Embodied Artificial Evolution

The Future of Artificial Evolutionary Systems

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ABSTRACT

This article is a vision paper about what we call embodied artificial evolution. The main objective is to offer an 'umbrella' term and vision to aid the development of a high potential research area. We introduce the vision by a few concrete examples and identify three major enablers. We also describe some possible benefits of embodied artificial evolution technology and discuss some of the essential challenges on the technical level, e.g., reproduction mechanisms, kill switch, and on a higher level, e.g., design methodology.

Categories and Subject Descriptors

I.2.m [**Computing Methodologies**]: Artificial Intelligence—*Miscellaneous*; A.1 [**General Literature**]: Introductory and Survey

General Terms

Algorithms, Design, Experimentation

Keywords

Embodied Evolution, Evolutionary Systems, Bio-Chemical Systems, Mechatronics

1. INTRODUCTION

This article is a position paper about what we call embodied artificial evolution (EAE). The main objective is to offer an umbrella term and vision, thereby catalysing the development of a high potential research area. The general concept of EAE can be defined by the following properties:

1. It involves physical units instead of a group of virtual individuals in a computer.
2. It has real 'birth' and 'death', where reproduction creates new (physical) objects, and survivor selection effectively eliminates them.
3. Reproduction and selection are not executed through a centrally orchestrated main loop, but in a fully asynchronous and autonomous manner by the individuals themselves. Consequently, the population size may increase or decrease by itself.
4. Evolution can be driven by a combination of task-based and open-ended, environmental fitness.

In general, we can identify two major enablers for EAE, distinguished by the physical medium: mechatrono-robotic systems (hardware, inorganic) and bio-chemical systems (wetware, organic). An example of the former is the *in vivo* evolutionary design of robot bodies, and controllers, for some task(s) in a certain environment. The main challenge here is formed by the reproduction operators crossover and mutation: how to engineer a system where robots can be born (and die)? An example of the latter is the design of bacteria for some medical or chemical task(s). The problem looks similar to the previous one, however, while (re)production of mechatronic bodies is a challenge, bacteria reproduce by themselves. This part of the evolutionary machinery is for free here. The challenge is to implement fitness evaluation and the selection operators suited to the given application objectives.

2. MOTIVATION, EXPECTED BENEFITS

There are multiple reasons to investigate EAE systems. First, EAE can lead to solving new design and engineering problems, and solving existing ones in new ways. In fact, EAE technology can be the basis of a transitional change in how design tasks are solved. Traditionally, the design process of some artifact ends with manufacturing it. Using embodied artificial evolution, design and manufacturing become an intertwined, continuous, on-line activity, propelled by the evolutionary operators (see Figure 1). Second, there is much evidence in traditional evolutionary computing showing that evolution can solve problems not solvable otherwise and that evolution can generate unexpected solutions. (Which, then, can be analysed and reverse-engineered, and thus lead to new insights and better understanding.) Once we equip certain groups of artifacts with the ability to evolve, we create the possibility that some of the evolved designs be truly original, stepping out of the box w.r.t. human thinking. Third, EAE systems can form the basis of a new experimentalism in biology, where evolution can be studied in a radically new way, based on controlled and repeatable experiments in a new medium. This will enable a deeper

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understanding of evolution in general, not restricted to (by) evolution-as-we-know-it within the existing life on Earth. Finally, they represent an interesting intellectual challenge. The science/art of designing and analysing evolutionary algorithms needs to reinvent itself, once we change the medium from purely digital to embodied, physical. In fact, EAEs mean a great paradigm shift from evolving digital code to *evolving things*.

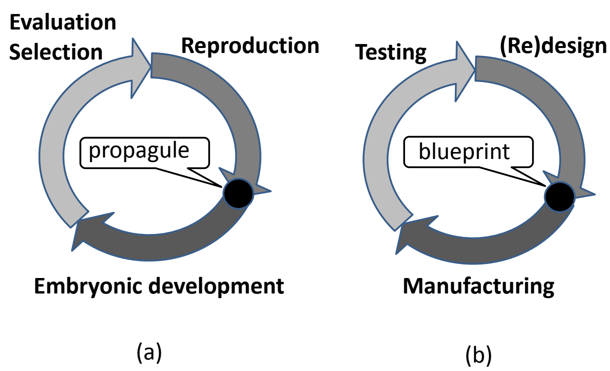

Figure 1: Two circles showing the analogies between the biological circle of reproduction (a) and the new kind of *in vivo* evolutionary design (b).

3. SOME GRAND CHALLENGES

At this stage we cannot tell exactly how the EAE vision will be realised. However, we can already identify some of the grand challenges that must be met along the way.

Body types The essence of embodied evolution is – the body. To this end, we could distinguish mechatrono-robotic systems (hardware) and bio-chemical systems (wetware), that may also be hybridised. Regarding wetware, we note that R&D can be bottom-up, relying on chemistry, or top-down, based on biology. Recent developments in microfluidics or functional fluids also seem very promising. The first grand challenge is thus to find body types suited for (self-) reproduction.

How to start – Reproduction The implementation of birth (reproduction operators) for human engineered physical devices is a critical prerequisite for EAE. These operators must also realise some form of inheritance. The three approaches based on mechatronics, chemistry, or biology differ greatly in this respect. (Self-)reproducing mechantronical and chemical units are far from being trivial, whereas it comes for free in biological systems.

How to stop – Kill switch A serious concern for EAE is the possibility of runaway evolution or the "grey goo" scenario, i.e., uncontrolled population growth, perhaps accompanied by the emergence of new, unwanted features in the population. Therefore, some kind of a "kill switch" is required to guarantee that human supervisors can shut down the system if necessary.

Rate of evolution Useful EAE systems must exhibit a high degree of evolvability and a high rate of evolution. In practice, they must achieve decent progress in real time: have short reproduction cycles and/or large improvements per generation. The main factors here are the application dependent time requirements and the speed of progress, determined by the evolutionary operators. For instance, medical nano-robots should adapt within 2 hours, while Mars explorers with a rough initial design can be given 2 months. Failing to meet this challenge could disqualify the whole approach for certain applications.

Process control & Methodology A radical change caused by EAE technology is that design and manufacturing become an intertwined, continuous activity. This allows systems to be autonomous and self-improving. Meanwhile, human users should perform on-line monitoring and steering in line with the given user preferences. Technically this means directed evolution that could be perhaps realised by directed selection (akin to breeding) and/or directed reproduction (as in genetic manipulation). On a conceptual level, this requires a new kind of methodology that must contain traditional elements, such as specifications and validation as well as address previously unforeseen aspects, e.g., mixing (the dynamics of) "free" evolution with specific design objectives on-the-fly.

4. FINAL REMARKS

In this paper we present the concept of embodied artificial evolution. In this context, the evolutionary systems are (i) embodied because operators (reproduction, selection, fitness evaluation) are implemented in/by the physical individuals that undergo evolution, and (ii) artificial because the individuals and the population as a whole were designed (or programmed) to fulfill a purpose, to execute a task, besides allowing open-ended evolution to take place. We foresee great potential benefits and mention a few application examples. We see three main areas of research that could deliver the physical EAE platform, mechatrono-robotic, bio-chemical, and hybrid systems. Finally, we elaborate on various grand challenges, ranging from implementing physical reproduction in robots to new methodologies.

In conclusion, even though some elements of EAE systems already exist, considerable scientific and technological advances are necessary to achieve the vision sketched here. However, we do expect that the first examples of such systems will arise in the near future.

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We also acknowledge the existence of several relevant papers and related research projects. However, forced by space limitations we have decided to follow a zero-citations policy such that we have the maximum available space for discussing the subject matter.