cellular Biology to Shape-Changing Artefacts

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Abstract. The HYDRA work provides insight into the exploitation of holistic behavioural and morphological adaptation in the design of new artefacts. The potential of the new design principle has been exemplified through the construction of robotic systems that can change morphology. Two prototype building block systems has been developed, HYDRON for a fluid scenario, and ATRON for a terrestrial scenario. In the HYDRON case, the individual module can perform 3D motion and is able to arrange in clusters of specific formation without the necessity of physical connections. In the ATRON case, the modules are individually simpler, attach through physical connections, and perform 3D motions by collective actions. Control mechanisms identified from cellular biology has been successfully transferred to the physical building blocks.

1 Introduction

The HYDRA project focuses on the design of building blocks for self-reconfigurable artefacts. The building blocks allow robust and efficient morphological development of artefacts, in order to allow end-users to design new artefacts in an easy manner. Inspired by biological principles, the HYDRA project realises engineering structures with the properties of differentiation and self-reconfiguration.

Investigations of biological principles reveal that the cell is an appropriate basis for this work, so we investigate building blocks modeled as cells. This leads to control mechanisms based on inspiration from cellular mechanisms such as cell division, cell motion, cell death, cell adhesion, change of cell shape, and cell differentiation and induction [6].

By exploring different possible building blocks in software and hardware development, the project defines physical building blocks that allow development of systems comprising hundreds of basic building blocks that exhibit self-assembly, self-repair, and shape-change. The potential of the new design standard has been exemplified through the construction of two robotic systems that can change morphology.

The controlling mechanism found in simulation has been modified, implemented and tested as control for the physical building blocks. Especially, the abstract gradient-based control mechanisms from the simulations has proven

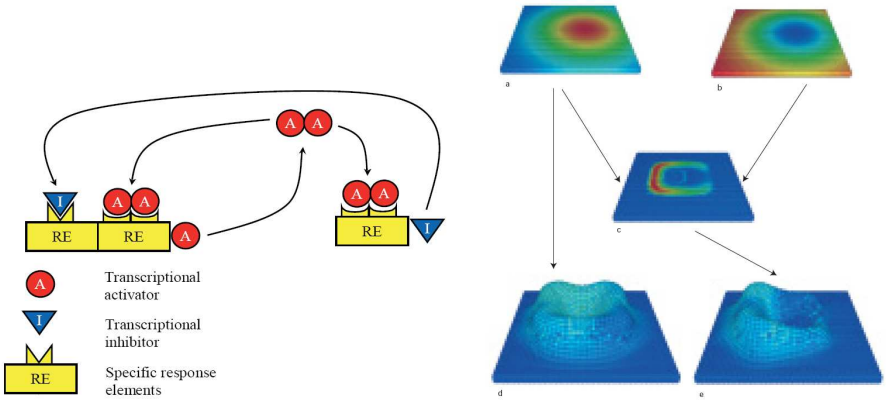

Fig. 1. Left: Example of gene regulation. Structural genes (A and I), are controlled by responsive elements (RE). A is here a transcription factor regulating its own synthesis and activating also inhibitor I. **Right:** Interactions of genes, morphogens and cellular physics. Physical strains of cells are controlled by the two chemical gradients, shown in a) and b). a) alone produces the shape in d), while their combination produces the shape shown in e). From [3].

useful to control real hardware systems. The HYDRA hardware includes 20 HYDRON modules for aquatic use and 100 ATRON modules for terrestrial use, both systems capable of self-reconfiguration in 3D.

2 Cellular Biology

The biological mechanisms of self-assembly and self-repair were investigated and modeled within an artificial evolutionary system in the context of cellular systems. Generic principles identified from these developmental mechanisms were used to implement control algorithms for the two HYDRA hardware platforms.

Having chosen the cell as our level of abstraction, our main task was to identify those developmental processes, which allowed an artificial evolutionary system to mimic growth and regeneration [4] in a cellular context. For this purpose, different developmental processes were simulated and explored by evolution. A set of basic cellular mechanisms was identified, which could be used to simulate a wide range of higher level mechanisms such as pattern generation or co-evolution of morphology and behaviour.

All the biological mechanisms that are essential for development, cell division, growth, differentiation, pattern formation and morphogenesis are mediated ultimately by proteins. They act either directly or as enzymes to produce other molecules. These proteins are encoded by genes, so development is controlled to a large degree by gene expression. The pattern of gene expression in the embryo determines where, when and in what quantity particular proteins are made and therefore governs the properties of each cell. Since proteins play such an important role for development, the mechanism ligand-receptor interactions

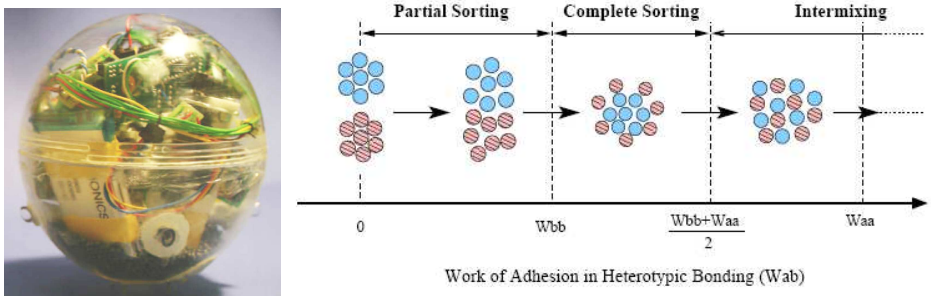

Fig. 2. Left: The HYDRON hardware. **Right:** Cellular Adhesion Control in 2D of a small group of simulated HYDRON modules. By changing the attractive and repulsive force between types of cells, different configurations can be achieved.

was implemented, which can mimic many specific interactions among proteins abstractly. A receptor is usually a large protein, folded in a way to be able to recognize specifically a partner molecule. For a ligand (a signaling molecule) to be useful it must act selectively on particular targets such as gene regulators or receptors. This means that a receptor will only recognize ligands of a certain precise type and ignore closely related molecules. This principle of binding-site and ligand specificity can be found almost everywhere in multicellular organisms. This complementary specificity, which is based on the very exact molecular recognition properties of molecules, is central to explaining many of the phenomena of developmental biology.

The basic mechanisms identified in cells - cell division, cell death, cell adhesion, expression of receptors, and production of signaling molecules - were used to evolve and simulate higher-level processes such as cell differentiation, pattern generation, morphogenesis, growth of neural networks with inter-neuronal communication and co-evolution of morphology and behaviour. Figure 1 provides an overview of the simulated cellular mechanisms.

3 The HYDRON Module

A HYDRON unit is shown in figure 2. Each unit is roughly spherical, with a diameter of approximately 11 cm, suspended in water, and actuated in the horizontal plane. A HYDRON unit has four nozzles which expel water drawn through an impeller at the bottom of the unit when activated, and which are selected by a rotating collar. A syringe draws or expels water through the bottom of the unit to control unit buoyancy, and thereby actuate the unit along the vertical axis. Each units hull also supports a small set of switchable optical sensors and emitters capable of transmitting data over short ranges. Optical sensors and transmitters were chosen because they provide a simple and flexible underwater communication mechanism.

Simulation work on a Cellular Adhesion Molecule (CAM) based control approach [8] shows how this simple, biologically-inspired approach to decentralized multi-robot control can be used for forming a variety of spatial patterns, as

shown in figure 2. This can be achieved in modules with limited capacity for communication and locomotion. The simulation results are also consistent with the predictions of Steinberg's Differential Adhesion Hypothesis for sorting of biological cellular aggregates [9]. The approach is flexible and robust, and the design of the controller permits easy transfer to the real HYDRON robots.

The combination of the CAM controller with the Genetic Regulatory Network (GRN) controller [10] shows that the GRN can be evolved to produce time-varying expression of CAMs on a robots (virtual) membrane in order to achieve specific behaviours. Especially for more complex tasks (such as reacting to an external signal, or producing differentiated behaviour from an initially homogeneous cluster), the evolutionary power of the combined GRN-CAM controller is able to produce better performance than could be achieved by either of the primitive controllers individually.

4 The ATRON Module

The ATRON modules, shown in figure 3 and further described in [5], are lattice based self-reconfigurable robot modules for 3D operation in land environments. Greatly simplified, an ATRON module is composed of two hemispheres joined together by a rotation mechanism

ATRON modules can connect using mechanical hooks which attach to an arrangement of bars on a neighbour, similarly adhesion proteins bind to ligands on the surface of an adjacent cell. On each half module, there are two female (bars) and two actuated male connectors (hooks). The novel mechanical connector design, ensures a strong and reliable connection. A module may communicate with neighbouring modules through IR communication.

When placed in the surface-centred cubic lattice structure, the modules can self-reconfigure to achieve different overall arrangements or movements. The shape allows one module to move to an adjacent hole in an otherwise fully packed structure (without colliding with other modules). Indeed, the design was guided by considerations on how to reduce control complexity of self-reconfiguration, while having a simple module design. However, compared to biological cells and the HYDRON module, the ATRON has very hard constraints on motion. Gravity related restrictions include static stability of the configuration, not exceeding motor torque limits, and obeying structural stiffness. Also, care should be taken during self-reconfiguration to avoid module collisions and to maintain structural connectivity. The system also has similarities with cellular systems, in that a cluster of ATRONs is composed of many identical semi-autonomous units. The question is how the principles from biology should be transferred to suit the hard constraints of the ATRON hardware.

In [1] we describe a GRN-style system, where each module is controlled by simple rules of the form $\{precondition, action\}$, based on the local neighbourhood and the modules actuators. The activation of rules is determined by the hormone gradients, such that the effort of each individual module is orchestrated from organism scale chemical gradients. Work along these lines have shown that such simple rules based on local morphology can generate scalable and robust

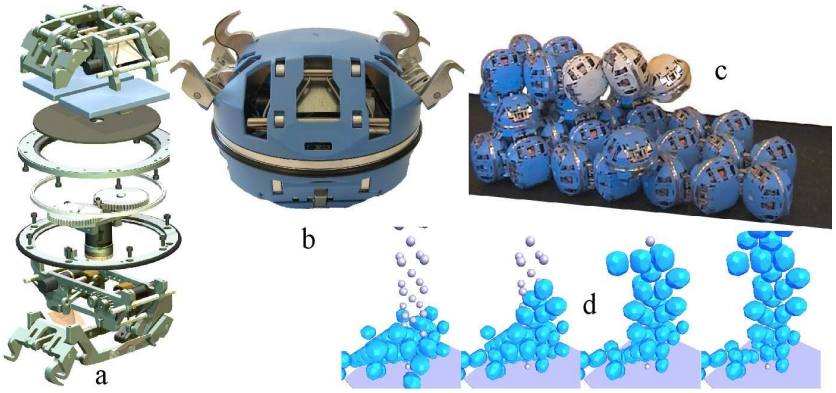

Fig. 3. a) Exploded view of the ATRON CAD drawing, and **b)** a photo of the final hardware. **c)** Experiment on the ATRON platform showing three white modules as a meta-module in the process of migrating on a substrate of modules. **d)** The simulated migration of ATRON meta-modules permits approximation of the target shape defined as attraction points.

behavior at organism level, such as cluster walk, obstacle avoidance and terrain following [7].

Chemical gradients are known to guide migrating cells [6]. In order to achieve a desired self-reconfiguration, this mechanism has been transferred to the ATRON platform [2]. ATRON modules can use their IR-based neighbour-to-neighbour communication to simulate a gradient that attracts other modules. Migration is achieved using a meta-module consisting of three modules, see 3 c). Such a meta-module has the ability to move relatively freely on the substrate of other modules. Meta-modules emerge from the structure of modules, migrate based on cues from its environment, and die when reaching their target, once again becoming part of the substrate. This approach is similar to the division and death of biological cells. The combination of gradients and migrating meta-modules enable the system to change its shape, see figure 3 d), and thereby adapt to the required functionality of the system.

5 Conclusion

The HYDRA work provides insight into the exploitation of holistic behavioural and morphological adaptation in the design of new artefacts.

Investigations of biological principles have revealed that the cell is an appropriate level of abstraction, so the building blocks are modeled as cells. This leads to control mechanisms based on inspiration from cellular mechanisms such as cell division, cell motion, cell death, cell adhesion, change of cell shape, and cell differentiation and induction. HYDRA simulation work shows how such mechanisms can be used to control the morphological creation of forms. The controlling mechanism found in simulation has been modified, implemented and tested as control

for the physical building blocks. In addition, gradient-based control mechanisms have been abstracted from the simulations.

20 HYDRON modules and 100 ATRON modules have been produced, and experiments has been been performed on these modules. The robotic system's ability to reconfigure in 3D has been high on the agenda. The successful outcome of the project has been videotaped for presentation and the physical modules demonstrations have been showcased at various PR events and scientific events worldwide.

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