Towards Efficient Evolution of Morphology and Control*

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ABSTRACT

We propose a novel algorithm for the evolution of body and control of three-dimensional, physically simulated virtual creatures controlled by artificial neural networks. The proposed algorithm is inspired by NeuroEvolution of Augmenting Topologies (NEAT) which efficiently evolves artificial neural networks. All three main components of NEAT algorithm (protecting evolutionary innovation through speciation, effective crossover of neural networks with different topologies and incremental growth from minimal structure) are applied to the evolution of both morphology and control system of the virtual creatures. Large-scale experiments have shown that the proposed algorithm evolves creatures using significantly less fitness evaluations than a standard genetic algorithm on all four tested fitness functions. Positive contribution of each component of the proposed algorithm has been confirmed with a series of supplementary ablation experiments.

Categories and Subject Descriptors: I.2.9 [ARTIFICIAL INTELLIGENCE]: Robotics; I.2.8 [ARTIFICIAL INTELLIGENCE]: Problem Solving, Control Methods, and Search

General Terms: Algorithms, Experimentation

Keywords: Artificial life, Computer aided/automated design, Evolutionary robotics, Evolving virtual creatures

1. INTRODUCTION

Research in the area of evolving virtual creatures was pioneered by Karl Sims in 1994 [2]. His virtual creatures inhabit a three-dimensional world with simulated physical laws and are controlled by a series of neural networks distributed along the body of each creature. Since the publication of Sims' work in 1994, original virtual creatures have inspired much research in this area. We propose a novel algorithm – Hierarchical NEAT (hNEAT) – inspired by a recent successful algorithm for the evolution of neural networks – NeuroEvolution of Augmenting Topologies (NEAT) proposed by Stanley and Miikkulainen [4]. NEAT is unique in its ability to efficiently evolve topology of the network along with weights of individual neural connections. The proposed algorithm takes advantage of this fact by applying concepts in NEAT algorithm to the evolution of morphology and control of the virtual creatures. Creatures are represented by a directed graph which is unfolded recursively to construct the phenotype as proposed by Sims. Each body part of the creature contains a local neural network.

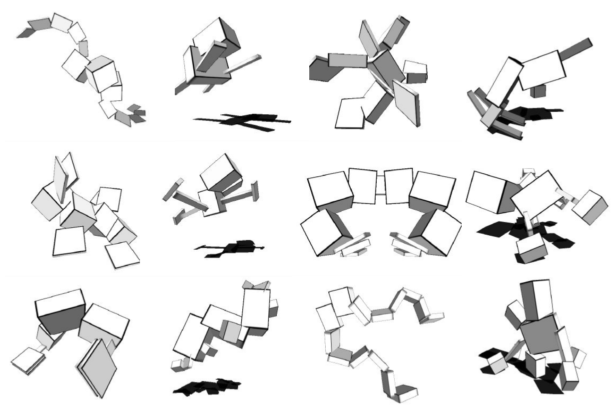

Figure 1: Examples of creatures evolved using hNEAT for light following (first column), jumping (second column), swimming (third column) and walking (fourth column).

2. THE PROPOSED ALGORITHM

NEAT uses the concept of *historical markings* to trace individual neurons and neural connections during the evolution of neural networks. The proposed algorithm – Hierarchical NEAT (hNEAT) – extends this concept by introducing *hierarchical* historical markings to trace structural elements of both morphology and control (for a comprehensive description see [1]). Markings on the level of morphology are managed as in NEAT: each body-part and each connection is assigned a unique inheritable historical marking upon its creation. In addition to that, markings are also assigned to all new neurons.

Creatures are represented by a complex data structure composed of a directed graph representing the morphology, with each node containing a local controller which is, again, a directed graph. Performing recombination of two creatures

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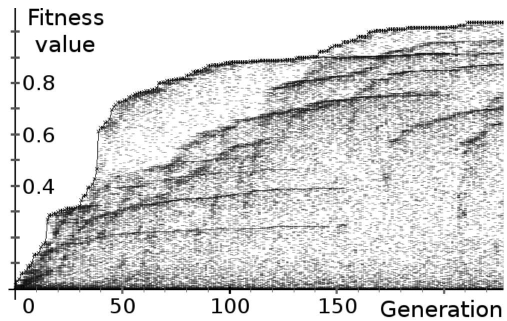

Figure 2: Graph of the fitness values of all creatures in a single evolution. Threads of black color in the graph correspond to individual species.

represented by graphs with different topologies without any additional information is therefore a challenging task. However, hierarchical historical markings offer an easy and efficient solution. Morphology graphs of both parents are first searched for the presence of nodes and connections with the same historical markings. The parent with higher fitness value is then copied to become the first draft of an offspring. Values of internal properties of all matching nodes and connections in the offspring are then randomly chosen from one of the parents. The only exception is the local neural network contained in each morphological node. When a pair of corresponding body parts is found, neural networks themselves are combined internally, based on the historical markings of individual neurons. Recombination thus occurs even on the level of individual neurons and neural connections inside morphological nodes of a creature. This is not possible with other methods such as crossover and grafting [2].

The proposed algorithm uses explicit fitness sharing as a mechanism for speciation (see Figure 2 for visualisation of the speciation). Creatures are assigned to species based on their similarity. Similarity of two creatures is defined, again, based on the correspondence between structural elements provided by the markings. Compatibility distance defined in this manner is capable of measuring differences on a very fine level of detail. It allows species to form not only according to the differences in their morphology, but also according to the differences in their neural networks.

It has been shown that starting from minimal structure increases the performance of the evolutionary search in NEAT algorithm [4]. The same approach has been taken in hNEAT. The initial population is filled with randomly generated creatures with small number of nodes in the genotype.

3. EXPERIMENTS AND RESULTS

Experiments have been carried out using a new implementation of the creatures based on ODE physics engine [3]. Each configuration has been tested independently 30 times using a cluster of 70 PC computers. Population size of 300 was used. Performance was measured as a number of fitness evaluations necessary to reach at least the *winning* fitness value (specified in advance). Unsuccessful evolution was stopped after 100 generations.

First set of experiments compares the performance of the proposed algorithm with the standard GA with grafting and crossover on four different fitness functions (light-following, walking, jumping and swimming). Results show (see Table 1), that the proposed algorithm is significantly faster in evolving virtual creatures than the standard GA (differences are statistically significant; $p < 10^{-7}$). Second set of experiments confirms that the performance of the ablated algorithm (without speciation, recombination based on historical markings or without minimal start) is significantly lower than that of the full algorithm. A large diversity of successful creatures has been evolved for each fitness function (see Figure 1 for examples of evolved creatures).

Behavior	Config.	Mean	Std	Failed
Following	hNEAT	16704.53	6339.75	8%
	GA	27873.94	5002.57	72%
Walking	hNEAT	11033.09	3419.77	0%
	GA	27230.64	4128.62	63%
Jumping	hNEAT	19221.51	7966.50	22%
	GA	29159.23	2068.91	80%
Swimming	hNEAT	10425.67	2707.13	0%
	GA	22438.95	5507.82	16%

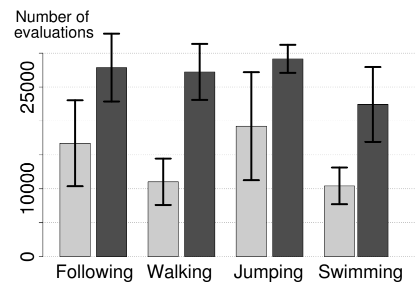

Table 1: Comparing hNEAT and the standard GA. Mean number of fitness evaluations, the standard deviation and the percentage of failed evolutions is shown. Standard GA is represented by dark color and hNEAT by light color.

4. CONCLUSIONS

This paper proposes a novel algorithm for evolving virtual creatures similar to those proposed by Sims [2]. The proposed algorithm is inspired by NEAT – an algorithm for the evolution of neural networks. Large-scale experiments have shown that the algorithm significantly increases the performance of the evolution on all four tested fitness functions. Ablation experiments have shown, that each individual component of hNEAT (recombination based on hierarchical historical markings, speciation and starting from a minimal topology) improves the performance of the search. For more information, visit http://ero.matfyz.cz.

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