EVOBODY Project

Deliverable 2.1

Report on the First Workshop

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EVOBODY

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New Principles of Unbound Embodied Evolution

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Prof. Dr. A.E. Eiben (VU University Amsterdam)

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Executive Summary

The EVOBODY project aims to organise consultation of multi-disciplinary communities, such as evolutionary computing, robotics, evolutionary biology and bio-molecular science, in order to support the formulation of ideas and initiatives regarding the topic of *embodied evolution* (EE). For this purpose, a number of different instruments will be used, among which the organisation of two workshops. For these workshops, attendees were invited according to a selective list of experts, people that play an important role in the different areas of research mentioned above.

The first EVOBODY workshop had as main aim the identification of the main challenges associated to the realisation of embodied evolution (EE). This workshop took place on September 23, 2010, and had a total of 17 participants (4 EVOBODY project members and 13 experts).

The workshop consisted of group discussions, when participants were divided into small working groups, and plenary discussions, when all participants took part in the dialogue. The morning session was called *What & How* and the questions/topics to be examined concerned mainly the definition of embodied evolution, its feasibility and the road to (i. e., milestones) to realise it. The afternoon session, the *Why (not)*, consisted predominantly of desirability and usefulness issues of embodied evolution. Together those sessions should give an overview of the most basic aspects of EE systems.

Even though no single definition of embodied evolution could be agreed upon, the most important aspect of embodiment, or *embodiedness*, seems to be that there is no separation between the information and the material that processes that information. In itself, this represents a revolutionary step, for instance, towards personal computers that become integrated into everyday environments. Besides, the goal of EE is not to understand evolution, but successfully using its principles and methods to obtain the computational systems of the future.

However, in order to obtain non-biological organisms (a mix of hardware, software and wetware components) that can perform complex computations and, in fact, evolve into even more advanced systems, a lot still needs to happen. For instance, if one consider reproduction as a essential part of evolutionary systems, great developments have to be made in the area of smart material engineering in order to obtain (self-)replicating non-biological systems. Moreover, if the control the designed EE systems is to be guaranteed, appropriate methodologies that allow EE systems' design and implementation have to be established.

On the other hand, existing dis-embodied methods, such as simulation and evolutionary computing, can be used as a design toolbox and remain relevant to the understanding of general properties of evolutionary systems, model and predict the behaviour of EE systems.

In this context, the interaction and cross-fertilisation between ICT, bio-techonology and material science is one of the major challenges. It is from these that the effective realisation of EE will come. On the way, the role of each discipline needs to be identified, the objectives and complexity of systems evaluated, as issues such as trust, controllability, reliability and safety discussed.

Based on the outline of the various relevant aspects of EE systems obtained from the first EVOBODY workshop, the follow-up event should have as main aim to bridge the gap between the two distinctive tracks of research, namely robotics and bio/chemical/material sciences.

Contents

1 Introduction

Workshops are the main instruments of the EVOBODY project in the course of creating awareness on the concept of *unbound embodied evolution* and engaging the (relevant) multidisciplinary community in the discussion on this promising research area.

The first EVOBODY workshop had as main aim the assembly of a group of top experts in order to identify the main challenges associated to the realisation of embodied evolution (EE). Those experts were from different disciplines such as evolutionary computing, evolutionary biology, bio-molecular science and (evolutionary) robotics.

This document, identified as deliverable D2.1, is a report on the organisation of the first EVOBODY workshop (WS1). In this report we will display the results of the workshop. In detail, we present a detailed account on the workshop sessions that allow us to draw conclusions about important aspects of EE (e. g., feasibility, desirability and usefulness) as well as the identification of insufficiently covered areas of expertise and gaps in challenges. Moreover, we include here a proposal of the topics and overall format of the second EVOBODY workshop, together with a list of the experts to be invited.

The organisation of the current document is as follows. In the next section we give an overview of the workshop, providing logistic information such as the names of participants and agenda, and report on the discussions carried out during the day. In Section 3 we provide the highlights of the workshop and feedback received from participants. In Section 4 we delineate the content and list of participants of the second workshop, based on the conclusions drawn from the first edition. Finally, in Section 5, we report on related literature. All references included here were suggested by the WS1 participants.

2 First EVOBODY Workshop

The first workshop of the EVOBODY project took place in Malta on September 23, 2010. The Corinthia Palace Hotel was chosen as accommodation and meeting venue.

Here, we will describe in detail the list of participants (Section 2.1), the format and discussion topics considered (Section 2.2), and we give a detailed account on the statements made throughout the day (Section 2.3).

2.1 Participants

In total seventeen people were present in the first EVOBODY workshop: four EVOBODY project members and thirteen scientific researchers from different areas of expertise. Below we list all participants, together with their affiliation. First, the organising committee, followed by the group of experts. In both lists all names appear in alphabetical order[1].

WS1 Organisers	
Gusz **Eiben**	VU University Amsterdam
Nivea **Ferreira**	VU University Amsterdam
Serge **Kernbach**	University of Stuttgart
Martijn **Schut**	VU University Amsterdam

[1] Three other experts were expected to attend the workshop, but were unable to come. They were: Marc Schoenauer, Eörs Szathmáry and Mihaela Ulieru.

WS1 Attendees	
Mikhail **Burtsev**	Russian Academy of Sciences (Russia)
Kirsty **Grant**	UNIC - CNRS (France)
José **Halloy**	Free University Brussels (Belgium)
George **Kampis**	Eötvös Loránd University (Hungary)
Yaochu **Jin**	University of Surrey (UK)
Sylvain **Martel**	Polytechnique Montréal (Canada)
Juan Manuel **Moreno**	Technical University of Catalunya (Spain)
Alexandra **Penn**	University of Southampton (UK)
Alfonso **Rodriguez-Páton**	Technical University of Madrid (Spain)
Thomas **Schmickl**	University of Graz (Austria)
František **Štěpánek**	Institute of Chemical Technology (Czech Republic)
Kasper **Stoy**	University of Southern Denmark (Denmark)
Gunnar **Tufte**	Norwegian University of Science and Technology (Norway)

In the EVOBODY WS1 we have covered the following areas of expertise:

WS1 Covered Areas of Expertise
(Evolutionary) Robotics
Chemistry
Evolutionary Computing
Evolutionary Biology, and
Bio-molecular Sciences

2.2 Workshop Format and Discussion Topics

Participants arrived in Malta on September 22, 2010. A dinner organised in the evening of that day allowed participants to get acquainted, and created an amicable atmosphere for the discussions of the following day.

We started the workshop, on September 23, with presentations from the organisers, who gave an introduction to the topic of embodied evolution. Participants were then randomly divided into three working groups. All groups received the same hand-out containing some example questions/issues to be considered during the discussion.

The first discussion session was called *What & How*, concerning the definition of embodied evolution, its feasibility and the steps necessary to achieve it. After one hour of animated discussion, all the participants were joined together as one group. In this plenary session setting, members of each group had the chance to state their thoughts, and - together with others - develop their ideas and visions further.

After lunch, the *Why (not)* brainstorming session took place. Following the same format as the morning session, the participants were reorganised in three groups. This time, groups had different members than in the morning session, in order to allow a greater interaction among experts. After the discussion in groups, participants were reunited for a corresponding plenary discussion. The afternoon session regarded mainly the desirability and usefulness of embodied evolution systems.

The last session of the workshop was reserved for the feedback on the day, together with relevant suggestions on the format and topics to be considered for the second EVOBODY workshop.

	WS1 Programme
09:00	Welcome
09:15	Organisers presentations
10:00	*What & How* session
11:00	Coffee-break
11:30	Plenary discussion on *What & How*
13:00	Lunch
14:00	*Why (not)* session
15:00	Plenary discussion on *Why (not)*
16:00	Coffee-break
16:30	Closing session
17:30	End of the workshop

In detail, below we list questions/issues used as a guideline for the discussion sessions:

	Discussing Embodied Evolution
1. What & How	
What is EE?	
Feasibility:	Does it already exist? / How far are we? / What do we miss? / What can't we do at the moment? / What can we already do?
Road to:	Pitfalls / Obstacles / Challenges / Dangers and counter-measures / Enablers (evolutionary computing, evolvable and bio-inspired hardware, mechatronics, evolutionary biology, bio-molecular science, . . .)
2. Why (not)	
Usefulness:	Measurable targets / What do we want, and when / What problems could then be solved? / How relevant are those problems?
Desirability:	What do we want? / What we don't want? / Will we be creating life? / Is it ethical to do it? / Do we want to exploit it (commercially)?

In the next section we present the outcome of brainstorm sessions in more detail.

2.3 Content of WS1 Sessions

2.3.1 What is embodied evolution?

In general, most probably due to the various disciplines that it involves, no single definition of the embodied evolution exists. A definition of *embodiedness* assumed here is that there is no separation between the information and the material that processes that information. This can be a revolutionary step towards personal computers, which become integrated into everyday environment. In other words, this can be an intelligent material (in any possible forms, shapes and structures), which performs sensing, computation, actuation and undergoes self-development (self-improvement).

Another suggestion is to consider *embodied adaptation* instead of embodied evolution. Embodied adaptation can be seen as a broader and possibly more appropriate definition as it includes systems adapting on a shorter time scale [2].

One important issue raised by the group of experts is that no complete understanding of evolution is required for a successful study on EE. In other words, one gets to understand evolution better on the course of working with it. In fact, the goal of such a study is not about understanding evolution, but successfully using (some of) its principles and methods to obtain the computational systems of the future.

[2] In principle, evolution may take an innumerable number of generations to be accomplished.

Embodied evolution, and particular EE in robotics, can also be understood in a broader way. For example, using bottom-up chemistry and minimal cells as simplest robots and to investigate EE of bio-chemical and bio-hybrid systems.

Furthermore, self-replication and self-assembling are considered relevant (if not, essential) for any form of embodied evolution.

2.3.2 Feasibility

On analysing the feasibility of EE systems, the main conclusion that could be drawn is that EE systems are to be expected in the near future. However, as a multi-disciplinary effort, the steps toward it are not straightforward. Some necessary elements to realise EE systems already exist, but there are still a number of crucial elements missing.

For instance, consider self-replication as an essential element for EE systems to be obtained. At the moment, there is no non-biological system[3] that can self-replicate. In this case, to obtain self-replicating non-biological systems, smart material engineering is required[4].

On the other hand, there is still room for studying disembodied evolutionary processes. Existing methods, such as simulation and evolutionary computing, remain relevant as they help understanding general properties of evolutionary systems and can be seen as a design toolbox. However, the level in which systems are described might need to suffer considerable changes.

With EE, we could easily end up with a system that we cannot fully understand or, perhaps, cannot control. In order to prevent this from happening, we need a method(ology) capable of controlling evolution. In particular, we need a methodology (or, methodologies) that is all-inclusive (e. g., adaptivity).

In this context, top-down and bottom-up engineering can be distinguished. Bottom-up engineering assumes that we have complete understanding of the effects of our manipulations, and this does not hold for complex adaptive systems). Therefore, is bottom-up engineering more likely to generate unexpected indirect effects? Or is top-down control (e.g., manipulation of selection or selective process) less likely to have some unexpected effects and, as a consequence, deliver more robust systems?

In case we do not want to have total control of the system, some smart dialogue/interface mechanism should be provided in order to obtain the best interaction between system and designer.

Finally, EE needs a fast turnaround time to be useful, e.g., should produce CO_2 eating bacteria before the climate changes.

2.3.3 Road to

Challenges The major challenges of EE identified during WS1 were:

[3] Here, non-biological is understood as systems that are primarily non-molecular. However, the concept can have a wide range of interpretation, see more in I. Zachar, A. Kun, C. Fernando, and E. Szathmáry. Replicators: From molecules to organisms. In Serge Kernbach (ed), Handbook of collective robotics, pp. 335-352, Pan Stanford Publishing, 2011.

[4] Note that this is not necessarily true, if you consider replication from available building blocks. See V. Zykov, E. Mytilinaios, M. Desnoyer, and H. Lipson. Evolved and Designed Self-Reproducing Modular Robotics. IEEE Transactions on Robotics 23 (2): 308-319, 2007.

- (Multi-disciplinary Collaboration) The interaction and cross-fertilisation between ICT, bio-techonology and material science. Putting those relevant areas together is imperative to realise EE. Incentive of basic, fundamental research is needed.
- (Materials and Energy) Another challenge can be formulated as "How to design evolvable system, which uses properties of free environmental materials and energy". What elements can be evolved and which principle(s) can underly this EE? Are these Darwinian principles?
- (Role of Disciplines) How to feed information into such a system? Or, more generally, what is the role of ICT in bio-chemical EE? How to perform a "programming" of biochemical systems?
- (Evolutionary Design) Being able to design systems based on evolution principles, a concept that we do not fully understand.
- (Embodiment) The realisation of hardware components that can effectively carry evolution through.
- (Mind & Body) body and controller (i. e., mind) should evolve together. In other words, there is a need to consider a parallel embodied evolution of body and mind.

Obstacles A number of obstacles could also be foreseen:

- (Complexity) The complexity of engineered systems can become intractable, unless the right design tools and methodologies are developed.
- (Objectives) Biological populations evolve to survive and reproduce, not to solve specific problems. But, here, it appears that we might want to develop systems with specific goals and that have a number of particular properties and characteristics.
- (Guaranteed Results) How can we accomplish what we want without an external evaluation loop?

Danger Moreover, that are some dangers associated to the achievement of EE:

- (Runaway Evolution) We should not run the risk of loosing control over the system. We may need 3 laws for embodied evolutionary systems (a la Asimov's 3 rules of robotics). We will need a stop button that can allow us to cease system execution at any point. We do not want a 100% open-ended evolution!
- (Unprecedented Legal Issues) It is necessary to distinguish the method and the end product. But what happens then? Could method(s) be of public domain, and the end product be owned? Who owns the evolving stuff? Can you, in fact, patent the evolutionary process?
- (Other Unprecedented Issues) Other issues regard trust, verification and liability of the EE systems. What, for instance, can we expect in terms of costs of test and evaluation before we can gain enough confidence that the system does what it was designed for?

2.3.4 Desirability

In general, designing and implementing different EE scenarios seem to be necessary before all aspects of such systems can be coherently analysed and evaluated. If the implementation of such systems is believed to be tied to the engineering of biological systems, than we want EE systems to start happening in the very near future.

Because we might not be able to predict all the properties and envision the true power of EE systems, we might run the risk of dealing with uncontrollable technology. And we might not want to simply accept this risk. So, once an evolving technology is in place, who has the right to push the "stop button?

With respect to commercialisation, the overall feeling among WS1 participants is that technologies and ideas should be of public domain. In this context, evolutionary technologies should be developed to make processes more energetically efficient and/or provide social benefits, rather than just being developed for the benefit of commercial interests.

On the other hand, commercialisation may "prove" relevance and it might be necessary in order to stimulate research funding. Examples of possible commercial applications of EE systems are

- Adaptive/evolutionary packaging in supermarkets. That is, physical packages (color, shape, letters, images) that are produced on-the-fly adapting to the customers' preferences.
- Adaptive/evolutionary recreational animals, i. e., artificial pets.
- Co-evolutionary vaccine development.

In any case, systems should be robust, fault tolerance is imperative.

2.3.5 Usefulness

In terms of potential fields of application of EE, the following could be identified: biomedical (already used for drug design), adaptive materials; and, adaptive robots.

In fact, one of the largest current application domains is the bio-medical research and drug discovery. One example of a potential market is the personal companion, integrated into the body and enchanting mental and physical capabilities of humans. For instance, enhancing immune system and performing EE for provide better resistance to new infections.

In general, the tasks performed by EE systems should have a high level of difficulty, including (but not restricted to): changing environments; multitasking and multi-objectives applications; problems where robust solutions are required; on designing emergent capabilities; and, where simulation is not enough to make use of numerical artifacts.

Furthermore, systems might present other interesting characteristics such as the capability of learning things about the environment, empowered by evolution and social networks; and, personalization of its components, where the machinery is adequate to one's personal needs and requirements.

EE systems exploit the features of the body: you need a body to be able to do something in the environment, to interact with the real world, but you get for free the properties of the material used, physical-chemistry and self-organization. Finally, artificial EE can represent a tool for studying properties of pre-Darwinian evolution.

2.3.6 Why not

There are a number of points that can constitute reasons on why we might not want embodied evolution systems to be accomplished. For instance, as mentioned in the previous section, those systems might be useful for the creation of personalised items, products and services that can fit one's needs and requirements. But this, of course, opposes the concept of general usefulness of systems. Besides, EE systems might become very much dependable on the applications that they were designed to.

Furthermore, evolution may not be fast enough when used as means of adaptation. That is the reason why some suggest the consideration of embodied adaptation instead.

Moreover, also briefly mentioned in the previous sections, the issues of stability, trust and controllability can be hardly ensured. Open-ended evolution and controllability are in opposition. Should/could we aim to steer or manipulate systems in a top-down way, rather than aim for complete bottom-up understanding or control?

And, yet, EE might produce things that we do not "understand, bringing up other issues such as reliability, safety, and responsibility in case of failure. Because EE systems are expected to be of high complexity, each product becomes a research project in itself.

Assume there is suboptimal configuration A and optimal configuration B but between these two configurations in feature-space there are configurations which are "lethal" for the embodied agent. Then EE will never be able to reach B from A, while "normal" evolutionary computing (operating in an unembodied world) does reach B. This is because physical/chemical constraints prevent those intermediate steps in a real embodied agent.The price of real physics. In biology such evolutionary pathways (channels) do exist as well, so they will exist for every embodied agent, as they have to follow the rules and constraints of chemistry and physics.

Finally, EE is time consuming and material consuming, and it (most probably) produces solutions that are not optimal and many individuals that fail. And, it might become trapped in history: once a path is chosen it is very difficult to reconsider and turn around.

3 Summary of Workshop 1

3.1 WS1 Highlights

In this section we highlight the most important points drawn from the discussions. First of all, it seems clear that there is no single definition of EE.

When discussing feasibility issues, self-replication was a recurrent topic of discussion. Some consider it as an essential part of EE, without it real embodiment cannot be achieved. Others, however, think that self-replication is not a fundamental requirement for evolution to take place.

With respect to usefulness and desirability of EE systems, it is in general difficult to identify the important issues without specific applications to look at. Bio-chemical evolutionary systems already exist, thus examples in this area were more popular during the discussions. Important issue: environment engineering.

In terms of relevant areas of research, two distinctive tracks can be identified: i) robotics, and ii) bio/chemical/material. One important conclusion is that material science should be involved more strongly into EE. Moreover, all WS1 experts identified an existing gap between RTD in material science and any forms of ICT research. Considering the role of bio-hybrid embodiment (combination of wet-molecular and hard-silicon systems), currently only fluidic systems-on-chip can provide any forms of such an integration.

In parallel to embodied evolution, there is a need for dis-embodied evolution (e.g., simulation), useful to model and predict EE.

Finally, an essential question was raised: is evolution so essential here? Or is adaptation, for instance, a more realistic and promising direction?

3.2 Future ICT: What's Next?

The participants also briefly addressed the future steps to be taken in order to realise EE. One of the suggestion was to start with a pro-active initiative in FET and, if successful, go for a bigger collaborative project. Another possibility to be considered is a project to be submitted to the FET Open. The clear disadvantages of the latter is the excessive number of submissions under that scheme, which results in a very low success rate.

Yet another alternative is to consider MNP incentive schemes instead of ICT. Project example: evolvable molecular systems.

In any of the situations, the project must show that EE can be advantageous on a use-case.

3.3 Feedback from Participants

After a day of discussions, we received a number of useful comments on the format used for the first EVOBODY workshop. This will help to improve the format and content of the follow-up event.

The first suggestion is to make the second workshop a 2-day event, as some participants felt that they were only getting to the key issues by the end of the day. Besides, WS2 should be more specialised (topic-specific), from multiple fields of interest. And, perhaps, we can also consider allowing participants to give presentations on recent developments of their research (in the context of the chosen topics).

In WS1, the plenary sessions worked very well. Therefore, the discussion format can be maintained, but one of the aims of the discussion can also be to come up with questions for more in depth exploration on the second day. And, if the participants are split up in smaller groups, then different and more specific questions should be given to each group.

Another suggestion is to think about running a session in a "world café" format, intended to mix everyone up and be a good energiser. Such a format is considered to be particularly useful to help identifying research opportunities and challenges, and potential solutions in a particular academic area.

4 Follow-up Workshop

4.1 WS2 Format

Given the feedback received at the end of the first workshop, we consider that the second workshop should be a 2-day event, allowing experts to engage deeper in the discussions.

Moreover, in the EVOBODY document "Description of Work", two scenarios for the second workshop were described. In the first scenario, the second workshop would be a generalisation of the first one, where different research challenges would be explored.

In the second scenario, the second workshop would be an specialisation of the first one, where participants prepare more extended talks regarding certain topics. This format allows, for instance, a more detailed consideration of relevant areas of expertise.

On the basis of the feedback on the first workshop, we should go for the second scenario.

4.2 WS2 Content

We should bring communities together. In special, those that need and those that can provide, such as robotics and material sciences. More specifically, three tracks can be identified : i) robotics, ii) bio/chemical/material, and iii) bio-hybrids.

We intend to maintain the combination of small group and plenary session discussions, but allow the small groups to focus on different questions/topics. This way we can cover more issues/perspectives of EE at the same time as we go deeper in some critical aspects of such systems. We should also attempt to develop further some implementation scenarios such as evolutionary robotics, cell robots, and materials that self-replicate.

4.3 WS2 Suggested Experts

Here we list some of the experts which will be invited to the second EVOBODY workshop (n alphabetical order):

- Martyn **Amos**, Manchester Metropolitan University (UK)
- Dario **Floreano**, EPFL (Switzerland)
- John **McCaskill**, Ruhr-Universität Bochum (Germany)
- Stefano **Nolfi**, Institute of Cognitive Sciences and Technologies (Italy)
- Norman **Packard**, Ca Foscari University of Venice (Italy)
- Rolf **Pfeifer**, University of Zurich (Switzerland)
- Steen **Rasmussen**, University of Southern Denmark (Denmark)
- Jon **Timmis**, University of York (UK)
- Andy **Tyrrell**, University of York (UK)
- Alan **Winfield**, University of the West of England (UK)

5 Literature Review

Here we list the published material (articles and books) that the WS1 participants consider relevant for the project.

1. K. Kobayashi, J.M. Moreno, and J. Madrenas. Implementation of a power-aware dynamic fault tolerant mechanism on the Ubichip platform. In: Proc. of the 9th International Conference on Evolvable Systems (ICES 2010), LNCS 6274, pp. 299-309, 2010.

2. J.M. Moreno, J. Madrenas, and L. Kotynia. Synchronous digital implementation of the AER communication scheme for emulating large-scale spiking neural networks models. In: Proc. of the 2009 NASA/ESA Conference on Adaptive Hardware and Systems, pp. 189-196, 2009

3. J.M. Moreno and J. Madrenas. A reconfigurable architecture for emulating large-scale bio-inspired systems. In: Proc. of the 11th Congress on Evolutionary Computation, pp. 126-133, 2009

4. R.P. Garcia, and J.M. Moreno Arostegui. A cooperative robotic platform for adaptive and immersive artistic installations. Computers & Graphics, 31: 809-817, 2007

5. J.M. Moreno, J. Iglesias, J.L. Eriksson, and A.E.P. Villa. Physical mapping of spiking neural networks models on a bio-inspired scalable architecture. In: Proc. of the 16th Intl. Conference Artificial Neural Networks, LNCS 4131, pp. 936-943, 2006

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7. S. Kumar and P. J. Bentley (eds.). On Growth, Form and Computers, Elsevier, 2003

8. R.A. Freitas Jr. and R.C. Merkle. Kinematic Self-Replicating Machines, Landes Bioscience, 2004

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11. Y. Jin and Y. Meng. Morphogenetic robotics: An emerging new field in developmental robotics. IEEE Transactions on Systems, Man, and Cybernetics, Part C: Reviews and Applications, 2010

12. J.A. Lee and J. Sitte. Morphogenetic Evolvable Hardware Controllers for Robot Walking. In: 2nd International Symposium on Autonomous Minirobots for Research and Edutainment (AMiRE 2003), Feb 2003

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14. M. Mazzapioda, A. Cangelosi, S. Nolfi. Evolving morphology and control: A distributed approach. IEEE Congress on Evolutionary Computation, pp. 2217-2224, May 2009

15. W. Shen, P. Will and A. Galstyan. Hormone-inspired self-organization and distributed control of robotic swarms. Autonomous Robots, 17, pp.93-105, 2004

16. Y. Meng, Y. Zheng and Y. Jin. Autonomous self-reconfiguration of modular robots by evolving a hierarchical mechanochemical model. IEEE Computational Intelligence Magazine, 2010

17. K. Stoy, D.J. Christensen, and D. Brant. Self-Reconfigurable Robots: An Introduction, MIT Press, 2010

18. D.J. Christensen, J. Campbell, and K. Stoy. Anatomy-based organization of morphology and control in self-reconfigurable modular robots, Journal of Neural Comput. Appl., 19(6): 787-805, 2010

19. G. F. Joyce. Directed evolution of nucleid acid enzymes. Annual Review of Biochemistry, 73: 791-836, July 2004

20. H.H. Wang, F.J. Isaacs, P.A. Carr, Z.Z. Sun *et al.* ChurchProgramming cells by multiplex genome engineering and accelerated evolution. Nature, 460:894-898, August 2009

21. J.W. Szostak, D.P. Bartel, P.L. Luisi. Synthesizing life. Nature, 409(6818):387-90, January 2001

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