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Programmable Organisms: Xenobots

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Abstract: What happens when you join stem cells from a frog heart and frog skin? Nothing much, that is until you program those to move. You have created a new organism called Xenobot that's part robot and part living. The skin-heart embryos are just one millimeter in size, but can still accomplish some things, like physically moving towards targets.

Index Terms **- Evolutionary computation, Artificial life Bioengineering, Nano biotechnology.**

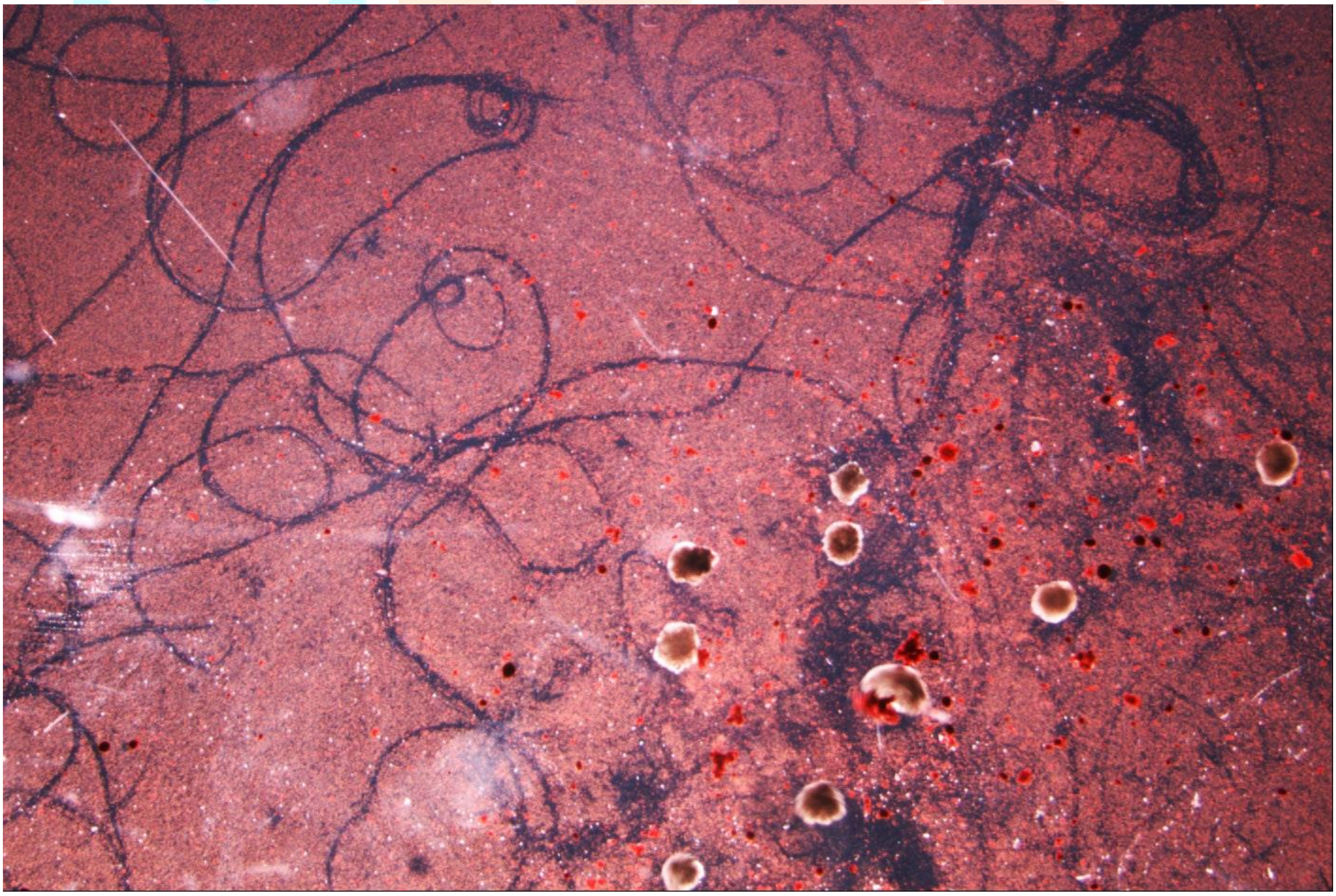

Figure 1 Xenobots carve traces through a field of particulate matter. These simple robots made of cells exhibit remarkably complex behavior.

I. INTRODUCTION

When you put together Evolutionary Computing and Bioengineering, you will get a miraculous invention called Xenobots. This has now allowed us to rapidly design living organisms continuously and to serve novel functions.

Xenobots, derived from the African clawed frog (Xenopus laevis), are synthetic organisms that are designed by the computer automatically using algorithms to perform the desired behavior and built by combining the pluripotent stem cells from Xenopus laevis and contractile tissue harvesting and embedding of Xenopus cardiac progenitor cells.

These Programmable organisms are designed livings systems in silico using an evolutionary algorithm and then manufactured using a cell-based construction toolkit. This approach takes a description of biological blocks to be used and a desired behavior as the input, and then gives out performant living systems that embody the behavior.

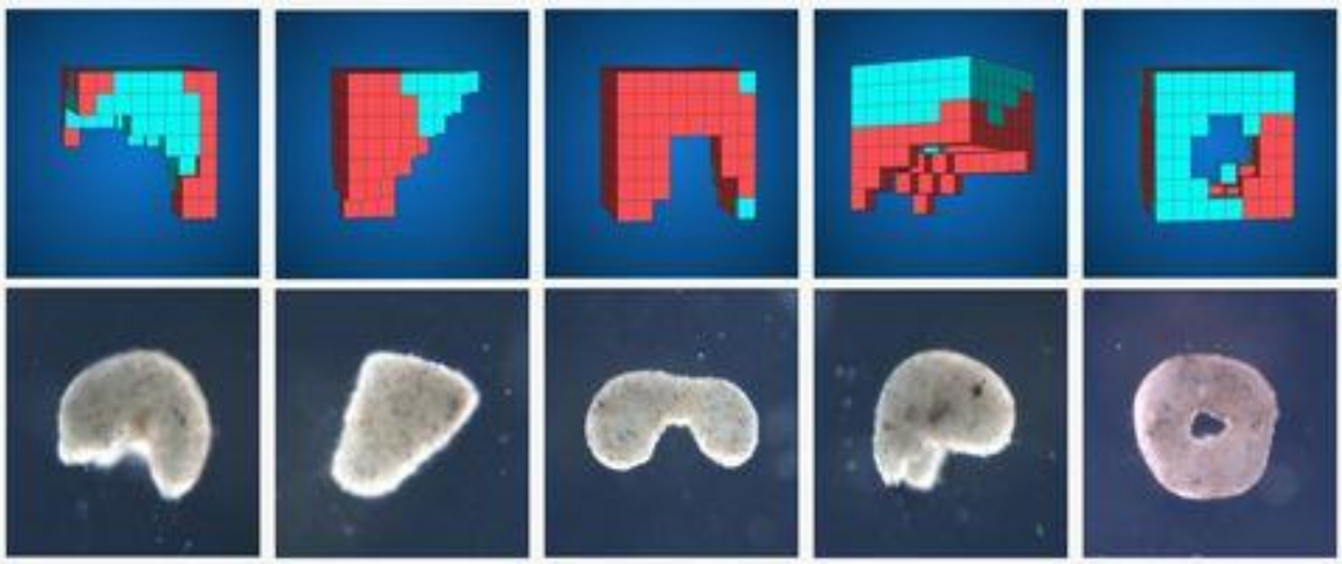

Figure 2 Top row designs are the in-silico designs and bottom row designs are in vivo designs.

II. PROCESS

2.1 Evolutionary Algorithm

An evolutionary algorithm uses mechanisms based on the evolutionary theory of Charles Darwin, such as reproduction, mutation, recombination, and selection. These algorithms are characterized by the existence of population exposed to environmental pressure, which leads to the survival of the fittest, and in turn, results in the rising average fitness of the population.

The first block in this process is the evolutionary algorithm. This algorithm discovers different ways of adding the biological blocks to result in the desired behavior. A random population is created and, then each design is simulated in the virtual environment which obeys the laws of physics and automatically assigned a performance score. Designs which have less performance score are deleted and are overwritten by the modified versions of the design who scored higher. This process is repeated to get performant and diverse designs for the desired behaviors.

2.2 Manufacturing the Design

The design that passed successfully through the evolutionary algorithm is then built out of biological living tissues. First Pluripotent stem cells are first harvested from *Xenopus laevis* embryos and incubated to achieve the desired number of cells. This aggregate tissue is then manually shaped by microsurgery forceps and a 13-µm wire tip cautery electrode, resulting in a biological approximation of the simulated design. Then, contractile tissue is layered into the organism through the *Xenopus* cardiac progenitor cells, an embryonically

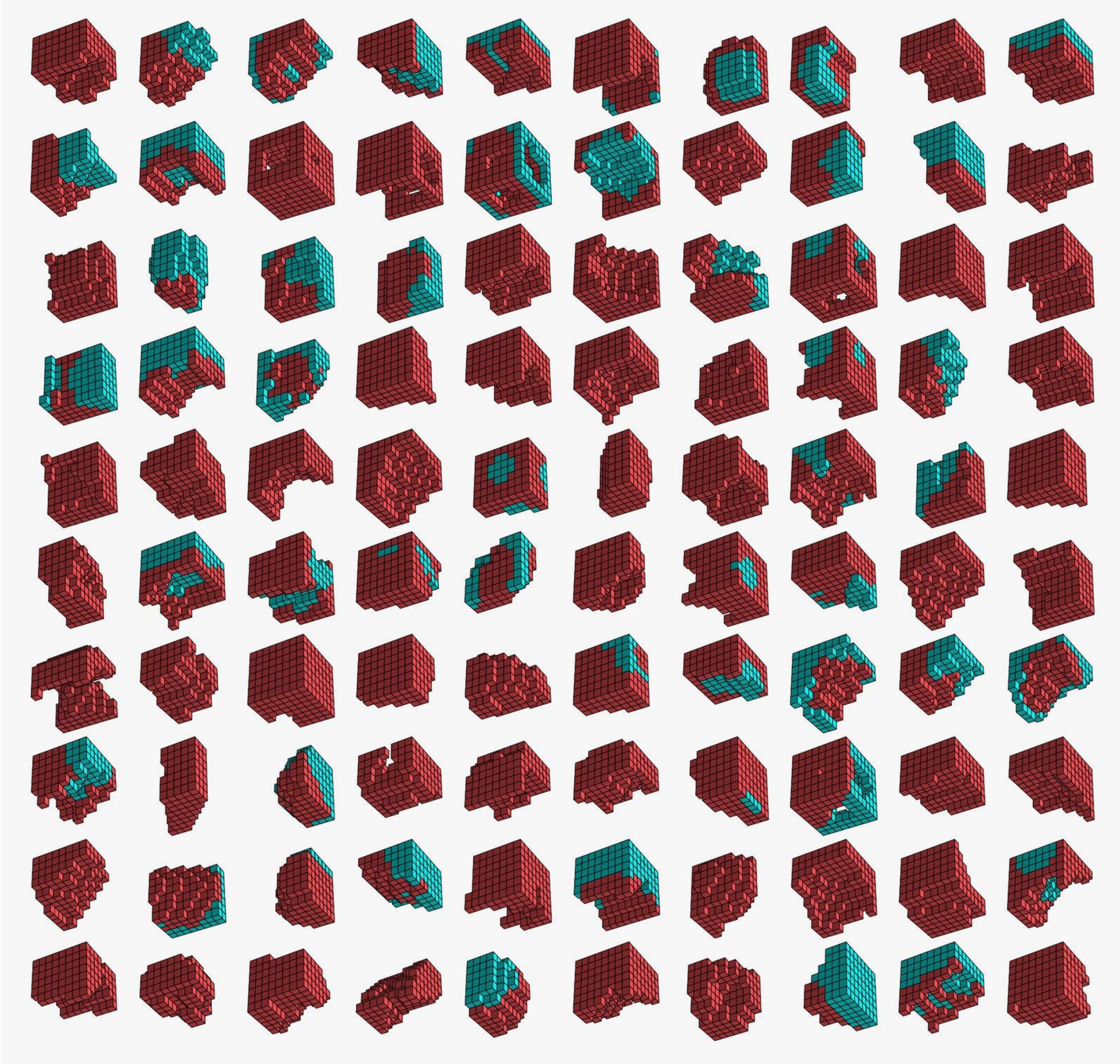

Figure 3 The evolutionary algorithms spit out a wide range of forms.

derived cell that develops cardiomyocytes (heart muscles) and produces contractile waves at specific locations.

This final living organism is a 3D approximation of the final design created in silico. This novel organism is now able to explore an aqueous environment for a period of days or weeks without additional nutrients. If this organism undergoes any damage then it will regenerate to its original form. These organisms are subjects to the physical environment and observed for their behavior. This behavior is compared against the predicted behavior by the simulation, which is in silico behavior is compared to in vivo behavior.
Reconfigurable organisms were evolved to exhibit four different behaviors: locomotion, object manipulation, object transport, and collective behavior. To achieve this, the pipeline was employed four times.

Locomotion. For a diverse population of designs, 100 independent trials of the evolutionary algorithms were conducted. (Fig. 3.) Each design was selected based on displacement in 10 second period. The fittest designs were extracted at the end of the trial and then passed through robustness and build filters. During this filtering process, buildable and scalable designs that retain their behavior were selected for manufacture. Trajectories of the manufactured designs (in vivo) were compared in silico designs, in two orientations (upright and inverted about the transverse axis) (Fig 4) thus eliminating the impact of design morphology between predicted and observed.

Object Manipulation. When the environment is strewn with particulate matter, moving designs spontaneously aggregate the external objects both in silico and in vivo. Then More precise object manipulation can be selected for a defined goal, such as specifying target areas from which debris should be cleared, or target objects to discard. The latter goal was implemented and primitive end-effectors evolved in simulation.

Object Transport. Some designs evolved with a hole in the center which acts as a pouch to store and transport objects.

Collective Behavior. Multiple designs when placed in the same environment, collective behavior is observed. Many of such behaviors predicted in silico were observed in vivo.

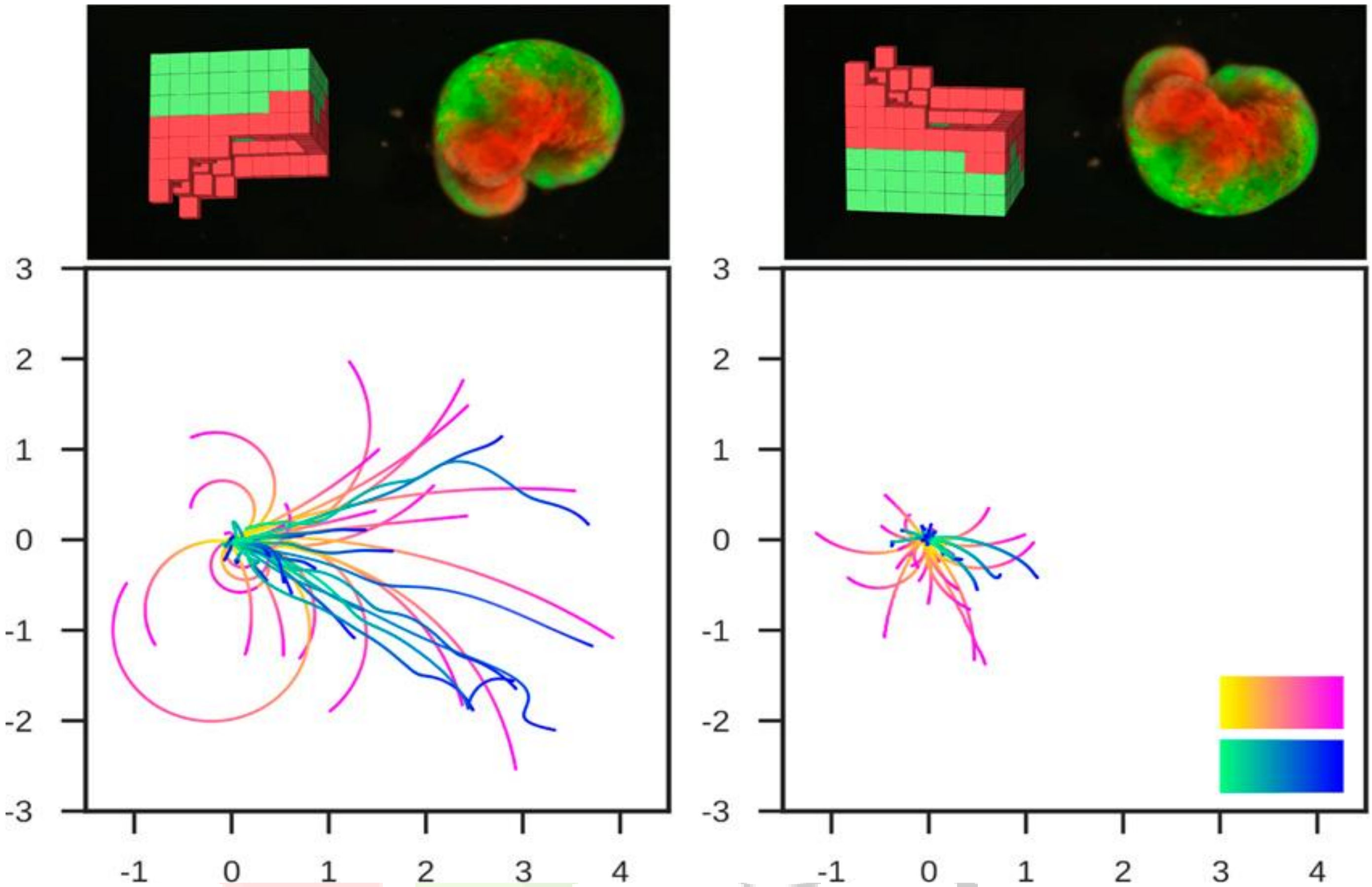

Figure 4 Comparison between the behavior of the organism when placed upright (left graph) and when placed inverted (right graph).

III. Discussion

Simulations and design of rigid structures and machines have been possible for some time but only recently it becomes computationally tractable to simulate the combined behavior of arbitrary aggregates of soft components with different material and behavior. As shown here, such well-constructed simulations can be embedded in the evolutionary search method to discover designs that can be manufactured by biological instead of artificial materials.

The application of this approach is as yet unknown. But, advances in machine learning, soft body simulations, and 3D bioprinting are likely to broaden the scope of this in the future. There could be many applications, given the ease of miss expressing novel proteins and synthetic biology pathways and computational circuits in *Xenopus* cells. Given their feature of being nontoxic and self-limiting lifespan, they could serve as a novel vehicle for drug delivery or internal surgery. If they are equipped to express signaling circuits and proteins for enzymatic, sensory and, mechanical deformation functions, they could find and digest toxic or waste products or identify molecules in an environment that are inaccessible to robots. In the biomedical field, one could envision biobots (made from patient's own cells) removing plaque from artery walls, identifying cancer.

IV. References

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