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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