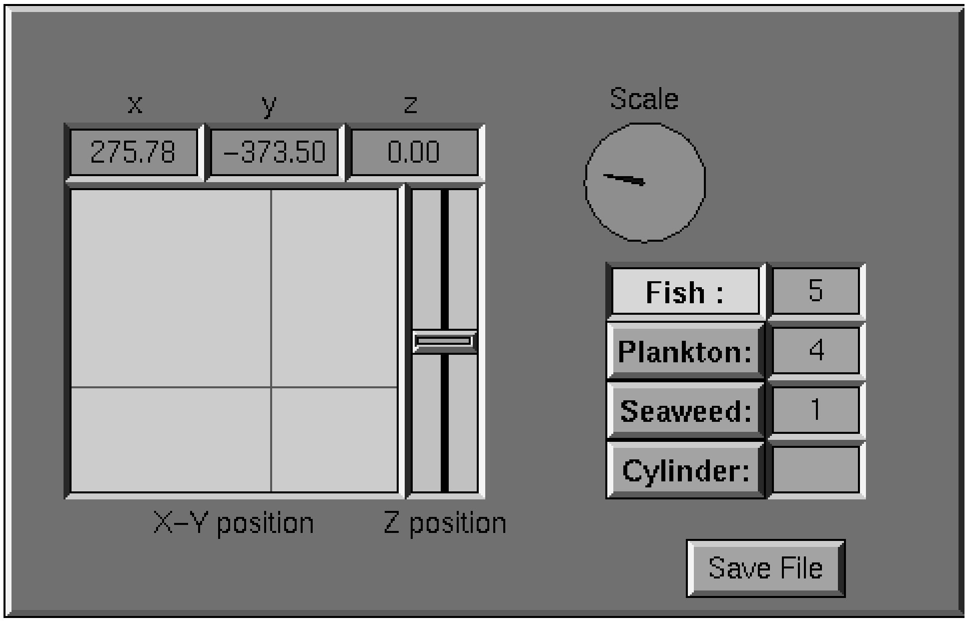

x: 275.78
y: −373.50
z: 0.00
Fish : 5
Plankton: 4
Seaweed: 1
Cylinder:

Figure 9.2: This panel allows the user to initialize the positions and sizes of objects in the virtual marine world.

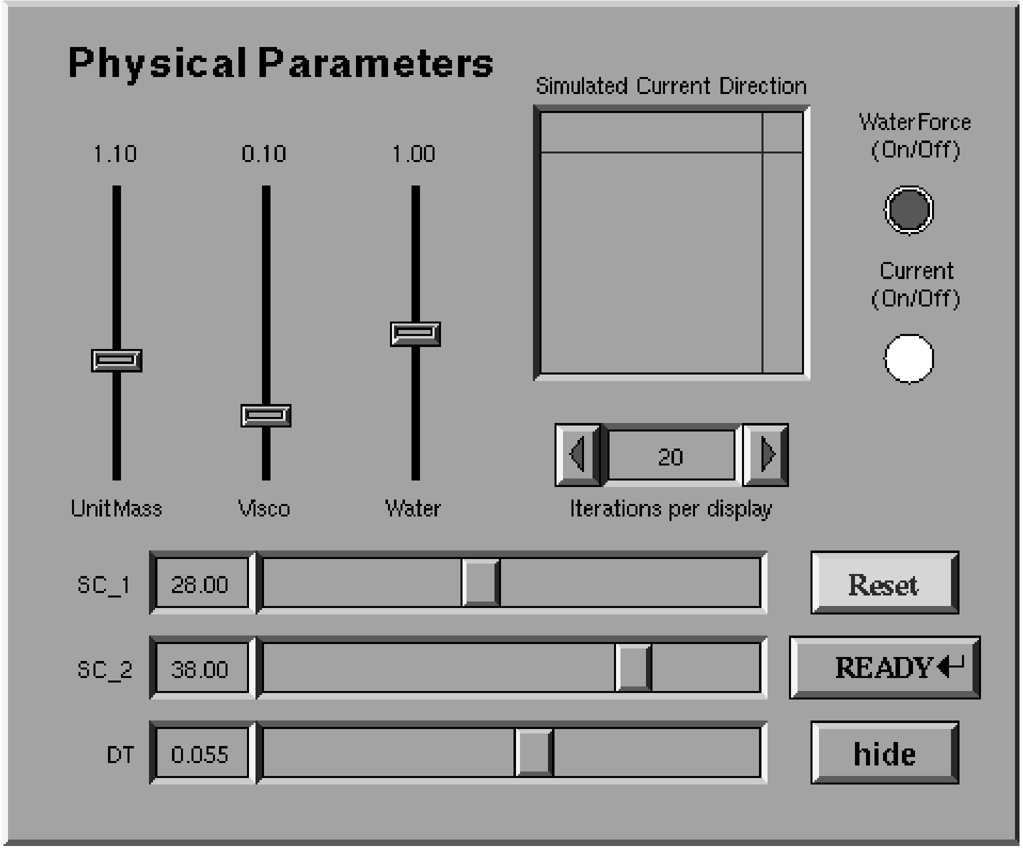
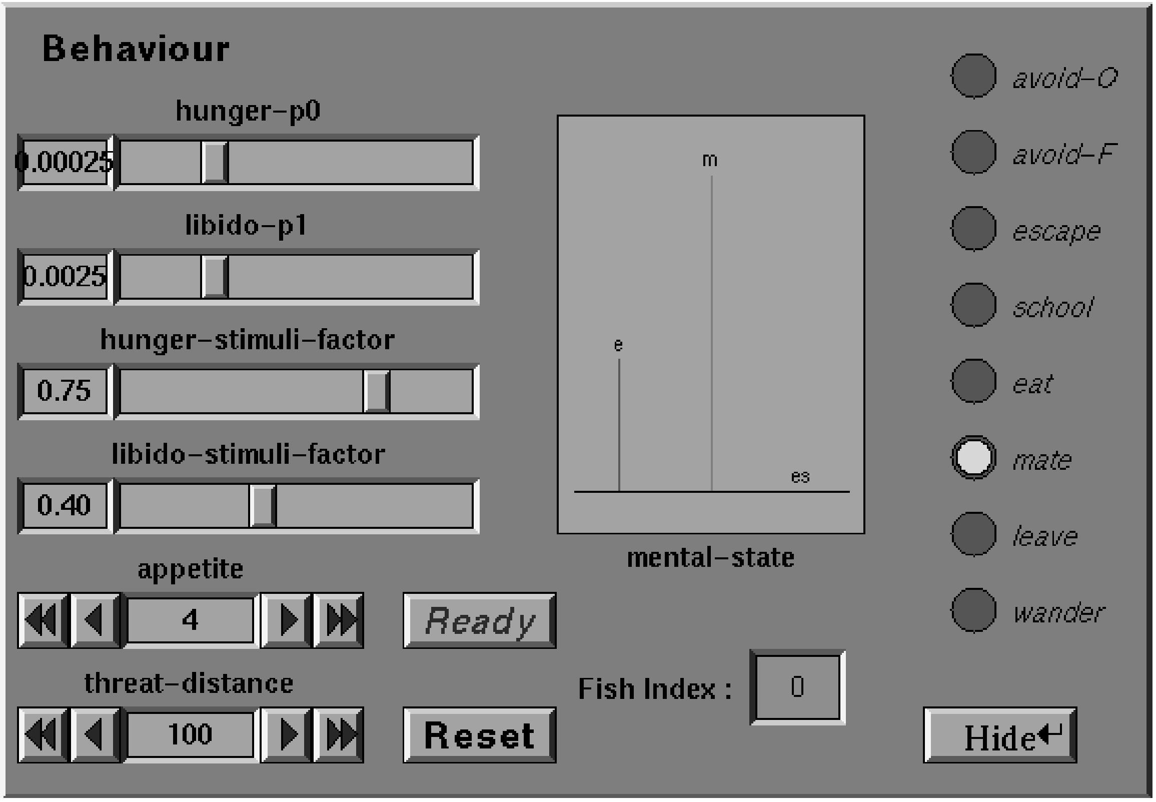

Physical Parameters
UnitMass: 1.10
Visco: 0.10
Water: 1.00
Iterations per display: 20
SC_1: 28.00
SC_2: 38.00
DT: 0.055

Figure 9.3: This panel allows the user to experiment with the physical and numerical parameters of the dynamic fish model.

Influencing a Fish's Behavior

The animator can influence each fish's behavior at the motivation level by varying the relevant behavioral parameters in its mental state variables through the behavior panel (see Fig. 9.4) and by changing its habits through the habit panel (see Fig. 9.5). Using the behavior panel, the animator can also view the dynamics of the mental state of a chosen fish and its current intention. A fish's habit is implemented as a binary string with '1' representing 'like' and '0' representing 'dislike'. If two conflicting features are both assigned '1', for example, if both 'cold' and 'hot' buttons are pushed, this is taken to mean 'don't care'. The fish is a female if 'sex' equals '1'.



hunger-p0 0.00025

libido-p1 0.0025

hunger-stimuli-factor 0.75

libido-stimuli-factor 0.40

appetite 4

threat-distance 100

Fish Index : 0

Figure 9.4: The behavior panel. The user can vary the behavioral parameters shown by the sliders. The chart shows the time-varying values of the fish's mental state variables (here the libido of fish '0' is the highest) and the lit round button indicates that the current intention is to mate.

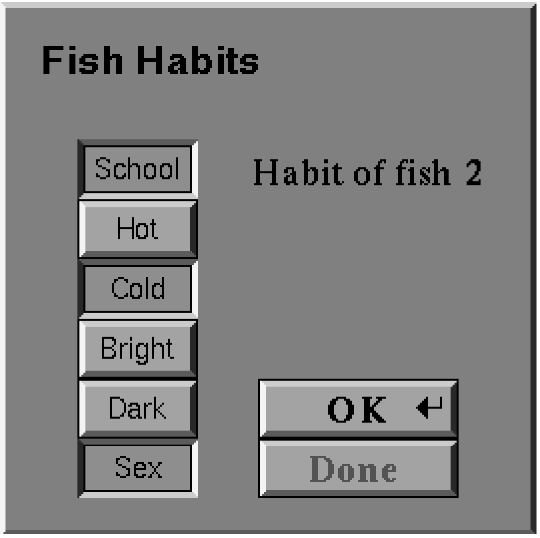


Figure 9.5: The habit panel is used to set a chosen fish's habits. Here, fish '2' is initialized to be female, to like schooling and cold temperature, and to not care about brightness of the environment.

9.3 Control Panels

There is a general control panel (see Fig. 9.6) where all the previously mentioned panels reside as pop-up icons. There are also a set of additional buttons for controlling various graphical attributes, such as different rendering modes, or for turning on and off certain features, such as drawing the indices of the fishes. Moreover, the user is able to push buttons to output certain data, such as the camera angles, or to dump the current graphics window into an image file, etc.

When the "Fish View" button is pushed, a fishview control panel (see Fig. 9.7) pops up, allowing the user to select to view binocular retinal images from a chosen fish's point of view. Slider "pan" gives the gaze angle specifying the horizontal rotation of the eyeball and slider "tilt" gives the gaze angle specifying the vertical rotation of the eyeball. The retinal images are normally rendered as if the fish is looking in the direction of swimming (pan $= 0$ and tilt $= 0$), but the user can 'interfere' by manipulating "pan" and "tilt" to get different views. The retinal identity maps mentioned in Section 6.7 (see Fig. 6.9) can be rendered on command by pressing the "ID map" button.

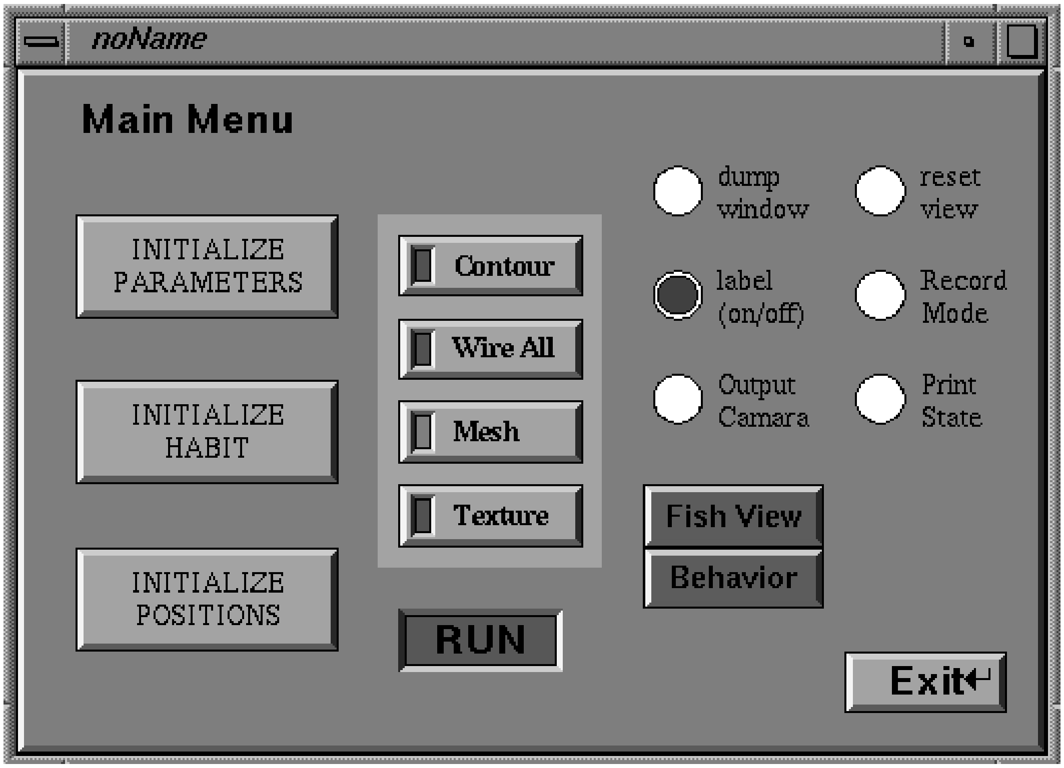
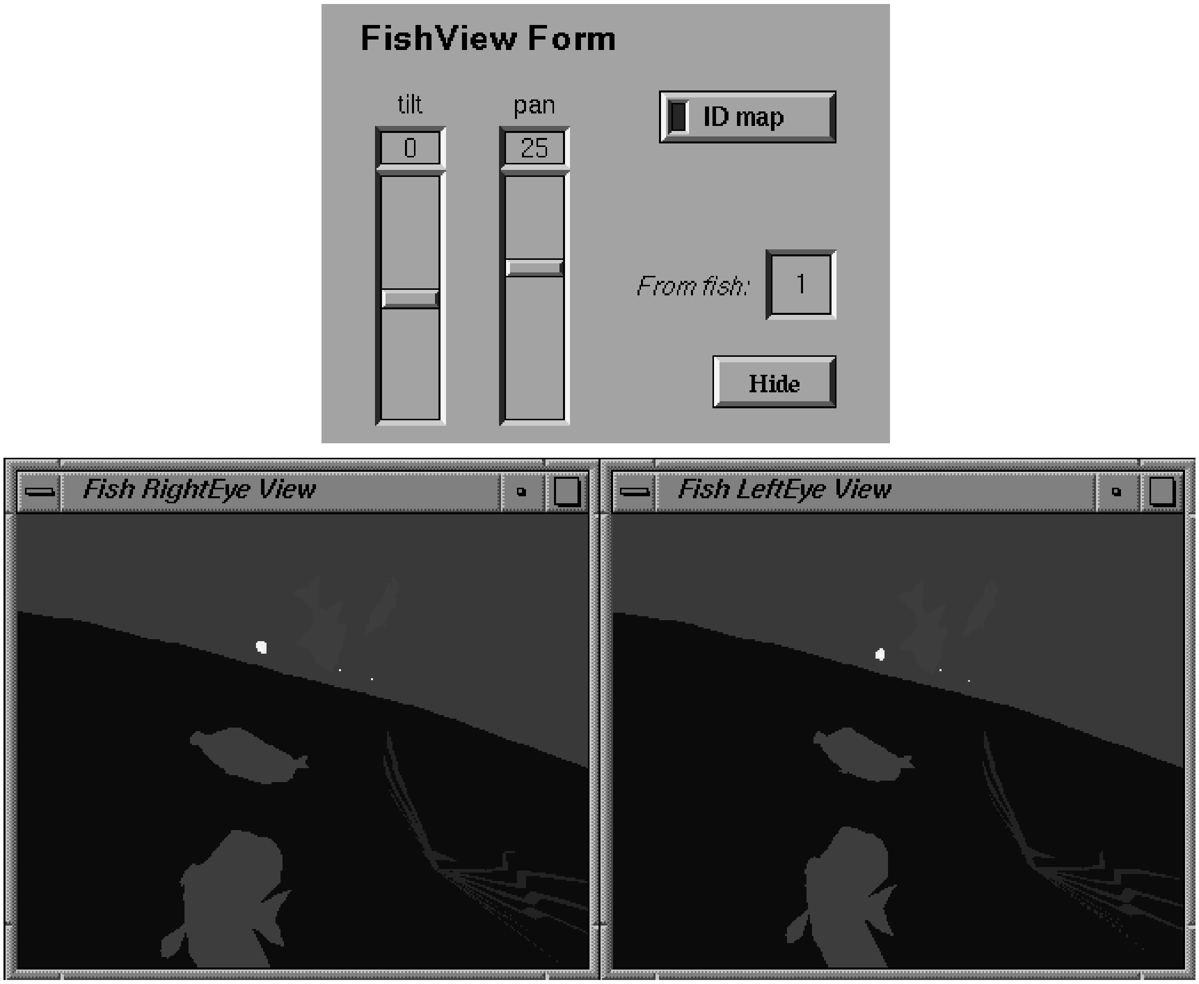


Figure 9.6: The general control panel.

9.4 Discussion

The current implementation of the user interface is rather basic. We would like to enhance it in the future by adding new features. In particular, we would like to be able to directly control the behavior of a particular fish through the interface. For example, this would allow the user to “become” one of the artificial fishes, to look through the fish’s eyes, and explore the virtual marine world. Or the user may be able to don a VR suit and become a virtual scuba diver swimming among artificial fish and eliciting their responses by, say, feeding them, etc.



tilt 0

pan 25

From fish: 1

Figure 9.7: The fishview control panel and the rendered identity maps from fish ‘1’.

Chapter 10

Animation Results

The visual results of the research described in this dissertation are captured in a number of short animation clips and two mini animation films “Go Fish!” and “A National Geo-Graphics Society Special: The Undersea World of Jack Cousto”. “Go Fish!” was made in 1993 and was selected and presented at the ACM SIGGRAPH’93 Electronic Theater Evening Program (Tu, Terzopoulos and Fiume, 1993). “The Undersea World of Jack Cousto” was made in 1994 and was presented at the ACM SIGGRAPH’95 Electronic Theater Evening Program. Both animations were subsequently broadcast in various television science programs internationally.[1] “Go Fish!” has also won several awards, including the 1994 *Canadian Academy of Multimedia and Arts and Sciences International Award for Technical Excellence*. In the following sections, we briefly describe “Go Fish!” and “The Undersea World of Jack Cousto”, as well as the contents of some additional animation shorts.

10.1 “Go Fish!”

“Go Fish!” runs for two minutes and four seconds and was produced by the author along with her supervisors, Professor Demetri Terzopoulos and Professor Eugene Fiume.

The animation first illustrates the construction of a dynamic fish model. The mass-spring-damper biomechanical substructure with its 12 primary contractile muscles is simulated in real time. The substructure is then enclosed in a realistically shaped NURBS surface to create the fish body. The fish

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[1] The interested reader is referred to the author’s home page http://www.dgp.toronto.edu/people/tu/go-fish.html for a list of programs in which the two animations were shown.

surface is texture mapped using textures extracted from photographs of real fishes.

Next we see the simulated foraging behaviors of a small school of wire-frame fish among cylindrical obstacles. We are also treated to a fisheye (“fishcam”) view of the virtual aquatic world.

The final sequence shows a colorful variety of fish feeding in translucent water. In the presence of underwater currents, the fishes explore their world as autonomous agents, foraging for edible plankton and navigating around fixed and moving obstacles such as other fishes and dynamic seaweeds that grow from the sea bed. A sharp hook on a line descends towards the fish. A hapless fish, the first to bite the bait, is caught and pulled to the surface. The following images show stills from the animation which was rendered using the Silicon Graphics GL graphics library.

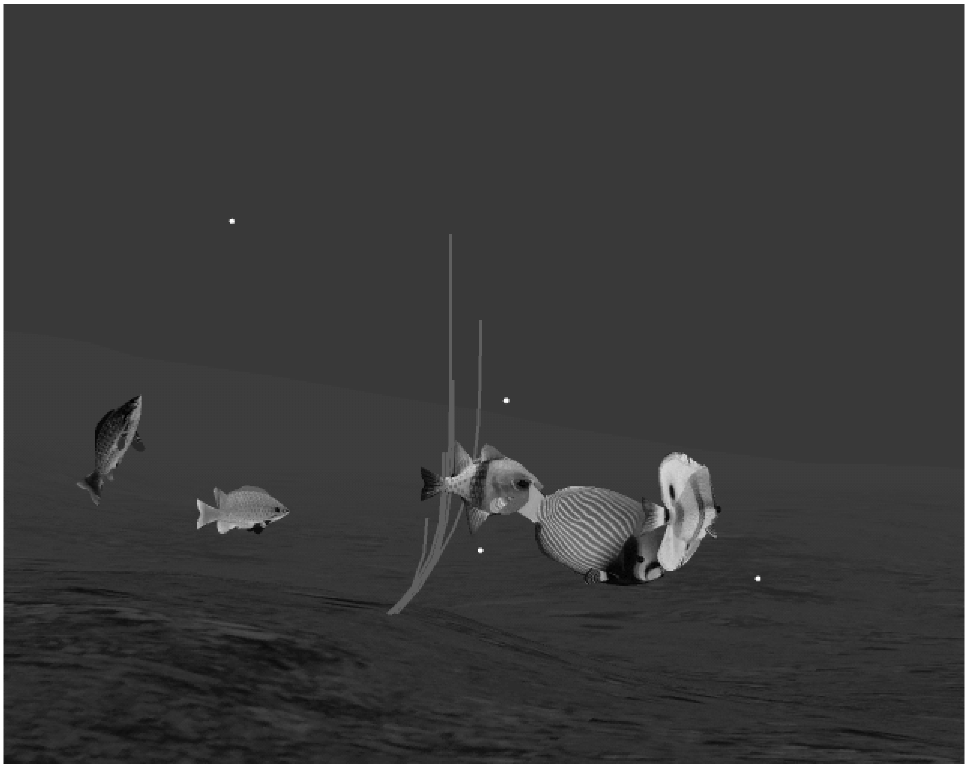

Figure 10.1: Denizens of the virtual marine world happily feeding on plankton.

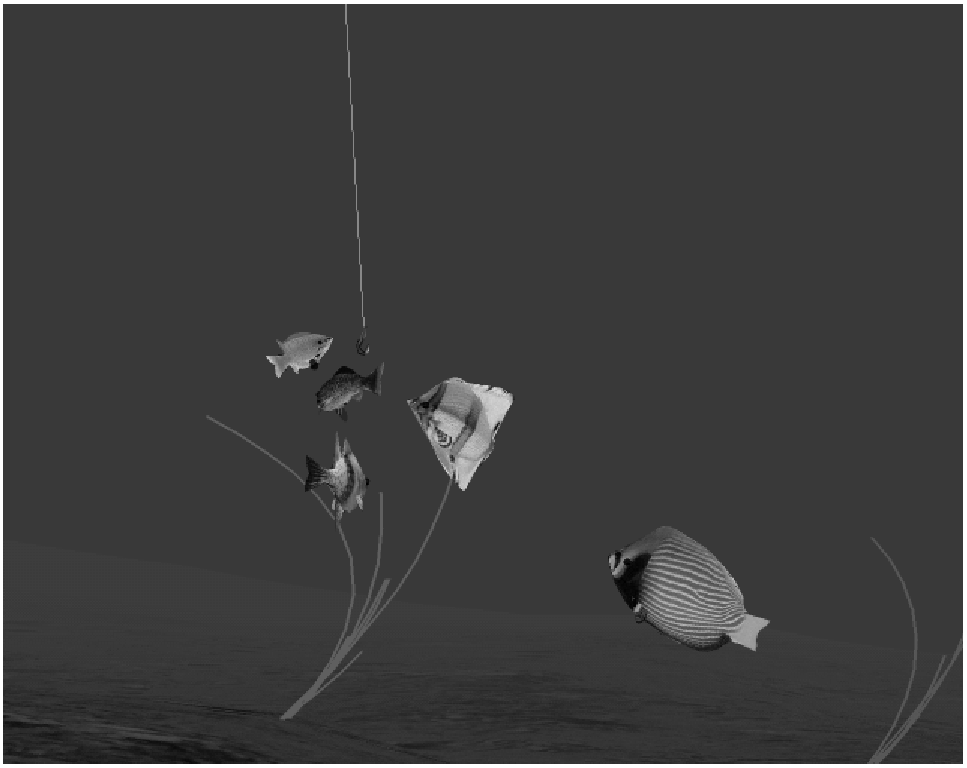

Figure 10.2: Hungry fishes approaching the hook.

Figure 10.3: A hapless fish is caught and pulled to the surface. See the original color image in Appendix D.

10.2 “The Undersea World of Jack Cousto”

The French oceanographer Jacques Cousteau has become legendary for his spectacular cinematography of natural marine life. The reader may be familiar with the magnificent underwater documentaries produced by the *Jacques Cousteau Foundation* or those of the *National Geographic Society*.

We have implemented an animation system that enables an animator to produce intriguing “nature documentaries” of an artificial undersea world, not by conventional means, but by assuming the role of a marine cinematographer analogous to that played by Cousteau. Unlike Cousteau, however, who must deal with a physical camera in a physical world, our animator uses a virtual camera to explore and record artificial life inhabiting a virtual marine world. To demonstrate this new gender of computer animation, we have created a mini animated parody of a National Geographic underwater documentary.

Our “National Geo-Graphics” documentary explores “The Undersea World of Jack Cousto”. Jack’s cinematography reveals a mysterious world of colorful artificial fishes. We observe mating rituals and other elaborate behaviors. Dangerous predators stalk in the deceptively peaceful habitat. The following images show stills from the animation, which was rendered using the photorealistic RenderMan^{TM} package.

“The Undersea World of Jack Cousto” runs for two minutes and thirty seconds and was produced by the author along with her colleague Radek Grzeszczuk and Professor Demetri Terzoupoulos.

10.3 Animation Short: Preying Behavior

At the beginning of the animation, the ‘food chain’ phenomenon of a small underwater ecosystem is displayed: various species of colorful ‘pacifist’ fishes are happily feeding on floating plankton (food particles) while a ferocious predator fish is stalking a prey fish, hoping to devour it. The remainder of the animation demonstrates the hunting behavior of the predator and the evasive behavior of the prey. We see the greedy predator chasing after each prey until the prey is in close proximity, at which point the predator opens its mouth and vigorously sucks in the prey. Moreover, we can see the five reddish prey fish of the same species forming a school in an attempt to escape from the predator while the predator is eating other prey. When the still hungry predator finally approaches the school,

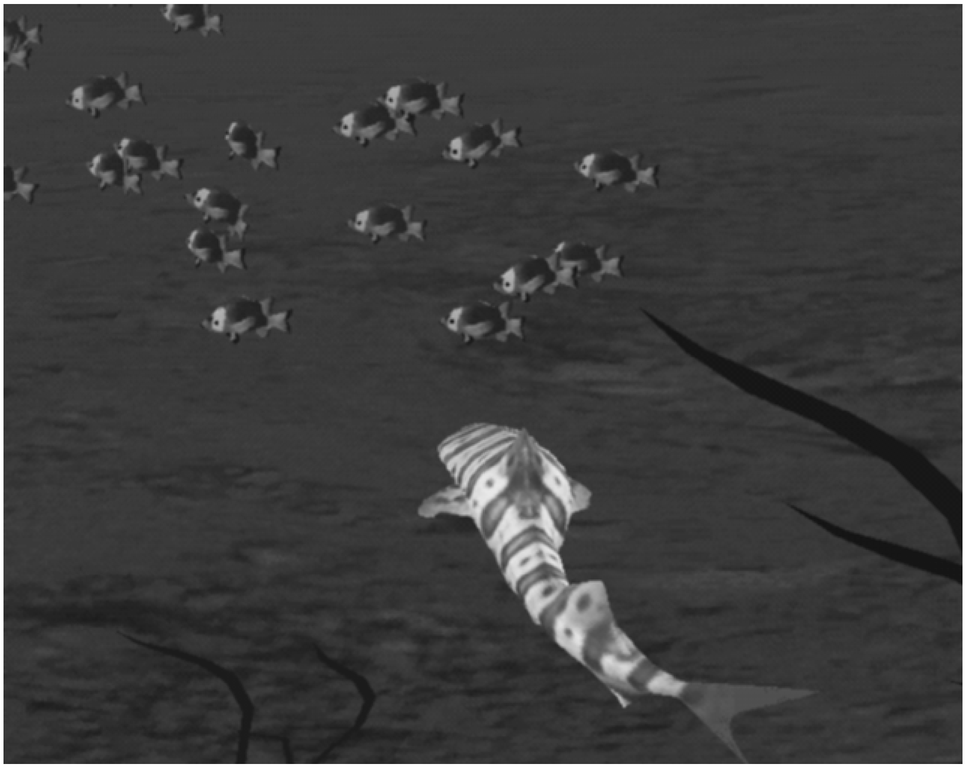

Figure 10.4: A dangerous shark stalking a school of prey.

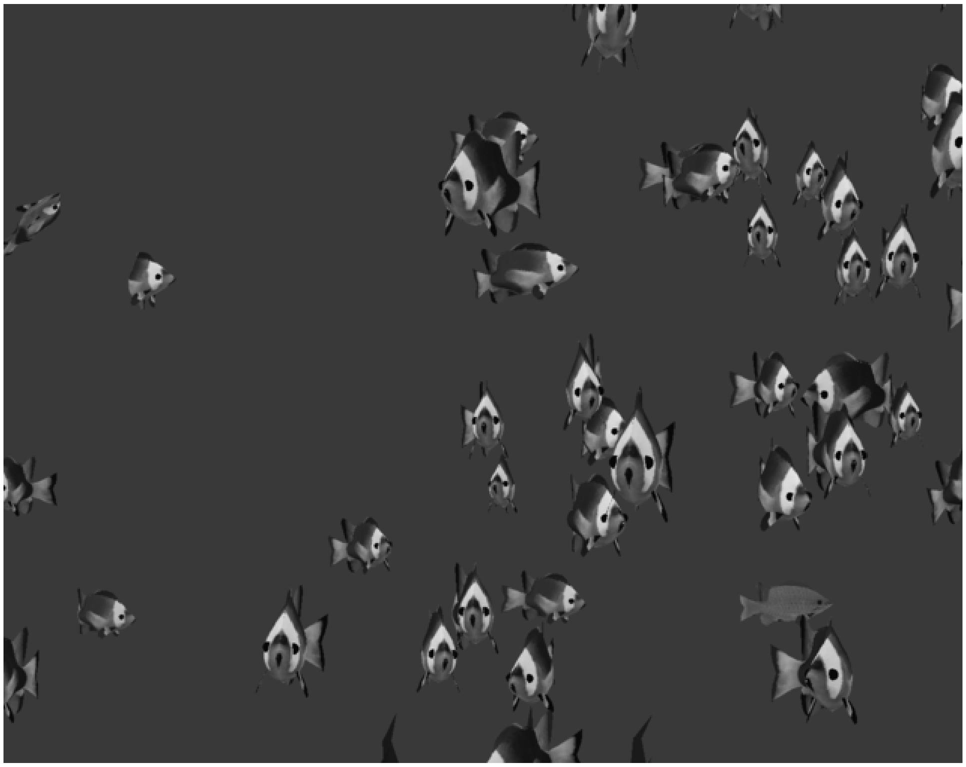

Figure 10.5: A school of fleeing prey. See the original color image in Appendix D.

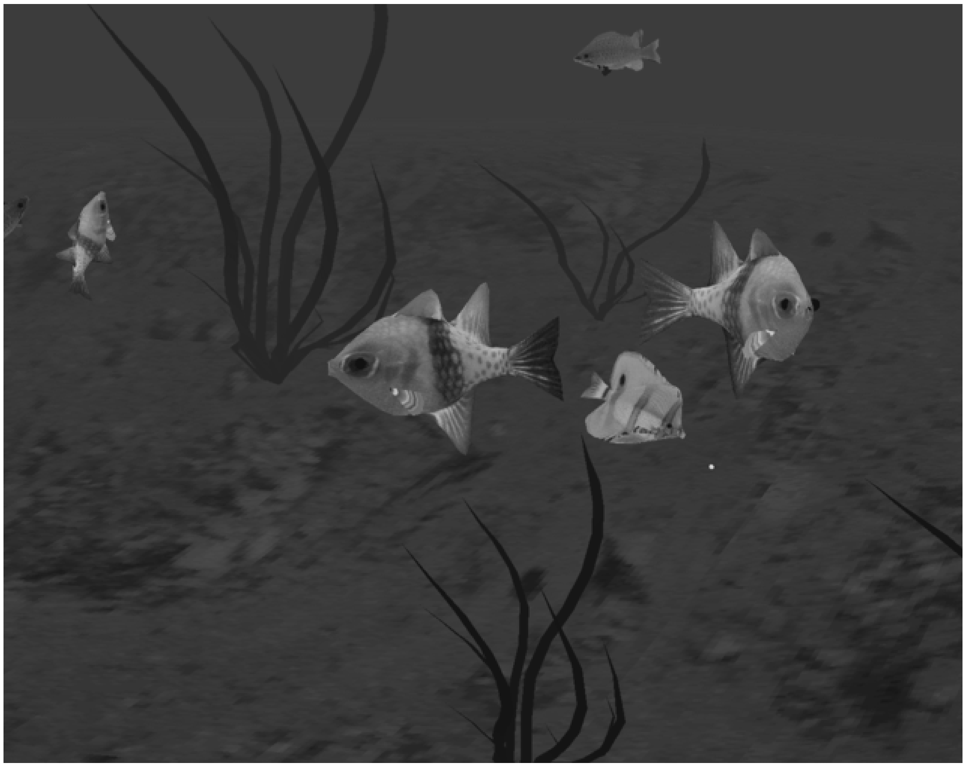

Figure 10.6: A pair of courting pokerfish. The male is on the right.

the little ‘fugitives’ scatter in terror and the school breaks into smaller schools. At the end of the animation, the satiated predator wanders away leaving one lucky survivor. Fig. 10.7 shows a still from this animation clip.

10.4 Animation Short: Schooling Behavior

This animation pictures a school of fish led by a larger fish that roams through the water in a zigzagging pattern. When it encounters a cylindrical obstacle, the school splits into two groups: one group consisting of a few fish passes by one side of the obstacle, while the other group comprising the remaining majority passes by the other side following the lead fish. As soon as the fish in the smaller group have cleared the obstacle they speed up to rejoin the school (see Fig. 7.16).

Figure 10.7: A large predator hunting small prey fishes while pacifist fishes, untroubled by the predator, feed on plankton.

10.5 Animation Short: Mating Behavior

This animation displays courtship looping and circling, spawning ascent, and nuzzling in fish mating behaviors. The animation starts with two libidinous male poker fish (the reddish ones) swimming towards one female poker fish. When the two males encounter the female, they begin courtship looping in the hope of attracting her attention, while she hovers and bobs her head trying to decide which one to choose. The smaller male loses the competition for her attention and turns away to ‘flirt’ with one of the female yellow butterfly fish. The victor proudly continues his up and down looping, while in the background scene the two striped emperor angelfish have just completed their courtship circling and the female starts her spawning ascent to the surface of the water. As the camera brings us closer to the pair of angelfish, we see that the male follows the ascending female and nuzzles her abdomen as she hovers. The camera rolls back to the pair of poker fish to show the last part of their courtship circling. Upon completion of the circling, the female ascends and the male follows to nuzzle her. After three successful nudges, the mating sequence ends and the male and female part.

Chapter 11

Conclusion and Future Work

11.1 Conclusion

In this dissertation we presented the results of research spanning the fields of computer graphics and artificial life. With regard to computer graphics, we have proposed, implemented, and demonstrated an animation framework that enables the creation of realistic animations of certain natural ecosystems with minimal intervention from the animator. In our approach, the virtual creatures are self-animating, as are real animals and humans. Thus, the strength of our approach to animation lies in the fact that it turns the role of the animator from that of a graphical model puppeteer to that of an virtual nature cinematographer, a job not unlike that done by nature cinematographers of the National Geographic Society. Our artificial life approach has advanced the state-of-the-art of computer animation, as evidenced by the unprecedented complexity and realism of the behavioral animations that we have been able to achieve without keyframing. With regard to artificial life, we have successfully modeled complete animals of nontrivial complexity. The convincing simulation results validate our computational models, which capture the essential features of all biological animals—biomechanics, locomotion, perception, and behavior.

In particular, we have developed a physics-based, virtual marine world inhabited by life-like artificial life forms that emulate the appearance, motion, and behavior of fishes in their natural habitats. Each artificial fish is an autonomous agent with a deformable body actuated by internal muscles, with eyes, and with a brain that includes behavior, perception and motor centers. 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. Though rudimentary compared to real animals, their brains are nonetheless able to capture many of the most important characteristics of animal behavior and carry out perceptually guided motor tasks. In accordance with their perception of the virtual world and their internal desires, their brains arbitrate a repertoire of behaviors and subsequently select appropriate actions. The piscine behaviors the fishes exhibit include collision avoidance, foraging, preying, fleeing, schooling, and mating. The easy extensibility of our approach to the modeling of additional behaviors is suggested most evidently by the complex patterns of mating behavior that we have been able to emulate in artificial fishes.

With regard to the implementation, we have pursued a bottom-up, compositional approach in which we started by modeling the basic physics of the animal and its environment. Upon the simulated physics substrate, we effectively modeled the animal's means of locomotion. This in turn positioned us to model the animal's perceptual awareness of its world, its motivation, and last but not least, its behavior. The compositional nature of our approach to synthesizing artificial fishes was proven crucial to achieving realism. Partial solutions that do not adequately model physics, locomotion, perception, motivation and behavior, and do not combine these models intimately within the agent will not produce convincing results.

In addition to realism, computational efficiency has been one of the most important design criteria of our implementation. The fidelity of our models was carefully chosen to achieve satisfactory computational efficiency. We have strived successfully to achieve visually convincing animations with low computational cost. Using a Silicon Graphics R4400 Indigo^2 Extreme workstation, a simulation of ten artificial fishes, fifteen food particles and four static obstacles can run at about 4 frames/sec, including wireframe rendering time and user interface running time. With a *Reality Engine*^{2} graphics board on the Silicon Graphics ONYX workstation, the same simulation with hardware-supported GL, fully texture mapped surface rendering runs at about 3 frames/sec. Considering the complexity of the animations, the simulation speed we have been able to achieve is more than satisfactory. The main tradeoffs that we have made in order to gain high simulation speed is the simplification of the virtual environment and the algorithms used for simulating the fish's perceptual capability.

11.2 Additional Impact in Animation and Artificial Life

The work reported in this dissertation has promoted further research on automatic motion synthesis for computer animation and on locomotion learning for artificial life. Grzeszczuk and Terzopoulos

(Terzopoulos, Tu and Grzeszczuk, 1994b; Grzeszczuk and Terzopoulos, 1995) have developed a learning technique that automatically synthesizes realistic locomotion for physics-based models of animals. This technique specifically addresses animals with highly flexible and muscular bodies, such as fish, rays, dolphins, and snakes. In particular, they have established an optimization-based, multi-level learning process on top of the motor system of the artificial fish. This process forms an additional "locomotion learning" center in the artificial fish's brain (see Fig. 11.1). This center automatically learns effective motor controllers for the artificial fish biomechanical model, and abstracts them into suitably parameterized form. On the one hand, the learning center enhances the functionality of our animation system by subsuming the original laborious hand-crafting of motor controllers. On the other hand, equipped with the locomotion learning ability, the artificial fish has now 'evolved' into a more complete artificial life form.

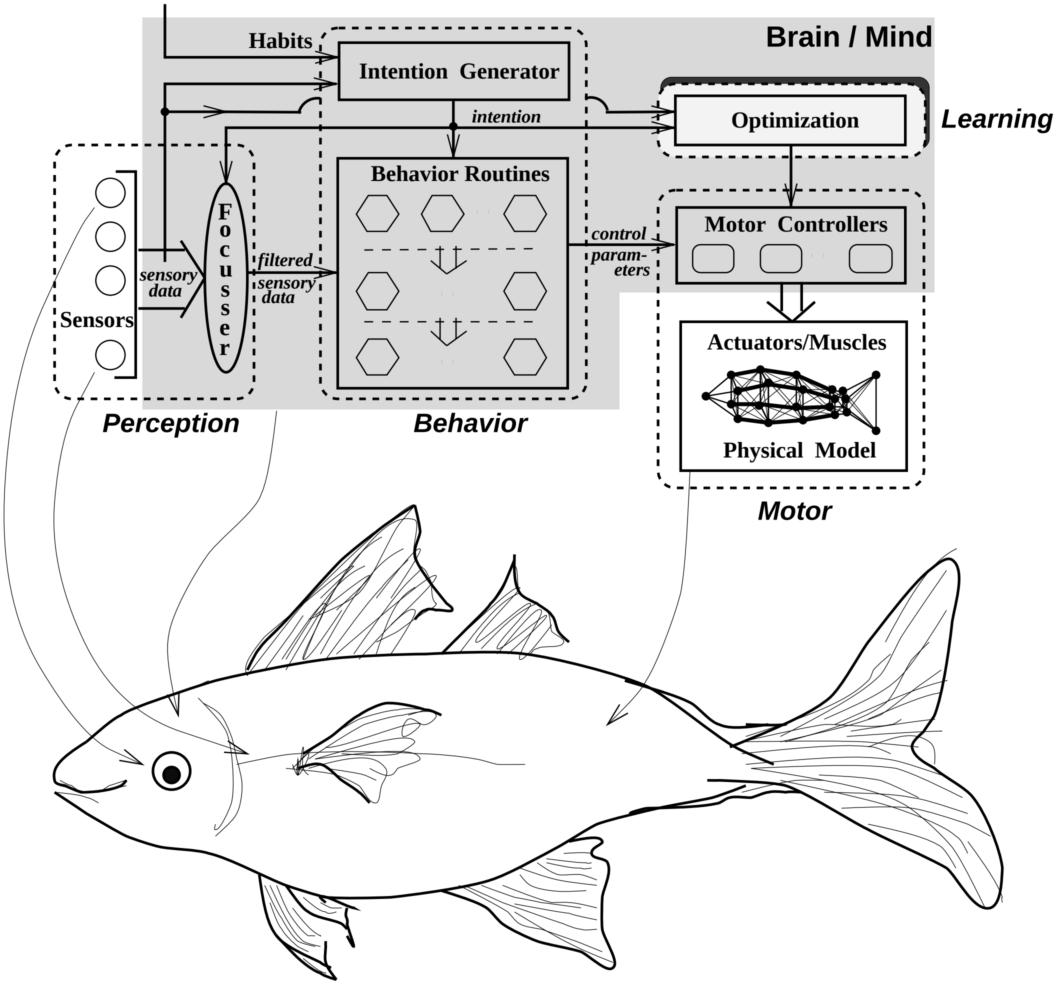

Figure 11.1: Locomotion learning center in the brain of the artificial fish.

The ability to learn also leads to the possibility of automatically generating simple sensorimotor tasks for artificial animals, such as the fish. First steps along these lines have already been made: Greszczuk and Terzopoulos (1995) imbue the artificial fish with the ability to learn to maneuver and reach a visible target. This is done by enabling the animals to learn to put into practice the compact, efficient controllers that they have previously learned. In this way, Grzeszczuk and Terzopoulos have developed dolphin models that can learn to perform a variety of "SeaWorld stunts".

11.3 Impact in Computer Vision and Robotics

Our work opens up several exciting avenues of research in related fields. For example, the software that we have developed has made possible interesting new approaches to computer vision and robotics.

Clearly the artificial fish is a situated virtual robot that offers a much broader range of perceptual and animate capabilities, lower cost, and higher reliability than can be expected from present-day physical robots like those described in (Maes, 1991b). For at least these reasons, artificial fishes in their dynamic world can serve as a proving ground for theories that profess competence at effectively linking perception to action (Ballard, 1991). To date, this thesis work has formed the basis for computer vision research—an approach termed *animat vision* that has been pioneered by Terzopoulos (Terzopoulos and Rabie, 1995; Terzopoulos, 1995).

The animat vision methodology employs artificial animals or animats as realistic, active observers of their dynamic world. This approach can potentially liberate a significant segment of the computer vision research community from their dependence on expensive robot hardware. It addresses the needs of scientists who are motivated to understand and ultimately reverse engineer the powerful vision systems found in higher animals. As is argued by Terzopoulos (1995),

> *Readily available hardware systems are terrible models of biological animals. For lack of a better alternative, however, [vision scientists] have been struggling with inappropriate hardware in their ambition to understand the complex sensorimotor functions of real animals. Moreover, their mobile robots typically lack the compute power necessary to achieve real-time response within a fully dynamic world while permitting active vision research of much significance.*

The artificial fishes and their habitats that we have developed are rich enough for grounding biologically inspired active vision systems as is shown by Terzopoulos and Rabie (1995). They have enabled active vision algorithms to be implemented entirely in software, thus circumventing the problems of hardware vision.

11.4 Potential Applications in Ethology

A picture is worth a thousand words...

Ethologists have long hoped to simulate animals in computers in order to facilitate the systematic study of animal behavior. As early as the seventies, ethologists Rémy and Bernadette Chauvin expressed their keen interest in such an approach to the analysis of animal behavior (Chauvin and Muckensturm-Chauvin, 1977). More recently, McFarland (1993b) and Roiblat (1994) also emphasized the importance of such an approach:

> “It is possible that ethologists will profit to a greater extent from the possibilities offered by simulation models... The availability of simulation programs makes it possible to identify which instructions devolve from a purely ethological interpretation and which from a cognitive one. A comparison of the program’s behavior with the behavior actually displayed by the animal should enable the validity of the corresponding interpretation to be assessed.” (Roiblat, 1994)

To this end, our artificial fish can act as a prototype model animal that provides a novel and potentially useful investigative tool. Although in several ways crude at this stage, our model can be furnished with more sophisticated behavioral mechanisms, more elaborate muscle models, etc.

Prior simulation models only allowed the modeling of one aspect of the problem to be investigated in isolation. Our model of artificial animals exemplifies a unified and complete system that allows a whole animal to be studied, from the biomechanical motor system to the perception-driven behavior system within a physics-based virtual world. In this way our approach allows the investigation of complex interactions between these different levels.

Moreover, the results of our simulation are displayed in a convenient and easy to interpret form. In effect what we have produced can be viewed as a sophisticated scientific visualization tool for ethologists that may enable new insights to be gleaned and new relationships discovered. Our work demonstrates the potential of realistic computer animation in applications to ethology.

11.5 Other Artificial Animals

The title of this dissertation emphasizes the generality of our artificial animal approach to computer animation, rather than its specific application in this thesis to fishes. The main components of our approach—modeling form and appearance, biomechanics, locomotion, perception, and behavior—carry over to the realistic modeling of other animals, although the details of each of these components may, to one degree or another, be animal specific. Consider, for example, the design of a realistic artificial cat.

- It is important to capture natural feline form and appearance, but clearly cats and fish differ dramatically, so different 3D models and textures would be needed to model a cat.
- Cat biomechanics obey Newton's laws of motion, as do fish biomechanics. Quite unlike the highly deformable fish body, however, an artificial cat would require the biomechanical modeling of an articulated skeleton actuated by skeletal muscles.
- With regard to locomotion, there are obvious differences between the hydrodynamic swimming of a fish and the natural quadrupedal gait of the cat that exploits gravity and friction due to foot-ground contact. Nevertheless, for both the fish and the cat, it is crucial to the design of the higher level behavioral modeling to abstract the locomotion ability of the animal into a set of parameterized motor controllers.
- Perceptual modeling is essential in both the cat and the fish. The perception model that we have developed can with slight modification emulate the basic visual capabilities of a cat, but one may also wish to model the auditory capability of cats.
- The artificial cat requires a behavior system at least as sophisticated at the one for the artificial fish, including habits, mental state, an intention generator and behavior routines. Certain innate characteristics, such as gender, mental variables, such as hunger, and behaviors, such as collision avoidance, are common to both fish and cats, but behaviors such as scratching in the litterbox are feline specific and would require the implementation of specific behavior routines. However, the structure of our behavior control scheme remains appropriate.

To develop more complex artificial animals patterned after humans and other primates that have sophisticated intelligent behaviors, our approach can serve in the development of a reactive behavioral substrate that supports a higher-level reasoning system.

11.6 Future Research Directions

11.6.1 Animation

The behavioral animation system that we have proposed and demonstrated can be improved and further developed in many aspects. We are interested in exploring future research in a number of directions.

Physics-based Motor Control

Physics-based modeling offers many advantages and has, in our case, proven to be successful in generating realistic motions of fishes. However, the associated control problem for more complicated creatures remains a difficult endeavor. We would like to explore ways of simplifying the control problem, perhaps by exploiting analytical solutions to the given physical system.

Better Hydrodynamics and a Greater Variety of Marine Animals

In the current implementation of the artificial fish system, we model only simplified hydrodynamics in the virtual environment. An interesting future research direction would be to establish more sophisticated models of hydrodynamics. This would allow us to further examine the complex interactions between the characteristics of such a hydrodynamic environment and the motion and behavior of the artificial fishes. Furthermore, we want to implement more marine animals to enhance our virtual undersea world, such as eels, seahorses and jellyfish, etc.

More Elaborate Perception Model

As we have mentioned in Chapter 6, we would like to develop more sophisticated algorithms for modeling artificial animal's perception in more complex virtual environment. We are also interested in synthesizing various elaborate sensing abilities of animals, for instance, modeling diffusion for olfactory sensing.

Modeling Emotion for Behavior Control

Emotion is an important factor of animal behavior. It plays an essential role in describing the 'personalities' of an animal. Unlike habits, the emotion of an animal is typically associated with one or more specific objects, rather than with some generic condition. The involvement of emotion may often cause an animal to exhibit 'unusual' behavior. For example, although is generally friendly to humans, a cat may dislike a particular person and react strongly against him/her. We would like to incorporate a model of emotion into our behavior control scheme to enhance the behavior realism of the animals being animated. This model will allow additional differentiation between characters in an animation as well as offering additional high-level means of controlling their behavior.

Higher Directability

Last but not least, we would like to explore an intuitive way of directing the autonomous artificial creatures to a high degree. In the current implementation, it is easiest to create animations in which we do not demand highly specific control over what the creatures do and when they do it, as long as they behave naturally. However, it is not unusual to want to create an animation which shows, say, two or more events happening at roughly the same time and place. For example, when making the animation "The Undersea World of Jack Cousto" (Tu, Grzeszczuk and Terzopoulos, 1995), we wanted to show, in a period of less than one minute of animation, two fishes displaying mating rituals while a large school of fish passes by in the background stalked by a predator shark. The most difficult part of achieving this sort of scenario is to roughly synchronize the mating, the schooling and the preying and to make schooling/preying happen in roughly the right place (the background).[1]

To achieve these sorts of synchronizations, the animator would have to spend a fair amount of time performing multiple trials, tuning the relevant parameters until the desired action sequence is achieved. An obvious way of simplifying the problem is to suspend the forward simulation of the school of fish and the shark and run a trial simulation to determine the time at which the mating occurs. Once this is known, we can start simulating the school of fish and the shark roughly around the same time. Of course, we may still need to influence the path of the school which is done by scripting the path of the 'lead' fish. Currently, these detailed manipulations are done by hand and hence may be cumbersome.

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[1] It is easy to let the mating happen early into the animation by setting the libido parameter of the two fishes high enough.

It may be possible, however, to build a higher level controller on top of the animation system we currently have in order to accomplish similar tasks in a much more convenient way. A promising approach for accomplishing this level of control would be employ some descriptive language for monitoring the animation process and exerting direct control over the various aspects of the simulation; e.g. the start time of some specific creatures and their paths, etc. Therefore, one of the future research directions could be to define and develop such a language and its interface to the current animation system. Blumberg and Galyean (1995) recently proposed and implemented a system that addresses interactive "directability" of animated autonomous creatures. Their work marked a first step towards the aforementioned future research direction.

11.6.2 Artificial Life

The long-term goal of our research in the regard of artificial life is a computational theory that can, potentially, account for the interplay of locomotion, perception and behavior in higher animals. We believe that a good touchstone of such a theory is its ability to produce visually convincing results in the form of realistic computer graphics animations with little or no animator intervention.[2]

An obvious research direction would address the goals of researchers interested in evolving artificial life. We may be within reach of computational models that can imitate the spawning behaviors of the female fish and fertilization by the male. Through simulated sexual reproduction in a competitive world, gametes representing artificial fish genotypes can be fused to evolve new varieties of artificial fishes. Interestingly, Pokhilko, Pajitnov, *et al.*, have already demonstrated the simulated breeding of fish models much simpler than ours using genetic algorithms, and this idea has resulted in the fascinating computer game program "El-Fish" (Corcoran, 1992).

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[2] In the context of artificial life there are no constraints on what should happen when.

Appendix A

Deformable Contour Models

A "snake" (Kass, Witkin and Terzopoulos, 1987) is a dynamic deformable contour in the x-y image plane. We define a discrete deformable contour as n equally-spaced nodes indexed by $i = 1, ..., n$, with time varying positions $\mathbf{x}_i(t) = [x_i(t), y_i(t)]$. The deformable contour's dynamic behavior can be influenced interactively by incorporating user-specified forces (e.g. mouse forces) into its equations of motion. Such behavior is governed by the system of first-order ordinary differential equations:

$$\gamma \frac{d\mathbf{x}_i}{dt} + \alpha_i + \beta_i = \mathbf{f}_i; \qquad i = 1, ..., n, \tag{A.1}$$

where γ is a velocity-dependent damping constant, $\alpha_i(t)$ are "tension" forces which make the deformable contour act like a series of springs that resist deformation, $\beta_i(t)$ are "rigidity" forces which make the contour act like thin wire that resists bending, and $\mathbf{f}_i(t)$ are forces in the image plane $\mathbf{f}_i^I(t)$ plus the simulated mouse forces applied to the contour.

A $m \times n$ deformable mesh consists of $m + n$ contours, n of which run vertically, each with m nodes, and m of which run horizontally each with n nodes. The crossing points on the deformable mesh are nodes shared by the intersecting contours.

We express α_i, the tension forces, in terms of the deformation of the springs connecting node i to its two neighboring nodes and β_i, the rigidity forces, in terms of the second order forward finite differences as follows:

$$\alpha_i = a_i e_i \mathbf{r}_i - a_{i-1} e_{i-1} \mathbf{r}_{i-1}, \tag{A.2}$$

$$\beta_i = b_{i+1}(\mathbf{x}_{i+2} - 2\mathbf{x}_{i+1} + \mathbf{x}_i) - 2b_i(\mathbf{x}_{i+1} - 2\mathbf{x}_i + \mathbf{x}_{i-1}) + b_{i-1}(\mathbf{x}_i - 2\mathbf{x}_{i-1} + \mathbf{x}_{i-2}) \tag{A.3}$$

where a and b are parameters, e_i is the deformation of the spring connecting node i to node $i+1$ (i.e. its current length minus its rest length), and $\mathbf{r}_i$ is the unit vector from $\mathbf{x}_i$ to $\mathbf{x}_{i+1}$. Note that α_i and β_i vanish in the absence of deformation and bending.

To make the outline of the fish in the image stand out, we convert the original RGB color image into a gray-scale image $I(x, y)$. The gradient of I, call it $P_I(x, y)$, forms a potential field whose "ravines" coincide with the dark outline of the profile of the fish. The image force field can then be expressed as the gradient of $P_I(x, y)$, i.e. $\mathbf{f}_i^I = \nabla P_I(x, y)$) such that the ravines act as attractors to deformable contours. The contours descend and stabilize at the bottoms of the nearest ravines. In order to let the ravines attract the deformable contours from some distance away, the potential function $P_I(x, y)$ is computed as follows:

$$P_I(x, y) = G_\sigma * ||\nabla I(x, y)||,$$

where $G_\sigma *$ denotes convolution with a 2D Gaussian smoothing filter of width σ which broadens the ravines of ∇I.

Often the user may initialize the border of the deformable mesh too far from the edges of the fish body and hence the deformable contours may become attracted by nearby dark features and fail to localize the correct outline. Should this be the case, the user can apply simulated spring forces $\mathbf{f}_i^m(t)$ by using the mouse to guide a deformable contour towards the ravine of interest (Kass, Witkin and Terzopoulos, 1987).

Another case frequently encountered is where the profile of the fish is not composed of edges that are consistently dark or consistently white. For example, in the fish image shown in Fig. 5.6(a), part of the profile that bounds the tail and the upper body is made of white edges while the lower body is demarcated from the background by dark lines. In this case if $\mathbf{f}_i^I$ is generated such that the deformable contours are attracted to dark edges then most of the profile in Fig. 5.6(a) can not be captured properly. It is hence useful to constrain certain nodes of the border contours to selected anchor points $\mathbf{c}_i$ in the image (the interface allows the user to interactively place anchor points using the mouse). The constraints prevent the deformable contours from straying far from the anchor points, regardless of the image forces and other mouse forces. This can be achieved by attaching the deformable contour nodes with springs to their corresponding anchor points:

$$\mathbf{f}_i^c = \lambda(\mathbf{c}_i - \mathbf{x}_i)$$

where λ is the spring constant. Using this mechanism we can also effectively deal with images where the profile of the fish is obscure.

The total external force $\mathbf{f}_i$ is therefore obtained by combining the image force $\mathbf{f}_i^I$, the mouse force $\mathbf{f}_i^m$ and the constraint force $\mathbf{f}_i^c$. The deformable contour can then be simulated by integrating the system of ordinary differential equations (A.1) forward through time using an Euler integration method (Press et al., 1986).

Appendix B

Visualization of the Pectoral Motions

The geometric model of a pectoral fin is a five-vertex polygonal surface with one vertex, i.e. the “root”, fixed at a certain control point of the NURBS surface of the display fish model. Let us denote the root vertex as $\mathbf{v}_0$ and the four other vertices, ordered clockwise, as $\mathbf{v}_1$ to $\mathbf{v}_4$ respectively (see Fig. B.1(a)). The visualization problem is then to determine the time-varying trajectories of $\mathbf{v}_i$, $i = 1, 2, 3, 4$. It is reasonable to assume constant lengths of the vectors $\mathbf{v}_{0i}$, $i = 1, 2, 3, 4$ pointing from $\mathbf{v}_0$ to the other vertices. Therefore the control problem becomes that of determining the directions of these vectors over time.

Expressing vectors $\mathbf{v}_{0i}$, $i = 1, 2, 3, 4$, in the fish’s local coordinate system (see Fig. 4.14) simplifies the implementation of the fin motions. Once the new positions of $\mathbf{v}_{0i}$’s are computed in the fish’s local coordinate system, they are transformed back to the world coordinates system for graphics display.

B.1 Animating the Pectoral Flapping Motion

To achieve the flapping motion, let us define displacement vectors $\mathbf{e}_i(t)$ which, when added to $\mathbf{v}_{0i}$, $i = 1, 2, 3, 4$, yield the new directions of $\mathbf{v}_{0i}$. Let the normal of the plane formed by $\mathbf{v}_{01}$ and $\mathbf{v}_{04}$ be a unit vector $\mathbf{v}_n$. The pectoral flapping motions are modeled by simply specifying the direction of the displacement vectors $\mathbf{e}_i(t)$ along $\mathbf{v}_n$ and then letting the lengths of $\mathbf{e}_i(t)$ vary over time in a

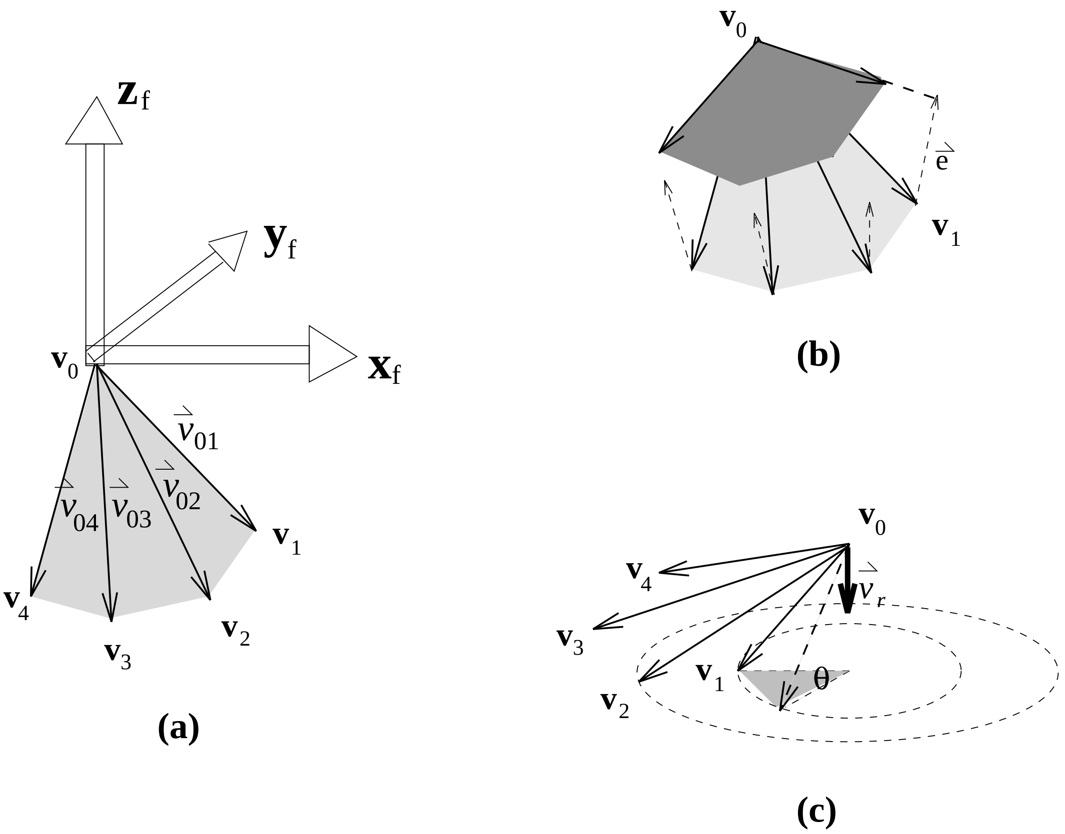

Figure B.1: Visualization of pectoral fin motion.

sinusoidal fashion. In particular, the $\mathbf{e}_i(t)$'s are defined as follows:

$$\begin{aligned}\mathbf{e}_1(t) &= a\sin(bt)\mathbf{v}_n,\\ \mathbf{e}_i(t) &= \frac{\|\ \mathbf{v}_{0i}\ \|}{\|\ \mathbf{v}_{01}\ \|}\mathbf{e}_1(t), \quad i=2,3,4,\end{aligned}$$

where a and b are parameters that define the amplitude and frequency of flapping, respectively; time t is discrete and equals the number of animation frames. Since the $\mathbf{v}_{0i}$'s are not coplanar (they are nearly coplanar), the shape of the fins deform slightly during the flapping motion. This is not undesirable since natural pectoral fins deform constantly due to hydrodynamic forces.

In our implementation, we choose a and b to be nearly proportional to $|\gamma - \pi/2|$ such that the faster the fish needs to ascend or descend, the greater the amplitude and frequency with which the fins flap. Note that a and b are nonzero values when $\gamma = \pi/2$ so the fins are kept in motion even when the fish is not engaged in pitching, yawing, or rolling. Fig. 5.11 shows four snapshots of the flapping motion of the pectoral fins.

B.2 Animating the Pectoral Oaring Motion

The oaring motion of the pectoral fins is most distinguishable in natural fishes with relatively large, flat bodies that do not bend as much when swimming or turning. We capture this visual detail in our artificial butterfly fish and emperor angelfish.

To achieve the oaring motion of the pectoral fins, we let $\mathbf{v}_i,\ i = 1, 2, 3, 4$ rotate about a predefined unit vector $\mathbf{v}_r$ such that each $\mathbf{v}_{0i}$ traces out a cone shape (see Fig. B.1(c)). The rotation is computed using unit quaternions $q = (\cos(\theta/2),\ \sin(\theta/2)\mathbf{v}_r)$, where θ is the rotation angle (Shoemake, 1985). Let the initial $\mathbf{v}_{0i}$, before rotation, be denoted by $\mathbf{v}^o_{0i}$, then we can compute the new $\mathbf{v}_{0i}$ with the formula

$$(0,\ \mathbf{v}_{0i}) = \bar{q}(0,\ \mathbf{v}^o_{0i})q$$

where $\bar{q}$ denotes the conjugate of q. With θ varying from 0 to 2π, each $\mathbf{v}_{0i}$ sweeps a complete cone corresponding to one full stroke of rowing. The speed with which θ changes represents the speed of rowing. We choose $\theta = \beta t$ where parameter β is proportional to the fish's swimming speed $||\mathbf{v}||$ thus the faster the fish swims the faster the fins beat. Note that the above q defines a “forward” oaring motion towards the direction of swimming X_f. To obtain a backward oaring motion, we can simply let $q = (\cos(\theta/2),\ -\sin(\theta/2)\mathbf{v}_r)$.

In our animations, when a butterfly fish or an emperor angelfish turns, one of the pectoral fins rows forward and the other backward as is observed in many natural, flat-body fishes. The backward oaring motions of both fins are useful when an artificial fish brakes and retreats. Fig. 5.12 shows snapshots of a butterfly fish with its forward oaring pectoral fins.

Appendix C

Prior Action Selection Mechanisms

C.1 Behavior Choice Network

Maes (1990; 1991a) proposed a distributed, non-hierarchical mechanism which takes into account both internal and external stimuli in making behavioral choices. The nodes of the network represent behavior units and are connected by special purpose links, such as inhibitory links. The overall behavior of the network is an emergent property of interactions among the nodes, and of interactions between the nodes and the environment. More specifically, activation energy flows from both external sensory readings and internal motivations to different behavioral components. Different components use the links of the network to excite and inhibit each other. After some time, the activation energy accumulates in the component that represents the "best" choice, which is taken as the winner, given the current situation and motivational state of an agent. This mechanism was originally used, and proven successful, in solving relatively simple problems in a traditional AI setting (i.e. blocks world), such as choosing actions in a correct sequence so as to sand a board or spray paint a block (Maes, 1990). By incorporating some biological aspects into the mechanism, it is able to deal with more complex action selection problems (Maes, 1991a).

The main advantages of Maes' action selection mechanism are: first, the activation energy is a continuous flow which allows smooth transition from behavior to behavior; second, it is more flexible and reactive as opposed to being centrally controlled; finally, the distributed structure makes the action selection process more robust.

Some limitations have also been pointed out by Maes herself and others (Sahota, 1994; Blumberg, 1994). For example, it is not clear how to achieve global functionality using this mechanism and careful tuning of parameters is needed. However, this is common to practically all distributed architectures and is not unique to this work. Also, since sensory inputs of each node are in the form of binary predicates, potentially useful information may be discarded. Moreover, Tyrrell (1993a) has made a critical investigation of the strictly non-hierarchical and distributed computational structure used by Maes. It is believed that the underlying structure for action selection, as suggested by ethologists, is intrinsically hierarchical, rather than "flatly" distributed. It is argued that some of the computational deficiencies due to the non-hierarchical structure of Maes' mechanism indicate that it is not well able to deal with animal-like action selection problems (Tyrrell, 1993a).

C.2 Free-Flow Hierarchy

In order to allow the combining of evidence from different behavioral candidates and the selection of compromised actions, roboticists Rosenblatt and Payton (Rosenblatt and Payton, 1989) proposed an alternative action selection process. In their mechanism, all behavior nodes express *preferences* for each of a set of motor actions, rather than making a decision as to which is the most suitable. The final choice is a weighted sum of all the preferences. This method was later extended by Tyrrell (1993b) to form what is known as *free-flow* hierarchies. A free-flow hierarchy implements Rosenblatt and Payton's selection process within a hierarchical action selection architecture like that of Tinbergen (1951). All nodes in the hierarchy can influence the subsequent behavior of the agent. Activities express weighted preferences for activities lower in the hierarchy. This process propagates throughout the whole hierarchy, and as a result, instead of making a decision at each layer, a decision is only made at the lowest (i.e. action) level when the most highly preferred motor action is chosen.

Simulation results (Tyrrell, 1993a) show that the free-flow hierarchy outperforms Maes' mechanism and several other mechanisms. However, as Blumberg (1994) points out, the relatively better performance of free-flow hierarchies may be gained at the expense of high complexity and low efficiency. This is because no focus of attention is employed in a free-flow hierarchy, and preferences need to be carefully weighted. In particular, real-time solutions may not be possible since decisions can only be made after all sensory information is processed and preferences from all components are calculated. Furthermore, all hierarchical structures suffer from a lack of flexibility in the sense that connections between components, i.e. precedences, cannot be easily altered. Free-flow hierarchies are no exception.

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Appendix D

Color Images