Animating Multiple Escape Maneuvers for a School of Fish

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Abstract

A school of fish exhibit a variety of distinctive maneuvers to escape from predators. For example, they adopt avoid, compact, and inspection maneuvers when predators are nearby, use skitter or fast avoid maneuvers when predators chase them, or exhibit fountain, split, and flash maneuvers when predators attack them. Although these escape maneuvers have long been studied in biology and ecology, they have not been sufficiently modeled in computer graphics. Previous works on fish animation only provided simple escape behavior, lacking variety. The classic boids models do not include escape behavior. In this paper, we propose a behavioral model to simulate a variety of fish escape behavior in reaction to a single predator. Based on biological studies, our model can simulate common escape maneuvers such as compact, inspection, avoid, fountain, and flash. We demonstrate our results with simulations of predator attacks.

Keywords: 3D animation, Behavior animation, Fish schooling behavior, Fish escape maneuvers.

Index Terms: I.3.7 [COMPUTER GRAPHICS]:Three-Dimensional Graphics and Realism - Animation;

1 Introduction

Fish school is one of the best examples of collective animal behavior and has been studied extensively in marine biology and ecology [1, 2, 3]. One of the main reasons for fish to school is to better defend themselves against predators, and they adopt different escape maneuvers to confuse and evade their predators [4, 5, 6, 7, 8].

Fish and fish schooling behavior has been simulated in computer graphics [9, 10, 11, 12, 13, 14]. Most previous works focus on simulating individual fish motion [10, 12] and adopt Reynold's boids model [9] for schooling behavior. However, Reynold's model and its various extensions [9, 15] do not include escape behavior, except for the obstacle avoidance [16] rules, which may be used to generate the "avoid" maneuver. But the other escape maneuvers exhibited by a school of fish cannot be easily generated by the existing flocking models.

In this paper, we propose a fish school behavior model to simulate more diverse and biologically more realistic escape behavior. The current model can simulate five escape maneuvers: compact, inspection, avoid, fountain, and flash. At the core of our behavior model is a set of state machines that are based on the biological observations of fish school escape behavior [17, 18, 19, 20, 21, 22].

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2 Background and Related Work

2.1 Biological research on fish school escape behavior

There has been a lot of research on fish school escape behavior in biology and ecology [4, 6, 8, 17, 19, 20, 21, 22]. Here we briefly introduce the biological foundation of our work. Our model does not distinguish different species of fish and we draw from different biological studies to build our escape behavior model.

Pitcher and Wyche [17] identified eight fish school evasive maneuvers: herd, avoid, flash expansion, fountain, split, vacuole, hourglass, and cruise. Magurran and Pitcher [21] identified additional maneuvers such as compact, inspection, and skitter.

Our current model can simulate five common escape maneuvers: compact, inspection, avoid, fountain, and flash. Our behavioral model for the compact, inspection, and avoid maneuvers are largely based on the biological research by Magurran [22] and Magurran and Pitcher [21]. Our fountain maneuver behavioral model is based on the model proposed by Hall et al. [18]. The flash maneuver is based on the observations made by Romey et al. [19].

We will add other escape maneuvers, such as herd, vacuole, and hourglass, in the near future.

Tunstrom, et al. [23] demonstrated that schooling fish can be described in terms of the degree of alignment and degree of rotation among group members. Using this model, they were able to simulate three distinct behaviors: swarm, polarized motion, and milling. Many others [24] have attempted to build models to describe collective motion in fish schools. Although these bottom-up dynamic models are more biologically correct, much work still needs to be done before these models can reliably generate a wide variety of maneuvers as observed in the real world. Instead, we adopt a top-down approach where we build our simulations to fit the high level observations of fish school escape behavior. This top-down model is easier to control and tune for computer animations.

2.2 Fish animation in computer graphics

In computer graphics, some behavioral, mathematical, and biomechanical models were proposed to simulate fish behavior. These models can be largely divided into two categories: group behavior simulation and individual behavior simulation.

Reynolds [9, 15] proposed the group behavioral model for a flock of birds, a herd of land animals, and a school of fish. This model is largely built on the rules of separation, alignment, cohesion, obstacle avoidance, and goal seeking. The original model does not include the escape behavior, but the obstacle avoidance [16] rules may be used to generate the avoid maneuver.

Tu, et al. [10, 14] and Satoi, et al. [12] focus primarily on simulating individual fish behavior. Tu et al. [10, 14] modeled an artificial fish, using intention generator (brain) to motivate the behavior routine. Eight behavior routines were modeled: avoiding static obstacle, avoiding other fish, eating food, mating, leaving, wandering, escaping, and schooling. The schooling behavior is largely based on Reynolds' model. The escape behavior routine, an avoidance maneuver, chooses a motor controller task that is either turning left or swimming forward based on the predator's position and orientation.

Satoi, et al. [12] modeled different sizes and skeletal structures of fishes and proposed a unified motion planner approach to generate various swimming styles. Their demonstration video includes some escape behavior, but little detail is provided. The schooling behavior is largely based on Reynolds' model, and their escape maneuvers seems to be a type of avoidance behavior.

Suppi et al. [11] presented an animation tool for an individual based model in fish schools but didn't explicitly address escape behavior.

Sahithi and Zhu [13] proposed a behavior model to simulate a predator fish attacking a school of prey fish. But this work focused on the predators and did not address the prey fish escape behavior.

Wang, et al. [25] proposed a dynamics model for simulating insect swarm behavior. The eleven parameters of this model can be modified to generate different swarm behavior, including escape behavior. The accuracy of this model depends on the insect motion capture data from the real world. The authors stated that their model may not apply to swimming insects. Li, et al. [26] also proposed a framework for simulating insect swarms. Although escape behaviour is not explicitly mentioned in this paper, the proposed model can simulate obstacle avoidance behaviour. Their model is also based on insect motion capture data, which is still difficult to obtain.

Overall, escape behavior has received little attention in the previous works. In most of them, only the avoidance maneuver is simulated. Our work is an attempt to address this issue and our goal is to simulate a variety of biologically realistic escape maneuvers in a school of fish.

The main difference between our models and these two insect swarm models [25, 26] is that our model depends on human generated, high level biological observations, not on motion capture data. While data-driven models provide more accurate low level simulation, our observation-driven models can simulate a wider variety of high level behavior patterns, such as the escape maneuvers described in this paper.

3 PREY FISH PERCEPTION MODEL

Prey fish's escape behavior is based on their perception of predators. To simulate its escape behavior, we need to first model a prey fish's perception.

In nature, a prey fish gathers information through its eyes and lateral line organs [27]. Our fish perception model is largely based on biological research but we also have to make simplifications and assumptions. In addition to the visual and lateral perception, we built a communication model for prey fish to send and receive information.

3.1 Visual Perception

Vision is an important sensory system for fishes, and many escape maneuvers are triggered by visual stimuli. A typical fish vision is modelled with a field of view of 300 degrees spherical angle and a blind angle of 60 degrees behind it [28]. Perception length (L) is the maximum distance a fish can possibly see and is a pre-defined value (section 6.1). An object is visible if any part of it enters this view volume unless another object is obstructing its view. The vision model gives a prey fish two pieces of information: object visibility (V) and distance to object (D). The field of view (θ) is determined by

$$\theta = \arccos((P.Q)/|P||Q|) \quad (1)$$

The distance (D_{ij}) between a predator and a prey fish is calculated from their positions $P_1(x_i, y_i, z_i)$ and $P_2(x_j, y_j, z_j)$.

$$D_{ij} = P_1(x_i, y_i, z_i) - P_2(x_j, y_j, z_j) \quad (2)$$

A prey fish can see the object (V = 1) if angle θ is in the range $-150^0 \leq \theta \leq 150^0$ and distance D is below the perception length (D<L). (predefined in section 6.1).

3.2 Lateral Perception

In our lateral perception model, a fish detects the speed (S), direction (Di) of the neighbors and predator, and the external force (F) through its lateral line. The external ripple force F_{iR} from an object (R) perceived by fish i is given below.

$$F_{iR} = m_R . D_{iR} / (T_{iD})^2 \quad (3)$$

m_R is the mass of the external object and D_{iR} is the distance between fish i and external object R. T_{iD} is the time delay for F_{iR} to reach prey fish i. The prey fish closer to a predator perceive a stronger force through their lateral lines than the fish that are farther away from the predator.

3.3 Communication System

A school of fish must have a way to communicate among themselves in order to move in the highly synchronized and disciplined fashion as observed in the real world. It is believed that vision is important for schooling, and the lateral lines and sound may play a minor role. Because the current biological research on fish communication in a school is not detailed enough to build a computational model, our communication model is loosely based on biological studies [22, 29], with many assumptions.

We assume that communications are mainly between neighbors in a school of fish. A prey fish transfers information such as the neighbor distance (NND) and the speed (S) and direction (Di) of the neighbors and the predator. This information is communicated to the nearest neighbors' and these fish further send it to their nearest neighbors and so on until the information is spread in the fish school. If a fish has multiple transmitter neighbors, the information is received from the nearest neighbor.

4 PREDATOR BEHAVIOR STATE MACHINE MODEL

Since the focus of this paper is the prey fish escape behavior, we adopt a relatively simple behavior model for the predator fish. The predator behavior is categorized into three states: predator present (P_P), predator chase (P_C), and predator attack (P_A). A predator may switch to each of these states randomly. In this paper, we only simulate a single predator. In the future, we plan to simulate multiple predators attacking a school of fish simultaneously.

5 PREY ESCAPE BEHAVIOR STATE MACHINE MODEL

Our escape behavior model is an extension of Reynolds' flocking behavior model. Each prey fish follows the same direction (Di) with the same speed (S), with some randomness added. Collision avoidance is handled by maintaining a minimum distance with neighbors (NND). This avoidance rule applies to each of the maneuvers discussed below.

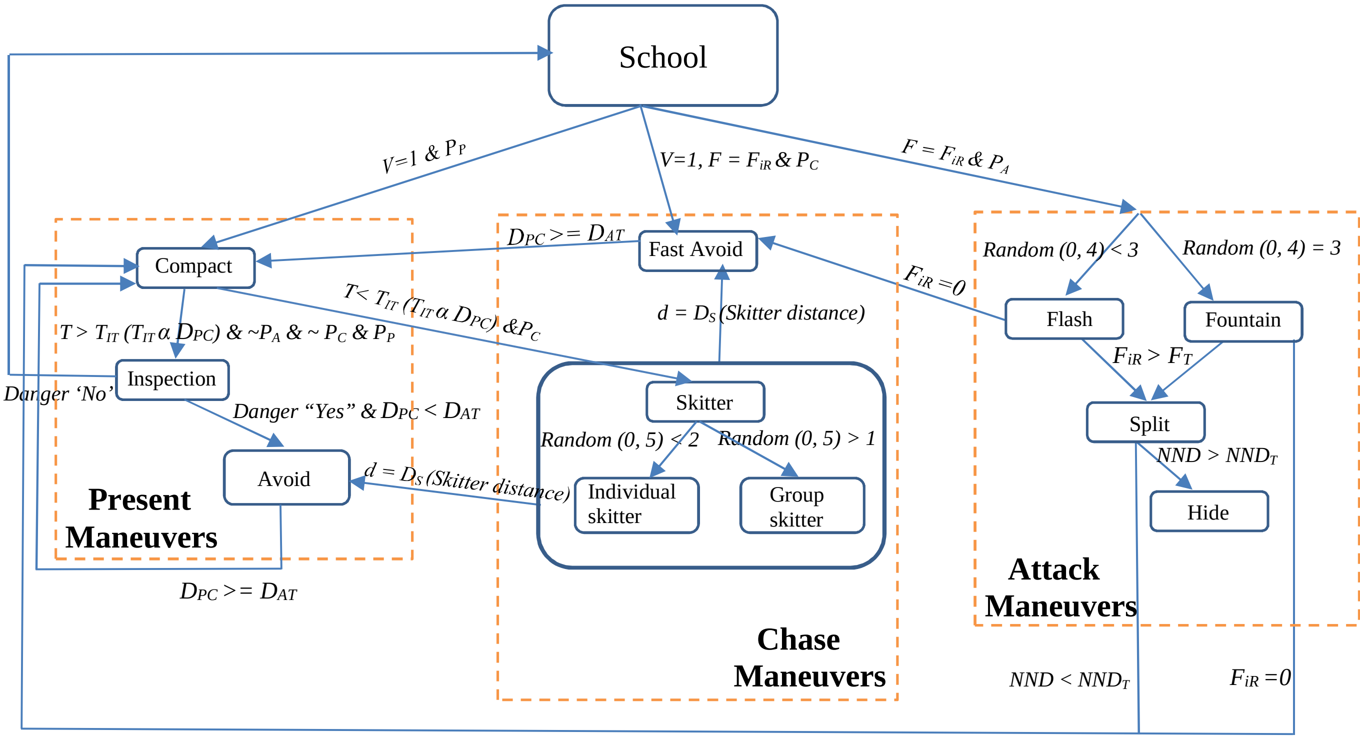

Figure 1: Prey fish escape behavior state machine.

Figure 1 illustrates the overall prey fish escape behavior state machine. The escape maneuvers are grouped based on the three predator states (section 4). This state machine is largely based on biological research [18, 21, 22]. Among the escape maneuvers in figure 1, we have implemented compact, inspection, avoid, fountain, and flash. Simulating other maneuvers will be part of our future work.

The compact, inspection, and avoid escape maneuvers are triggered when a predator is detected by vision (section 3). The prey fish school usually switch to a compact maneuver. The next tactic, if there is time, may be to inspect the predator. In this case, the amount of time for the fish school to perform the compact maneuver (T) should be greater than the time to inspect (T_{IT}), and the predator has not started the attack or chase ($\sim P_A$ & $\sim P_C$). Otherwise, they start the skitter maneuver. The prey fish school swim away from the predator (avoid maneuver) if the predator is dangerous, otherwise they continue the compact maneuver. D_{PC} is the distance between the predator and the centroid of the prey fish school. When the prey fish school reach the threshold avoid distance (D_{AT}) away from the predator ($D_{PC} >= D_{AT}$), they switch to the compact maneuver.

Skitter and fast avoid are the maneuvers exhibited during the predator chase (P_C). Fast avoid, which is similar to avoid but with higher speed, is exhibited when the predator is actively stalking. This maneuver is often preceded by a group skitter, flash, and followed by a compact maneuver. Skitter maneuver is often preceded by the compact maneuver when there is no time to inspect ($T < T_{IT}$ (T_{IT} α D_{PC}) &P_C). Based on the statistics [21], individual skitters are less frequent (5 times) than group skitters. If each individual fish starts skittering and reaches the skitter distance ($d_i = D_S$), then they end up in the avoid maneuver.

The flash, fountain, split, and hide maneuvers are the costly maneuvers in reaction to a predator's final strike. The flash and fountain maneuvers are exhibited randomly by prey fish school. It has been observed that the flash maneuver is exhibited twice more often than the fountain maneuver [21]. After the flash maneuver, the prey fish school may return to the fast avoid state ($F_{iR} = 0$) or the split maneuver if the predator's ripple force (F_{iR}) is more than the threshold force ($F_{iR} > F_T$). F_T is defined in section 6.1.

Similarly, after exhibiting the fountain maneuver, a prey fish school switch to the compact maneuver if $F_{iR} = 0$ or to the split maneuver if $F_{iR} > F_T$. After the split maneuver, they switch to the compact maneuver if the nearest neighbor distance is within range ($NND < NND_T$). The nearest neighbor distance threshold NND_T is defined in section 6.1. Otherwise, they go to the hide maneuver.

5.1 Compact Maneuver Behavior Model

The compact maneuver is similar to the normal school formation but the distance between fish is smaller. The compact maneuver is divided into two states: alert and reaction (figure 2).

5.1.1 Alert State

Once a predator is sighted, the school of fish enter the alert state. The transmitter fish who see the predator (V=1, see section 3) start the communication and transfer the new nearest neighbor distance (NND_N) and new speed (S_N) to its neighbors. The receivers then enter the alert state. NND_N and S_N for prey fish is given below.

$$NND_N = NND_C / f_d, \tag{4}$$

where NND_C is the current nearest neighbour distance and f_d represents the distance factor value (section 6.1) but varies with respect to the type of the maneuver.

$$S_N = S_C * f_s, \tag{5}$$

where S_C is the current speed of prey fish and f_s represents the speed factor (section 6.1) but varies with respect to the type of the maneuver.

5.1.2 Reaction State

In this state, each prey fish moves closer to its neighbors with the new nearest neighbor distance (NND_N) and cruise with the new speed (S_N). Each prey fish enters the reaction state at different times because of the time delay in communication. The increased polarization and reduced neighbor distance result in a compact school. After every prey fish reaches this state, the fish school exhibit the compact maneuver for a time period (T).

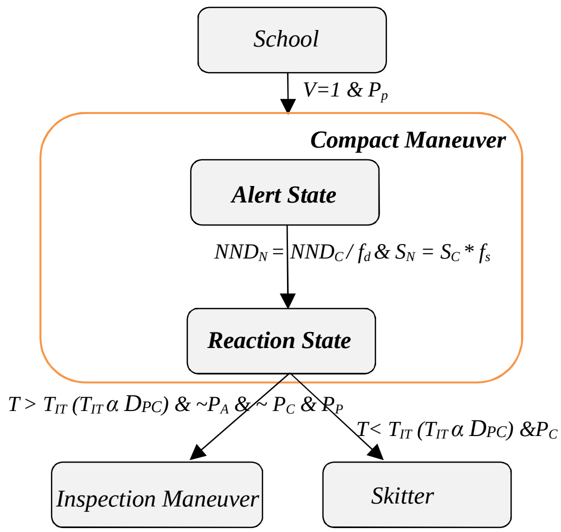

Figure 2: State machine of the compact maneuver.

5.2 Inspection Behavior Model

The prey fish use the inspection maneuver to gather information (*danger = "yes" or "no"*) about the predator. This information gathering task can be performed by either individual fish, a small group, or the entire fish school. But most of the time the inspection is performed by a small group ranging from one to fifteen percent of the fish school [21]. Each fish in this small group is called inspection leader (I_L). The state machine of the inspection maneuver is given in figure 3.

5.2.1 Alert State

The prey fish school enter the alert state if the predator does not chase or attack for a specific period (T_{IT}). After all the prey fish enter the alert state, the inspection leaders (I_{iL}) are chosen based on their distances to the predator (D_{iP}). If a prey fish is regarded as leader, then $I_{iL} = 1$, otherwise $I_{iL}=0$.

5.2.2 Reaction State

If a prey fish is chosen as an inspection leader, then it will have two sub-states: divide and share. The other prey fish will maintain the compact maneuver.

Divide Phase

The inspection leaders are given new directions (Di) towards predator and new speed (S_N). They swim away from the group after T_{IT} time and go near the predator to assess the danger.

Inspection distance (I_D): The inspection distance is how close the inspection leaders get to the predator during an inspection. This inspection distance is generally four to six body lengths of the predator.

Inspection time (I_T): The inspection is usually performed for a few seconds to learn the motive of the predator and then the inspection leaders swim away. I_T is defined in the section 6.1.

Share Phase

The information (*danger = "yes" or "no"*) is shared among the fish school using the communication system describe in section 3.3. If

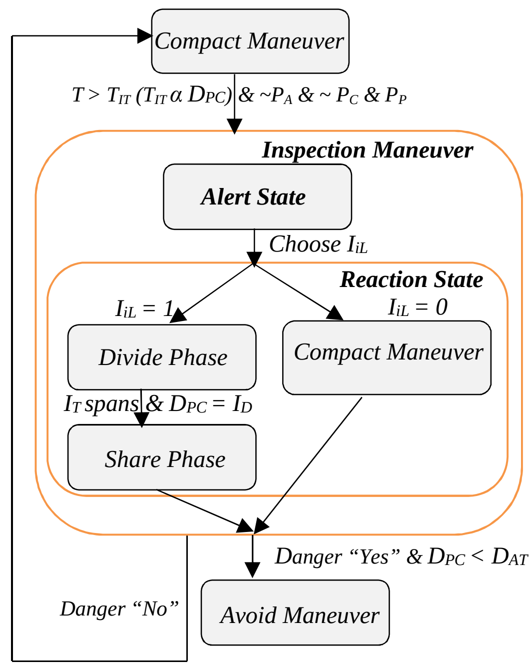

Figure 3: State machine of the inspection maneuver.

the predator is deemed dangerous, then the fish school enter the avoid maneuver, otherwise, they maintain the compact maneuver.

5.3 Avoid Maneuver Behavior Model

In the avoid maneuver, a school of prey fish alter their course to escape from the predator. The avoid behavior may also follow the skitter behavior (figure 1). The avoid maneuver is similar to the compact maneuver but the fish closest to the predator move even closer to each other while moving away from the predator. The state machine for the avoid maneuver is shown in figure 4.

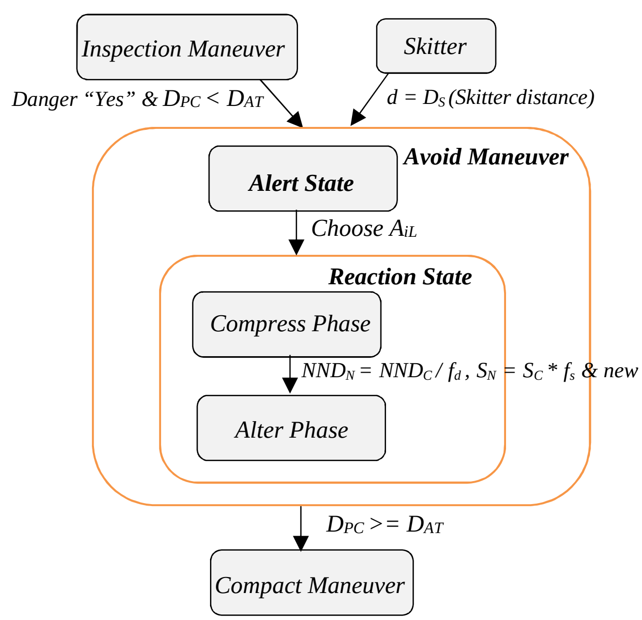

Figure 4: State machine of the avoid maneuver.

5.3.1 Alert State

In this state, the avoid leaders (A_{iL}) first enter the alert state and send the information throughout the fish school. The avoid leaders are determined in a way similar to the inspection leaders (I_{iL} in 5.2.1).

5.3.2 Reaction State

The reaction state has two sub-phases: compress and alter.

Compress phase

In the compress phase, the avoid leaders move closer to each other with the new neighbor distance NND_N (eq. 4), direction Di (away from the predator), and speed S_N (eq. 5). This information is transferred to the neighbor fish. To alter the path of the entire fish school, a critical number of 16% of the fish need to be in the compress sub-phase [21].

Alter Phase

In the alter phase, when the avoid leaders begin to swim away from the predator, the rest follow. After the school reach the avoid distance ($D_{PC} >= D_{AT}$), they go back to the compact maneuver.

5.4 Fountain Maneuver Behavior Model

The fountain maneuver occurs when a predator attacks from behind a school of fish. The fish school splits up and then rejoins behind the predator. During the split, the prey fish increase speed and swim towards the predator's tail. The predator cannot easily make a sharp turn to catch them. This was termed "fountain maneuver" by Pitcher [30]. The behavior model for the fountain maneuver is divided into two states: alert and reaction. The state machine for the fountain maneuver is shown in Figure 5. It is assumed that the fountain maneuver is triggered by a predator attacking the centroid of the fish school from behind. Because the fish cannot see behind them, this attack is sensed by their lateral lines (section 3.2).

5.4.1 Alert State

Each prey fish enters the alert state after sensing the ripple force ($F = F_{iR}$) from the predator. This force reaches the prey fish at different times as described in section 3.2. If F_{iR} is stronger than the threshold force (F_T), then the fish school will enter the split maneuver.

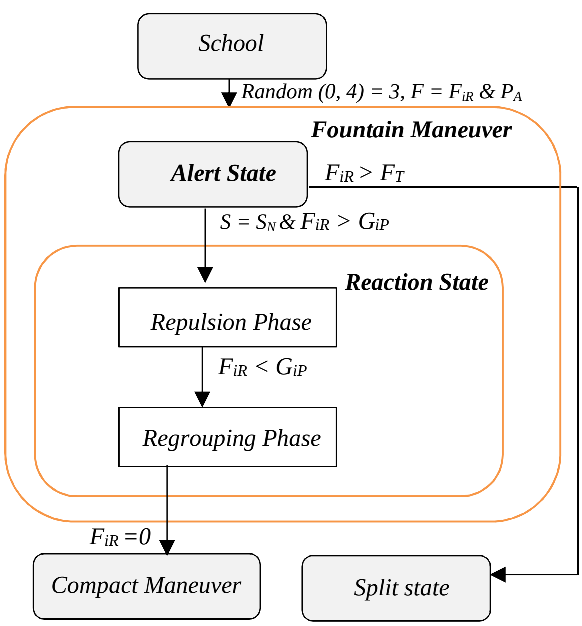

Figure 5: State machine of the fountain maneuver.

5.4.2 Reaction State

The reaction state is comprised of the repulsion and regrouping phases. In the repulsion phase, the prey fish split into two groups from the centroid (x_c, y_c, z_c) of the school and are pushed away from the predator with the ripple force stimuli (F_{iR}). As the repulsive force decreases and the gravity pulling force increases, the prey fish enter the regrouping phase.

Repulsion Phase ($F_{iR} > G_{iP}$)

The force F_{iR} from the predator pushes each prey fish to turn away from the predator's path. While the prey fish are pushed aside by the predator's force, they are still attracted to their original positions. This original position is the gravity center (G_{iC}) for each prey fish. The gravity force (G_{iP}) pulling each fish towards its gravity center and the repulsive force (F_{iR}) pushing away from the predator act as balancing forces, creating the curved path for each prey fish (figure 6) and the fountain pattern for the fish school.

The prey fish closer to the predator are pushed away by stronger forces (F_{iR}) and their curved paths have larger radii. The radius of a curve (R_i) for a prey fish i is given below.

$$R_i = C_1 / D_{iP}, \quad (6)$$

where C_1 is a constant value, determined based on the simulations and D_{iP} is the distance between the prey fish (i) and the predator (P).

Regrouping Phase ($F_{iR} < G_{iP}$)

The regrouping phase starts when the influence of the predator's force decreases and the prey fish try to reach their gravity center G_{iC}. The influence of F_{iR} from the predator decreases as the prey fish move farther from the predator. In the meantime, the gravity force pulling the prey fish towards their original positions (G_{iC}) grow stronger. The force F_{iR} enables individual prey fish to monitor the threat and respond accordingly. After reaching their G_{iC}, the prey fish try to form a school.

5.5 Flash Maneuver Behavior Model

The flash escape maneuver is triggered by a predator's final attack. Our behavior model is based on a detailed analysis by Romey et al. [19]. The flash maneuver behavior is divided into two states: alert state and reaction state (Figure 7). The reaction state is further divided into the explosion and regrouping phases. Each state is described below.

5.5.1 Alert State

After sensing the ripple force ($F = F_{iR}$) from the predator, prey fish enter the alert state. The force stimuli (F_{iR}) from the predator causes the prey fish to startle for a few seconds (T_s) in random directions with increased speed (eq. 5) before they explode in the flash maneuver. T_s is defined in section 6.1.

5.5.2 Reaction State

Explosion Phase

After a certain amount of time (T_s) in the alert state, the prey fish enter the explosion phase. First, we define a 3D coordinate system with the origin at the centroid of the school, with the x and z axes as the horizontal axes, and the y axis as the vertical axis. Each prey fish's path is calculated based on its angle (Sp_i) with the x-z plane, horizontal distance (d_{hi}) and vertical distance (d_{vi}) from the origin. The horizontal escape angle (α_h) is calculated based on its angle (Sp_i) with the x-z plane and its horizontal distance (d_{hi}). The vertical escape angle (α_v) is determined by considering the range of the vertical axis (r_v) for the group and vertical distance (d_{vi}) for each prey fish (i). These angles are used for rotating each fish in the explosion maneuver.

Suppose that x-z is the horizontal plane and y is the vertical axis, (x_i, y_i, z_i) is i^{th} prey fish position, and (x_c, y_c, z_c) is the group centroid.

y_m is the y co-ordinate of the top most prey fish,
y_n is the y co-ordinate of bottom most prey fish.
We calculate the aforementioned parameters as follows.

$$Sp_i = z_c - z_i / x_c - x_i \quad (7)$$
$$d_{hi} = x_c - x_i \quad (8)$$
$$d_{vi} = y_c - y_i \quad (9)$$
$$r_v = y_m - y_n \quad (10)$$

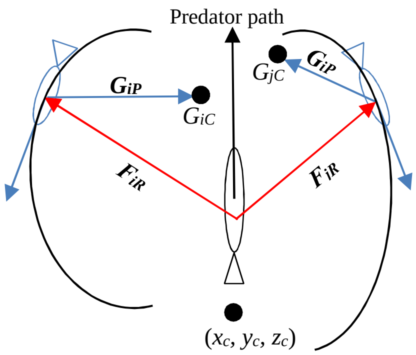

Figure 6: Forces acting on the prey fish.

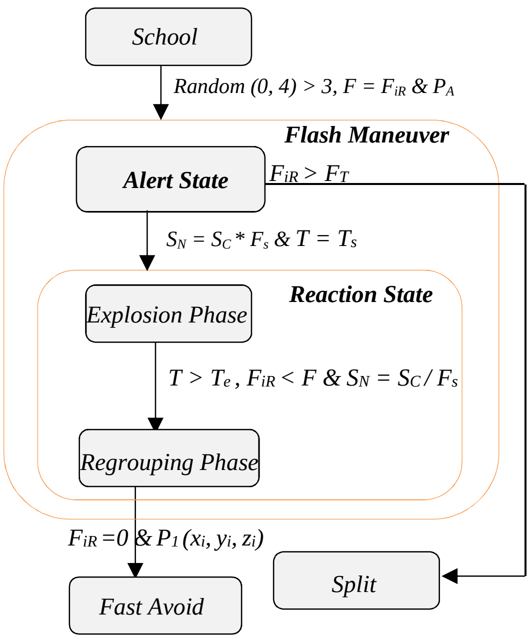

Figure 7: State machine of the flash maneuver.

The horizontal escape angle (α_h) for each prey fish is given by

$$\alpha_h = C_2 * Sp_i \quad (11)$$

α_h is positive if d_{hi} is positive (fish is located to the right side of the centroid) and is negative if d_{hi} is negative (fish is located to the left side of the centroid).

The vertical escape angle (α_v) for each prey fish is given by

$$\alpha_v = C_3 (r_v / d_{vi}) \quad (12)$$

α_v is positive if d_{vi} is positive (fish is above the centroid) and is negative if d_{vi} is negative (fish is below the centroid).

Prey fish rotate either clockwise or counterclockwise based on the direction of α_h and α_v. Prey fish stay in the explosion phase for a time (T_e) based on predator's force stimuli (F_{iR}) and is given by

$$T_e = C_4 * F_{iR} \quad (13)$$

C_2, C_3, and C_4 are constants, which are determined based on the simulations.

Regrouping Phase

After time T_e, each prey fish turns back towards its original position with its normal speed (S_N). When they return to their original position, they enter the fast avoid maneuver. If F_{iR} is greater than a threshold force (F_T) defined in section 6.1, the school will enter the split maneuver.

$$S_N = S_C / f_s \quad (14)$$

6 Results

6.1 Implementation Details

We implemented the proposed behavioral models in Unity 3D. The 3D models for the prey fish and predator were obtained from Unity's asset store. The values for the key parameters in our behavior models are listed below. The result of our simulations will be discussed in the subsequent sections.

Table 1: Values for the key parameters

Parameter	Value
Threshold nearest neighbour distance (NND_T)	4.0
Inspection time (I_T)	0.3
Inspection distance (I_D)	3
Perception length (L)	10.0
Threshold force (F_T)	20
Startle time (T_s)	0.01
Time in compact maneuver	0.9
Skitter Distance (D_s)	1.0
Threshold avoid distance (D_{AT})	6
Speed factor (f_s)	3
Distance factor (f_d)	2

6.2 Compact Maneuver

Figure 8 shows the compact maneuver where all the fish are in the reaction state, swimming with twice the normal speed.

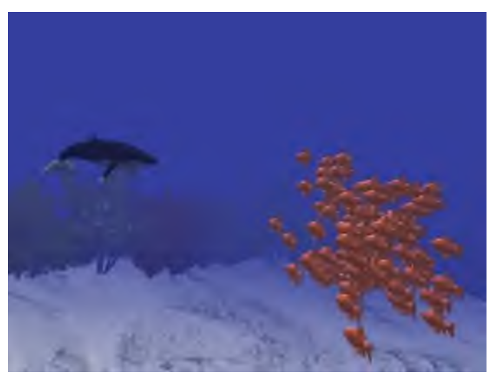

Figure 8: Compact maneuver.

6.3 Inspection Maneuver

The inspection maneuver is shown in figure 9. The inspection leaders (I_{1L}, I_{2L}, I_{3L}) are gathering information from the predator.

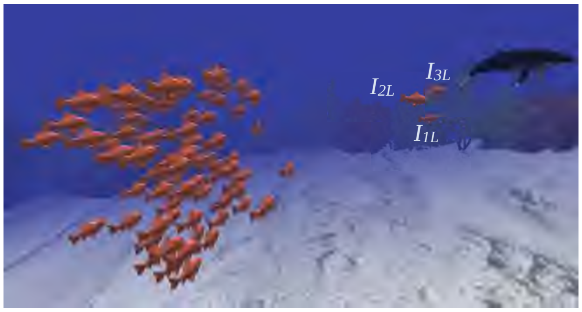

Figure 9: Inspection maneuver with three inspection leaders I_{1L}, I_{2L}, I_{3L}.

6.4 Avoid Maneuver

Figure 10 shows the avoid maneuver. The green circle marks the fish (leader) who are starting to compress with a new nearest neighbor distance (NND_N = 1.0). NND_N is communicated throughout the fish school, and the school enter the alert state with an increased speed (S_n = 4.0). They move away from the predator to a distance D_{AT} = 6.0.

Figure 10: The prey fish in the green circle are starting to compress and ready to transfer into alter phase.

6.5 Fountain Maneuver

Figures 11 and 12 are the frames captured from the fountain maneuver's reaction state. Figure 11 illustrates that all the prey fish are in the repulsion phase of reaction state. Figure 12 illustrates the regrouping phase of the reaction state.

Variations in the repulsive forces result in different prey fish taking different curved paths as shown in Figure 11. The force is generated based on the size of the predator and the distance between the predator and prey fish.

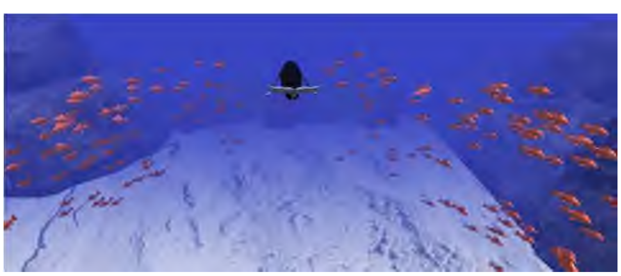

Figure 11: All the prey fish are in the reaction state (repulsion phase).

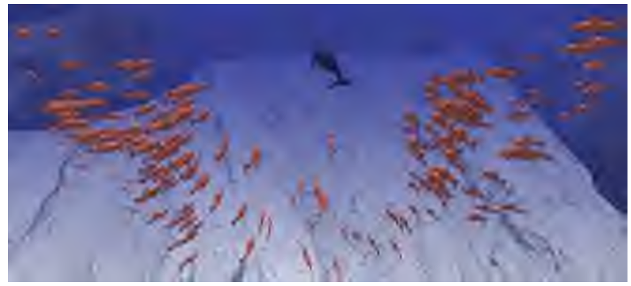

Figure 12: Fishes are in the reaction state (regrouping).

6.6 Flash Expansion Maneuver

Figures 13 and 14 are the frames captured from the flash expansion maneuver. Figure 13 shows the fish exploding in different directions.

Because of its size, the predator cannot easily deviate from its path and take a sharp turn, so it continues to move forward. Figure 14 shows the prey fish turning back. Once the school explode, the prey fish move away from the centroid of the school with triple the speed. If they sense no immediate threat (F_{iR}<F), then they will turn back and start moving towards their original positions with their normal speed. Once the prey fish reach their original positions, they form school again.

Figure 13: The fish are in the reaction state (explosion phase).

Figure 14: The fish are in the reaction state (regrouping).

7 Conclusion, Limitations, and Future Work

A school of fish exhibit a variety of escape maneuvers when they are under attack. However, the existing fish behavior models developed for computer graphics cannot simulate such diverse behavior. To address this issue, we have developed a fish escape behavior model to simulate a variety of biologically realistic escape behavior. Specifically, we have developed a set of state machines that specify the transitions between multiple escape maneuvers. Our current model can be used to simulate five common escape behavior: compact, inspection, avoid, fountain, and flash escape maneuvers. This behavioral model is largely based on biological observations and research. Our simulation results are verified and compared with the patterns visualized by Pitcher and Wyche [17]. Our simulation results are also comparable to the footage of real life fish escape behaviors.

Our model relies on high-level human observations of fish escape behavior in the form of state machines. The underlying fish school simulations are tuned to fit these state machines. Therefore, our animations can be seen as "scripted" -- the escape patterns are limited to the ones in the state machines. To add a new escape pattern, one modifies the state machine and create an underlying behavior simulation model. On the other hand, a truly dynamic model may generate emergent behavior in a school of fish and is more biologically correct. A new maneuver is created by adding and tuning system parameters. Although such dynamic models are highly desirable, we still do not have enough research data to create a dynamic model that can reliably and naturally generate a wide variety of escape behavior. At this point, "scripted" fish school animation provides better control and stability for computer animation. However, moving towards a truly dynamic model for fish school behavior remains our long-term research goal.

In the near future, we will continue to develop more models for fish escape behavior, such as bait ball, hourglass, etc. We also plan to simulate multiple and simultaneous predator attacks.

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