Co-Evolution of Morphology and Behavior in Self-Organized Robotic Swarms

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I. Extended Abstract

THIS research relies on the premise that robots should be able to improve their swarm by co-evolving their bodies and their minds. Small autonomous robots should work as a swarm and, if and when needed, they should be able to physically cooperate in order to better perform the given task - Figure 1; this might be by physically interacting with each other to temporarily form a larger organism [1].

By co-evolving both morphology and controller, the evolutionary process is expected to converge faster than by doing each evolution at separate times, as seen in [2], which came to these conclusions using a single robot in a simulated environment. There is very little work on any kind of co-evolution in the field of swarm robotics, as it will be discussed in the Related Work; therefore, by providing exclusive data, this research will help solidify the scarce knowledge in the area or even contest it, as the field is still not well established and the state of the art could be restrained to specific scenarios. For example, no research could be found about the impact of evolving the robot's body in a swarm, and consequently, specially at the same time as evolving their controllers.

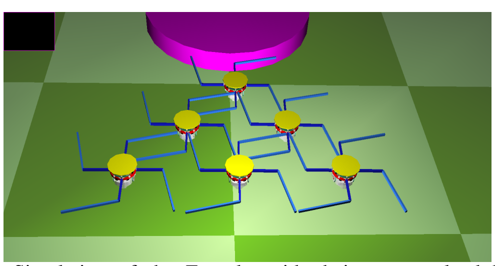

Fig. 1. Simulation of the E-pucks with their new evolved body parts (represented in blue) cooperating to push an object to a determined location.

The controller originally starts with a simple behavior of moving the robots forward, while the interaction between them would be solely due to their morphology. This way, part of the computation that the controller would have to perform is being attributed to the robot's body instead, taking advantage of the morphological computation phenomenon [3], where the controllers tend to be simpler, relying on their physical shapes [4] to compute more sophisticated interactions.

The main two questions that this research raises are whether a trade-off of complexity between morphology and behavior in a swarm of robots exits and if the co-evolution of the morphology and behavior is positive for the swarm.

A. Methodology

The research is being approached using the experimental method. A Genetic Algorithm was developed, where the robots form a population that evolves over time, accordingly to pre-established rules. The algorithm was ran on simulation using Webots, a well-known simulation software. The simulated robots are a direct representation of the E-pucks.

In order to better approach the research hypothesis, the simulation was divided in three stages: the morphological evolution, the behavioral evolution and the co-evolution of both morphology and behavior. In the morphological evolution, arm-like structures are being evolved to improve the robots' bodies. In the behavioral evolution, the conditions that determine the state transitions of a Finite State Machine - FSM - are being evolved to optimize the robots' controllers. In the co-evolution, both arms and transitional conditions are being evolved in order to create the best swarm adapted for the task at hand.

An appropriate task was chosen to test the performance of the robots in a simulated environment specially designed for the situation. As a promising scenario could be search and rescue for example, to start evaluating the robots, a task as simple as pushing a large object forward - Figure 1 - gives an adequate fitness feedback for the evolution to happen.

Following successful co-evolution of the hardware and software of a robotic swarm, the evolutionary process is stopped and the latest robotic generation will be the desired final population of evolved robots, forming an optimal swarm.

In the future, as the robots' controllers and shape specifications can be transferred to their physical bodies - Figure 2, the experiments could be run in a real environment, making use of a 3D printer. Some steps to show its viability were taken and will be presented in the Future Work chapter. With High-Performance Computing (HPC) more available, the processing of the evolution could be run in parallel in simulation, being inspired by Surrogate Models [5], in a continual adaptive process. Controller, morphology and simulation could be co-evolved to address a reality gap between the real world and the simulator [6]. This way, the real robots would be able to adapt to the unforeseen scenarios almost immediately, making them susceptible to evolution in an accelerated pace. It would give the robots a way to predict what could happen and therefore better prepare themselves. Temporal verification techniques for the swarm [7] could also be applied. A combined technique

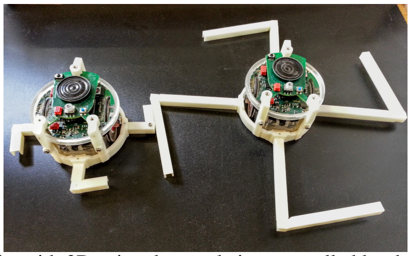

Fig. 2. E-pucks with 3D-printed arms, being controlled by the FSM, showing it is possible to directly transfer the experiment to the real world.

setup like this would greatly benefit and maybe only be possible by having the access to HPC; it could give the robots a sense of ethics as they could simulate the outcome before acting [8], being able to know if their actions would be safe for humans, acquiring what could be called the first steps towards a conscience. The combination of my research with HPC and these new techniques would make the robots as real as they could get while not being biologically alive. They would be able to predict, reflect, adapt, evolve their entire selves, not only based on nature, but faster.

B. Contribution

The direct contribution of this research would be, firstly, new methods and algorithms for hardware/software co-evolution and, secondly, the new types of evolved swarms and their capabilities.

Most importantly, the experiments proposed will gather valuable data in the areas of co-evolutionary robotics and morphological computation, answering some pending questions. Both of these fields are gaining more ground recently and further research is needed to better establish them in the scientific community. Besides the crucial fact that they are both uncharted territory for swarm robotics.

The longer-term impact of the proposed research will be to open up the possibility of robots able to physically evolve and adapt themselves to be able to collectively operate in an unknown or changing environment without human intervention, like for instance in disaster scenarios or planetary exploration.

My research aligned with HPC and 3D printing would enable a real-life robotic evolutionary system that could revolutionize the field. For example, search and rescue robots would be able to be optimized on the go, both physically and behaviorally, giving the victims the best survival chances.

C. Conclusion

It was expected that the robot's morphology would impact on the performance of the swarm, and that the morphology could then be improved through evolution. Given the obtained results, it is shown for the first time that the evolution of the robot's shape can improve the swarm performance for the task of group transport. The robots in their original shape performed worse than the robots with an evolved morphology, independently of the controller's complexity.

The experiments show that the complexity of the controller can be decreased and still achieve good results if there is morphological evolution, thus exploiting the morphological computation phenomena in the transport of objects by multi-robot systems. A more complex controller with a simple morphology does not perform as well as a simpler controller with an evolvable morphology.

It was observed that the evolved robots act as a single organism, they connect with each other almost instantly and combine their forces in the most efficient way, i.e. without creating opposing forces within the swarm. The arms facilitate the connection with the object, making one of the robots touch it, while the other robots connect with one another pushing in unison in the same direction, thus increasing their performance. All of these improvements were solely due to the morphological evolution, with the robots performing better due to the morphological computation. The hypothesized computational savings in the controllers open up possibilities for new improvements in the robot's minds that would not be possible otherwise.

The results from the controller and co-evolution are still being gathered. The swarms that went through the co-evolution seem to be the most successful ones. Since a good controller for a specific shape is not always good for another shape, and vice-versa, evolving both shape and controller concomitantly is not only enabling the best of both to emerge together in a single swarm but, more importantly, they are being tailored to be the best as a whole.

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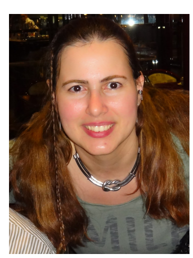

Jessica Meyer has two BSc's degrees, both obtained in Brazil: one in Computer Science at the Federal University of Bahia and another in System Analysis at the State University of Bahia. Her bachelor theses are about Fuzzy Controllers for a 2D robotic goal-keeper, summa cum laude. She has a MSc's degree in Cognitive Science at the University of Osnabrück, Germany, with focus areas in Artificial Intelligence and Robotics. Her master thesis is about a Mixed Reality Robotics Soccer Team based on Swarms, summa cum laude. Jessica has been involved with RoboCup from 2006 to 2011, in the Soccer Simulation League (2D and Mixed Reality). In 2013 she was involved with the SYMBRION project. She is finishing her PhD in Swarm Robotics at Uni Osnabrück, which first 3 years were at the Bristol Robotics Laboratory, England. Her interests are: Swarm Robotics, Evolutionary Computation, Modular Robotics, Self-Reconfiguring Robotics, Self-Assembling Robotics, Swarm Intelligence, Bio-Inspired Computing.