Impact of Energy Efficiency on the Morphology and Behaviour of Evolved Robots

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ABSTRACT

Most evolutionary robotics studies focus on evolving some targeted behavior without considering energy usage. In this paper, we extend our simulator with a battery model to take energy consumption into account in a system where robot morphologies and controllers evolve simultaneously. The results show that including the energy consumption in the fitness in a multi-objective fashion reduces the average size of robot bodies while reducing their speed. However, robots generated without size reduction can achieve speeds comparable to robots from the baseline set.

CCS CONCEPTS

• **Computing methodologies → Artificial intelligence**; **Artificial life**; **Evolutionary robotics**.

KEYWORDS

evolutionary robotics, modular robots, energy efficiency, multi-objective evolution

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1 INTRODUCTION

The matter of energy consumption is especially important in evolutionary robotics applications, where not only the controllers are being optimized by evolution, but also the morphologies. In such a system the number of components that use power, e.g., servo motors or wheels, can vary. The study reported in this paper investigates the issue of energy efficiency in such a system. The main objective is to gain insights into how the evolution of locomotion skills is affected if we include energy consumption into the fitness. To be specific, we are interested in the 'dominant life forms' that evolve under these new conditions. This motivates the following research questions:

Q-1 How does the energy use affect the behavior of the evolved robots?

Q-2 How does the energy use affect the morphology of the evolved robots?

Regarding the evolved morphologies, we have an intuitive hypothesis: Using energy efficiency as part of the robots' fitness will result in smaller robots with the same speed and/or faster robots with the same size.

2 SYSTEM DESCRIPTION

For the robot simulations the **R**obot **Evolve**[1] (Revolve) [2] toolkit was employed. Revolve incorporates a set of tools to allow an easy robot definition, evolutionary operators, and, objective functions to evaluate a robot's performance. For more information about the operators and robot encoding please refer to [4].

To compute the energy consumption of the robots a new battery module was developed and added to Revolve. We assume that the only components consuming power are the servo motors. The energy needed by a robot is the sum of all its joints instantaneous power given by $\Delta C_i = \sum_{j=0}^{m} max(0, M_{ij} \cdot \Phi_{ij})$, where ΔC_i is the robot's energy consumption at simulation step i, m is the number of joints present in the robot's body, and, M_{ij} and Φ are the torque and angular speed respectively. The total energy consumption is the sum of ΔC for all simulation steps. In the beginning of a simulation interval, the battery is filled with an initial charge that decreases by ΔC_i at each simulation step. Once the remaining charge reaches zero the simulation is stopped. This implies that robots depleting their battery faster will have a shorter evaluation period.

We choose to use speed to define the fitness of a robot, measured by the Euclidean distance between position of the robot's core module at the start and end of the simulation divided by the simulation time. This penalizes robots that do not move in a straight line.

[1] https://github.com/ci-group/revolve

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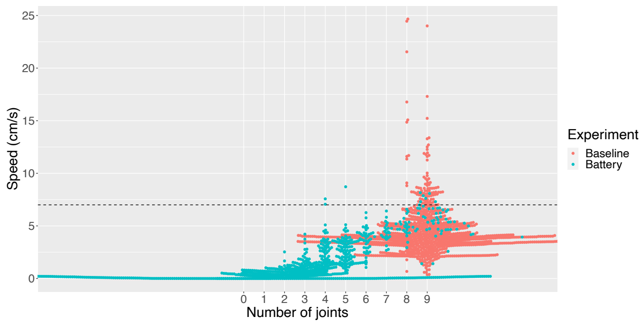

Figure 1: Distribution around speed and number of joints for the robots in generation 100 for all repetition runs

3 EXPERIMENTS

Two different experiments are run to answer our research questions. The baseline consists of an evolutionary run where the objective is to evolve the best body-brain combination that maximizes the robots speed. In the battery experiment, speed and energy consumption are considered as separate objectives. The non-dominated sorting genetic algorithm 2 (NSGA-II) [1] is implemented. The goal is to maximize speed and remaining battery level. The size of the robots was limited to a maximum of 10 joints and 20 bricks. For both experiments the initial battery charge is set to $C_{Start} = 10Nm/s$. The population size was set to $\mu = 100$ with offspring size $\lambda = 100$. The evolution was run for 100 generations. Parents were selected using tournament selection with size $k = 4$. Tournament selection was again used to select the next generation. Each experiment was run 10 times for statistical significance. All the code can be found in https://github.com/ci-group/revolve/tree/battery-master

4 RESULTS

The behavior differences between the two experiments are clear. The mean speed of the robots with energy fitness is considerably lower than that of the baseline experiment. For lower speed their gait was also more balanced. The baseline robots evolve very early to use all of the available battery charge. The algorithm learns that the addition of more joints or including more movement during the simulation is beneficial to achieve a better speed. Morphologies in both experiments converge mostly to snake-like forms which has been shown to be one of the most effective bodies for locomotion for the implemented evolution and encoding system [3]. One of the most noticeable differences between the resulting morphologies is the number of joints included in the body. Robots evolved with the battery constraint can achieve a similar speed as robots from the baseline while having a reduced size. The robot's bodies in the estimated Pareto front for energy consumption and speed on the last generation for all runs can be found in the attached supplementary material.

The speed and size of the resulting robots in all runs for generation 100 are compared to gain more insight into the size/speed behavior of the robots. Figure 1 illustrates this distribution. We define a minimum speed threshold of $7cm/s$ as an acceptable speed for a robot to achieve. Recalling our initial hypothesis we can say that the experiments do not support the first option stating that the inclusion of battery will result in smaller robots with the same speed. However, focusing only on robots with 9 joints the results seem to corroborate the second part of our initial hypothesis, as seen in Table 1. The battery constrained experiment will result in robots of the same size, but faster on average than the baseline (Welch's t-test ($p<0.001$))

Table 1: Mean speed for robots with over 8 Joints

Experiment	No. Robots	Mean speed	SD
Battery	71	5.35	1.29
Baseline	940	4.33	2

5 CONCLUDING REMARKS

This paper addresses the issue of energy consumption on the evolution of robot's body and controller. In order to answer our research questions and assess our initial hypothesis two series of experiments were conducted. The baseline with speed as single objective, and, a battery experiment with speed and energy consumption as objectives. Based on the results we can answer our research questions as follows:

[Q-1] How does the energy use affect the behavior of the evolved robots? We measure the behavior of the evolved robots as the speed achieved at the end of their simulation time. The median speed along the evolutionary run was considerably lower for the robots with battery limitations. This is exacerbated by the inclusion of robots with high battery efficiency but no ability to move as they are also part of the estimated Pareto front. However, this does not exclude the possibility of obtaining high speed robots. Robots with battery limitations tend to move differently at lower speeds but this behavior disappears in higher speeds.

[Q-2] How does the energy use affect the morphology of the evolved robots? The most visible influence on the morphology of the robots is the reduction in the number of joints along the evolutionary process. Morphologies with the ability to move mostly converged to a snake-like shape which from the baseline and other experiments using the same system seems to be one of the most efficient shapes for locomotion in this system.

Regarding our hypothesis: Using energy efficiency as part of the robots' fitness will result in smaller robots with the same speed and/or faster robots with the same size. The experimental results seem to support the hypothesis that robots of the same size can be faster when evolution takes energy consumption into account.

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