Robotic Organisms - Artificial Homeostatic Hormone System and Virtual Embryogenesis as Examples for Adaptive Reaction-Diffusion Controllers

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***Abstract*— Generating artificial organisms from robotic modules (cells) is a challenging and fascinating task. In this article, we discuss the most important challenges that such systems pose to the engineer and how these challenges are met by introducing bio-inspired mechanisms into the core functionality of such robotic systems. We develop a list of key functionalities that allow such a system to overcome the limitations of 'monolithic' single robotics. In addition, we elaborate on the similarities and differences of two bio-inspired control software architectures that support the unfolding of potential in multi-modular reconfigurable robotics. We focus especially on issues like robustness and scalability and emphasize the power that arises from exploiting bio-inspired control mechanisms that show self-organization and evolutionary adaptation in such artificial 'robotic organisms'.**

I. INTRODUCTION

In nature, higher organisms grow in a modular way (cell-by-cell) from one fertilized egg cell. Homeostatic control, self-organization and genetic adaptability are key characteristics of any living system. Thus, for adaptive, robust and scalable robots, a modular approach is an interesting engineering paradigm which can easily be enriched by incorporating bio-inspired morphology (shape) and physiology (mechanisms, processes). However, multi-modular and self-reconfiguring robotics is still a very challenging task. Compared to monolithic robotic units, modular robotics offers several significant benefits: A modular robot has the potential to be scalable, because by adding modules the collective system might increase not only its size but also its actuation-force. It might be more robust, because failures in one module can be compensated by other modules, and in addition, broken modules might even be replaced by working ones during reconfiguration. Such robotic systems might have increased capabilities as each single module could be equipped with different sensors and actuators, thus specialization of modules might lead to enriched overall potential of the system. It might also be more flexible and adaptive, at least when reconfiguration alters the robot's 'morphology'.

However, these potential benefits are only reachable with hardware that supports the above described functionality. Also the control software that drives the system, is required to support these functions, otherwise a multi-modular robotic system cannot unfold its theoretical potential.

In the projects SYMBRION and REPLICATOR [1], [2], a robotic system is engineered that consists of up to 100 autonomous robot modules which can move independently (screw-drives or tracks), which are able to dock to each other forming 'robotic organisms' this way (Fig. 1). Such robotic organisms are able to move, e.g., by bending the hinges of the modules. Reconfiguration is possible, as modules can dock and un-dock also at runtime autonomously.

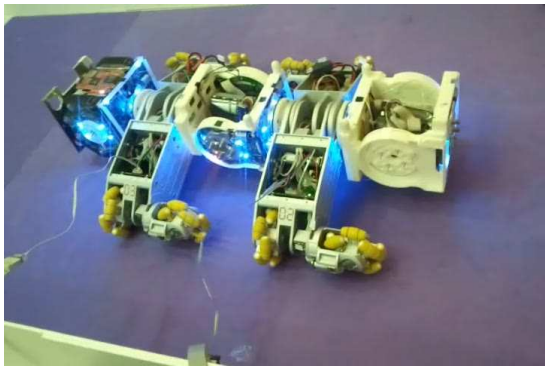


Fig. 1. Modular robot organism consisting of five heterogeneous modules. They are controlled by AHHS. The modules are designed and produced by the consortium of the projects SYMBRION and REPLICATOR.

The hardware design of the projects SYMBRION and REPLICATOR clearly fulfill these requirements to allow the system to unfold the power of multi-modular robotics. In contrast, software used to drive such robots is less obviously constrained: In principal, every software architecture, ranging from macroscopic organism-level hand-coded programs to state-of-the-art neural networks could drive such robots.

However, the number of different body configurations of such robotic organisms grows strongly super-linear with increasing numbers of modules. Each module can dock to other modules on four sides, and each of these modules can face four different directions. Thus, a few modules can build thousands of morphologies and 50 modules can build more than a billion of configurations. It is clearly infeasible to code control software by hand for each module for each possible body shape. Thus online-adaptation (e.g., artificial evolution) is a strong requirement for such a software system. In consequence, a software that supports the potential of multi-modular systems has to be *evolvable* on the one hand and, on the other hand, it has to consider the modularity and reconfigurability of the system from the beginning.

At the Artificial Life Lab at University of Graz, we take the approach of *evolving self-organizing reaction-diffusion-based homeostatic control mechanisms*. Specifically, we developed the 'Artificial Homeostatic Hormone System' (AHHS, aka 'hormone controller') [3], [4] and the 'Virtual Embryogenesis' (VE) [5]. Both systems share many common mechanisms, most prominently the simulation of the diffusion of virtual chemical substances, which are called 'hormones' in AHHS and 'morphogens' in VE. Also other mechanisms, like inter-chemical interactions and genetic encoding of basic rules are common features. Both software systems are bio-inspired. Although they are derived from different sources of inspiration, they both share their principles of *redundancy*, *adaptability*, *self-organization* and *modularity*, which are common principles in all biological organisms, in all biological processes and which are acting on all size scales and time scales in nature.

Despite the obvious similarities there are also significant differences between these two control software paradigms. The main focus of this article is to elaborate on these differences and to discuss their implications. These implications are important, because both software frameworks have significantly different potential concerning their capability to fulfill specific functional core requirements in any multi-modular robotic system. In the following sections a comparison between the two software frameworks is presented.

In addition, we elaborate a basic list of functional requirements for multi-modular robotic systems. It is a list of general requirements, not only valid for the systems developed in SYMBRION and REPLICATOR. This discussion of functional requirements in the context of two existing control systems is the major difference to existing review articles in the field of modular self-reconfigurable robotics (e.g., see [6]). We also discuss how these requirements have to be supported by the control software. Our basic claim is that control software has to reflect the principles of modularity and self-organization, otherwise potentially well working multi-modular robotic hardware would be impaired by a software that diminishes this potential and converts the multi-modular system back into a monolithic one.

II. SIMILARITIES AND DIFFERENCES OF VE AND AHHS

Both software frameworks basically establish a simulation of a chemical reaction network, in which important programming primitives (e.g., AND, OR, XOR) and structures like loops and conditional execution are not directly programmed. However, corresponding functionality can arise as a consequence of thresholds and chemical-interaction rules in both systems. Both systems are subject to evolutionary adaptation. They are represented by rule tables which mostly hold continuous (floating point) numbers, thus both systems are not close to genetic algorithms [7] but close to evolution strategies [8], [9]. In both systems a set of rules (genome) that govern the program's dynamic behavior and not only a final (static) solution vector is altered by evolution, thus we would rather categorize both systems together with genetic programming [10]. However, in contrast to classical genetic programming it is not the program code itself that is directly mutated, it is more the 'rules of simulated physics and chemistry' in our systems that are mutated in a way so that desired functionality emerges from the simulated chemical interactions. Thus, both systems, AHHS and VE, would be best named 'indirect genetic programming'.

The concept of AHHS is derived from the homeostatic interactions of cell signals inside of uni-cellular organisms and by the interactions of hormones in multi-cellular organisms. In an AHHS, the control software runs in parallel on each autonomous robot module, which is able to communicate with docked neighbor modules. Each AHHS is principally a simulated simple physiological model, mainly a chemical reaction network. Virtual hormones can diffuse from one module to docked neighbors and they are able to interfere with other hormones by changing their local concentration inside of robot modules. Virtual hormones are also affected by sensor data. Local concentrations of specific hormones affect actuator control. Thus, AHHS are diffusion-coupled non-linear dynamic systems that are affected by the body plan of the robotic organism, as diffusion is limited to coupled modules. The basic parameters for sensor-hormone, hormone-to-hormone, and hormone-to-actuator interactions are stored in a table-like genome, which is altered during evolution. This table holds also the parameters that govern the diffusion of each hormone. For more details on AHHS implementation, please see [11], [12], [13], [14], [11], [15].

The basic principles of VE are derived from processes observable in nature during the embryogenetic development of biological organisms [16], [17]. These processes, based on the interaction of genes, diffusing substances (morphogens) and developing body structure, are well evolvable. The interplay of genetic, embryogenetic and evolutionary development are investigated in the field of evolutionary developmental biology (EvoDevo). The VE process mimics mechanisms researched in EvoDevo [18], [19]. Individual cells are implemented as agents, each of them able to duplicate, to emit substances, or to change their receptivity for morphogens. The behavior of a cell depends on the local morphogen level and the genome, which determines which cellular action is triggered by which morphogen concentration. Within the growing virtual embryo a self-organized positioning system develops, allowing the cells to develop into different tissues with different abilities. For more details on VE see [5], [20], [21], [22], [23]

In SYMBRION and REPLICATOR the VE framework is not planned to control the robot during movement. Thus, the sensors of the robotic modules are not connected to VE. To start the VE growth process, another controller (e.g., the AHHS) has to trigger the VE framework, starting the growth process of a robotic organism at this point in time. After the robotic organism has finished to grow, VE hands over the control to another controller, which is then in charge for the body movement (e.g., AHHS). Despite this concept of alternating division of labor between AHHS and VE, we can enumerate several mechanisms/concepts that have a high

degree of similarity in both systems:

1) **Genetic encoding:** The dynamic of both systems is determined by a genome, encoding the reaction of an agent to a given hormone/morphogen level.
2) **Diffusion:** In both systems virtual chemical substances diffuse through a virtual body.
3) **Decay:** Chemicals decrease over space and time. The decay rate can vary form substance to substance, and during runtime. These changes of the decay rate can be preprogrammed, or triggered by genes.
4) **Interactions between chemicals:** Chemicals interact directly via rules encoded in the genome. A given chemical concentration can lead to a change of the concentration of another chemical by additional emission or by increased decay rates.
5) **Degree of specificity of chemicals:** In both systems, AHHS and VE, hormones and morphogens are encoded by integer numbers in an ordered manner ($0 \leq i \leq i_{max}$). In VE, each gene cannot only be triggered by a single morphogen, but within some extend also by other (neighboring) morphogens. These other morphogens have to have a higher concentrations to trigger the given gene. The amount of morphogen needed depends on the distance within the list of morphogens between the triggering morphogen and the actual morphogen. In AHHS, weighted indices achieve a similar functionality: A real-valued parameter h in the genome for every rule of the AHHS defines which two hormones (with indices $\lfloor h \rfloor$, $\lceil h \rceil$) are able to trigger a certain behavior with intensity depending on $|h - \lfloor h \rfloor|$ and $|h - \lceil h \rceil|$.
6) **Chemical-induced activation of actuators:** The actuators of an agent (e.g., movement of robots in AHHS and division of cells in VE) are controlled by rules encoded in genes, that are activated by a given chemical concentration.
7) **Spatially self-organizing gradients:** Due to the process of diffusion there are spatio-temporal gradients within the robotic organisms in both software frameworks. Thus, the concentration of a chemical substance in each module is strongly related to the position of this module within the organism. Changes in the morphology of the organism lead to self-organized reshaping of the gradient, thus to different concentrations inside the modules.
8) **Disturbances of local equilibria:** Local equilibria or homeostasis is disturbed by sensor input or by changes in body configuration. Both systems target an equilibrium value when there is no disturbances for a certain time period.

However, also significant differences between the two software frameworks exist:

1) **Integration of chemicals over time:** In the VE process morphogens do not accumulate over time and space. In contrast, in the AHHS hormones accumulate until they leave the system by decay. The accumulation of hormones leads to the emergence of buffer systems which can compensate noise-affected sensor input.
2) **Local reflection of sensor input:** In AHHS it is a crucial feature that sensor input affects/modulates the production of hormones locally. This allows robotic organisms driven by AHHS to react to the environment and to perform adaptive body motion. Due to the fact that VE was not aimed to control the robot during movement, the sensors are not connected with VE.
3) **Shape of gradients:** Morphogen gradients in the VE system are linear and there is no conservation of mass implemented. This gives a better resolution for identifying the individual position of a cell in the self-organized relative positioning system that emerges within the growing virtual organism in VE. In AHHS spatial gradients emerge in the shape of an exponential decay. The steepness of these gradients can be adjusted by the evolutionary procedures by altering either the diffusion coefficients of hormones or by changing their basic production rates and decay rates.
4) **Division of cells:** The cells in the VE system are able to divide and to build growing body structures. Growing cells influence all other cells by physical interaction like pushing, which results in the relocation of large body structures. In the AHHS there is a different concept of the 'cell' itself. In this approach even a single cell or module is structured internally. These inner structures are called compartments, which can change due to evolutionary processes. But in contrast to VE there is no division of cells or modules themselves during runtime.
5) **Cell death:** In the VE system cells can die, and leave an empty patch inside the developing virtual embryo, which can lead to a change in the distribution of morphogens. In the AHHS there is no equivalent to cell death. At most, evolution could change the diffusion coefficients to zero which would isolate all cells.
6) **Dynamic sensitization or habituation to chemicals:** In VE, cells change their sensibility for a given morphogen. This way, the finished embryo consists of specific groups of cells that react differently to a given morphogen, analogous to tissues in biological organisms. There is no change of sensitivity concerning hormone concentrations in the AHHS.
7) **Multi-functionality of genes:** In the VE process a gene has one function only (e.g., cell division). In the AHHS a rule gene usually defines a set of functions. One rule serves in parallel as a sensor input processor, as an actuator control, and as a hormone-to-hormone interaction with individually adjustable weights.
8) **Gene-specific mutation rates:** Each gene in the VE has its own mutation rate encoded in the gene itself. This allows to evolve genes at different 'evolutionary speeds', which enables well working genetic structures to become more resistant against mutations. This is also comparable with the differing mutation-rates of genes in biological organisms.

III. IDENTIFICATION OF FUNCTIONAL REQUIREMENTS

In this section tasks for multi-modular robots are pointed out. Some of these are prerequisites while others are benefits of using modular systems.

1) **Reconfiguration:** For a modular-robotic system it is essential to be able to reconfigure itself. Otherwise a huge fraction of the system's potential would stay unused. From our point of view multi-modular robot systems are ideal for dealing with unpredictable environments. Thus, the engineer will seldom be able to predict the requirements posed by the environment onto the robot's body plan. Thus, being able to reconfigure, increases the flexibility of such a system.
2) **Growth:** A special case of reconfiguration is growth. A system that is able to grow can be initially started with one single cell. As soon as an obstacle (e.g., barrier) is found that cannot be overcome by one single module, growth of the organism might be able to solve the problem.
3) **Healing:** In modular robotics, it is essential to compensate damages of the robotic organism in a self-organized manner. If a part of the body is lost, or has to be rejected, due to malfunction or damage, the robotic organism has to detect these changes and regrow or reconfigure to provide the functionality of the robotic organism.
4) **Replication:** A special case of healing is replication on the robotic organism level. If one complete organism can split into two 'incomplete' parts, which are able to regenerate, this results (after a healing period) in two new complete robotic organisms.
5) **Self-localization within the body:** To enable modules of a robotic organism to react adequately in the interplay with the other parts of the body it is necessary that each unit can localize itself within the body. In biological systems, this localization is based on self-organized processes [19]. The mimicking of these processes allows to develop controllers, which are able to interact with the robotic units of the organism in an optimal way. Note that the resulting network of robotic unit controllers organizes itself based only on local cues within the robotic organism.
6) **Compartmentalization:** In modular robotic systems the body of a robot organism consists of many building blocks. In biology a structure which is physically and functionally separated is called compartment. A compartment can be a structure inside a single cell (e.g., mitochondria), a single cell itself or a cell colony to form a tissue. These different levels do also exist in modular robotics. First, the single robot module can be divided into virtual compartments. Second, the module itself builds one compartment and third, specialized connected cells build 'virtual tissues'. The inner structure of one module in the AHHS approach and the outer morphology of the robot organism are jointly responsible for the functionality of the system. This makes the compartmentalization process an important task in modular robotics. In the following we will refer to 'compartmentalization' as the process which establishes the inner structure of a module.
7) **Location specific functionality & action selection:** There is both a need and a cause for local specificity concerning function in modular robotics. The modules have to be locally controlled to allow high standards of scalability and robustness. Still, a global synchronization is necessary as well to generate regular actions of the whole system. While locality is forced by feeding only local information into the modules, synchronization effects have to be based on self-organizing processes. For example, in case of a legged modular robot many details of the actual gait in each leg can be controlled locally but the phase needs to be synchronized at least on a leg-to-leg basis. Action selection is another process that demands some global interaction. Hence, also a self-organizing, global decision process is necessary to avoid the simultaneous execution of conflicting actions [24].

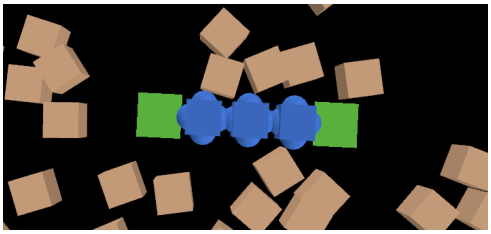
IV. RESULTS

Here we report exemplary results concerning most of the tasks described above. At the current level of research, not all tasks are achieved with AHHS and/or VE. For example experimentation concerning 'self-replication of organisms' are currently work in progress, thus not reported here. We identify which software framework was capable of achieving specific tasks.

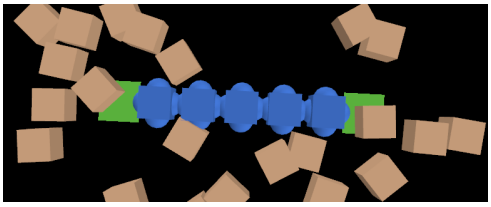
Growth: By using VE it is possible to organize the growth process of a robotic organism. Instead of duplication processes of the original VE process [5], [22] docking signals are used to signal autonomous mobile robotic units where to dock to the already existing robotic organism (Fig. 2)

Healing: The bio-inspired VE process is able to compensate damaged done to the robotic organism during the growth process (Fig. 3). Although the regeneration abilities are limited we plan to investigate the evolutionary conditions which lead to higher regenerative abilities of the robotic organisms.

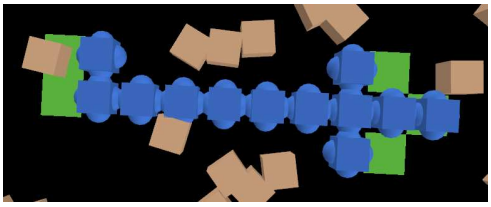
Self-localization in body and 'tissue-specialization': For a multi-modular robotic system that consists of autonomous modules it is important that not all modules behave the same all the time, otherwise no complex organism behavior may emerge. In AHHS, all modules share the same genome, thus they all have a 'private' instance of an identical AHHS controller. In consequence, they have to switch to different modes of operation depending on the status of their neighbors but also depending on their location within the organism. For example, to allow a gait motion of a four-legged organism, a module that is part of the leg should act in an oscillatory manner while a module in the 'backbone' should be rather stiff. In addition, it is desired that such an ego-positioning is adaptive and not hand-coded, so that after a reconfiguration of the organism (e.g., four legs $\rightarrow$ six



(a) three cell phase

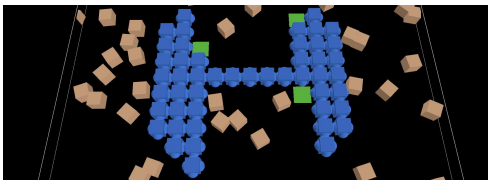


(b) five cell phase

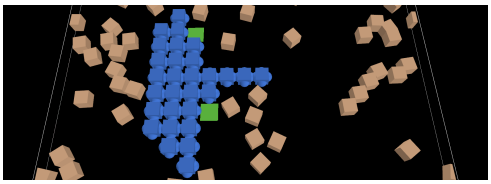


(c) twelve cell phase

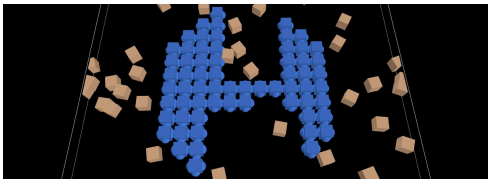
Fig. 2. Growing robotic organism. Blue cubes indicate docked robotic modules which are part of the robotic organism. Brown boxes indicate autonomously driving robotic modules. Green areas indicate docking signals.



(a) undamaged embryo



(b) damaged embryo



(c) regenerated embryo

Fig. 3. Healing of damage in the VE system. During the growth process (a) a part of the robotic organism is removed (b). Due to the regenerative abilities of the VE system, the robotic organism can regenerate the lost parts (c). Note that the regenerative abilities are limited, and small differences during the regeneration process lead to small differences in the resulting body shape. Blue cubes indicate docked robotic modules, which are part of the robotic organism. Brown boxes indicate autonomously driving robotic units. Green areas indicate docking signals.

legs) the modules again are able to achieve this functional positioning.

To investigate whether or not the AHHS has the potential to exhibit such a functional ego-position awareness of modules, a set of randomized genomes was created and introduced into the modules of a simple organism. The system was parametrized with 10 hormones and 60 rules for hormone-to-hormone and sensor-to-hormone interactions. All organisms were immobilized and only equipped with distance sensors, thus sensor data was stable during these runs. After the AHHS started we observed first heavy fluctuations in the local hormone concentrations which damped within approximately 10-30 time steps to local equilibria of all hormones. We realized that in almost 30% of all organisms at least one hormone showed position dependent equilibria. Thus, in these cases, modules could identify their position within the robot organism by considering the local concentration of this hormone. In consequence, based on these concentrations, they were able to alter their behavior in a location-dependent manner. Fig. 4 shows four instances of these organisms in which the concentration of the location-specific hormones were color-coded.

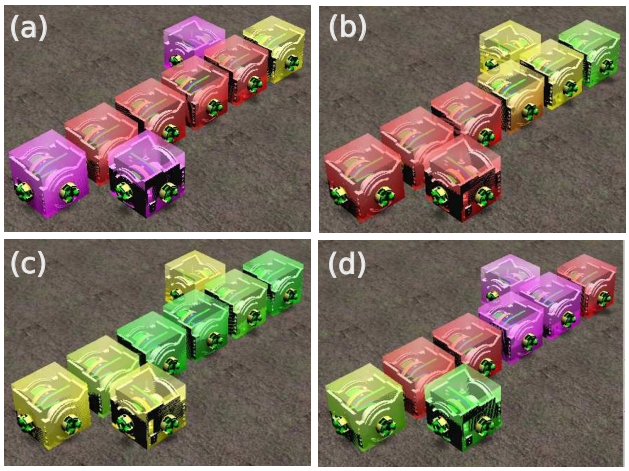
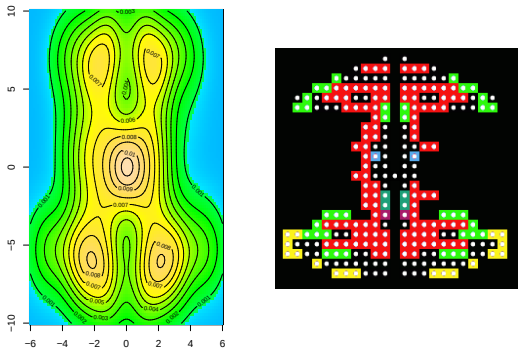


Fig. 4. Self-localization of modules based on position-specific equilibria of hormone concentrations. Hormone concentrations are color coded: Different color types show different virtual hormones. The brighter a color the higher is the local hormone concentration. These controllers are parametrized in a random way, no selection was applied. Approx. 30% of randomly created controllers exhibit this capability.

Investigations in the VE process showed, that during the growth process different sets of tissues develop (Fig. 5). The different tissues of the virtual embryo differ in their receptivity for morphogens. Due to these differences cells of different tissues start to behave differently under comparable chemical conditions.

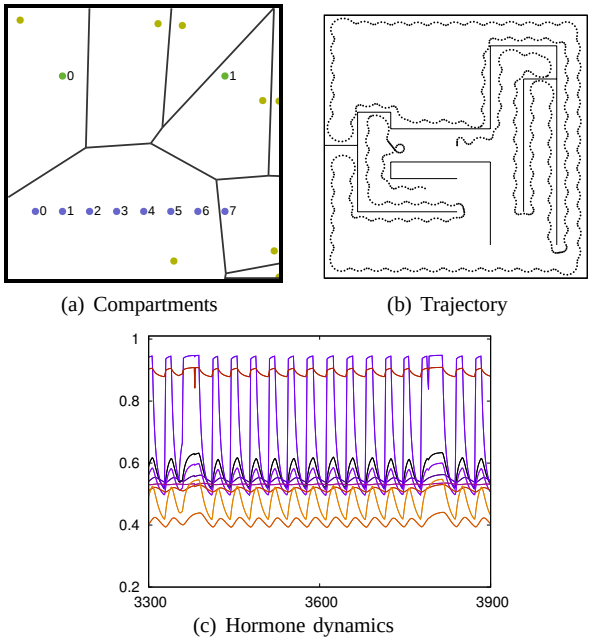
Compartmentalization: The compartmentalization process is crucial for the functionality of the AHHS controller. An elegant way to describe compartments in a robot module is to use Voronoi diagrams [25], [26], [27]. Using artificial evolution to delete, insert or move Voronoi points allows to optimize the inner morphology of the robot.

In Fig. 6 the task of a single robot module was to



(a) genetic activity (b) different tissues

Fig. 5. Development of different tissues during the VE process. Due to different activity levels of genes (a) different types of cells emerge during the growth process (a). In (a) colors indicate the activity of a gene, which leads to a differentiation during the growth process. In (b) white circles indicate cells, colors indicate different levels of a cell property, which influences the detection of a morphogen on cellular level. These differences in receptivity for a given morphogen are analogous to the development of tissues within a biological organism. (a) redrawn from [22]



(a) Compartments (b) Trajectory

(c) Hormone dynamics

Fig. 6. An AHHS controller with evolved compartmentalization. Sensor/actuator anchor points are fixed. (a) Voronoi diagram of the compartments with anchor points of actuators (green), anchor points of sensors (blue), Voronoi sites (yellow). (b) Trajectory of the agent in a maze. (c) Hormone dynamics of the hormone in all 8 compartments in a short period of the run that is shown in (b).

explore a maze. Artificial evolution was used to shape an inner structure for the AHHS controller, which consisted of one hormone. In Fig. 6(a) the evolved compartments are plotted as a Voronoi diagram. The key point of the functionality of the controller arising from the inner structure is the separation of sensor 7 into its own compartment. This proximity sensor points to the left front of the robot module. It is strongly activated when the robot approaches a wall from the left. This leads to a high concentration of the hormone in this compartment (Fig. 6(c)), purple line with oscillations of high amplitude). An oscillation occurs because of 'on/off' intervals in the perception of the wall to the left. This oscillation of the hormone concentration is clearly communicated to actuator 1 by diffusion but only weakly to actuator 0 which results in a wall following behavior shown in Fig. 6(b). This behavior is one solution for a task in which a maze has to be explored and it was discovered by artificial evolution that was only adapting the compartmentalization. No adaptation of the other AHHS parameters was allowed.

Location specific functionality: In the experiments with self-localization of AHHS mentioned above, random genomes and immobilized robots were used. However, this only shows the basic capability of AHHS of self-localization in undisturbed environments. As soon as the robotic organism moves in any way, sensor inputs will become dynamic. To investigate how these sensor dynamics affect the AHHS system, we evolved several programs with the same body plan using AHHS and visualized the dynamic hormone gradients again color-coded. All organisms were evolved to maximize the traveled distance within 1000 time steps and all evolutionary runs evolved sophisticated (and often different) motion principles. We observed caterpillar-like motion, snake-like motion, gait-walking, jumping, and 'dancing'. In all of these cases we observed that high concentrations of specific hormones propagated through the organism in a wave-like manner. However, despite these motion-producing hormone waves we sometimes still observed the functional self-positioning as it was demonstrated above. Fig. 7 shows an evolved organism which emerged in generation 4 from a population of 50 individual AHHS. This organism showed a 'dancer' behavior which means that it partly performs caterpillar motion, then stretches and bends and also jumps from time to time. During this quite complex motion behavior, it expresses high values of a specific hormone (shown in green) only in those parts of the body that currently are in a bended mode, thus these modules form an arch-like shape. This hormone is thus not bound to a specific region anymore, it is bound to a local functionality which goes beyond the individual module. Thus it is functionally group-specific or neighborhood specific. Interestingly two of the modules, the right most end and one of the short limbs, never express this hormone in high concentrations, thus there is also still a location-specific positioning included.

V. DISCUSSION

As we demonstrated in this article, AHHS and VE are not mutually exclusive solutions to control a multi-modular robotic system. Such systems have a clearly defined list of functional requirements, which we elaborated in this article. For some of these requirements, both, AHHS and VE seem to be equally suitable solutions. For example, both are parameterized by a quite similar evolution-friendly representation of rules. Both techniques show promising results concerning evolvability and also concerning computational potential.

Fig. 8 shows a graphical comparison of causal relationships and feedback loops in both systems. The figure clearly

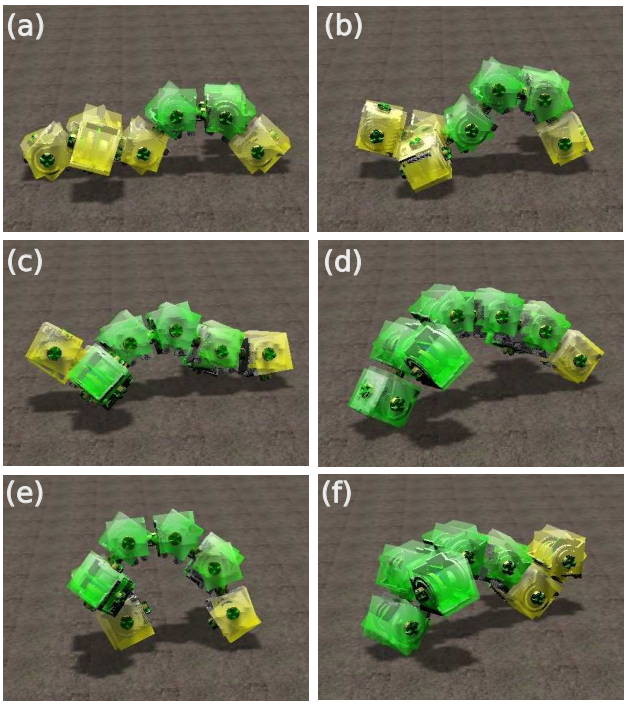


Fig. 7. This organism has evolved a complex motion program in AHHS, which we call 'dancing'. One hormone, shown in green color, is expressed only in those modules which actually bend, that is that they form an arch-like structure.

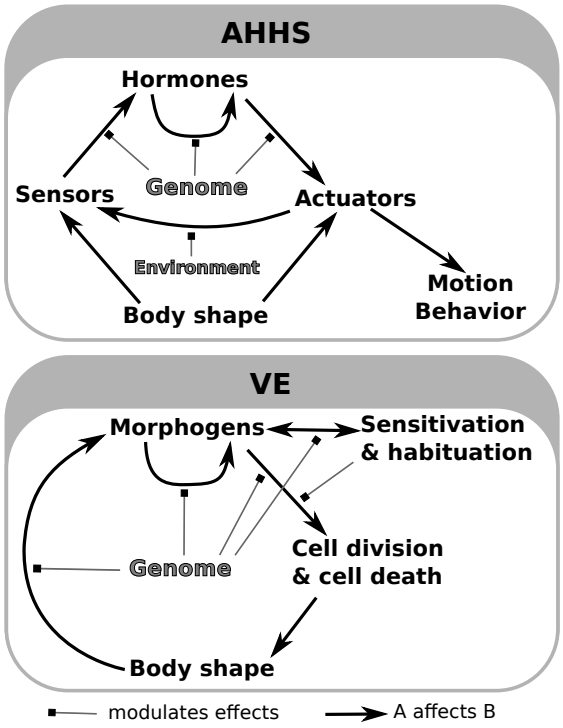


Fig. 8. Schematic comparison (causal loop diagram) of AHHS and VE. Arrows indicate causal relationship between system components. Blocks indicate mechanisms of modulation of the strength of these causal relationships.

identifies significant differences in the feedback loops that exists in both software frameworks. Due to these differences, some software requirements for multi-modular robotics seem to be best addressed by one of the two bio-inspired control frameworks. We demonstrated that short evolutionary runs (several tens of generations with several tens of individuals) suffice to achieve motion behaviors in robotic organisms with AHHS. Even without selection, a high fraction of AHHS systems which were randomly parameterized showed collective dynamics which allowed self-localization of individual modules inside of the organism (see Fig. 4). While this was achieved in AHHS within a readily-constructed organism a similar self-localization functionality emerges in VE during the growth process of robotic organisms. AHHS showed to be able not only to encode the location of a module within an organism but also the functional state of modules (see Fig. 7).

We have shown that also internal structuring of robots into virtual compartments leads to promising behavior in tasks like exploring a maze by using AHHS. In the example shown in this article artificial evolution provided a solution that separated the two actuators of the robot into two distinct compartments. This led to a spatially specific influence of a crucial sensor on these two actuators, leading to a beneficial turning behavior. This simple example is just one step in the direction which combines form and function in controllers for modular robots.

The VE process has shown to be suitable to develop body shapes of modular robots using artificial evolution. The resulting building process and body shapes are stable against damaging and have regenerative abilities (Fig. 3). Damages during the building process, based on noise in the environment (e.g., temporary leak of docking modules) or malfunction can be compensated to a certain extent [22]. The advantage of VE compared to other methods to organize robots [28], [29] is the evolvability, the high tolerance against noise and the low communicational and computational requirements. VE uses little communication bandwidth and requires little computational power, which results in some limitations of the regenerative abilities [22]. These advantages originate from the biological examples, which inspired the concept of VE [18], [30]. Detailed models with focus on simulation of the physical and chemical processes during the embryogenetic growth process are shown in [31]. Closely related to the usage of the VE for robotic body formation is the development of controller structures using bio-inspired processes (for a review see [32]). Especially the development of Artificial Neural Networks is currently investigated (e.g., see [33], [34]).

During the last 10 years several hormone-inspired control approaches were suggested. Some use virtual hormones to modulate the behavior of a neural network [35], [36], others apply the hormone metaphor to represent 'moods' of a robot [37]. In other applications robot-to-robot communication is implemented via virtual hormones (or pheromones) to control geometric pattern formation and 'pattern healing' [38]. The described system does not build morpho-

logical structures, but does develop patterns comparable to those built by the Turing processes [39]. In swarm robotic approaches virtual hormones are meant to establish a gradient field [40], [41], [29] for coordination purposes. For regenerative pattern formation, a 'robotic stem cell' is described in [42], which is able to support self-repair in a robotic organism. The high regenerative ability of the system described by [29] is based on complex algorithms requiring the ability to use high level communication and localization between robots. The approach of [42] operates on inter-robotic communication, which is based on the hormone-inspired communication principles described in [43]. Thus, it significantly differs from the AHHS approach, which emulates the changes of concentrations similar to chemical concentrations. In view of multi-modular reconfigurable robotics AHHS can be seen as unsteady coupled oscillators. An outstanding work of using coupled oscillators in modular robot organisms is [44], but they don't deal with the problem of reconfigurability. Also coupled oscillators in the form of reaction-diffusion systems were used in [45], in which most similarities to the AHHS approach might be discovered. However, it is based on a mostly fixed reaction network and there is a difference in the number of compartments (differs by the order of magnitudes) which will arguably result in qualitatively different processes.

VI. CONCLUSIONS AND FUTURE WORKS

One of the goals in modular robotics is to develop robotic systems, that have reproductive abilities. We plan to investigate, how to use evolved regenerative abilities of the VE process to generate new robotic structures. Thus, we will investigate how to enable robotic organisms to regenerate into a set of new robotic organisms after they got broken it into pieces.

Future development of AHHS will be focused on investigations of scalability (e.g., evolving behaviors with given module numbers and applying them to organisms with more modules) and robustness (fault tolerance in case of module break downs etc.). Furthermore, another approach will go in the direction of combining inner structure (e.g., compartments) with the functionality of the control system during the evolutionary shaping. It will also be necessary to develop tools for a more theoretical investigation of these reaction-diffusion processes. If they are investigated as information processing devices, it should be possible to foresee which complex behavior they can achieve.

Finally, we can conclude that a merged system, or a system that holds both software components (AHHS and VE) and selects between these two control paradigms depending on the context, might be a very good solution to control and to reconfigure multi-modular robots. In such a combined framework many sub-components of both systems can be used in a combined way, for example the program code for managing and altering (mutation, recombination, inheritance) of 'genome' can be fused to support both software frameworks.

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