Evolutionary Developmental Soft Robotics: towards adaptive and intelligent soft machines following nature's approach to design

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Abstract Despite many recent successes in robotics and artificial intelligence, robots are still far from matching the performances of biological creatures outside controlled environments, mainly due to their lack of adaptivity. By taking inspiration from nature, bio-robotics and soft robotics have pointed out new directions towards this goal, showing a lot of potential. However, in many ways, this potential is still largely unexpressed. Three main limiting factors can be identified: 1) the common adoption of non-scalable design processes constrained by human capabilities, 2) an excessive focus on proximal solutions observed in nature instead of on the natural processes that gave rise to them, 3) the lack of general insights regarding intelligence, adaptive behavior, and the conditions under which they emerge in nature. By adopting algorithms inspired by the natural evolution and development, *evolutionary developmental soft robotics* represents in a way the ultimate form of bio-inspiration. This approach allows the automated design of complete soft robots, whose morphology, control, and sensory system are co-optimized for different tasks and environments, and can adapt in response to environmental stimuli during their lifetime. This can be useful for several purposes, from the evolutionary design of soft robots for practical applications, to the study of general properties of soft bodied creatures, which could help realizing the full potential of this field.

1 Introduction

Researchers in the field of biologically inspired robotics [1] (which includes soft robotics [2]) take inspiration from the natural world in order to distill effective mech-

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anism observed in animals and plants into new engineering solutions. Although this procedure has a number of positive effects (e.g. a deeper comprehension of biology – *"understanding by building"*, the possibility to overcome technological barriers by finding alternative solutions to complex problems, etc.), there is an aspect of conventional bio-inspired design that deserves to be highlighted.

Researchers in this field take inspiration from the *products* of a number of natural processes (most notably, *evolution*) that occur in the natural world. This has a number of important consequences. First, the creatures that populate our world are the result of a single evolutionary trajectory, determined by continuous incremental adaptations that allowed them to survive in a changing environment, facing the opponents that happened to compete for the same resources at a given time. Therefore, they are not necessarily optimal in general terms, as we would like machines to be in the engineering field. Secondly, animals and plants are optimized for the biological substrate that was available on earth (e.g. bodies are made of cells, which require specific conditions to survive). In robotics, however, we are not limited to that. Humans have invented sophisticated technologies (e.g. robust and lightweight materials, high-speed computation and communication technologies, all sorts of sensors and actuators, etc.) that cannot be found in nature, and could not be, therefore, exploited during natural evolution. Third, animals and plants are "designed" to cope with challenges such as survival, foraging and reproduction. Although a parallelism can be made among these tasks and those that robots are (or will be) required to accomplish (e.g. surviving = avoid being destroyed in a hostile environment, foraging = harvest energy and resources in order to self-sustain), robots are not in general required to solve tasks that are of paramount importance in the natural world (e.g. they do not need to mate and reproduce), which shaped natural evolution.

These observations entail a paradigm shift in bio-inspiration: despite the solutions that we observe in the natural world being clever and astonishing, what is really special about them is, more than each specific mechanisms, the *processes* that produced them, and the fact that they managed to do so with neither guidance, nor goals. This justifies fields such as *developmental robotics* [3] and *evolutionary robotics* [4], in which inspiration is taken from biological *processes*, that are generalized and applied to artificial systems. In some cases, this also allows moving from the study of *"life-as-we-know-it"* to that of *"life-as-it-could-be"* [5]. For example, with algorithms inspired by natural evolution (*evolutionary algorithms*) it is possible to set up sophisticated simulations that allow us to observe different evolutionary trajectories (as opposed to the single one that we can observe on earth) and perform all sorts of evolutionary study by changing the environment, the starting conditions, and the elements that evolution can manipulate.

In what follows some examples will be briefly described in which evolutionary algorithms are applied in soft robotics, combined, in some cases, with developmental paradigms. This research area can be broadly referred to as *evolutionary developmental soft robotics* (*evo-devo-soro*), a subfield laying at the intersection between artificial life and robotics, in which entire soft robots —both their morphology and control systems— are automatically evolved and grown instead of being manually designed. As the reported examples will point out, this can be done with several dif-

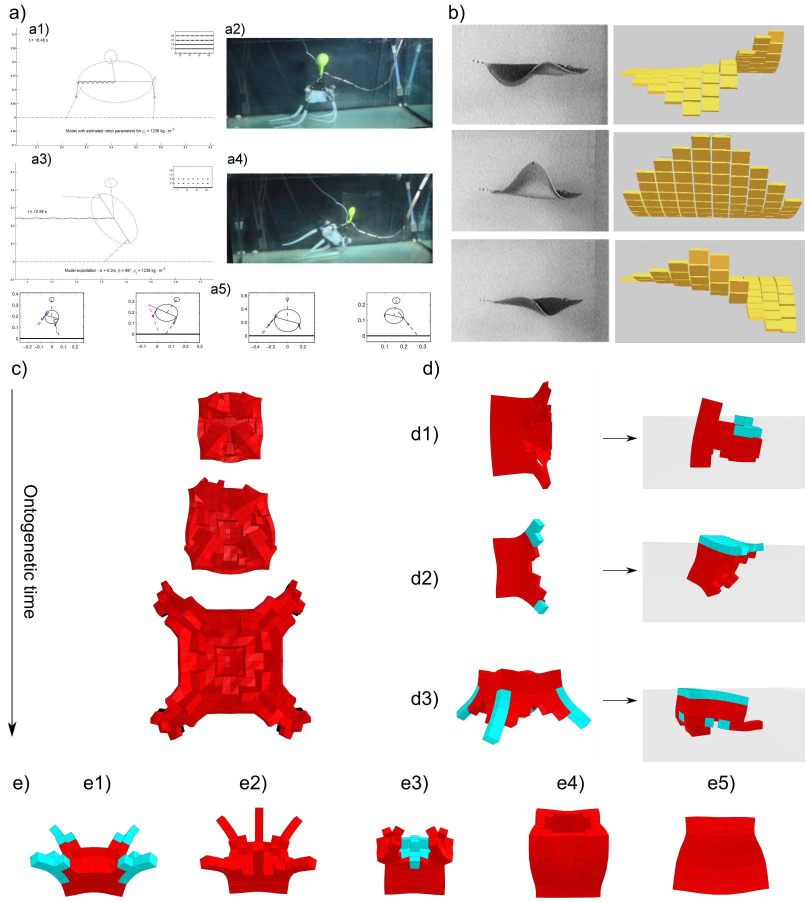

Fig. 1 Examples of *evo-devo-soro*. a) Evolutionary algorithms have been extensively applied in the design of the PoseiDRONE robot. Shown are examples of a successful transfer from evolutionary simulations (a1, a3) to the real robot (a2, a4), entailing in some cases substantial performance improvements. In (a5) a subset of alternative designs suggested by evolution are shown. b) Evolutionary simulations have been adopted to study specific animals too, such as *batoid* fished (e.g. the manta ray). Pictures show the qualitative match between the animal and a simulated compliant wing, that was evolved to study the emergence of oscillatory dynamics involved in the locomotion of these fishes. c) A growing soft robot whose morphology and developmental processes were co-evolved in order to reach out four light sources (not depicted) placed at the four corners. d) A study focused on the effect of environmental transitions water $\leftrightarrow$ land on morphological evolution. Robots evolved to swim (left) are moved to land and further optimized in order to study exaptation phenomena (e.g. tentacles become legs in (d3)) and the relationship between swimming and walking. e) A set of soft robots evolved to swim. A wide array of life-like morphologies and behaviors emerged. See all these evolved robots in action at `https://goo.gl/ka3clE`

ferent purposes in mind: from the design and optimization of real robots for specific tasks, to the study of general properties of soft bodied creatures.

2 Examples of evolutionary developmental soft robotics

Fig. 1 summarizes the examples that will be be briefly described in this section.

2.1 Evolutionary design of real robots

Evolutionary algorithms have been extensively applied in the design of the PoseiDRONE robot, an octopus-inspired soft underwater drone (Fig. 1a). They were first used to achieve a faithful dynamical model of the robot (*genetic parameters identification* [6, 7, 8]) (Fig. 1, a1, a2), then to explore its design space and suggest alternative configurations [9, 10, 11] (Fig. 1, a3-a5). Many insights were gained from these studies, and in some cases evolved behaviors (Fig. 1, a3, a4) correctly transferred to the real world, with a significant improvement of locomotion performances.

2.2 Studying specific properties of soft-bodied animals

In another work [12], evolutionary simulations were employed to study the emergence of oscillatory phenomena involved in the locomotion of *batoid* fishes such as the manta ray (Fig. 1b), and to identify the key morphological traits for the adaptation of such a morphology to different environments (e.g. fluids with different density). The tools and the insights developed with these studies could be useful both to evolutionary biologists and robotic engineers.

2.3 Studying general properties of soft-bodied creatures

A recent article [13] starts investigating the properties of morphologically-plastic soft robots, i.e. soft robots that are able to adapt during their lifetime in response to environmental stimuli (*environment-mediated development*). This aspect (also referred to as *developmental plasticity*) could be key to realizing the huge potential of soft robots in terms of morphological adaptation. Several technologies already allow soft robots to adapt some aspects of their body during their lifetime, but this adaptation is usually controlled by humans and is rarely triggered by environmental stimuli, as it happens in nature. In order for soft robots to be effective and adaptive in the face of changing environmental conditions, insights should be gained regarding when and how such phenomena occur in nature.

This is particularly important if we take into account *embodied intelligence* [14], which postulates that effective behavior is often the result of the dynamic interplay of many factors (not only control, but also morphological structure, material properties, passive dynamics, interaction with the environment etc.). In robotics, these aspects are often carefully tuned by the human designer, in order to have the robot behaving in a desirable ”sweet spot”. It is clear that if the environment happens to change (as it does, in the real world), that sweet spot can only be maintained if the robot is able to recognize that change, and control a suitable adaptation, that can of course happen in the control system, but could leverage body properties as well. This is also related to the concept of *morphosis* [11, 9] (see the related chapter in this volume).

Motivated by these observations, growing soft robots are evolved in [13] to perform a simple phototaxis task, elected as case study (Fig. 1c). Preliminary results show that artificial evolution is able to find effective morphologies and associated developmental processes, often exploiting passive dynamics and *morphological computation* [15]. It is shown, however, that material properties have a dramatic effect on evolution’s ability to exploit such beneficial phenomena, that are quantified in information-theoretic terms. This further highlights the importance of morphology, and shows how evolutionary simulations can be used to investigate the conditions under which adaptive and, ultimately, intelligent behavior emerge.

2.4 Answering evolutionary biology questions through evolutionary simulations

Another recently introduced setup [16] allows the evolution of swimming soft robots. Despite a very simplified fluid model, it is remarkable how artificial evolution came up with a wide arrange of life-like morphologies and behaviors (Fig. 1e). This setup is currently being used for several studies, concerning the role of softness in (underwater) locomotion, the relationship between underwater and terrestrial locomotion and, particularly, the effect of environmental transitions (e.g. water $\leftrightarrow$ land) on morphological evolution (Fig. 1d). This kind of studies have the potential to contribute not only to robotics and soft robotics, but also to fields such as evolutionary biology.

3 Conclusions

In this chapter some considerations in favor of evolutionary developmental soft robotics have been discussed, presenting four different application scenarios. It is expected that the adoption of such automated procedures will become more and more necessary in order to optimize increasingly complex robots that, with progresses in fields such as smart materials, will soon embed massively distributed sensing and actuation systems. A tight integration among different subsystems will be more and more required: the unique ability of evolutionary algorithms to co-optimize all aspects of a robot could be extremely useful in that. In addition to representing a viable way to design and optimize complete soft robots for specific tasks and environments (even more so with advances in digital fabrication and in techniques aimed to preserve the effectiveness of evolved behaviors into the real world), it has been suggested that evolutionary simulations can be used to investigate general properties of soft-bodied creatures, contributing to a deeper understanding of the phenomena and the conditions that lead to the emergence of adaptive and intelligent behavior, possibly unleashing the full potential of this field.

References

1. Barbara Webb and Thomas Consilvio. *Biorobotics*. Mit Press, 2001.
2. Daniela Rus and Michael T Tolley. Design, fabrication and control of soft robots. *Nature*, 521(7553):467–475, 2015.
3. Max Lungarella, Giorgio Metta, Rolf Pfeifer, and Giulio Sandini. Developmental robotics: a survey. *Connection Science*, 15(4):151–190, 2003.
4. Josh C Bongard. Evolutionary robotics. *Communications of the ACM*, 56(8):74–83, 2013.
5. Christopher G Langton. *Artificial life: An overview*. Mit Press, 1997.
6. Marcello Calisti, Francesco Corucci, Andrea Arienti, and Cecilia Laschi. Dynamics of underwater legged locomotion: modeling and experiments on an octopus-inspired robot. *Bioinspiration & Biomimetics*, 10(4):046012, 2015.
7. Marcello Calisti, Francesco Corucci, Andrea Arienti, and Cecilia Laschi. Bipedal walking of an octopus-inspired robot. In *Biomimetic and Biohybrid Systems*, pages 35–46. Springer, 2014.
8. Francesco Giorgio-Serchi, Andrea Arienti, Francesco Corucci, Michele Giorelli, and Cecilia Laschi. Hybrid parameter identification of a multi-modal underwater soft robot. *Bioinspiration & Biomimetics (under review)*, 2016.
9. Francesco Corucci, Marcello Calisti, Helmut Hauser, and Cecilia Laschi. Novelty-based evolutionary design of morphing underwater robots. In *Proceedings of the 2015 Genetic and Evolutionary Computation Conference (GECCO2015)*, pages 145–152. ACM, 2015.
10. Francesco Corucci, Marcello Calisti, Helmut Hauser, and Cecilia Laschi. Evolutionary discovery of self-stabilized dynamic gaits for a soft underwater legged robot. In *Proceedings of the 17th International Conference on Advanced Robotics (ICAR2015)*. IEEE, 2015.
11. Francesco Corucci, Marcello Calisti, Helmut Hauser, and Cecilia Laschi. Shaping the body to shape the behavior: a more active role of the morphology in the brain-body trade-off. In *Proceedings of the 13th European Conference on Artificial Life (ECAL2015), Late Breaking Proceedings*, pages 7–8. 2015.
12. Vito Cacucciolo*, Francesco Corucci*, Matteo Cianchetti, and Cecilia Laschi. Evolving optimal swimming in different fluids: A study inspired by batoid fishes. In *Biomimetic and Biohybrid Systems*, pages 23–34. Springer, 2014.
13. Francesco Corucci, Nick Cheney, Hod Lipson, Cecilia Laschi, and Josh Bongard. Material properties affect evolution's ability to exploit morphological computation in growing soft-bodied creatures. In *ALIFE XV, The Fifteenth International Conference on the Synthesis and Simulation of Living Systems*, pages 234–241. MIT press, 2016.
14. Rolf Pfeifer and Josh Bongard. *How the body shapes the way we think: a new view of intelligence*. MIT press, 2006.
15. Helmut Hauser, Auke J Ijspeert, Rudolf M Füchslin, Rolf Pfeifer, and Wolfgang Maass. Towards a theoretical foundation for morphological computation with compliant bodies. *Biological cybernetics*, 105(5-6):355–370, 2011.
16. Francesco Corucci, Nick Cheney, Hod Lipson, Cecilia Laschi, and Josh Bongard. Evolving swimming soft-bodied creatures. In *ALIFE XV, The Fifteenth International Conference on the Synthesis and Simulation of Living Systems, Late Breaking Proceedings*, page 6, 2016.