Modelling Fish Behaviour

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Binh Pham
Queensland University of Technology

Aster Wardhani
NanoString Technologies, Inc.

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Kingsley Stephens, Binh Pham and Aster Wardhani,
School of Software Engineering and Data Communications,
Queensland University of Technology,
2 George St, Brisbane QLD 4001
email: {k1.stephens@student, b.pham@, a.wardhani@}qut.edu.au

Abstract

This paper studies the problem of creating artificial fish for real-time interactive virtual worlds aimed at desktop environments with hardware 3D support. The artificial fish developed have the ability to move, sense, and think. Each fish is modelled with a Keyframed skeletal animated body, semi-physics based movement model, sensory abilities, internal motivations, a set of behaviour routines, and a behavioural selection mechanism. These features allow the fish to act autonomously using behavioural rules in response to sensory input from the environment and other fish. This autonomous ability enables definite behaviours to be described and observed in the fish that are not simply random, cyclic, or scripted.

Excellent work has been previously done on modelling sophisticated artificial fish. The contribution of this paper is to focus on the practical modelling of fish for game production.

CR Categories: I.3.7 (Computer Graphics): Three-Dimensional Graphics and Realism – Animation

Keywords: modeling techniques, autonomous characters, behavioural animation, schooling, fish, artificial life

1 Introduction

Artificial fish are a type of a*utonomous character* which are in turn a form of *autonomous agent* designed for use in computer animation and interactive media such as computer games. The agent represents a character in a story or game that has the ability to determine its own actions rather than being scripted or controlled by a human. These agents are also referred to as *synthetic characters*, *intelligent virtual agents,* or simply *characters*.

The original artificial fish were created by Terzopoulos and Tu [Tu 1996] and contain a dynamic biomechanical muscular movement model, photo-realistic texture mapping, accurate sensory abilities, a model of desires, and a decision tree based action selection mechanism. With the following development of the ALife movement [Terzopoulos 1999] there has been the production of a variety of sophisticated fish, rays, and sharks [Frohlich 2000; Tu 1996; Yu 1998] as well as dolphins [Grzeszczuk and Terzopoulos 1995; Sepulveda et al. 1999]. These systems have primarily been designed to run in big installations on high-end graphics machines.

Animation approaches have been varied and range from Keyframing [Frohlich 2000] through to fully dynamic muscular models [Tu 1996].

Current behavioural systems focus on either advanced development of the animation or artificial intelligence aspects, but do not seem to emphasise both simplicity and efficiency in both. They also tend to suffer from excessive coupling between modules [Barros et al. 2002]. In the world of autonomous fish, Tu [Tu 1996] has modelled a sophisticated ethological inspired behavioural system while Sepulveda [Sepulveda et al. 1999] has modelling emotional characteristics of dolphins in an installation offering a limited form of user interaction. A prominent contributor to the autonomous character movement has been Blumberg and his involvement with the MIT Synthetic Characters Lab. Their most recent development has been a comprehensive generalised behavioural based architecture [Burke et al. 2001].

The work produced most similar to our goals was Reynold's production of large numbers of pigeons reacting to the interactive presence of a user [Reynolds 2000]. This work combined large numbers of autonomous birds with simple behavioural models interacting with the user and each other in real-time.

2 Fish

When studying real fish we are concerned with the aspects of locomotion, sensory ability, and behaviour.

2.1 Locomotion

Fish locomotion is classified on what parts of the body move, and whether the body or fins undulate or oscillate. Three undulatory forms of swimming found in common fish species are *anguilliform*, *carangiform*, and *subcarangiform*.

Anguilliform swimming occurs in fish with long, thin, and flexible bodies such as eels and sharks. Apart from the head the entire undulation of the body contributes to the propulsive force.

Carangiform swimming occurs in fish with fusiform bodies and narrow tails such as herrings, mackerels, and tuna. In this form the posterior portion of the body and tail undulate with the amplitude largest at the end of the tail.

Subcarangiform swimming is intermediate between anguilliform and carangiform and occurs in fish with fusiform bodies such as trout and cod. In this mode up to two-thirds of the fishes body undulates with the amplitude increasing rapidly and becoming wide over the posterior one-half to one-third end of the body.

2.2 Sense

Fish have many sensory abilities from which the most common three are, mechanoreception (hearing), vision, and chemoreception (smell and taste) [Helfman 1999].

Mechanoreception is involved with the detection of movement in the water around the fish. The two major mechanoreception systems are the inner ear and the lateral line. The inner ear is responsible for equilibrium, balance, and hearing. Sharks in particular are highly sensitive to low-frequency pulsed sounds such as those emitted by erratically swimming or injured fish with a range of up to 250 m. The lateral line system runs the length of the fishes body and allows the detection of vibrations in the water that originate from or reflect off prey, predators, other schooling fish, or obstacles. The effective range is around 32 m.

Fish eyes are similar to those of all vertebrates including humans but are more varied due to the large variety of underwater lighting conditions. In waters such as rivers or lakes vision is only useful for around 1-2 m, while in oceanic waters the limit is around 30 m.

Fish rely greatly on their sense of smell and taste to detect chemical clues in the water. Smell is mainly used in the location of food and mates. Sharks are particularly known to be able to follow a long scent trail in the pursuit of prey. Tastebuds operate in a similar fashion to smell and are mainly used for the detection of food.

2.3 Behaviour

Fish may act as predators, prey, or social animals. As predators, fish hunt for prey. As prey, fish attempt to avoid detection, evade pursuit, and prevent attack from predators. In a social context fish mate, act as parents, communicate, compete for dominance, and form groups.

Predators

The predation cycle involves the searching, pursuing, attacking, capturing, and handling of prey (see [Helfman 1999] for an overview). Often the distinction between the phases is blurred, eg attack and capture could occur simultaneously.

Searching can be active or passive. Active search utilises locomotion while using sensory abilities to detect prey. Passive search is lying in wait for prey while camouflaged or hidden. Pursuit may use superior speed to overtake prey or deceptive tactics such as lures or camouflage to get in close. Attack and capture occurs when the predator lunges at the prey and takes it into its mouth. Taking the fish into its mouth may occur by suction or impaling of prey on its teeth.

A large challenge for predators is attacking schools of fish. The larger the number of fish the greater chance there is that the predator will become “confused” by the multitude of similar appearing fish and not know which one to target. Typically predators attack a school and then focus on the individual fish that become separated from the rest of the group. In general, oddity of appearance of a fish in a school stimulates attack.

Handling occurs after the prey has been captured and involves the manipulation required to make the prey ingestible such as removal of poisonous spines.

Prey

Prey tactics aim to break each phase of the predation cycle to avoid being eaten. This involves avoiding detection, early predator detection, evading pursuit, preventing or deflecting attack and capture, discouraging of handling, and ultimately escaping from the predator.

To avoid detection a fish can use camouflage to either disappear into the surroundings or appear to be an inedible object. To appear invisible a fish can use countershading or transparency. Countershaded fishes grade from dark on top to light on bottom. When viewed in the water column the dark top absorbs the strong light from above and the lighter bottom reflects the weak light from below. The effect is to eliminate the contrast between the fish and its background.

Early detection of a predator removes its element of surprise. This can be achieved by hiding in shadows or moving with other fish in a group. When seeing a predator schooling fish will decrease their distances from each other and their movements become more synchronised. A behaviour known as “mobbing” occurs when prey fish act aggressively towards a predator in order to inform the predator that it has lost the element of surprise and to notify other fish in the area of its presence.

Evading pursuit involves appearing to be inedible, finding shelter, outdistancing or outmanoeuvring the predator, or disappearing into the background. To discourage being eating certain fish contain spines that can be poisonous, or posses toxic chemicals in their skin or organs such as fugu puffer fish. These fish generally have clear markings that indicate their toxicity. When fish are close to the bottom structure they can take shelter in coral, sand, or vegetation. In open water prey fish can either be highly manoeuvrable or have the ability to increase their speed by becoming airborne - flying fish can double their speed after jumping out of the water.

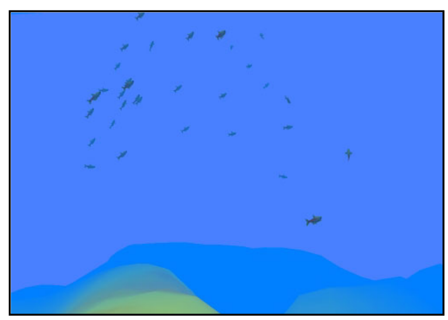


Figure 1 Schooling Fish

When attacked a fish can either make a quick evasive move, use an active defence, or rely on structural defences. Almost all fish posses the ability to make rapid, fast-start escape movements that lead to maximal acceleration away from an attacking predator.

The response of a shoal or school under attack varies with intensity of the predator attack. Groups of fish generally avoid a slowly moving predator by creating a vacuole around the predator as it moves through the group. In more active attacks the school expands rapidly out from the point of attack, scattering in different directions and fleeing the scene or seeking refuge. Various fish use different techniques while in a group to increase the size of the confusion effect in the predator when it is faced with a large number of edible objects in view. Fish will choose to join the larger of two schools when given the opportunity.

To discourage capture and eating certain fish become larger in size and enhance body armour to make it difficult for the predator to take the prey into its mouth and swallow it.

Social Animals

Social behaviour in fish includes courtship and spawning, parental care, territorial behaviour, communication, shoaling and schooling, parasitism, and mutual relationships. In this paper we focus on predator-prey relationships and will only look at the schooling aspect of social behaviour.

Fish generally shoal in an random manner when foraging and spawning. At the approach of a predator the shoal becomes directed and moves as a single school from which point anti-predatory tactics are used.

3 Behavioural Model

The fish behavioural model incorporates sets of motivations and behaviours that together define particular species of fish. We define a fish species as a specific configuration of motivations and behaviours. This section will first define the different motivations, then the set of behaviours available, and finally use subsets of motivations and behaviours to define two different species of fish.

3.1 Fish Motivation

The following motivations of hunger and fear allow the specification of predator and prey style behaviour.

Hunger is a model of a fish's energy level, appetite, and digestion rate. This is a measure of how much food a fish has eaten, how much food a fish needs to eat, and also the time between meals. For example by altering these parameters a predator fish can be made to appear greedy by constantly being on the hunt for large amounts of food.

Fear is a model of the perceived threat from the behaviour, closeness, and number of predators. For example a tasty looking prey fish can be set to be only mildly worried about the presence of predators that are idly swimming and not looking for food, or it can be made to be very worried about the presence of multiple predators on the hunt for food.

3.2 Fish Behaviour

The following behaviours define what a fish can do with respect to the world and other fish. The behaviours chosen allow the description of predator/prey interactions.

Wander randomly swims around the world either without purpose or while searching for food.

School occurs in the presence of fish of the same species and allows them to swim together as a group.

Hunt occurs when a predator becomes hungry and finds prey. It involves the hunting and eating of fish until the predator's hunger has been satisfied.

Flee occurs when a fish becomes scared of a direct predatory threat and allows it to rapidly move away from the predator.

3.3 Fish Species

Different species of fish contain different combinations of motivations and behaviours. We loosely use this term to refer to the two classes of fish to be implemented: *fish*, and *sharks*.

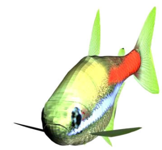


Figure 2a Neon Tetra

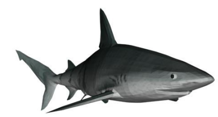


Figure 2b Bull shark

Fish represent the classic prey fish in that they simply exist to be eaten. They contain the *fear* motivation to let them know when they are in the presence of a predator. When they are not using the *flee* behaviour to escape from predators they like to hang around other fish using the *school* behaviour, or in the absence of other mates use *wander* to endlessly roam the world alone. The Neon Tetra (figure 2a) is a colourful and popular schooling fish.

Sharks are the nemesis of the fish in that they are the classic predators. They use the *wander* behaviour to tirelessly roam the world in search of prey. When their high *hunger* motivation tells them its time to eat they use the *hunt* behaviour to chase and eat the first tasty looking prey fish they come across. The Bull shark (figure 2b) is a particularly aggressive ocean going predator that also frequents fresh water rivers.

4 Design Framework

The architecture in figure 3 defines and connects the modules used for the sense-think-act paradigm. The architecture was inspired by C4 [Burke et al. 2001] and is designed to be modular and extensible. The three high-level modules to be implemented are *perception*, *mind*, and *body* that correspond to sensing, thinking, and acting respectively.

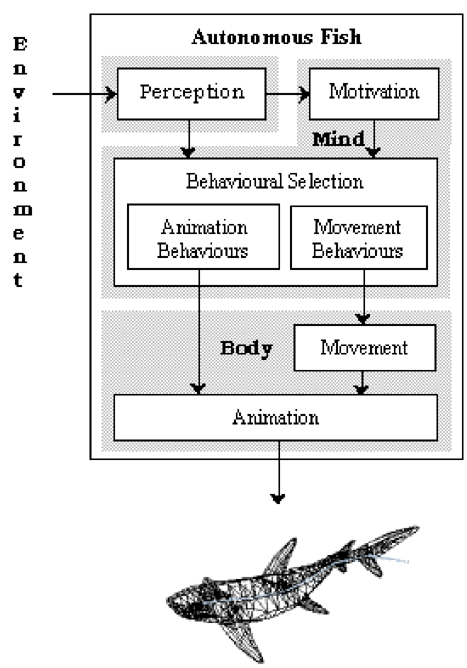


Figure 3 Fish Architecture

The *perception* module is the interface to the world model that allows a fish to see the world and the other fish around them.

The mind module contains a *motivation* model to maintain the fish's particular motivations and a *behavioural selection* mechanism to make behavioural choices based on both motivational and sensory data. The selected behaviour may be either an *animation behaviour* or a *movement behaviour*. Animation behaviours are simply animations that do not affect movement, while movement behaviours update the position of the fish in the world that in turn affects animation.

The body module contains a *movement* model to move the fish around the world and an *animation* component to display the fish's swimming motions or behavioural animations.

The design of each of the different modules will be discussed in the following sections.

5 Fish Animation and Movement

The animation model determines how the fish look as they move and behave in the environment. The method chosen to animate the fish is to use current skeletal animation and "skinning" techniques. To animate a fish in this manner firstly requires attaching a skeleton to a texture mapped fish mesh, and secondly describing the movement of the skeleton for swimming and behavioural animations.

5.1 Construction of Skeletal Fish Mesh

The process of mapping a skeleton onto a texture mapped fish mesh involves the import of a suitable fish mesh into a 3D modelling tool, mesh texture mapping, and the creation and attachment of a skeleton to the mesh.

High quality fish meshes can be freely obtained from [*Toucan Corporation* 2002] for non-commercial use. The meshes are imported into a modelling tool and texture mapped using the accompanying image maps.

The skeletal model for our fish is a variation of that developed in [Gates 2001] and consists of a backbone running the length of the fish body that is used to describe both swimming motion and turning. A two-dimensional body coordinate system is used with the origin at the root bone and the resting skeleton lying on the positive x-axis.

The skeleton consists of n bone segments of equal length l with each bone segment i=**1..**n having a joint rotational angle θ_i in the xy plane. The position x of each joint along the backbone is determined by $x = il$. The choice of number of bones required depends on the size and shape of the mesh and the quality of the deformations required.

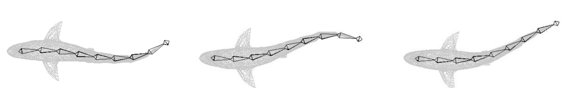


Figure 4 Skeletal fish animation

Mapping the skeleton to the outlying mesh requires specifying the influence region of each bone on the vertices of the mesh. Figure 4 shows the skeleton deforming a shark mesh.

5.2 Animation of Fish Swimming

The method of describing the swimming motion of fish is adopted from [Gates 2001; Tu 1996]. In this method the muscular contractions observed in fish while swimming are emulated using the following travelling sine wave:

$$\mathbf{F}(\mathbf{x},\mathbf{t}) = \mathbf{A}(\mathbf{x})\ \mathbf{Sin}\left(\frac{2\pi}{\lambda}(\mathbf{x}-\omega\mathbf{t})\right)$$

$$\theta_i = \tan^{-1}\left(\frac{\partial \mathbf{F}}{\partial \mathbf{x}}(\mathbf{x},\mathbf{t})\right)$$

where

x is position in local coordinates along backbone,
t is time,
θi is size of bone joint angle i,
λ is wavelength,
ω is frequency,
$A(x)$ is the amplitude at position x defined linearly by
$(x\ /\ nl)\ *\ maxAmplitude$ to emulate propagation of strength along the length of the fish's body.

The different forms of swimming motion discussed in 2.1 can be achieved by varying the wave's amplitude, frequency, and wavelength. Figures 4 shows Keyframes of a fish swimming.

A 3D modelling tool is used to map the sine wave to the backbone with forward kinematics. A script in the modelling tool alters the joint angles over time and allows adjustment of the sine wave parameters. Keyframes are taken of the resulting animation and a clean swimming animation loop isolated.

5.3 Movement Model

The movement of the fish is modelled around an underlying point mass as discussed by Reynolds [Reynolds 1999, 2000]. The point mass describes the fish's orientation, position, velocity, and acceleration. The skeletal animations are mapped onto the point mass and adjusted according to its movements.

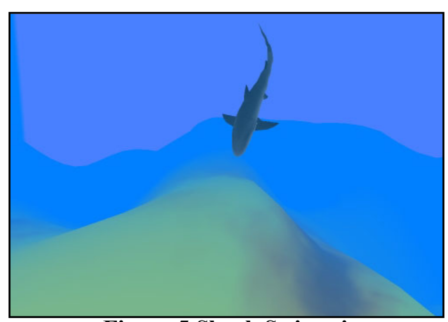


Figure 5 Shark Swimming

A point mass is a semi-physics model in that the point has mass and can have forces applied to it to produce directional and velocity changes, but it has no momentum. Reynolds refers to the movement forces as *steering forces*. These forces can produce changes in orientation or acceleration to affect speed and heading. There are limits on the maximum force that can be applied and on maximum speed.

The speed and orientation of the point mass is used by the animation module to choose the appropriate pre-defined animation to play and to suitably adjust the animation speed.

6 Perception

The perceptual model implements simple vision that enables the fish to observe its environment. The model incorporates vision with sensory honesty to see other fish and collision detection to determine collisions with terrain and other fish.

6.1 Vision

The vision model combines all of the fish's senses as discussed in 2.2 into a single simplified perception model. The fish "sees" by having direct access to the world model from which it can retrieve the absolute position of every other fish in the virtual world. This super-natural sensing ability is limited with a visual field of view to ensure sensory honesty. This method has complexity O(n) but can be optimised through the use of localisation techniques. Within the field of view other fish, terrain, and world bounds are visible.

6.2 Collision Detection

Collision detection and prediction is used to determine actual and potential collisions with other fish and the environment. Bounding spheres centred on the point mass and encompassing the fish mesh are used to perform collision testing. Collision tests are performed with other fish and environmental aspects such as terrain and world bounds. Collision detection only tests for collisions in the next velocity increment, while collision prediction extends this trajectory to the extent of the fish's vision to test for future possible collisions.

Testing collisions with the bounding box around the world is a matter of sphere/plane intersection tests. Collisions with the terrain are determined by level of terrain height collision tests. Testing collisions between fish is a matter of performing sphere intersection tests and is simply achieved by subtracting the size of the two sphere radii from the distance between the fish.

7 Mental Model

The mind of the fish is responsible for choosing a behaviour to perform based on internal motivations and external sensory information. This section describes the internal motivational model, behaviour routines, and the behavioural selection mechanism used to choose between competing behaviours.

7.1 Motivational Model

The motivational model is responsible for describing the characters motivations described in Section 3.1.1. The model used is partially adopted from Tu [Tu 1996] and models each motivation as a continuous variable in the range [0..1] where 0 indicates the absence of a motivation and 1 the extreme presence of a motivation. These values vary with time and the changing states of the internal and external environments. For example, the weight of hunger increases over time as food is digested, and decreases in fixed values with acts of eating. Hunger is modelled on a decay and topup model, while fear is based on the proximity and number of predatory threats.

Hunger is updated at every time step where the current food level is decremented by the digestion rate and topped up if food was eaten. The hunger value is calculated as simply being the proportion of food in the fish's stomach. This algorithm is as follows:

```
at each time step
    fl = d*t*fl                       // food decay
    if fishEaten
        fl = truncate(fl + f, a)      // topup limited to appetite
        hunger = 1.0 - fl / a         // update hunger value
```

where
d is digestRate $0 < d < 1$,
a is appetite,
t is time increment,
f is food value of eaten fish,
fl is current food level in fish's stomach.

The size of *digestRate* determines how ravenous the fish are, while fish of different sizes can be given suitably sized *appetites*.

Fear shown in the following equation is modelled based on the number, closeness, and behaviour of predators.

fear = min [∑i comfortZone / PredDistance(i), 1]

where
∑i sums the fear value of all predators in perceptual range,
comfortZone is the distance within which a prey fish feels threatened by a predator. This distance is greater if a predator is currently feeding,
PredDistance(i) is the distance to predator i.

The value of *comfortZone* can be modified to determine how complacent or skittish the fish are.

7.2 Behaviour Routines

The behavioural routines are the actions the fish can perform in the virtual world. The behavioural model is based on the classes of fish discussed in section 3.3. The behaviours may affect either movement, animation, or both. The behaviour routines are largely adapted from Reynolds "steering behaviours" [Reynolds 1999] in that directed movements are generated from applying specific steering forces to the movement model. Multiple forces may be acting on a fish at any one time as shown in figure 6. The resulting force is the sum of the composite forces where each force has an associated weighting value.

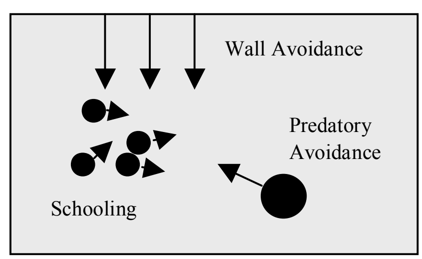


Figure 6 Forces acting on a fish

In addition to the higher level behaviours already defined in 3.2, we also require the additional lower level behaviour of *avoid obstacle*. The implementation of each behaviour will now be discussed.

Avoid obstacle is used to avoid collisions with static objects and other fish. Obstacle avoidance is not a distinct behaviour as such, but rather a continuous source of force pushing the fish away from collisions. This collision avoidance force is generated by other fish, the terrain, and the world bounding walls, and is added to the other behavioural forces with a set weighting.

Wander produces casual random steering around the environment. It sets the fish swimming at a steady rate and intermittently sends random turn commands to the steering controller. These commands combined with obstacle avoidance are sufficient to produce a fish that can idly roam around the virtual world.

To generate the steering commands we use the method devised by Reynolds [Reynolds 1999] which models a sphere placed in front of the fish that limits the changes in steering force updates. This sphere models the full range of steering movement while another smaller sphere regulates the size of the random update to the existing wander force.

To generate a wandering force at each time step:

- increment the wander steering force in a random direction constrained to a small sphere
- constrain the force generated to a large sphere in front of the fish

Hunt occurs when a fish's hunger motivation reaches the hunger threshold. This behaviour will pursue and eat nearby prey until the predator is full again, ie hunger becomes zero. This model allows the emergence of a "feeding frenzy" in which a predator will continue feeding until it is satiated.

To catch the prey, hunt implements moving target pursuit. When the shark collides with the fish feeding occurs, the fish is removed from the world, and the shark's hunger motivation is updated with the food value of the fish. The hunt behaviour generates a steering force to steer the predator towards the future position of the prey based on how close it is. The force produced is displayed in figure 7 with the calculation as follows:

hunt point p' = p + r*d*v

where
p' is the prey's predicted position,
p is the prey's current point,
v is preys current velocity,
d is the distance between them,
r is a ratio of distance

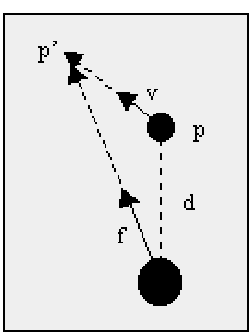


Figure 7 Moving target pursuit where p' is predicted prey position, p is current prey position, v is prey velocity, d is distance, and f is hunt force

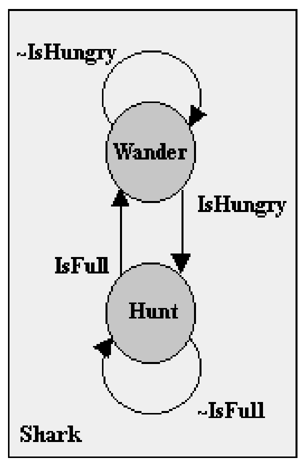
Flee is an escape mechanism for prey fish and generates a steering force based on the position and orientation of a predator that enables a fish to move away in the opposite direction at high speed. Flee negates the force produced by *hunting* the predator. This enables the prey to move away from the predicted position of the predator.

School defines classic group behaviour using the rules described in [Reynolds 1987] of alignment, cohesion, and separation. Cohesion steers towards the average position of the group, separation steers away from the centre of the group, and alignment steers towards the average group velocity. The weighted summation of the forces generated from these rules enables the emergence of group behaviour. Adjusting the weights can produced different school configurations, eg set separation force low to have a tightly packed school, or set alignment force to low for a school that acts more like it is shoaling.

7.3 Behavioural Selection

The behavioural selection mechanism chooses the behaviour to invoke based on information from the motivational model and the external environment. Only one behaviour is active at any one time and the possible transitions to other behaviours are a subset of all possible behaviours. The method used to model this mechanism is a state machine.

The state machines model each behaviour as a separate state and defines the predicates *IsHungry*, *IsScared*, and *IsFull* to allow transitions between states. The predicates access the relevant internal variable and define a motivation value of 0 as *false* and 1 as *true*. This model is sufficient to select between the limited number of behaviours implemented and the nature of the state machine enables a natural hierarchy of priorities for behaviours and motivations. For example, a fish's fear leads to a higher priority on fleeing from a predator than satisfying hunger.



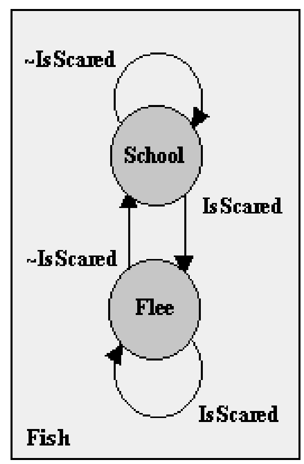


Figure 8a Shark States **Figure 8b Fish States**

To simplify the design of the state machines collision detection is treated as a special state. Unlike other behaviours it is able to run concurrently with a desired behaviour at a specific priority based on the immanency of the collision. For example, while schooling the propulsive force from a close bounding wall will cause the fish to school away from the wall.

Each species of fish requires its own state machine. Figure 8a shows the state machine for the shark and 8b shows the fish state machine.

8 Implementation

The system was developed using Visual C++ 6.0 using the Auran Jet [1] version RC1 game development platform with 3DSMax 4.0 and Maxscript used for 3D modelling and animation.

The production process involved modelling and animating the fish in 3DSMax, exporting the resulting animations and meshes to Jet format, and then loading the assets into the game engine.

The development and test machine was an Athlon 1100 with 512Mb of RAM and a GeForce2 MX graphics accelerator running Windows ME. On this platform smooth results without optimisation techniques were achieved with up to 50 fish.

When running the virtual world the user has two modes of control over the camera. The first mode is free movement that allows the user to move at will around the world. The second mode is follow view in which the camera tracks behind a specified fish.

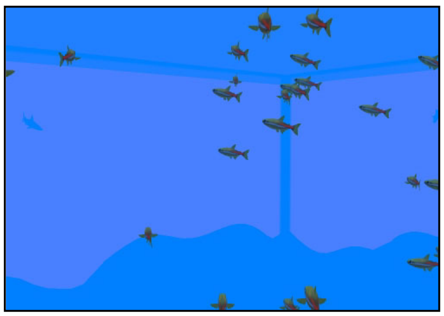


Figure 9 Follow fish view

The major limitations to the implementation are performance problems due to lack of optimisation techniques. Specifically there is no level-of-detail mesh reduction used on the fish, and the sensory lookup has an O(n) complexity and does not utilise optimal timing. The number of maximum fish in the world could be significantly increased with additional optimisation.

9 Results and Evaluation

This section qualitatively evaluates the resulting animation, behaviours, and the general production process for creating artificial fish. Suggestions are made for addressing the limitations identified.

9.1 Fish Animation and Movement

The fish swimming animation is realistic and the movement is suitably smooth. Only basic fish swimming was implemented. Additional swimming animations would be to include turning animations when the fish makes a sudden change in direction, and gliding animations for when the sharks are wandering. The current animation to run would be chosen based on the state of the movement model.

The movement model produces suitably smooth movements. When adding new behaviours to the system it is necessary to tweak the weights of the forces generated by each behaviour so as to achieve a suitable balance between the competing forces.

9.2 Fish Behaviour and Interaction

The simple behavioural system is effective in producing a dynamic marine environment in which powerful sharks pursue schooling prey fish. The sharks idly wander until they become hungry and then increase speed when seeing a fish. When the shark gets close to the school, the fish scatter in an attempt to avoid the shark. The shark targets a fish and a chase ensures until the fish is eaten or the shark changes to a different target. Meanwhile the other fish have since re-grouped and moved away from the shark.

Unfortunately due to time constraints only a small number of fish species and behaviours were implemented. However in terms of fish interaction it is apparent that only a small number of behaviours are required to achieve interesting results. More dynamic results could be achieved by the addition of an animal such as a dolphin that could act both as predator and prey. This animal would have both fear and hunger motivations, the full range of current behaviours, and also posses extra behaviours such as predator mobbing and social interaction.

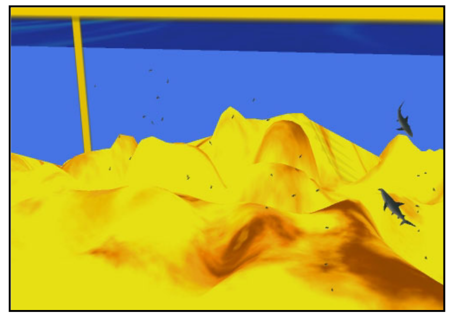


Figure 10 Fish scattering from sharks

9.3 Production Process

The methodology has proven effective for creating different varieties of fish. The benefit of our approach is that arbitrary fish meshes can be mapped to the movement model. The quality of the animation and movement can be improved with a "good eye" by adjusting a small number of animation parameters and movement weights. To create new behaviours it is possible to combine lower level steering routines to achieve higher order behaviours, eg flee + school = fleeing school!

Overall the methodology produced is simple, modular, and practical. Certainly a different action selection mechanism could be used if required, or a new sensory ability added to the fish. The approach allows a variety of fish (and conceivably other animals such as snakes and worms) to be animated and given distinct behaviours.

10 Conclusions and Future Work

This paper has looked at the problem of describing fish behaviour in an interactive real-time setting. The goal was to produce fish that could act individually based on their own motivations and view of the world. The aim was to develop these fish for real-time environments on desktop machines with the overriding theme for development of practical simplicity and efficiency.

Behavioural modelled fish consist of an appearance and movement model utilising pre-defined animations, and contain a state machine for choosing behaviours based on sensory and motivational data. It was found that movement models previously used for birds mapped equally well to describing fish behaviour. Keyframed animation of fish swimming was easily created and applied to the movement model. Complex behaviours were easily created through the steering behaviour paradigm with state machines proving to be effective action selection mechanisms using sensory and motivational data.

In our approach we utilised ideas from highly sophisticated fish productions and implemented them in a more simplified environment using a commercial grade game engine. The results produced effective animation, movement, and behaviour for large numbers of fish in a real-time setting.

This work forms a solid foundation for further improvement in the complexity and accuracy of the animation and behaviours. To incorporate higher order functionality an advanced framework such as [Burke et al. 2001] is required. Possible movement extensions are in the development of hydrodynamic movement models [Gates 2001; Tu 1996], fully dynamic movement models based on muscular modelling [Tu 1996], or locomotion training [Grzeszczuk and Terzopoulos 1995] so the animal can learn the most efficient way to move.

Possible extensions to the behavioural model are the inclusion of learning, emotion, and evolutionary models (see [Aylett and Cavazza 2001; Isla and Blumberg 2002] for an overview). However, the current trend in artificial animal research is ascribing them with goal based reasoning abilities, otherwise know as the field of "cognitive modelling" (see [Zhao 2001] for a review). Cognitive models are able to co-exist with behavioural models [Funge 2000]. In these hybrid models the behavioural model handles low-level behaviours such as avoid obstacle and schooling, while the cognitive model is responsible for reasoning about the possible affects of actions and formulating plans.

References

AYLETT, R., AND CAVAZZA, M. 2001. *Intelligent Virtual Environments - A State-of-the-art Report.* Paper presented at the Eurographics, Manchester, United Kingdom.

BARROS, L., EVERS, T., AND MUSSE, S. 2002. A Framework to Investigate Behavioural Models, *Conference Proceedings, WSCG'02* Plzen - Bory, Czech Republic.

BURKE, R., ISLA, D., DOWNIE, M., IVANOV, Y., AND BLUMBERG, B. 2001. CreatureSmarts: The Art and Architecture of a Virtual Brain. *Proceedings of the Game Developers Conference, San Jose, CA*, 147-166.

FROHLICH, T. 2000. The Virtual Oceanarium. *Communications of the ACM, 43,* 7, 95-101.

FUNGE, J. 2000. Cognitive modeling for games and animation. *Communications of the ACM, 43,* 7, 40-48.

GATES, W. F. 2001. *Animation of Fish Swimming* (Technical report): Department of Computer Science, University of British Columbia.

GRZESZCZUK, R., AND TERZOPOULOS, D. 1995. Automated learning of muscle-actuated locomotion through control abstraction, *Proceedings of SIGGRAPH 95*: ACM Press / ACM SIGGRAPH. 63-70.

HELFMAN, G. S. 1999. *The Diversity of Fishes* (3rd ed.): Blackwell Science.

ISLA, D., AND BLUMBERG, B. 2002. *New Challenges for Character-Based AI for Games.* Paper presented at the AAAI Spring Symposium on AI and Interactive Entertainment, Palo Alto, CA.

REYNOLDS, C. 1987. Flocks, Herds, and Schools: A Distributed Behavioral Model, *Computer Graphics (Proceedings of ACM SIGGRAPH 87)*: ACM Press / ACM SIGGRAPH.

REYNOLDS, C. 1999. *Steering Behaviors For Autonomous Characters.* Paper presented at the Game Developers Conference 1999, San Jose, California.

REYNOLDS, C. 2000. Interaction with Groups of Autonomous Characters, *Game Developers Conference 2000*: CMP Game Media Group. 449-460.

SEPULVEDA, T., MARTINHO, C., PROENA, J., AND GOMES, M. R. 1999. Emotional Characters In Virtual Environments. In V. Skala (Ed.), *Conference Proceedings, WSCG'99*: Univ.of West Bohemia Press.

TERZOPOULOS, D. 1999. Artificial life for computer graphics. *Communications of the ACM, 42,* 8, 32-42.

TOUCAN CORPORATION. 2002. Available: http://www.toucan.co.jp/.

TU, X. 1996. *Artificial Animals for Computer Animation: Biomechanics, Locomotion, Perception, and Behavior.* Phd thesis, University of Toronto.

YU, Q. 1998. *Synthetic Motion Capture for Interactive Virtual Worlds.* M Sc thesis, University of Toronto.

ZHAO, L. 2001. *Cognitive Modeling for Computer Animation: A Comparative Review* (Technical Report): Computer and Information Department, University of Pennsylvania.