Foreword

After nearly half a century of research, the Holy Grail of the field of artificial intelligence (AI) remains a comprehensive computational model capable of emulating the marvelous abilities of animals, including locomotion, perception, behavior, manipulation, learning, and cognition. The comprehensive modeling of higher animals – humans and other primates – remains elusive; However, the research documented in this monograph achieves nothing less than a functional computer model of certain species of lower animals that are by no means trivial in their complexity.

Reported herein is the 1996 ACM Doctoral Dissertation Award winning work of Xiaoyuan Tu, which she carried out in the Department of Computer Science at the University of Toronto. Tu presents "artificial fishes", a remarkable computational model of familiar marine animals in their natural habitat. Originally conceived in the context of computer graphics, Tu's is to date the only PhD dissertation from this major subfield of computer science (and the only thesis from a Canadian university) to win the coveted ACM award.

Computer graphics addresses the problem of synthesizing images of virtual worlds modeled mathematically on the computer. Computer animation, in particular, is concerned with the computer synthesis of moving images, and it has become an essential technology for the motion picture, advertising, interactive game, and related industries. Over the decades, modeling for computer animation has progressed from an early reliance on purely geometric models to more powerful simulation models that also incorporate physical principles, such as Newtonian mechanics. Tu's pioneering thesis dramatically advances the state of the art by also bringing into play key biological principles. Indeed, her work firmly connects computer animation with artificial life, an emerging discipline which transcends the traditional boundaries of computer science and biological science.

From the perspective of computer animation, Tu's artificial fishes are *not* just highly realistic graphical puppets like the dinosaurs of the landmark feature film *"Jurassic Park"* whose moves were painstakingly plotted by highly skilled human animators. Rather, Tu's models are *self-animating* artificial animals with "eyes" to see their virtual world and "brains" that autonomously govern their actions. They swim, forage, eat, and mate entirely on their own. The significance of her work is that artificial fishes represent not only the geometry and superficial appearance of the animal, as would a traditional computer graphics model. Her sophisticated creations go much deeper to also encompass the function of the animal's muscle-actuated body, sensory organs, and brain. Empowered by artificial life simulations such as Tu's, computer animators can begin to play a role less akin to that of puppeteers and more like that of (National Geographic Society) nature cinematographers, or perhaps some day, like that of motion picture directors of skilled human actors.

This monograph reveals the technical details behind a spectacular accomplishment in computer graphics and artificial life research which has captured mass media attention and has been featured internationally in reputable television programs, news magazines, and newspaper dailies. Readers will see how Tu has interpreted theoretical essentials from biomechanics to perception to ethology and cast them in concrete computational terms within a realistic, computer-simulated virtual world. An important dimension of Tu's work that is not easily conveyed via written document, however, is the beautifully realistic animations of artificial marine ecosystems that are simulated and rendered by her software. Her animations "The Undersea World of Jack Cousto" and "Go Fish!" captured spots in the prestigious computer animation showcase, the *SIGGRAPH Electronic Theater* (1995, 1994). Among other recognition, her animation work received the 1994 *Canadian Academy of Multimedia Arts and Sciences International Digital Media Award for Technical Excellence* and in 1995 it was cited by the computer animation jury of *Prix Ars Electronica*, the premier competition for creative work with digital media.

In my opinion, Tu's work is the most impressive attempt to date towards the elusive dream of AI research that I mentioned earlier. Furthermore, her research (and software) has already helped give impetus to the CS theses of several other graduate students at the University of Toronto, including John Funge's thesis on cognitive modeling for autonomous characters, Radek Grzeszczuk's thesis on learning in artificial animals, Tamer Rabie's thesis on active vision in artificial animals, and Qinxin Yu's thesis on real-time VR. Clearly, Tu's research will continue to have far-reaching implications. Indeed, her artificial fishes have received favorable review from the distinguished evolutionary biologist Richard Dawkins in his bestseller *Climbing Mount Improbable* (Viking, 1996). That a computational model with such interdisciplinary impact can emerge from computer graphics is a testament to the richness and scope of the graphics field today.

As the advisor of Xiaoyuan Tu's thesis, I proudly recommend her book not only to graduate students, computer scientists, and computer animation practitioners, but also to anyone at large interested in computational theories of "how animals work".

February 1999 *Demetri Terzopoulos*

Preface

This book develops an artificial life paradigm for computer graphics animation. Animals in their natural habitats have presented a long-standing and difficult challenge to animators. We propose a framework for achieving the intricacy of animal motion and behavior evident in certain natural ecosystems, with minimal animator intervention.

Our approach is to construct artificial animals. We create self-animating, autonomous agents which emulate the realistic appearance, movement, and behavior of individual animals, as well as the patterns of social behavior evident in groups of animals. Our computational models achieve this by capturing the essential characteristics common to all biological creatures – biomechanics, locomotion, perception, and behavior.

To validate our framework, we have implemented a virtual marine world inhabited by a variety of realistic artificial fishes. Each artificial fish is a functional autonomous agent. It has a physics-based, deformable body actuated by internal muscles, sensors such as eyes, and a brain with perception, motor, and behavior control centers. It swims hydrodynamically in simulated water through the controlled coordination of muscle actions. Artificial fishes exhibit a repertoire of behaviors. They explore their habitat in search of food, navigate around obstacles, contend with predators, and engage in courtship rituals to secure mates. Like their natural counterparts, the artificial fishes' behavior is based on their perception of the dynamic environment and their internal motivations.

Since the behavior of the artificial fishes adapts to events in their virtual habitat, their detailed motions need not be keyframed nor scripted. This book therefore demonstrates a powerful approach to computer animation in which the animator plays the role of a nature cinematographer, rather than the more conventional role of a graphical model puppeteer. Our work not only achieves behavioral animation of unprecedented complexity, but it also provides an interesting experimental domain for related research disciplines in which functional, artificial animals can serve as autonomous virtual robots.

Acknowledgments

Based on a thesis submitted in 1996 to the Graduate Department of Computer Science at the University of Toronto in conformity with the requirements for the degree of Doctor of Philosophy, this book was completed while I was employed at Intel Corporation. The original acknowledgments in the dissertation are reproduced below with minor revisions.

First, I would like to thank my thesis advisors, Professors Demetri Terzopoulos and Eugene Fiume. This thesis would not have been possible without their support.

Demetri has been my mentor in the exciting fields of computer animation and physics-based graphics modeling. His many remarkable qualities have benefited me greatly. I am most impressed by his breadth of knowledge, his ability to seize new ideas, his openmindedness, and his perfectionism towards technical writing. I am especially grateful for the unfailing encouragement he has given me through the years. I would not have come this far this quickly without his expert guidance and the substantial time and effort he put into my thesis.

I thank Eugene for giving me the opportunity to join the graphics group in 1992. Without his kindness and support, I would have been stuck studying operating systems (no offense intended). I appreciate his many insightful comments that have helped to improve my thesis and to put my view into perspective.

My special thanks go to Professor Daniel Thalmann for generously agreeing to serve as external examiner of my thesis, despite his busy schedule and the long distance he had to travel. Special thanks also go to Professor Janet Halperin for serving as internal examiner and Professor Michiel Van de Panne for serving as internal appraiser on my thesis committee. Many thanks to Professors Ken Sevcik and Geoffrey Hinton for serving on my committee and providing valuable comments on my thesis. Special thanks also go to John Funge, for his friendship and support, his consistent encouragement during my thesis research and his assistance in helping to improve my English writing skills.

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I dedicate this book to my parents, for their endless love and support, for their unwavering confidence in me, and for their limitless patience.

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