Pareto Multi-Objective Evolution of Legged Embodied Organisms

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Abstract

The automatic synthesis of embodied creatures through artificial evolution has become a key area of research in robotics, artificial life and the cognitive sciences. However, the research has mainly focused on genetic encodings and fitness functions. Considerably less has been said about the role of controllers and how they affect the evolution of morphologies and behaviors in artificial creatures. Furthermore, the evolutionary algorithms used to evolve the controllers and morphologies are pre-dominantly based on a single objective or a weighted combination of multiple objectives, and a large majority of the behaviors evolved are for wheeled or abstract artifacts.

In this thesis, we present a systematic study of evolving artificial neural network (ANN) controllers for the legged locomotion of embodied organisms. A virtual but physically accurate world is used to simulate the evolution of locomotion behavior in a quadruped creature. An algorithm using a self-adaptive Pareto multi-objective evolutionary optimization approach is developed.

The experiments are designed to address five research aims investigating: (1) the search space characteristics associated with four classes of ANNs with different connectivity types, (2) the effect of selection pressure from a self-adaptive Pareto approach on the nature of the locomotion behavior and capacity (VC-dimension) of the ANN controller generated, (3) the efficiency of the proposed approach against more conventional methods of evolutionary optimization in terms of computational cost and quality of solutions, (4) a multi-objective approach towards the comparison of evolved creature complexities, (5) the impact of relaxing certain morphological constraints on evolving locomotion controllers.

The results showed that: (1) the search space is highly heterogeneous with both rugged and smooth landscape regions, (2) pure reactive controllers not requiring any hidden layer transformations were able to produce sufficiently good legged locomotion, (3) the proposed approach yielded competitive locomotion controllers while requiring significantly less computational cost, (4) multi-objectivity provided a practical and mathematically-founded methodology for comparing the complexities of evolved creatures, (5) co-evolution of morphology and mind produced significantly different creature designs that were able to generate similarly good locomotion behaviors. These findings attest that a Pareto multi-objective paradigm can spawn highly beneficial robotics and virtual reality applications.

Keywords

Artificial intelligence, artificial life, artificial neural networks, body-brain co-evolution, complexity measures, differential evolution, evolutionary algorithms, evolutionary multi-objective optimization, evolutionary artificial neural networks, evolutionary robotics, morpho-functional machines, multi-objective optimization.

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Jason Teo
Canberra, 2003.

Declaration

I hereby declare that this submission is my own work and to the best of my knowledge it contains no material previously published or written by another person, nor material which to a substantial extent has been accepted for the award of any other degree or diploma at UNSW or any other educational institution, except where due acknowledgement is made in the thesis. Any contribution made to the research by others, with whom I have worked at UNSW or elsewhere, is explicitly acknowledged in the thesis.

I also declare that the intellectual content of this thesis is the product of my own work, except to the extent that assistance from others in the project's design and conception or in style, presentation and linguistic expression is acknowledged.

Signed: ....

Date: ....

Publications

Peer-reviewed publications arising from research work conducted in this thesis are listed chronologically below (latest to earliest):

- Jason Teo and Hussein A. Abbass. "Search Space Difficulty of Evolutionary Neuro-Controlled Legged Robots", Accepted to appear in the International Journal of Knowledge-Based Intelligent Engineering Systems, Special Issue on Evolutionary Computation, July 2003.

- Jason Teo, Minh Ha Nguyen and Hussein A. Abbass. "Multi-Objectivity as a Tool for Constructing Hierarchical Complexity", Accepted to appear as a full orally-presented paper in the Proceedings of the Genetic and Evolutionary Computation Conference (GECCO-2003), Evolutionary Robotics Track, LNCS, Chicago, July 2003.

- Jason Teo and Hussein A. Abbass. "Multi-Objectivity for Brain-Behavior Evolution of a Physically-Embodied Organism", Artificial Life VIII: The 8th International Conference on Artificial Life, pp.312–318, R. Standish, M.A. Bedau, and H.A. Abbass (Eds.), ISBN 0-262-69281-3, Sydney, December 2002.

- Jason Teo and Hussein A. Abbass. "Trading-off Mind Complexity and Locomotion in a Physically Simulated Quadruped", Proceedings of the 4th Asia-Pacific Conference on Simulated Evolution And Learning (SEAL'02), Volume 2, pp. 776–780, L. Wang, K. Tan, T. Furuhashi, J. Kim, and X. Yao (Eds.), ISBN 981-04-7522-5, Singapore, November 2002.

- Jason Teo and Hussein A. Abbass. "Coordination and Synchronization of Locomotion in a Virtual Robot", Proceedings of the 9th International Conference on Neural Information Processing (ICONIP'02), Volume 4, pp. 1931–1935, L. Wang, J.C. Rajapakse, K. Fukushima, S.Y. Lee, and X. Yao (Eds.), ISBN 981-04-7524-1, Singapore, November 2002.

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List of Acronyms

1D	1-Dimensional
2D	2-Dimensional
3D	3-Dimensional
ANN	Artificial Neural Network
CMM	Co-evolution of Morphology and Mind
CPG	Central Pattern Generator
EA	Evolutionary Algorithm
EANN	Evolutionary Artificial Neural Network
EMO	Evolutionary Multi-objective Optimization
GA	Genetic Algorithm
GP	Genetic Programming
HT	Hand-Tuned *
PDE	Pareto-frontier Differential Evolution
SD	Standard Deviation *
SO	Single-Objective *
SPANN	Self-adaptive Pareto Artificial Neural Network
SPDE	Self-adaptive Pareto Differential Evolution
WS	Weighted Sum *

Table I: List of acronyms used in the thesis.

* *denotes acronyms used only in tables, List of Figures and List of Tables (due to page width limitation).*

List of Mathematical Abbreviations

$\sum$	Sum of
$\|x\|$	Absolute value of x
$\neq$	Not equal to
$\approx$	Approximately equal to
$\sim$	Approximate value
$\ncong$	Not equal to, for vectors
$\prec$	Less than, for vectors
$\log_n$	Logarithm to base n
$\log$	Logarithm to base 10
$\ln$	Natural logarithm
∞	Infinity
$[x, y]$	Closed interval: include all points between x and y including x and y
$]x, y[$	Open interval: include all points between x and y excluding x and y
$\{\ \}$	Set notation
$\in$	Belong to
$\cup$	Union
$\subseteq$	Proper subset
ϕ	Empty set
$\lfloor x \rfloor$	Floor of x (largest integer less than or equal to x)
$\leftarrow$	Maps to
$\rightarrow$	Implies
$\Uparrow$	Maximize
$\Downarrow$	Minimize
$\|$	Given
iff	If and only if
$\exists$	There exists
$\nexists$	There does not exist
$\forall$	For all

Table II: List of mathematical abbreviations used in the thesis.