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Evolvability signatures of generative encodings: Beyond standard performance benchmarks

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ABSTRACT

Evolutionary robotics is a promising approach to autonomously synthesize machines with abilities that resemble those of animals, but the field suffers from a lack of strong foundations. In particular, evolutionary systems are currently assessed solely by the fitness score their evolved artifacts can achieve for a specific task, whereas such fitness-based comparisons provide limited insights about how the same system would evaluate on different tasks, and its adaptive capabilities to respond to changes in fitness (e.g., from damages to the machine, or in new situations). To counter these limitations, we introduce the concept of "evolvability signatures", which picture the post-mutation statistical distribution of both behavior diversity (how different are the robot behaviors after a mutation?) and fitness values (how different is the fitness after a mutation?). We tested the relevance of this concept by evolving controllers for hexapod robot locomotion using five different genotype-to-phenotype mappings (direct encoding, generative encoding of open-loop and closed-loop central pattern generators, generative encoding of neural networks, and single-unit pattern generators (SUPG)). We observed a *predictive* relationship between the evolvability signature of each encoding and the number of generations required by hexapods to adapt from incurred damages. Our study also reveals that, across the five investigated encodings, the SUPG scheme achieved the best evolvability signature, and was always foremost in recovering an effective gait following robot damages. Overall, our evolvability signatures neatly complement existing task-performance benchmarks, and pave the way for stronger foundations for research in evolutionary robotics.

1. Introduction

Evolutionary robotics (ER) is a promising approach to achieve one of the prominent long-term goals of artificial intelligence research: creating machines with the adaptive and cognitive abilities of animals. Since the eighties, the ER field has made amazing progress to both design sophisticated artifacts and to endow machines with impressive adaptive abilities. For instance, it allows for the automated construction of modular, three-dimensional, physically locomoting robots, [48], to synthesize neural networks to control robot behaviors (e.g., [69,72,84,99]), and discover a multitude of walking gaits for multilegged robots following unforeseen mechanical damages [10,22,66]. However, even the most advanced evolved artifacts are still far behind the state of the art in mainstream robotics [11,59]: conventionally engineered robots are capable

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of operating successfully in a wide variety of indoor and outdoor environments (e.g., locomotion with the BigDog quadruped robot, [91]), whereas the best evolved robots are still only capable of simplistic behaviors (e.g., walking in a straight line on a flat terrain, or avoiding obstacles in an enclosed indoor arena). To progress further, ER needs to go beyond the mere "stamp collecting" of proofs of concept, evident in the infancy of many scientific fields [44], and build strong theoretical and methodological foundations for future research. The objective of the present study is to move in this direction.

In most ER studies, fitness comparison is the main instrument used to compare different evolutionary systems and assess their progress. Such a benchmark-based comparative approach has led to incremental improvements in the robot's performance in specific tasks (e.g., for multilegged robot locomotion, the inclusion of evolved gaits on the commercial release of Sony's AIBO [50,112], and the progressive improvements in walking speed of the QuadraBot [70,118]), and is sufficient if excelling at the given function is the ultimate goal for the robot. Nonetheless, if the evaluated task is treated as a tool to compare different evolutionary systems, and as a stepping stone to harder problems, then a mere comparison of performance does not suffice. This is because such a methodology of comparison only provides a very limited amount of information about the behavior of the system. In particular, it does not provide any insights on, (i) how efficiently does the evolutionary process explore the search space (e.g., can it also lead to solutions for other similar tasks, or is it biased to the type of solutions useful only for a very specific task?), and (ii) what capabilities are provided to the evolved population to respond to novel situations (e.g., an unexpected breakage of the multilegged robot's limbs, or changes to its weight distribution). Furthermore, while adaptive evolutionary systems utilize a variety of population-diversity maintenance methods to operate in changing environments [57], they are mostly concerned with numerical optimization problems (e.g., [81]), and constrained to fitness-based indices to evaluate available approaches [115]. In summary, there is a need for additional metrics when comparing evolutionary systems, especially if one is interested in the adaptive abilities provided by evolution.

In benchmark-based comparative approaches, the fitness value in an evolutionary system is often used as a proxy for the *evolvability* provided by the system [15,43,48,65]—the capacity of the evolved population to rapidly adapt to novel environments [51]. However, such a fitness-based proxy provides little information on the potential of the evolutionary system to generate novel phenotypes, and consequently rapidly adapt to new, untested environments. While fitness landscape models can provide interesting insights on search difficulty in the Genotype-to-Fitness map [90,116], the models 3D landscape can be deceptive when analyzing highly multidimensional genotypes [39,60,78]. Additionally, in NK fitness landscape models [61,110], the value of K that controls the degree of epistasis is not easily transferable to more complex and open-ended Genotype-to-Fitness mappings. Also, the individual solutions in all these models are positioned in the landscape solely based on their measured fitness. In the present paper, to counter the limitations of the fitness measure, we introduce a new evolvability metric that features both the quality and quantity of phenotypic variation following genetic change. With this new metric, we can *visualize* evolvability in the behavior-diversity/performance space and *predict* the performance of the population in previously untested environments.[1] Such predictive insights on the adaptive characteristics of evolved individuals is particularly important, since it is difficult if not impossible to consider and evaluate a priori every possible scenario the robot may encounter during its operation. We employ our new approach to "signaturize" evolvability to compare many different encodings of controllers extracted from the literature. Numerous encodings have been proposed in ER, taking inspiration from natural developmental processes, in particular, to evolve control systems for robots (e.g., [14,15,43,64,70,74,82]). Given the multitude of available encodings, it is crucial to compare them and understand their differences, so that the ER community can focus on the most promising ones. In the selection of encodings investigated in our study, both direct and generative schemes are considered. Direct encodings encompass a one-to-one mapping between genes and phenotypic traits, and are the simplest form of encoding thus serving as a reference for comparison (e.g., [66]). We also evaluate the more complex generative encodings characterized by a one-to-many mapping between genes and phenotypic traits, i.e., a single gene describes several phenotypic traits [103,104]. These state of the art encodings are expected to exploit geometric information of the robot morphology to generate regular and modular phenotypic patterns (e.g., [19,82,105]).

Overall, we investigate five encodings for the classical ER problem of legged robot locomotion [10,15,18,19,43,50,66,70,74,118]: (1) open-loop central pattern generator (CPG) evolved with a direct encoding, (2) open-loop CPG based on non-linear oscillators [21], evolved with a Compositional Pattern Generator (CPPN) [104], (3) closed-loop CPG evolved with a CPPN, (4) artificial neural network (ANN) evolved with CPPN, inspired by HyperNEAT [19,105], and (5) the recently introduced single-unit pattern generator (SUPG) [82]. For all these encodings, the pertinent questions are the same: are these encodings facilitating evolvability, and are the encoded individuals capable of adapting rapidly to novel situations? Furthermore, does the inclusion of a sensory feedback mechanism improve the evolvability provided, and the adaptive capabilities of the individual? To both answer these questions and evaluate the relevance of our measure of evolvability, our experiments are divided into two phases: first, we compare the evolvability signature obtained with each encoding, and consequently predict their adaptability to novel scenarios, then we evaluate the accuracy of our predictions by analyzing the ability of each encoding to effectively deal with the new scenarios (here, when some of the robot's legs are damaged).

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[1] A preliminary study on our approach to visualize evolvability is published in a conference paper [108].