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Reconfigurable swarm robots produce self-assembling and self-repairing organisms

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HIGHLIGHTS

- Development and production of 100 modular and reconfigurable robots (three types).
- Formulating and implementing of Grand Challenges 1: 100 robots, 100 Days, a cognitive approach.
- Formulating and implementing of Grand Challenges 2: Evolutionary Robotics, an evolutionary approach.
- Self-coordinated framework dealing with both GCs.

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ABSTRACT

Reconfigurable robots are set to become a vital factor in the theoretical development and practical utilization of robotics. The core problem in this scientific area is steady information transfer between a swarm and its organisms and vice versa. To this end, we present a basic theoretical framework that stipulates the interoperation between the two modes. We evaluate our proposed framework by constructing 100 mobile microrobots of three different types that initiate the processes of self-reconfigurability and self-repair. The autonomous decision to self-aggregate to an organism mainly derives from the necessity to overcome existing obstructive environmental conditions, e.g. ramps or clefts. The methodological dichotomy that we have chosen to evaluate our concept was to pursue in parallel an approach based on embodied distributed cognition and an evolutionary path mainly based on artificial genomes and reproduction. In this paper, we evaluate these two different approaches in two distinct grand challenges and present the main results.

1. Introduction

Self-reconfigurable, mobile robots can adapt to changing conditions (e.g. in emergency and rescue situations) and are hence favorably utilized in many applications. Therefore, this special branch of robotics has received much attention in the last 25 years. Here, we differentiate between five different directions of research. The first studies considered this area from the perspective of cellular robotics in micro-fabrication experiments [1]. The second developmental endeavor was characterized by the extended utilization of technical and physical phenomena, e.g. M-Blocks [2]. The third approach explored aspects of distributed embodied cognition, e.g. [3]. The fourth line of research was biology oriented and mainly inspired scientists and engineers to mimic natural principles and structures and apply them to technical systems [4], or soft robots like Roboy [5], or AquaJelly [6]. The fifth direction and most recent work investigate biological processes even more deeply, considering evolutionary approaches. Most of the studies utilize hormone-based controllers, e.g. [7,8], or involve elementary evolutionary algorithms.

However, reconfigurable modular robots can now be considered as powerful, distributed computer systems, hence evolutionary algorithms can be extended although they are computationally very demanding. Thus, we resumed the evolutionary approach but greatly amended it by applying artificial genomes and, applied reproduction technologies, performing parent selections and optimizing fitness functions. Consequently, by cross-disciplinary cooperation we could bring the wide diversity of the cognitive approach and the augmented evolutionary path into one common overall endeavor. By combining these two diverse directions, the advantages of both can be linked, while the shortcomings of each are reduced. This hybrid linking has generated considerable interest into new conceptual methods for building reconfigurable robots. As a result, two EC-funded IP-projects REPLICATOR (representing the distributed embodied cognition approach [9]), and SYMBRION (representing the evolutionary approach [10]), were approved for

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Fig. 1. **Three different robot modules were constructed**: (A) Scout [11], (B) Backbone [12], and (C) Active Wheel [13]. All three are equipped with different sensors and actuators. (D) Shows a swarm of single robots and already assembled organisms collected in our in-door arena of 35 m^2. It is characterized by different zones containing ramps, gaps, various flooring styles, and power sockets that are installed at various heights (these zone are clearly visible in Figs. A17, A18 of the supplementary material, Appendix A).

a period of five-and-a-half years (until September 2013). In both ventures, 17 institutes, with a total man power of about 70 persons, have participated. This paper outlines the most important results in hardware and software of both projects.

1.1. Modular robots

The core hardware problem was the design of mobile, modular robots that are able to operate equally well in swarm mode or in organism mode. Organisms should self-construct, maintain their functionality by self-repair, and finally return by self-reconfiguration to the swarm mode (symbiotic organisms) [14]. To fulfill these design requirements we were faced with two main challenges. First, all requirements of the cognitive approach (e.g. autonomous decisions, sustainability) and all evolutionary conditions (e.g. morphogenesis, reproduction) have to be fulfilled by the same robots. Second, we have been coping for several decades with the problem of complexity and miniaturization when constructing micro-robots. I-Swarm robots are the smallest robots (at about 1 cm^3) that have ever been built [15]. But these robots could not fulfill the main requested goals, like sufficient energy supply to establish durability, or appropriate motion pattern, and they could not dock independently. Finally, a tradeoff between engineering prerequisites like mobility, reliability, and stability and mandatory scientific stipulations like collective decision-making, situation awareness, and generation of off-spring led to the final robot constructions equipped with powerful main processors, several peripheral microcontrollers and 14 different types of sensors. We constructed three different robots (due to heterogeneity reasons) that are primarily differentiated by their drives and 3D features (Fig. 1(A–C)). The smallest size that complies with our requirements is about 10 cm^3. All hardware details and corresponding videos can be found in the supplementary material (see Appendix A).

Fig. 1(D) shows the majority of the 100 robots that have been built and can operate in both modes. It is worth noting that the hardware requirements of the swarm and organism modes are fundamentally different; the control-based differences between the two modes will be explained under Fig. 2.

2. Grand challenges

To evaluate both approaches separately, we defined two expedient grand challenges [16]. The first one is: 100 *Robots*, 100 *Days*. This name originates from the catalog of classic, cognitive-based tasks that have to be performed by self-reconfigurable and self-repairing robots. In short, all relevant tasks in this challenge depict the main aspects of cognition-based self-organization and autonomous, collective decisions.

The second grand challenge is entitled: *Evolutionary Robotics*. This challenge focuses on artificial genomes, evaluated by online, on-board evolution, and analyzes regulatory and homeostatic functionalities of multi-cellular organisms [17]. A typical genome is a sequence that contains the description of the shape of the organism and usually a motion controller. It also serves as a technical experiment to try to describe the development of multi-cellular organisms from single cells (e.g. by information optimization [18] or energy sharing).

Both challenges exhibited the ability of reconfigurable robots to survive without human interactions for a relatively long period (e.g. 100 days), thereby performing various tasks that are essential for cognitive mechanisms and/or evolutionary algorithms. Some goals are common to both approaches (e.g. survivability); other tasks, like the generation of descendants (or establishment of a species), are only possible with the evolutionary approach. Nevertheless, all tasks were accomplished in the same arena.

The conceptual characteristics of the two approaches have not been described in depth in the literature. To close this knowledge gap, we developed overall frameworks that portray and differentiate between the two alternative approaches illustrated in Fig. 2. Within this framework, the Swarm–Organism–Swarm-Cycle (*SOS-C*) [19] refines the cognitive approach and the *Evolutionary-Life-Cycle* (*EL-C*), originally called *The Triangle of Life* [20], and characterizes the evolutionary approach.

2.1. Grand challenge 1: 100 robots, 100 days

In designing the SOS-C, using the cognitive approach, we assumed that external conditions can be so hard that robots can only

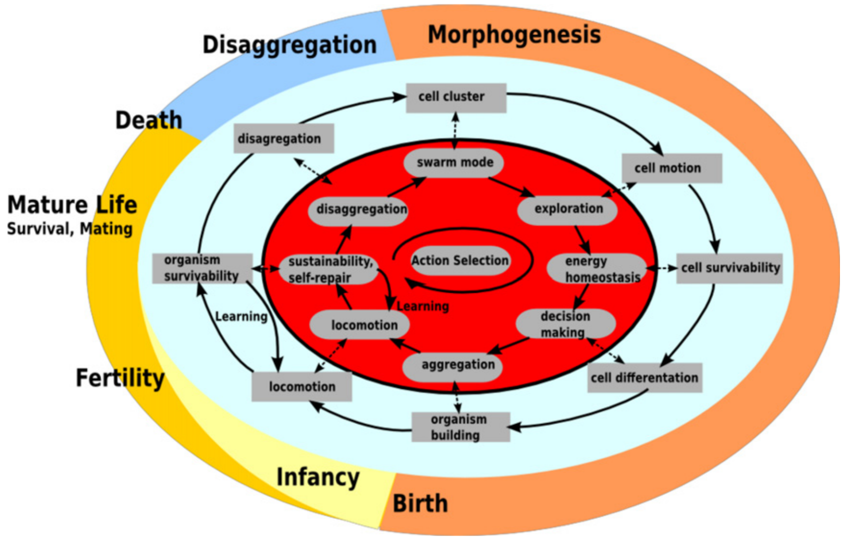

Fig. 2. Overall framework, with the *SOS-C* (red cycle) and the EL-C(light blue ring). The outer-most cycle (multicolored) condenses the *EL-C* into a short description using analogous biological expressions. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

survive when they are assembled to form a specialized organism, or reconfigured in modified organisms, or again disassembled into a swarm. These high-level requests ensure goals like adaptation, situation awareness, communication, and decision-taking. In addition, the robots must possess basic supplementary functionalities like docking and undocking, energy regulation, maintenance performance and locomotion control. All high-level goals, together with the basic functionalities, are controlled by an action selection mechanism [21], actuating a traversal of the SOS-C. All tasks that have to be performed within the catalog of the first grand challenge can be read off from the SOS-C captions in Fig. 2. One typical scenario that illustrates both modes is foraging, where swarm robots try to detect power sources, however they can only reach them when they assemble themselves into a three dimensional organism. Fig. 3 presents snapshots of 12 steps that robots have to perform in order to self-organize and switch from the swarm to the organism mode in a target application. This aggregation process starts at (A), it gradually generates a quadruped (B–I), and finally assembles a mobile four-leg organism (J–L).

If a module, e.g. a ped (Fig. J) malfunctions; the organism passes to the self-repair phase via the disaggregation phase. The self-repair process could result in a reconfigured organism, e.g. when the correct spare module is not available. When the sustainability phase is attained (multiple reload is possible), this organism traverses the *SOS-C* – maybe in a changed shape – as long as it does not need to disaggregate.

2.2. Grand challenge 2: evolutionary robotics

The concept behind the evolutionary approach *EL-C* (Fig. 2) is generic. The only significant assumption we make is the genotype–phenotype dichotomy: the phenotype is encoded by a genotype. In other words, any robotic organism can be seen as the expression of a piece of code called an artificial genome. The standard evolutionary operators are applied to the genotypes and not to the phenotypes. The individual implicitly strives for maximum fitness by optimizing motion patterns, or cell or organism viability, or reproduction processes [22]. All individual tasks that have to be performed within the challenge *Evolutionary Robotics* can again be read off from the *EL-C* ring captions in Fig. 2.

The first relevant part of the *EL-C* is the morphogenesis phase. This process begins with a cluster of roaming cells (or moving cells) receiving an initial genome. A robot starts as a roaming cell in a cell cluster (like a totipotent cell). All of these cells contain a population of various genomes received from fertilizing organisms, or generated as the result of evolutionary processes. Through this subassembly process, the path toward multi-cellular organisms is tread. Organism-building proceeds as follows. A robot selects a genome out of the genome pool, which determines the organism shape and the corresponding controller. It initiates the aggregation process by the exchange of cell signals. The process of cell differentiation assigns specific functionalities to a robot cell, and includes the selection of sensors. The desired functionality of a robot cell will mainly be dictated by its predetermined position in the organism. In this way, the process of organism building will be finished iteratively.

The next stage, infancy, begins with on-board, on-line learning of a certain locomotion pattern, during which the gait is continually improved (Fig. 4). The corresponding locomotion controller can be hormone-based [23], or use a central pattern generator, or be implemented by an artificial neural network [24]. Once an organism fulfils certain fitness criteria (i.e. locomotion, reliability, and survivability), it becomes fertile. The organism enters the mature life phase and is able to distribute its genome (mating and reproduction). This phase expires with the death of the organism, whereby, its cells can become new roaming robots in the cell cluster. A non-occupied robot receiving a new genome can act as a new initial robot cell and can start a new *EL-C* with the mission to process to the morphogenesis phase that results in the organism-building phase as mentioned above. The whole cycle is considered as an open-ended evolutionary process, with the continuous creation of new generations of descendants [25].

Up to now, we have concentrated our descriptions exclusively on separate traversals of the two cycles. But both approaches can also be combined to reduce their drawbacks. For example, the organism building process of the *EL-C* is slower than the goal-directed aggregation process of the *SOS-C*. The passive search of power sources (foraging in the *EL-C*) is more quickly performed if executed in the active exploration and sustainability phase of the *SOS-C*. Conversely, the three processes of cell differentiation, organism-building and locomotion in the *EL-C* are more effective when carried out in the corresponding phases of the *SOS-C* if the form of the resulting organisms is not clearly defined from the beginning. This might happen in situations where the environmental

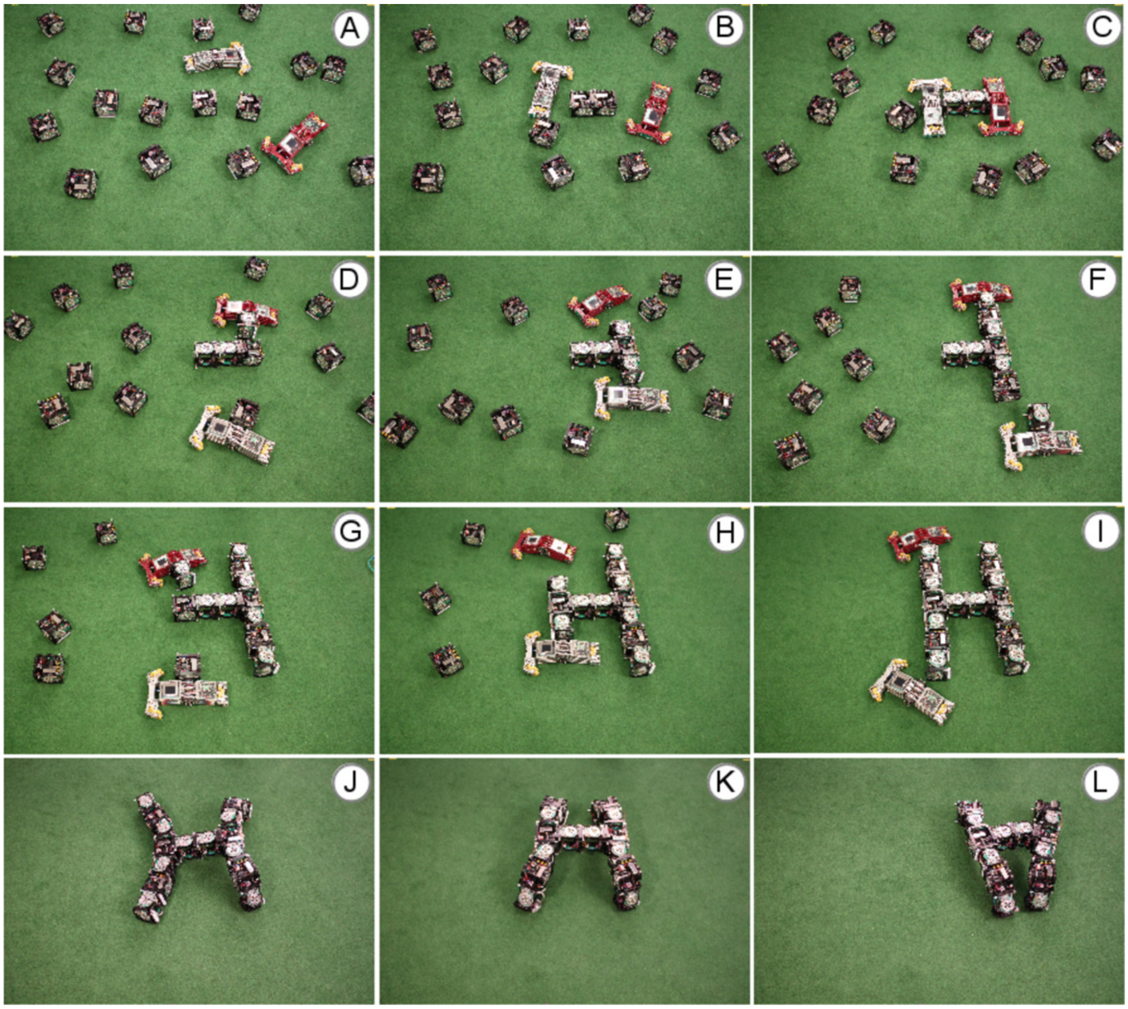

Fig. 3. Snapshots of several traversals of the SOS-C. A swarm of robots detects a power station and decides to aggregate into a quadruped in order to connect to the power station located above (A–C). Parts of the target organism are sequentially aggregated. First, the body is shaped, then the front legs (D–F) and the rear legs (G–I). Aggregation is performed by recruiting other modules to dock at prescribed docking positions. Two Active Wheel robots transport the single modules to the correct docking position and rotate them to the dockable side of the module. Afterwards the quadruped starts its locomotion phase (J–L) (predefined controllers for all regular motion patterns are already implemented). The learning process has been finished successfully and the organism enters the survivability phase. It switches directly again to the locomotion phase and begins the charging process.

conditions are not well known since the area is difficult to access for humans, or objects are barely visible.

3. Conclusion

The main goal of both projects to aggregate multi-robot organisms with the ability of self-assembly from a swarm and self-disassembly again in a swarm remains unprecedentedly valid as a strong vision for future achievements in reconfigurable robotics. These claimed capacities are tackled from both perspectives of engineering (Grand Challenge 1) and evolution (Grand Challenge 2). Both Grand Challenges do not fully meet the requirements that are associated with them. Nevertheless, all the requirements of both challenges represent unaltered significant scientific and engineering aims of future projects in the field of reconfigurable robotics.

Thus, the experimental results that could be achieved during the evaluation time of both Grand Challenges over a period of about 6 months clearly demonstrate the principal power and feasibility of our theoretical cycle approaches. However, the main goal mentioned above could not be achieved because the experimental results clearly reveal the following weak points.

At first, our 100 reconfigurable robots are not enough reliable, robust, scalable (e.g. different organisms with various sizes) and are too complex to "survive" all different assembly and disassembly operations of reconfigurable organisms. This means, that mainly the multiple transfers from swarm mode to organism mode and reverse cause e.g. energy and communication problems, and some of the robots need hereby human support because they run out of order. Therefore we could not demonstrate the autonomous organism survivability for 100 days, but only for some days (mostly 1 to 2 days). Secondly, self-repair operations can only be performed if the defect module can be un-docked, carried away by a transport robot (Active Wheel) and a new, available part can move (or to be moved) to the original position.

The remaining question about the essential information why a survivability of 100 days could not be realized can very clearly be answered. The architecture of the Hardware was too complex and not matured enough thus failures appear all too often and the robots could not solve the corresponding problems (e.g. often assembly or disassembly operations) by themselves. Robots that are much simpler constructed are less prone to errors and are better suited to correct losses in a self-organized manner.

Thirdly, basic evolutionary algorithms must be substantially augmented e.g. by artificial gene regulation networks and by the integration of physical restrictions (e.g. force, torque and gravity) that are considered in the engineering-based approach. Thus,

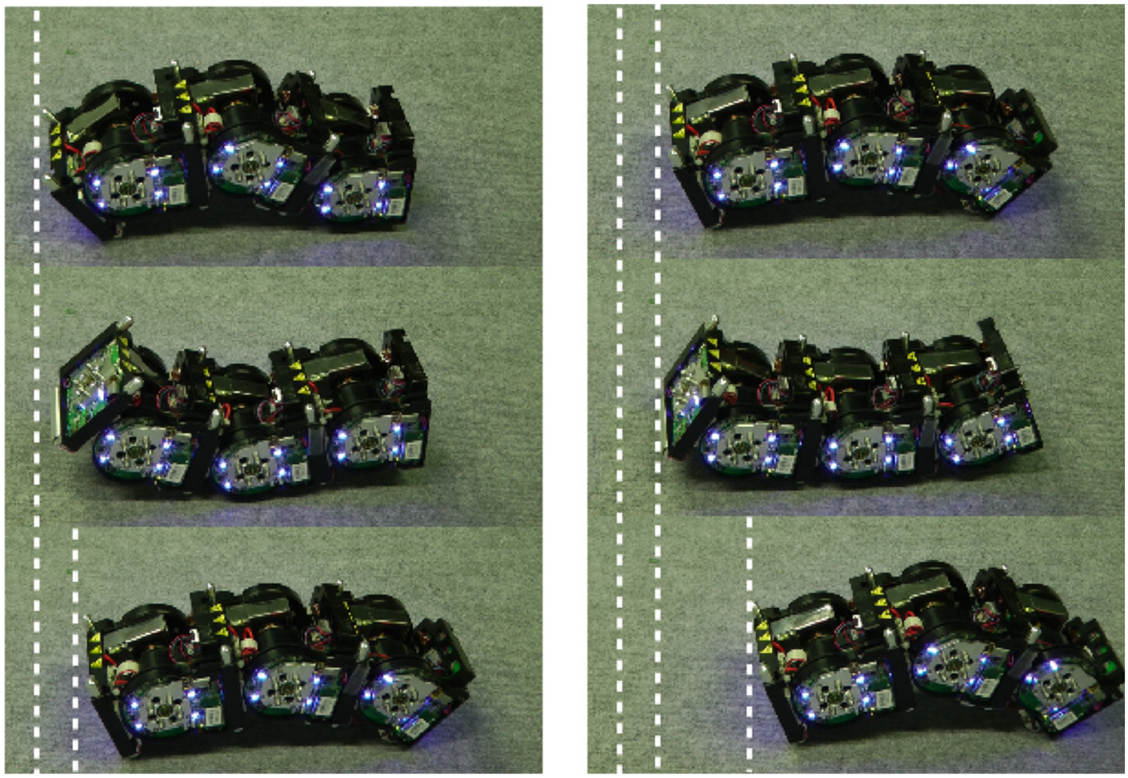

Fig. 4. Sequences of evolutionary-based (hormone-controlled) locomotion in the infancy phase of a caterpillar-like organism of three robot cells.

e.g. the procedure of motion learning a lot of times destroys some legs because the technical constraints have not been included into the evolutionary algorithms. For future applications we will remedy these missing parts and integrate them into evolutionary algorithms.

What is still missing is the connection to the brain signals. Here neurorobotics within the framework of the European Human Brain Project delivers nowadays the possibility to close for robots the missing link between the genome and the brain level. Hereby, neurorobotics utilize the signals from the internal neural level of the brain in order to control a robot. This will bring the genome-based and the brain-based approaches closer together. Regarding the design of reconfigurable robots this implies a notable redesign of the robots in order to direct acceptance of neural-based signals by the new hardware and the execution of these commands.

Nature does not create symbiotic organisms at higher levels, essentially due to aggregation problems and controller switches (co-evolution of shape and gait). Despite the obvious evolutionary complications, the big challenge for scientists and engineers lies in the realization of the combination of our two approaches. In the future, robots will construct themselves autonomously, conforming to the existing restrictions.

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Appendix A. Supplementary data

Supplementary material related to this article can be found online at http://dx.doi.org/10.1016/j.robot.2014.07.001.

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