Artificial Animals in Realistic Virtual Worlds

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Abstract

This paper describes a virtual marine ecosystem inhabited by realistic artificial life that emulates the appearance, movement, and behavior of real fishes. Each artificial fish is an autonomous agent in a simulated physical world. It has (i) a three-dimensional body with internal muscle actuators and functional fins, which deforms and locomotes in accordance with biomechanic and hydrodynamic principles, (ii) sensors, including eyes that can image the environment, and (iii) a brain with motor, perception, behavior, and learning centers. Artificial fishes exhibit a repertoire of piscine behaviors that rely on their perceptual awareness of their dynamic habitat. Furthermore, they can learn how to locomote through practice and sensory reinforcement.

Introduction

The modeling of animals is an important theme in the field of artificial life.[1] In this paper, I present research about virtual artificial animals. Analogous to natural animals, artificial animals are endowed with functional bodies and brains, and are the autonomous inhabitants of a simulated physical world.

We have created realistic artificial animals in the form of fishes. Imagine a virtual marine world inhabited by a variety of artificial fishes. In the presence of underwater currents, the fishes employ their muscles and fins to swim gracefully around immobile obstacles and among moving aquatic plants and other fishes. They autonomously explore their dynamic world in search of food. Large, hungry predator fishes stalk smaller prey fishes in the deceptively peaceful habitat. Prey fishes swim around contentedly until the sight of predators compels them to take evasive action. When a dangerous predator appears in the distance, similar species of prey form schools to improve their chances of survival. As the predator nears a school, the fishes scatter in terror. A chase ensues in which the predator selects victims and consumes them until satiated. Some species of fishes seem untroubled by predators. They find comfortable niches and feed on floating plankton when they get hungry. Driven by healthy libidos, they perform elaborate courtship rituals to secure mates.

To simulate worlds with the level of complexity of the one depicted above, we have taken a bottom-up, compositional modeling approach. We model the form, appearance, and basic physics of the animal and its environment, the animal's means of locomotion, its perceptual awareness of its world, its behavior, and its ability to learn. I review the artificial fish model in the next section before presenting some of the results of our research (see [1, 2, 3, 4] for further technical details and a review of relevant prior work).

[1] For an engaging survey of the field, see, e.g., S. Levy, *Artificial Life* (Pantheon, 1992). Journals such as *Artificial Life* and *Adaptive Behavior* document the state of the art.

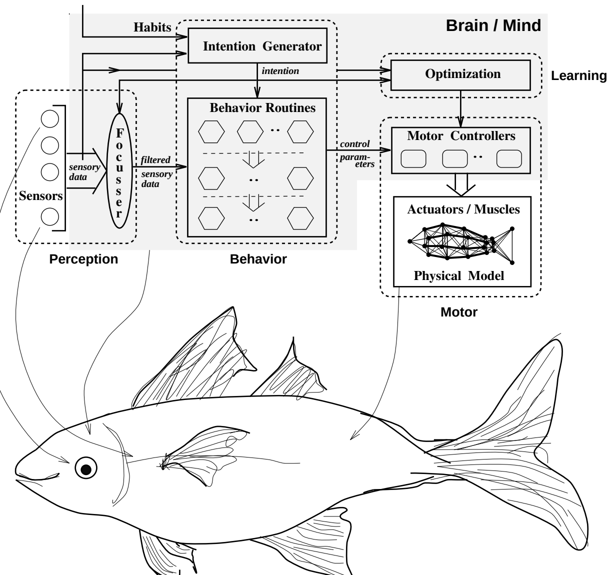

Figure 1: Overview of an artificial fish. The functional body harbors a brain with motor, perception, behavior, and learning centers.

An Artificial Fish

The artificial fish is an autonomous agent with a realistic deformable body actuated by internal muscles, eyes, and a brain that includes behavior, perception, and motor centers. Fig. 1 presents a functional overview of the model. Through controlled muscle actions, artificial fishes are able to swim through simulated water in accordance with simplified hydrodynamics. Their functional fins enable them to locomote, maintain balance, and maneuver in the water. Thus the artificial fish captures not just the 3D form and appearance of real fishes, but also the basic physics of these animals in their environment. Though rudimentary compared to their natural counterparts, artificial fish minds are nonetheless able to learn some basic motor functions and carry out perceptually guided motor tasks. In accordance with their perceptual awareness of the virtual world, their

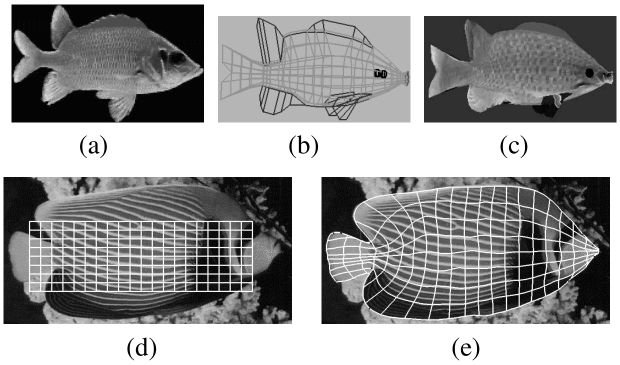

Figure 2: (a) Digitized color image of a fish photo. (b) 3D NURBS *surface fish body. (c) Color texture mapped 3D fish model. Initial (d) and final (e) deformable grid on an image of a different fish.*

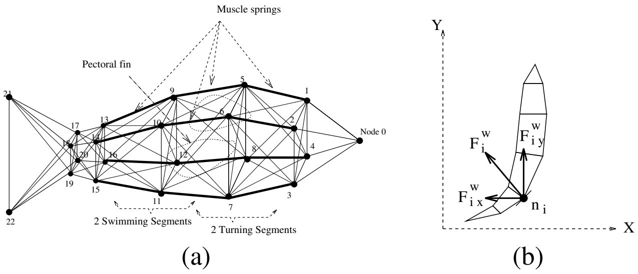

Figure 3: (a) Biomechanical fish model. Nodes denote lumped masses. Lines indicate uniaxial elastic elements (shown at natural length). Bold lines indicate muscle elements. (b) Hydrodynamic locomotion. With tail swinging towards positive X axis, reaction force $\mathbf{F}_i^w$ at point n_i acts along the inward normal. Component $\mathbf{F}_{ix}^w$ resists the lateral movement, while $\mathbf{F}_{iy}^w$ is forward thrust. Aggregate thrust propels fish towards positive Y axis.

minds arbitrate a repertoire of piscine behaviors, including collision avoidance, foraging, preying, schooling, and mating. The following sections present the main components of the artificial fish.

Modeling Form and Appearance

We want our artificial fishes to capture the form and appearance of a variety of natural fishes with considerable visual fidelity. To this end, photographs of real fishes, such as the image shown in Fig. 2(a), are converted into 3D spline (NURBS) surface body models (Fig. 2(b)). The digitized photographs are analyzed semi-automatically using a deformable grid tool that is demonstrated in Fig. 2(d–e) on another fish image. As the deformable grid floats freely over the image, its boundary contours adhere to intensity edges demarcating the fish from the background, and the remaining contours relax elastically to cover the imaged fish body. This yields a smooth profile shape and a nonuniform coordinate system (Fig. 2(e)) for mapping the texture onto the spline surface to produce the final texture mapped fish body model (Fig. 2(c)).

Biomechanics and Locomotion

The motor system of the artificial fish comprises a biomechanical model of a fish, including its muscle actuators, and a set of motor controllers. Fig. 3(a) illustrates the mechanical body model which produces realistic piscine locomotion using only 23 lumped masses and 91 elastic elements. These mechanical components, whose dimensions and physical parameters are modified to model different fishes, are interconnected to maintain the structural integrity of the body as it flexes due to the action of its 12 contractile muscle springs.

The artificial fish locomotes like real fishes do, by autonomously contracting its muscles. As the body flexes it displaces virtual fluid which induces local reaction forces normal to the body. These hydrodynamic forces generate thrust that propels the fish forward (Fig. 3(b)). The dynamics of the biomechanical model is governed by a system of coupled second-order ordinary differential equations driven by the hydrodynamic forces. A numerical simulator continually integrates these equations of motion forward through time.[2]

The model is sufficiently rich to enable the design of motor controllers by gleaning information from the piscine biomechanics literature. The motor controllers (see Fig. 1) coordinate muscle actions to carry out specific motor functions, such as swimming forward, turning left and right, ascending and descending. They translate natural control parameters such as the forward speed or angle of the turn into detailed muscle actions that execute the function. The artificial fish is neutrally buoyant in the virtual water and has a pair of pectoral fins that enable it to navigate freely in its 3D world by pitching, rolling, and yawing its body. Additional motor controllers coordinate the fin actions.

Perception

Artificial fishes are aware of their world through sensory perception. The perception system relies on a set of onboard virtual sensors to gather sensory information about the dynamic environment. As Fig. 4 illustrates, it is necessary to model not only the abilities but also the limitations of animal perception systems in order to achieve natural sensorimotor behaviors.

The perception center of the artificial fish brain (see Fig. 1) includes a perceptual attention mechanism which allows the artificial fish to sense the world in a task-specific way, hence filtering out sensory information superfluous to its current behavioral needs. For example, the artificial fish attends to sensory information about nearby food sources when foraging.

[2] The fish model achieves a good compromise between realism and computational efficiency. To give an example simulation rate, the implementation can simulate a scenario with 10 fishes, 15 food particles, and 5 static obstacles at about 4 frames/sec (with wireframe rendering) on a Silicon Graphics R4400 Indigo^2 Extreme workstation. More complex scenarios with large schools of fish, dynamic plants, and full color texture mapped GL rendering at video resolution can take 5 seconds or more per frame.

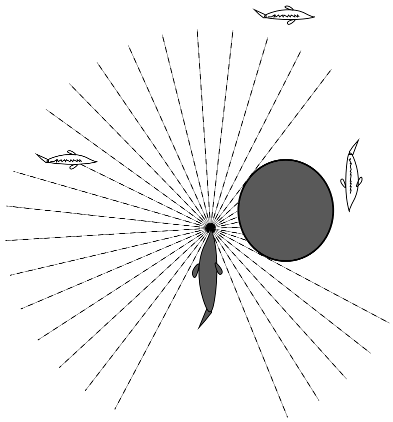

Figure 4: Artificial fishes perceive objects within a limited field view if objects are close enough and not occluded by other opaque objects (only the fish towards the left is visible to the fish at the center).

Interestingly, we have employed the artificial fish as a platform for developing computational theories of animal vision [3]. In particular, we have developed computer vision algorithms for simulating foveated retinal imaging, retinal image stabilization, color object recognition, and visually-guided navigation. We have incorporated these algorithms into the perception center of the artificial fish's brain.

Behavior

The innate character of the artificial fish is established by a set of habits that determine whether it is male or female, predator or prey, etc. The behavior center of the artificial fish's brain mediates between its perception system and its motor system (see Fig. 1). The behavior system runs continuously within the simulation loop. An intention generator, the fish's cognitive faculty, harnesses the dynamics of the perception-action cycle. Fig. 5 illustrates a generic intention generator which is responsible for the goal-directed behavior of the artificial fish in its dynamic world.

At each simulation time step, the intention generator takes into account the habits of the fish, its mental state as represented by hunger, fear, and libido mental variables, and the incoming stream of sensory information to generate dynamic goals for the artificial fish, such as to avoid an obstacle, to hunt and feed on prey, or to court a potential mate. The intention generator ensures that goals have some persistence by exploiting a single-item memory. Persistence supports sustained behaviors such as foraging, schooling, and mating. The intention generator also controls the perceptual attention mechanism. At every simulation time step, it activates behavior routines that attend to sensory information and compute the appropriate motor control parameters to carry the fish one step closer to fulfilling its current intention. The behavioral repertoire of the artificial fish includes primitive, reflexive behavior routines, such as obstacle avoidance, as well as more sophisticated motivational behavior routines such as schooling and mating whose activation depends on the mental state.

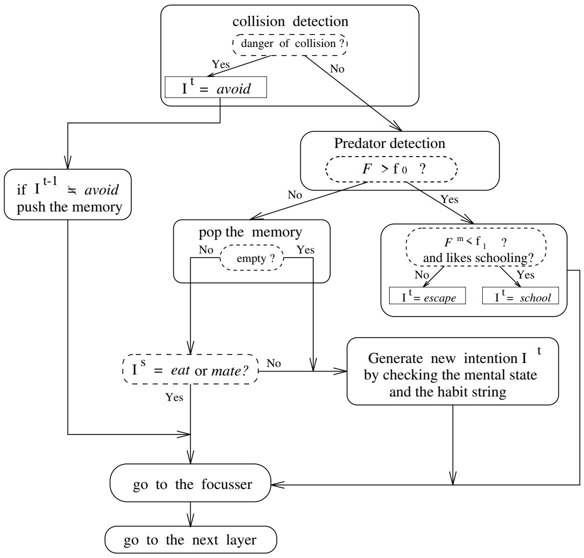

Figure 5: Generic intention generator (simplified). Set of intentions: { avoid, escape, school, eat, mate, leave, wander }. f_0 and f_1 are thresholds with $f_0 < f_1$.

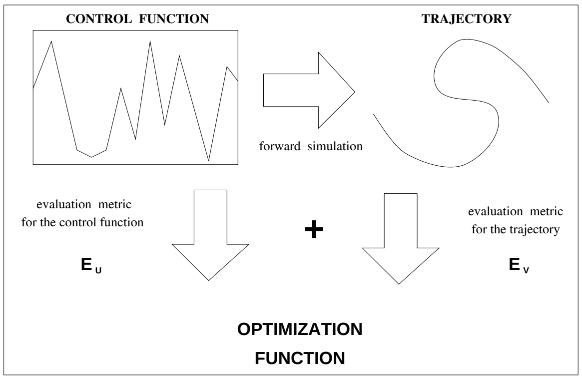

Figure 6: Low-level algorithm for learning locomotion. Muscle control inputs actuate body of artificial animal to produce a locomotion trajectory through forward physical simulation. A fitness function measures the quality of input control and output trajectory.

Learning

The learning center of its mind (see Fig. 1) enables the artificial fish to learn how to locomote through practice and sensory reinforcement. Through optimization, the motor learning algorithms discover muscle controllers that produce efficient locomotion. Fig. 6 illustrates the optimization process.

Muscle contractions that produce forward movements are "remembered". These half-success then form the basis for subsequent improvements in swimming technique. Their brain's learning center also enables the artificial fishes to train themselves to accomplish higher level sensorimotor tasks, such as maneuvering to reach a visible target

(a)

(b)

(c)

Figure 7: Artificial fishes in their habitat. (a) Three center fish are mating; others are foraging among seaweeds (white dots are edible). (b) Female (top) is courted by large male. (c) Predator shark stalking school of prey.

or learning more complex motor skills (see [1, 4] for the details).

Selected Results

A good application of our research is the production of realistic computer graphics animation with little or no animator intervention. The detailed motions of the artificial fishes emulate the complexity and unpredictability of movement of their natural counterparts, which enhances the visual beauty of the animations. The animator plays the role of an artificial life cinematographer.

Fig. 7 show stills from our recent animation "The Undersea World of Jack Cousto" [5]. Fig. 7(a) shows a variety of animated artificial fishes. The reddish fish are engaged in a mating ritual, the greenish fish is a predator hunting for small prey, the remaining fishes are feeding on plankton (white dots). Dynamic seaweeds grow from the ocean bed and sway in the current. In Fig. 7(b), the large male in the foreground is courtship dancing with the female (top). The prey fish in the background are engaging in schooling behavior, a common subterfuge for avoiding predators. Fig. 7(c) shows a shark stalking the school. An earlier animation "Go Fish!" [6] shows a colorful variety of artificial fishes foraging in translucent water. A sharp hook on a line descends towards the hungry fishes and attracts them. A hapless fish, the first to bite the bait, is caught and drawn to the surface.

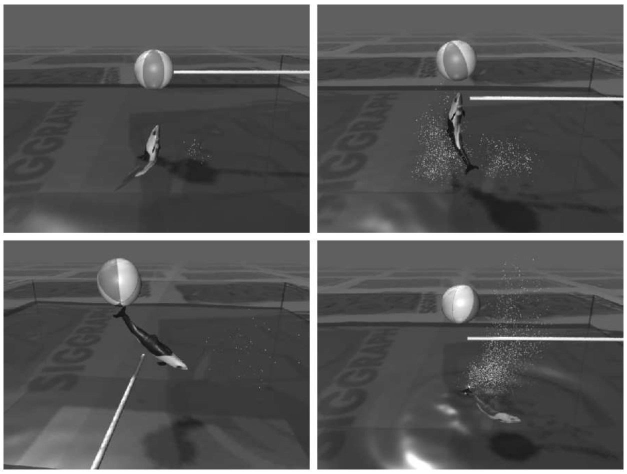

Figure 8: SeaWorld tricks learned by the artificial dolphin.

As an application of our learning algorithms, in [4] we describe, among other artificial animals, the construction of an artificial dolphin that has learned to perform the sort of stunts that elicit applause at marine theme parks like SeaWorld. For example, we can give the artificial dolphin the task of leaping out of the water and it discovers a combination of muscle controllers that accomplishes the task. In particular, the artificial dolphin discovers that it must build up momentum to leap out of the virtual pool of water by thrusting from deep in the pool up towards the surface. Fig. 8(a) shows a frame as the dolphin exits the water. The dolphin can also learn to perform acrobatic tricks while in the air. Fig. 8(b) shows it using its nose to bounce a large beach-ball off a support. The dolphin can learn to control the angular momentum of its body while exiting the water and during ballistic flight so that it can perform aerial spins and somersaults. Fig. 8(c) shows it in the midst of a somersault in which it has just bounced the ball with its tail instead of its nose. Fig. 8(d) shows the dolphin right after splashdown. In this instance it has made a dramatic bellyflop splash. By discovering controllers that enable it to control its body in these complex ways, the dolphin can amuse and entertain the animator and the audience.

Conclusion and Research Directions

This paper has presented research spanning the fields of artificial life, computer graphics, and computer vision.

In particular, we have developed a physics-based, virtual marine world inhabited by astonishingly lifelike artificial life forms that emulate the appearance, motion, and behavior of marine animals in their natural habitats. Each artificial fish is an autonomous agent with a deformable body actuated by internal muscles, eyes, and a brain that includes learning, behavior, perception, and motor centers. Artificial fishes have enabled us to produce complex, realistic computer animation of natural environments in a highly automated fashion.

Our work opens many avenues of research. For example, we may be within reach of computational models that can imitate the spawning behaviors of female fishes and fertilization by males. Through simulated sexual reproduction, gametes representing artificial fish genotypes can be fused to evolve new varieties of artificial fishes that can be subjected to natural selection in a competitive virtual world.

A long-term goal of our research is a computational theory that can potentially account for the interplay of physics, locomotion, perception, behavior, and learning in higher animals. It may be possible to arrive at such a theory by creating artificial animals so realistic that they may serve as "artificial lab-rats". These zoological robots (or "zoobots") would serve biologists and computer scientists alike in their efforts to comprehend and, ultimately, to reverse engineer the sensory, motor, behavioral, and other processes of natural animals [7].

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References

1. D. Terzopoulos, X. Tu, and R. Grzeszczuk. Artificial fishes: Autonomous locomotion, perception, behavior, and learning in a simulated physical world. *Artificial Life*, 1(4):327–351, 1994.
2. X. Tu and D. Terzopoulos. Artificial fishes: Physics, locomotion, perception, behavior. In *Computer Graphics* Proceedings, Annual Conference Series, Proc. SIGGRAPH '94 (Orlando, FL), pages 43–50. ACM SIGGRAPH, July 1994.
3. D. Terzopoulos and T.F. Rabie. Animat vision: Active vision in artificial animals. In *Proc. Fifth International Conference on Computer Vision (ICCV'95)*, Cambridge, MA, June 1995, pages 801–808.
4. R. Grzeszczuk and D. Terzopoulos. Automated learning of muscle actuated locomotion through control abstraction. In *Computer Graphics* Proceedings, Annual Conference Series, Proc. SIGGRAPH '95 (Los Angeles, CA). ACM SIGGRAPH, August 1995.
5. X. Tu, R. Grzeszczuk, and D. Terzopoulos. A National Geo-Graphics Society Special: The Undersea World of Jack Cousto. Computer animation presented at ACM SIGGRAPH'95 Electronic Theater, Los Angeles, CA, August, 1995.
6. X. Tu, D. Terzopoulos, and E. Fiume. Go Fish! Computer animation in ACM SIGGRAPH Video Review Issue 91: SIGGRAPH'93 Electronic Theater, 1993.
7. D. Terzopoulos, T.F. Rabie, R. R. Grzeszczuk, Perception and learning in artificial animals. In *Artificial Life V: Proc. Fifth International Conference on the Synthesis and Simulation of Living Systems*, Nara, Japan, May, 1996, 313–320.