Chapter 1

Introduction

> *"The controlling Intelligence understands its own nature, and what it does, and whereon it works."*
>
> (**Marcus Aurelius, 167A.D.)**

1.1 Overview

The automatic synthesis of embodied and situated creatures through artificial evolution has become a key area of research in artificial life (Sims 1994a; Sims 1994b; Komosinski and Rotaru-Varga 2000; Bongard and Paul 2001; Komosinski and Rotaru-Varga 2001; Taylor and Massey 2001; Hornby and Pollack 2002), robotics (Mataric and Cliff 1996; Harvey, Husbands, Cliff, Thompson, and Jakobi 1997; Husbands, Harvey, Jakobi, Thompson, and Cliff 1997; Floreano 1998; Nolfi and Floreano 2000; Pollack, Lipson, Hornby, and Funes 2001; Pollack, Lipson, Ficici, Funes, and Hornby 2002), and the cognitive sciences (Dautenhahn 1996; Mataric 1997; Pfeifer and Scheier 1999; Dautenhahn 1999; Nolfi and Floreano 2002). This concept stresses the importance of studying systems that have a body and are situated in a physical environment. It also emphasizes the utilization of artificial evolution as the primary mechanism for driving the self-organization process. This approach enables artificial creatures to autonomously develop intelligent behavior through the dynamic interactions between its body, nervous system and environment.

Research into evolving artificial creatures typically involves real-life robots or physically simulated artifacts and in some cases, a combination of both. There are a number of theoretical as well as technological considerations that needs to be addressed in order to conduct such artificial evolution. Theoretical considerations include the genetic encodings of the creature, the kinds of algorithms for driving the evolutionary process and the types of controllers suitable to act as the creature's mind. Here, the term mind is simply used to reflect the creature's artificial neural network (ANN) that act as its body's controller. We will use the terms mind and controller interchangeably throughout this thesis. As Franklin (1995) points out,

> "The overriding task of Mind is to produce the next action. Minds are the control structures of autonomous agents." (p.412)

Technological considerations for virtually simulated creatures include the physics engine for simulating the creature and its surroundings. For real-life physical robots, the technological issues include robotic platforms suitable for evolutionary design approaches and techniques for automatically generating robots with variable controllers as well as morphologies.

This thesis is about the evolution of morphology and mind in virtual organisms. We are interested in understanding how the evolution of the creature's mind affects the evolution of its behavior as well as its morphology. Although our study focuses on the evolution of simulated creatures, we believe that the results from our investigation will also help to further the understanding and development of real-life autonomous robots. On a more general level, it will also provide some useful insights into the relationship between the co-evolution and co-adaptation of body and mind in real creatures.

1.2 Motivation

There have been numerous significant contributions to this area of research over the last decade (Sims 1994a; Sims 1994b; Harvey, Husbands, Cliff, Thompson, and Jakobi 1997) and especially in the early part of this new millennium (Nolfi and Floreano 2000; Komosinski and Rotaru-Varga 2001; Taylor and Massey 2001; Bongard and Pfeifer 2002; Hornby and Pollack 2002). We have seen how artificial evolution allows the engineering of robotic lifeforms to be fully autonomous from the initial design of morphologies and controllers to fabrication of real working robots (Lipson and Pollack 2000). Captivating communities of evolving 3D virtual organisms that live and die in a complex physics-based virtual world have given insights into the emergence of complex dynamical life-like systems (Komosinski and Rotaru-Varga 2001) as well as the general question of evolvability (Komosinski and Rotaru-Varga 2000). Studies have also shown how learning complements evolution in generating adaptive and robust controllers for wheeled robots (Floreano and Urzelai 1998; Nolfi and Floreano 1999). This is just a small sampling of the recent exciting and highly significant advancements that have been contributed by research in embodied and situated artificial creatures. The potential future contributions to the engineering, biological and cognitive sciences stemming from further research in this area are clearly evident.

The emphasis of most studies in evolving embodied artificial creatures have been on the role of genetic encodings and how different types of genotype-phenotype representations allow for greater evolvability (Bongard and Pfeifer 2001; Hornby and Pollack 2001a; Komosinski and Rotaru-Varga 2001; Bongard 2002b; Hornby and Pollack 2002). There have also been some investigations into the role of fitness functions and how they affect the direction of the evolutionary process (Floreano and Urzelai 2000; Komosinski and Rotaru-Varga 2000; Ray 2000). A very recent investigation explored how morphological complexity itself affects the emergence of more complex behavior in artificial creatures (Bongard and Pfeifer 2002). However, considerably little has been said about the role of controllers in the artificial evolution of such creatures.

In Nolfi's (2002) very recent overview of the current state-of-the-art, this gap in the literature is further supported by his remark that

> "...the potential to design systems that exploit sensory-motor coordi-

nation remains largely unexplored." (p.31)

As such, there is currently a lack of understanding of how the evolution of controllers affects the evolution of morphologies and behaviors in embodied and situated creatures. It remains unclear what properties of an artificial creature's mind allow it to exhibit the desired action and form. Our motivation for this thesis stems from the fact that a better fundamental understanding of the controller's role in terms of its search space characterization, evolutionary dynamics, operational dynamics, complexity and representational power should pave the way towards our understanding of the emergence of more complex artificial creatures with a variety of morphologies and behaviors.

1.3 Research Question and Hypothesis

Life, as we all know too well, seldom allows us to survive by solely focusing on a single objective alone. Rather, it presents us with a myriad of choices and often forces us to choose between conflicting goals that in one way or another affects our chances for survival. As such, we believe that the introduction of multi-objectivity for the evolution of embodied artificial creatures will allow for this important aspect of biological life to be captured and modelled naturally as part of the evolutionary process in artificial life systems.

In this thesis, we wish to specifically answer the following research question:

> ***Is a Pareto evolutionary multi-objective optimization (EMO)[1] approach beneficial for evolving artificial creature controllers?***

Our hypothesis is that a Pareto EMO approach will reduce the computational cost of evolving effective locomotion controllers compared to non-Pareto EMO algorithms

[1] It should be noted that another acronym commonly used to refer to EMO algorithms is MOEA, which stands for Multi-Objective Evolutionary Algorithms (Deb 2001; Coello Coello, Van Veldhuizen, and Lamont 2002). In this thesis, we use only the acronym EMO to refer to this class of algorithms.

and single-objective evolutionary algorithms (EAs). Hence our main research objective is to prove or disprove that a Pareto EMO approach is advantageous for evolving locomotion controllers of artificial creatures. This objective will be achieved by comparing the trade-off between the optimized controllers and computational cost involved in finding these optimized controllers from using a Pareto EMO methodology against weighted sum EMO and single-objective EA approaches. Although the results of this thesis can be generalized to the area of evolutionary robotics, our focus will be only for simulated legged artificial organisms.

In order to answer the main research question, a number of other related sub-questions will need to be investigated as well:

1. **What are the characteristics of the underlying search space associated with finding effective locomotion controllers for artificial creatures?**

   The underlying search space associated with generating artificial creature controllers for legged locomotion needs to be understood in order to gain an idea of the difficulty associated with this problem. If the fitness landscape is highly smooth and unimodal, then a gradient-based algorithm such as greedy hill-climbing would perform well. On the other hand, if the fitness landscape is highly rugged, an evolutionary optimization approach will perhaps be of benefit in solving this problem.

2. **What types of controller architecture are suitable for evolving locomotion controllers?**

   There are a number of different ANN architectures that can be used as the artificial creature's controller. The question here is what types of ANN architecture are easier to search for generating locomotion abilities in artificial creatures. Perhaps simple feed-forward ANNs are sufficient for generating the required locomotion controllers. On the other hand, recurrent architectures might be more efficient in capturing the state-dependent dynamics of the artificial creature's legged limb motions.

3. **What is the minimum hidden layer size required to produce locomotion controllers?**

   The capacity of an ANN is determined by its so-called Vapnik-Chervonenkis (VC) dimension (Vapnik and Chervonenkis 1971), which in turn is determined by the number of free parameters in the network such as the connection weights (Haykin 1999). One way to control the weights is by controlling the number of hidden units present in the ANN. Hence, the importance of implementing a suitably-sized hidden layer within the ANN architecture needs to be ascertained. Firstly, finding the ANN controller with the minimum network size will reduce the amount of computation that needs to be carried out by the artificial creature's controller, thereby further enhancing its efficiency during operation. Secondly, to be able to use the controller as some type of complexity measure (see next item), we need to ensure that the amount of redundancy in the network is minimized as far as possible in order to avoid false indications given by large redundant networks. Thirdly, although redundancy may be beneficial for life-long learning, we need to avoid evolving networks with unseen redundancy to be able to reduce the risk of unpredictable behavior. Redundancy can be later added manually, with its corresponding effects analyzed by the designer. Thus, minimizing the number of redundant hidden units can reduce the amount of "*surprise*" (Ronald and Sipper 2001) arising from the use of biologically-inspired solutions (see Section 2.3).

4. **How can we compare between the complexities of artificially evolved creatures?**

   Another question that needs to be addressed is how can the complexity of the artificial creatures that have been evolved be measured or characterized. It is important to be able to make objective comparisons between the evolved characteristics of the artificial creatures such as their controllers, morphologies and emergent behaviors. For example is controlling a four-legged robot more complex than controlling a six-legged robot? Conversely, is a six-legged robot able to achieve more complex behaviors that are not achievable by a four-legged robot? Being able to answer such questions will establish a methodology that allows for a better understanding of the cost trade-offs between different designs, controller requirements and operational capabilities.

5. **What effects does the simultaneous evolution of morphology together with controller have on the evolutionary optimization process?**

   The evolutionary search process for automatically generating locomotion controllers for artificial creatures can be carried out by either using a fixed hand-designed morphology for the artificial creature or by allowing self-organization to occur simultaneously for both the controller and the morphology through a co-evolutionary process, which may help to produce innovative designs. Perhaps by allowing the artificial creature's morphology to freely change and evolve as the corresponding controller evolves may ease the search space difficulty of this problem. Using co-evolution, the evolutionary search process can experiment with unconventional and previously unexplored morphological designs that may be easier to control for legged locomotion. On the other hand, adding more parameters to the evolutionary optimization process may cause an explosion in the search space subsequently causing the search algorithm to perform dismally. Hence, it is important to determine whether a co-evolutionary process is actually beneficial or otherwise in evolving locomotion controllers for artificial creatures.

1.4 Organization of the Thesis

This thesis has nine chapters and is organized as follows:

In Chapter 1, an introduction to the thesis is presented. It first provides an overview of the research field, followed by the motivation and research questions raised in the thesis. An outline of the thesis is then given and the chapter closes with a list of scientific contributions stemming from this research work.

In Chapter 2, a survey of the literature is undertaken for research conducted in evolving artificial creatures. This review is divided into three main sections, first emphasizing the relevance of conducting such research based on the principles of embodiment and situatedness, then a survey of the work carried out using real physical robots and finally a survey of the work carried out using simulations. The survey includes both evolution of controllers alone as well as co-evolution of morphology and mind.

In Chapter 3, the virtual environment in which the experiments in this thesis are carried out is explained. Firstly, a description of the physics engine used to simulate the creature and its world is given, followed by the physical setup of the creature's morphology. Then, an explanation of the ANNs used to control the creature's movement is presented, followed by a discussion of the genotype representation of the ANN controller. Finally, the basic evolutionary and simulation parameters used in the experiments are outlined.

In Chapter 4, we investigate the question of search space difficulty associated with four different types of ANN architecture. A basic characterization of the fitness landscape involved in searching for ANN controllers that exhibit good locomotion capabilities is performed using random search, hill-climbing and random walk algorithms.

In Chapter 5, we explore the possibility of using a Pareto EMO methodology for evolving artificial creature controllers. A self-adaptive Pareto EMO algorithm called Self-adaptive Pareto Artificial Neural Network (SPANN) is presented and used to evolve ANN controllers for the artificial creature. Detailed analysis is then conducted on the evolutionary search process and comparisons made against the controllers obtained from random search, hill-climbing and random walk algorithms. The operational dynamics of the best evolved controllers are also analyzed.

In Chapter 6, we answer the main research question of whether the Pareto EMO methodology is actually beneficial for the evolution of locomotion controllers. The SPANN algorithm is compared against more conventional EAs, namely a hand-tuned EMO algorithm, a weighted sum EMO algorithm, a single-objective EA, and a recent Pareto EMO algorithm (Non-dominated Sorting Genetic Algorithm II

(NSGA-II) (Deb, Agrawal, Pratab, and Meyarivan 2000)), to verify that the self-adaptive Pareto EMO algorithm is actually beneficial for evolving artificial creature controllers. An analysis into the redundancies of the evolved networks is also given.

In Chapter 7, we tackle the question of how to compare creature complexities. A multi-objective view is presented for characterizing and comparing between the complexities of the different evolved controllers using the EMO approach. Examples are also given as to how this multi-objective approach towards understanding complexity can be useful in other disciplines.

In Chapter 8, we conduct the simultaneous evolution of both morphology and controller. The constraint of fixing the artificial creature's morphology when conducting the evolutionary optimization process is relaxed and the SPANN algorithm is augmented to enable this co-evolution of the creature's morphology and mind to occur.

In Chapter 9, the main findings from this thesis are summarized. The chapter concludes the thesis with a discussion of possible future research directions.

This thesis has an accompanying CD-ROM which can be found on the inside back cover of the thesis. The CD-ROM is divided into two main sections containing the video clips of the artificial creatures in simulation and the graphs generated during the analysis of the experimental data. The nature of this investigation necessitated the generation of a large number of graphs, not all of which could be included into the pages of the thesis itself but have been inserted into the CD-ROM. An index to the contents of the CD-ROM can be found in Appendix A.

1.5 Original Contributions

A list of original scientific contributions arising from this thesis is given in this section.

- A Pareto evolutionary approach for evolving locomotion of a quadruped is presented. Although Pareto methods have been used for designing intelligent control systems (Tan and Li 1997; Gacogne 1997; Coello Coello, Christiansen, and Aguirre 1998; Pirjanian 1998), no study to our knowledge has attempted to use such methods for evolving locomotion of a quadruped. Previous methods for conducting this type of evolution have focused on using single-objective EAs or weighted sum EMO methodologies for optimizing the desired behavior. The Pareto EMO approach is shown to offer significant advantages for evolving artificial creature controllers. This will open up an entirely new paradigm into evolving controllers not only for simulated quadrupeds but also for all other types of artificial life and physical robots.

- An analysis of the fitness landscape for quadruped locomotion and a critical evaluation of the current literature for fitness landscape analysis are presented (Chapter 4). The analysis provides an insight into the variety of fitness landscape features that can significantly affect the outcome of evolutionary searches for locomotion controllers. An understanding of the underlying search space characteristics is paramount towards the design of more effective search strategies and optimization algorithms for the purpose of generating quadruped locomotion controllers. The deficiencies noted with current methods of characterizing fitness landscapes will pave the way for more insightful and practical solutions to be devised for future investigations into the search spaces of artificial creature evolution.

- A systematic study of the relationship between quadruped locomotion and controller size is presented, and a modified version of the SPANN algorithm suitable for evolving ANNs for robotic control is developed (Chapter 5). A fundamental understanding of the size requirement of ANN controllers for quadruped locomotion will allow for more efficient use of computational resources in the control of autonomous robot and virtual creature locomotion. The proposed SPANN algorithm allows for the use of a Pareto approach for the automatic generation of ANNs that can serve as effective autonomous control units for virtual artificial creatures.

- Presenting the advantages of SPANN by comparing it with a hand-tuned, weighted sum, single-objective, and NSGA-II algorithms (Chapter 6). The much lower computational cost offered through the self-adaptive Pareto EMO approach can significantly reduce the amount of time required to carry out artificial life and evolutionary robotics experiments for finding effective artificial creature controllers.

- First attempt to formulate the problem of hierarchical complexity as a multi-objective optimization problem and establish EMO as a platform for studying complexity (Chapter 7). The measurement and comparison of complexity between different objects have always been a problematic issue across multiple research disciplines. An entirely different perspective towards characterization of hierarchical complexity can be achieved by taking a multi-objective viewpoint. The multi-objective characterization of complexity can open up radically different avenues into complexity research and in general how researchers think about complexity. We show that complexity characterization can be carried out in a simple and practical manner using an EMO approach. This highly accessible method of capturing complexity has significant implications not only within the scope of artificial life and evolutionary robotics but across a much wider spectrum of research fields.

- Proposing a methodology for studying the impact of morphological constraints on behavior and evolution (Chapter 8). The imposition of pre-designed morphologies on both physical robots and simulated agents may require more complex controller requirements as well as entailing a more involved evolutionary search. The co-evolution of both morphology and controller through the relaxation of certain morphological constraints can lead to similarly good locomotion behavior as well as new and interesting artificially evolved morphological designs. This can allow for previously unexplored robot bodies or simulated characters to be engineered and synthesized. At the same time, the co-evolutionary approach represents an important step towards truly evolvable materials and physical constructs, especially in the field of nanotechnology.