Chapter 9

Conclusion

> *"And in the future? Who knows? But it seems almost certain that the first forms of alien life we see will not be through telescopes, but through the windows of our computer screens into digital universes. The first person to hold a conversation with an alien intelligence will not be an astronaut: it will be a computer scientist or computational neuroscientist, talking to an evolved digital neural network. The first glimpses of non-human cultures and technologies will occur in our research labs, where the digital biology grows more complex day by day."* (p.14)
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> **(Peter J. Bentley, 2002)**

9.1 Summary of Results

In this thesis, we presented a systematic study of evolving ANN controllers for the legged locomotion of virtual organisms using a Pareto multi-objective evolutionary optimization approach. A virtual and physically accurate world was created to simulate the evolution of locomotion behavior in a quadruped creature. A self-adaptive Pareto EMO algorithm called SPANN, which allowed for the generation of Pareto solutions that optimized multiple objectives distinctly, was implemented to evolve the ANN-based control mechanism for the quadruped. The search spaces underlying four classes of ANNs with different connectivity types were characterized. SPANN was then used to evolve Pareto solutions that maximized the locomotion distance of a fixed morphology quadruped and minimized usage of hidden units in its ANN controller. More conventional methods of evolutionary optimization were subsequently compared against SPANN to ascertain the true advantages offered by the self-adaptive Pareto EMO methodology. An approach for the characterization of the morphological and behavioral complexity was then proposed based on a multi-objective viewpoint. Finally, the simultaneous evolution of morphology and controller was conducted by relaxing some of the morphological parameters imposed on the artificial creature to explore the different creature designs that can be found through the co-evolutionary optimization methods.

The main findings from the investigations carried out in this thesis are as follows:

1. Search space characterization of four different types of ANN controller architectures (NNType0, NNType1, NNType2 and NNType3) using random search, hill-climbing and random walk showed no significant differences in terms of the ease of finding good quality locomotion controllers.

2. The fitness landscape of the evolutionary search spaces had both rugged and smooth sections depending on the sub-spaces being explored. The variety of rugged shapes on the landscape was high indicating that epistatic interactions between genes in the genotype were high. A correspondingly high degree of modality in the fitness landscape was also noted.

3. The solution space was found to be highly heterogeneous. A uniform sampling of the genotype space yielded a highly skewed distribution of solutions in the objective space.

4. An EMO algorithm called SPANN was implemented for the multi-objective evolution of artificial creature controllers. Artificial creature controllers were successfully evolved for minimum hidden layer size and maximum horizontal locomotion distance using four different types of ANN architecture. Although

the overall best solution was found using the NNType3 architecture, statistical tests showed no significant difference existed between the results obtained.

5. A comparison between SPANN and random search, hill-climbing and random walk showed that the evolutionary search implemented in SPANN produced statistically superior solutions.

6. Recurrent connections did not provide any significant advantages over conventional feed-forward neural network architectures for evolving locomotion behavior in a quadruped.

7. Pure reactive agents not requiring hidden layer transformations in the ANN controller produced sufficiently good locomotion capabilities. The use of direct input-output connections in a perceptron-like controller was sufficient for generating a basic locomotion behavior in the quadruped.

8. The SPANN algorithm discovered reasonably good quality controllers but required significantly less overall computational costs compared to a single-objective EA, a weighted sum EMO algorithm as well as a hand-tuned EMO algorithm. The controllers evolved using SPANN were comparable to those obtained with NSGA-II, one of the current state-of-the-art Pareto EMO algorithms. The self-adaptive Pareto EMO approach implemented in the SPANN algorithm provided significant advantages over conventional evolutionary optimization algorithms by: (1) reducing the number of runs required to test different design factors associated with the synthesis of artificial creatures, (2) preserving genetic diversity, and (3) offering extra-dimensional bypasses for the search process to reach fitter solution spaces.

9. The overall best locomotion controller evolved using SPANN had the least amount of redundancy present in the ANN compared to the overall best locomotion controllers evolved using a hand-tuned EMO algorithm, a weighted sum EMO algorithm and a single-objective EA.

10. Some level of coordination and synchronization was achieved by the overall

best locomotion controller evolved using SPANN. The controller continued to perform well despite the presence of low levels of noise in the quadruped's sensors and actuators.

11. Taking a multi-objective view towards complexity provided a useful platform for comparing between the evolved behavioral and morphological complexities of embodied creatures. A Pareto-based methodology for characterizing complexity was implemented and using this approach, it was found that the morphological complexity of a hexapod was higher than a quadruped while the behavioral complexity of a quadruped was higher than a hexapod.

12. Significantly different locomotion behaviors emerged together with radically different body designs when certain morphological constraints were relaxed to allow for co-evolutionary optimization of morphology and controller to occur in the SPANN-CMM algorithm. Dynamic locomotion gaits based on a jumping motion generated mainly from hind legs were found in creatures that were essentially bipedal and tripedal in locomotion behavior. A comparison between solutions evolved with and without co-evolution of morphology showed that creatures existing on the global Pareto-frontier of both evolutionary systems had similar complexities in terms of both controller requirements and locomotion behavior.

9.2 Future Work

Numerous avenues for further explorations and investigations have emerged from this body of work. Some open research questions have already been highlighted in the respective chapters where they directly followed on from the work completed in the experiments. Here we outline more diverse and philosophical future research directions that encompass the evolution of artificial organisms at a higher level.

Other forms of control mechanism can be used in place of these basic ANNs. On a lower level, CPGs and other types of algorithmic controllers would certainly be also useful to evolve for simpler artificial organisms. On a higher level, more advanced forms of ANNs such as those having higher-order activation functions, GasNets that use temporally and spatially adaptive neurons (Husbands, Smith, Jakobi, and O'Shea 1998), as well as Pulsed Neural Networks that use spiking neurons (Floreano and Mattiussi 2001) may allow for the emergence of more complex behaviors in artificial organisms that are required to perform more complicated tasks and in changing environments.

The power of a Pareto multi-objective approach lies in the flexibility and ease of incorporating new objectives and elements into the artificial evolutionary process. The inclusion of elements such as compactness of genetic material in EAs that utilize variable length chromosomes or other more elaborate developmental encodings as a distinct and separate objective on top of the primary objective will not only provide useful ways of improving the efficiency of the EA but may possibly also provide interesting insights into why vastly different genome lengths are found in biological organisms. Other elements that will be fruitful to investigate as separate evolutionary objectives from an artificial life perspective include phylogenetic diversity, number of body parts/joints and physical energy consumption to name but a few.

The SPANN algorithm can be beneficial in evolving controllers not only for legged robots but also wheeled and other forms of physical robots. Again, the multi-objectivity of the artificial evolution can easily incorporate additional engineering factors such as noise and stress tolerance into the optimization process. It will also be interesting to expand the SPANN-CMM algorithm to allow for fully and freely evolvable robotic forms that are not based on any underlying body plan and evolved from very basic structures, perhaps even at the atomic level. This can have far-reaching implications on the evolution of minimal controllers and morphologies of recyclable micro-machines that can be created with nanotechnology and evolvable hardware. The fully automated design, fabrication and re-use cycle of such evolvable systems would then truly constitute a form of artificial life. On an even grander scale, although representing a scenario which perhaps demands more serious ethical discussions, such artificial creatures can at later generations even fabricate microfactories capable of re-designing and evolving existing creatures into more efficient and effective forms of life and intelligence.

9.3 Concluding Remarks

The automatic synthesis of embodied and situated artificial creatures that are fully autonomous and intelligent is a truly lofty goal. Significant advancements have been made through numerous artificial evolutionary studies and in this thesis, we have proposed the use of a Pareto multi-objective approach to this end. We have shown that multiple objectives can be treated as distinct and separate optimization goals in a Pareto EMO algorithm when evolving such organisms. This body of work should not be seen as merely an attempt to present a new artificial life system or an evolutionary robotics algorithm, although it does exhibit many useful characteristics in these respects, but as a new paradigm in which evolutionary computation can be used in a truly purposeful and powerful way in terms of designing, generating and synthesizing intelligent machines and artifacts that do not only mindlessly avoid walls or react to our facial expressions but are able to exhibit a host of other intelligent behaviors that constitute the multi-objective nature of our world. This technology will pave the way for such intelligent creatures to be realized in the not-too-distant future, which will then truly revolutionize the way in which we humans think about and live life.