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# Animating Predator and Prey Fish Interactions

Sahithi Podila

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# ANIMATING PREDATOR AND PREY FISH INTERACTIONS

by

SAHITHI PODILA

Under the Direction of Ying Zhu, PhD

## ABSTRACT

Schooling behavior is one of the most salient social and group activities among fish. They form schools for social reasons like foraging, mating and escaping from predators. Animating a school of fish is difficult because they are large in number, often swim in distinctive patterns that is they take the shape of long thin lines, squares, ovals or amoeboid and exhibit complex coordinated patterns especially when they are attacked by a predator. Previous work in computer graphics has not provided satisfactory models to simulate the many distinctive interactions between a school of prey fish and their predator, how does a predator pick its target? and how does a school of fish react to such attacks?

This dissertation presents a method to simulate interactions between prey fish and predator fish in the 3D world based on the biological research findings. Firstly, a model is described by representing a school of fish as a complex network information flow with structural properties. Using this model, a predator fish targeting isolated peripheral fish is simulated. Secondly, the escape behavior state machine model and escape maneuvers exhibited by fish schools are described. The escape maneuvers include compact, avoid, fast avoid, skitter, fountain, flash, ball, split, join, herd, vacuole, and hourglass are identified in the biological studies. This proposed escape behavior animation model can free an animator from dealing with the low-level animations but instead, control the fish behavior on a higher level by modifying a state machine and a small set of system parameters. With the state machine and relatively few system parameters, the proposed system is stable, predictable, and easy to tune, which represent important properties for animators to control the outcome. This system is developed in Unity (3D). In addition, a plug-in is also developed for full-fledged graphics tool Blender software to simulate escape maneuvers. The animator has to simply select escape maneuvers, adjust parameters and work on animating predator using keyframe method. It does not deal with the state machine model. The proposed model is useful not only in generating group behaviors but also in scientific visualization tool for studying fish behavior.

**INDEX WORDS:** Crowd simulation, Behavior animation, Fish schooling behavior, Fish escape maneuvers

# ANIMATING PREDATOR AND PREY FISH INTERACTIONS

by

SAHITHI PODILA

A Dissertation Submitted in Partial Fulfillment of the Requirements for the Degree of

Doctor of Philosophy

in the College of Arts and Sciences

Georgia State University

2019

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2019

# ANIMATING PREDATOR AND PREY FISH INTERACTIONS

by

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May 2019

## **DEDICATION**

This dissertation is dedicated to my always encouraging husband Sairaj Bharath, parents Dr. Sankara Pitchaiah, Rajani Devi and my loving sister Anjani. Thank you for all the unconditional love, guidance, and support that you have always given me.

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## 1 INTRODUCTION

In computer graphics, animation is the process of creating an illusion of movement and can be generally created by the key frame or procedural method. The idea of key frame animation is based on the 3D object start and end conditions in the timeline defined by the animator whereas in procedural animation the animator defines the initial conditions and adjust properties later. In the key frame method, start and end conditions can be change in position, color and speed of the objects. In procedural animation, 3D object moments are automatically generated in real time based on initial conditions. The effect of changing a property value is unpredictable. To see the results, the animator has to run the simulations. Behavioral animation is one of the procedural animations and in this animation, the character determines its own actions to some extent and synchronizes the individual movements. These autonomous characters are closely related to artificial life. This reduces the burden for animators to animate each detail involved. It is majorly useful in simulating the group behaviors.

Group behavior or collective behavior is one of the most salient social activities among animals. This is the coordinated behavior of a large group of similar animals at the time of social activities as well as emergent situations. The components of the group behavior are interaction among individuals, information transfer, group decision-making process, group synchronization and locomotion. Typical examples of group behaviors are flocking birds (Figure 1.1 [1]), schooling fish (Figure 1.2 [2]), herding ungulates (Figure 1.3 [3]), swarming krill (Figure 1.4 [4]), pods of dolphins (Figure 1.5 [5]), and nest building ants (Figure 1.6 [6]). Many graphic companies have embedded the techniques with in their software 3d tool that can simulate group behaviors. For example, in Maya 3d graphics tool [7] and Blender [8], group simulations can be created with the



*Figure 1.1 Flocking birds*



*Figure 1.2 Schooling fish*



*Figure 1.3 Herding ungulates*



*Figure 1.4 Swarming krill*



*Figure 1.5 Pods of dolphins*



*Figure 1.6 Nest building ants*

particles system by adjusting the parameters. Also, several plug-ins were developed to create the flock behaviors. For instance, Cinema 4D Flock Modifier [9]. Cinema 4D is a 3D modelling,

animation, and rendering engine. C4D with the flock modifier plug-in implements a flocking and swarming system. These tools are complex enough to create simulations of group behaviors but not flexible to create special patterns exhibited by the species like fish school.

Fish school is a complex model that has complex behavior repertoires and autonomous interactions among individual fish. Each fish decides its behavior based on its perception of the local environment mainly the location of its neighbors. This grouping behavior enhances the hunting activity in attacking the prey from the perspective of predators, from the prey standpoint, escaping from the predators is one major advantage they benefit from the group size. It is observed that if an individual fish is separated from school then there is a risk of being eaten by the predator.

Fish school behaviors are the subject of some very popular animated films. In computer animation, researchers have developed methods to simulate crowd behavior [10, 11, 12, 13, and 14], fish swimming [15, 16, 17], and schooling [15, 18]. The primary interactions between predator and prey fish are the various escape behavior by the prey fish. To survive in a predator rich environment, fish escape activities have led to a variety of behavioral and morphological adaptations [19-27]. For example, Pitcher and Wyche [24] identified nine fish school evasive maneuvers in response to predator attacks: herd, avoid, flash, ball, split, vacuole, hourglass, join and cruise. Magurran and Pitcher [25] identified additional maneuvers such as compact, fountain, and skitter. These evasive maneuvers are described in Appendix A.

## **1.1 Problem Statement and Motivation**

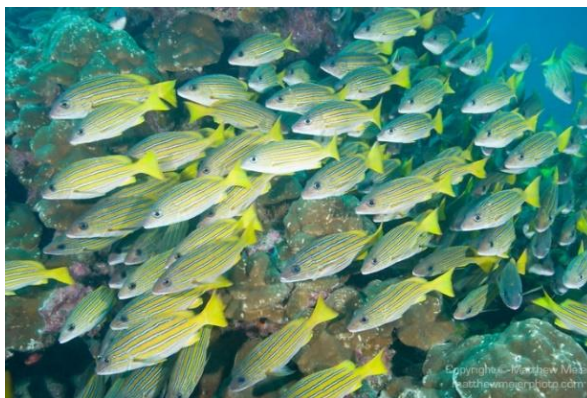
### ***1.1.1 Prey Selection***

The predator attacking prey fish school is complex and involve a number of phases, such as circling, approaching, choosing a target, attacking, and retreating. Choosing a target among fish school is one crucial phase of animal intelligence. In nature, the large complex schools visually

attract a predator and the predator selects the target first before it decides to swim. The predator fish repeats this decision process once it understands its target position and target speed [23]. The most isolated and peripheral prey fish are the ones that are easily targeted by the predator. In computer graphics, Tu et al., [15] described the predator model in three-dimensional space to select the target, however fish being isolated and peripheral were not handled in the cost. Prey fish being isolated and peripheral are the two major factors that influences the predator's selection of prey to attack and finding the peripheral nodes in three-dimensional space is one of the challenging tasks to be addressed.

### ***1.1.2 Fish School and Escape Maneuvers***

Fish school is one of the best examples of collective animal behavior and has been studied extensively in marine biology and ecology. The school of fish is described as a group of discrete individual fishes (discrete objects) moving in visually complex patterns on a large scale. They do not form a regular geometric structure like a crystal lattice that is the distance among them and direction is not maintained ideally. This results in approximated structures of fish schools and generally take the shape of wedge, squares, ovals, lines or amoeboid. The factors that describe fish school are size, density, polarity, nearest neighbor distance and nearest neighbor position. School size is the number of fish in the school, density is the number of fish divided by the volume occupied by the school, polarity is the extent to which all the fish in school are pointing in the same direction which is also known as orientation (Figure 1.7 [28], Figure 1.8 [29]), nearest neighbor distance is the distance between the centroid of one fish to the centroid of other fish (Figure 1.9 [30], Figure 1.10 [31]) and nearest neighbor position of individual fish in the coordinate system is described as the angle and distance to the nearest neighbor fish.



*Figure 1.7 High polarity*

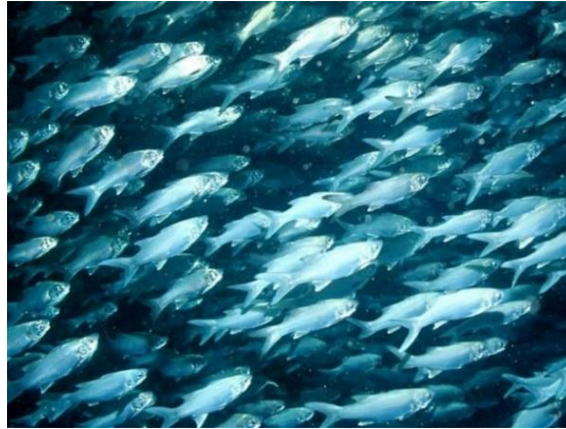


*Figure 1.8 Low polarity*



*Figure 1.9 Low nearest neighbor distance*



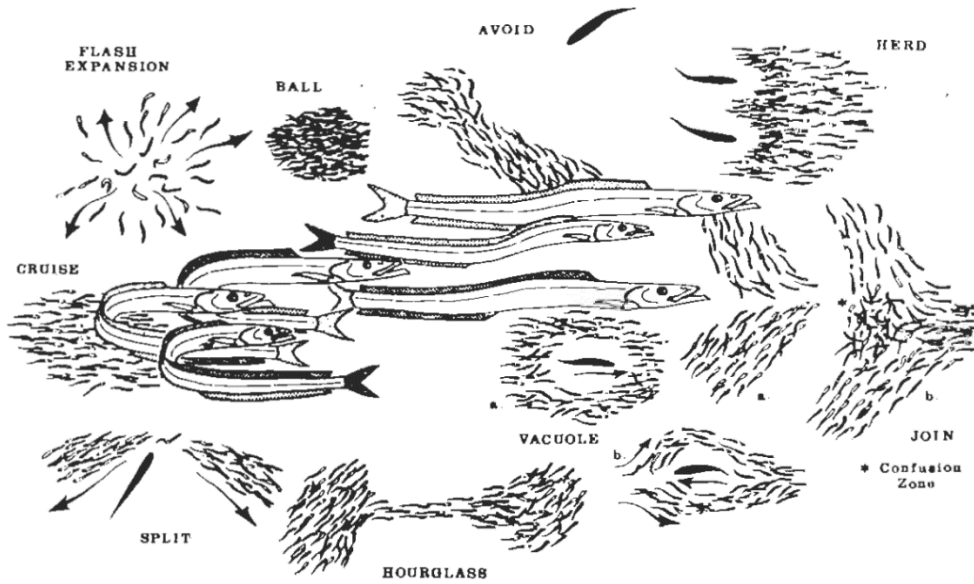


*Figure 1.10 High nearest neighbor distance*

Fish depend greatly on vision and lateral line as a source of sensory information [32]. The vision sensory system is important for maintaining the position and angle between fish. The lateral line system in fish is used to detect movement and vibration. These sensory systems can respond with great speed to the changes in the speed and position of neighbor movements. There are no leaders in fish school and each fish maintains its position, adjusts its speed and direction with respect to the nearest neighbors. To escape from predator, fish activities has led to a variety of behavioral escape maneuvers [33]. One of the main reasons for the fish to school is to better defend themselves against predators, and they adopt different escape maneuvers to confuse and evade their predators [19-23, 27, and 34]. The combination of the two sensory organs vision and lateral line provide the basis for exhibiting all maneuvers (Figure 1.11 [24]) of the school and the stimulant factors like distance, angle and environmental factors [35] can create escape responses in individual fish.

In computer graphics, crowd simulation has been an active research area (see [13, 14] for a review). Most of the research work in this area is about human crowds. There are significant differences between human mass panic and fish escape behavior. Human moves largely on 2D space, with many obstacles in the environment. A large part of human escape behavior is about





*Figure 1.11 Escape maneuvers of fish school*

seeking cover and exit. On the other hand, fish can move freely in 3D space with few obstacles. Human crowd rarely exhibits the highly coordinated escape behavior patterns that a fish school often use. Therefore, human crowd simulation methods cannot be easily applied to fish simulation.

Craig Reynolds [10, 11] proposed the boids behavioral model for simulating collective behavior, such as a flock of birds. This model is based on the rules of separation, alignment, cohesion, goal seeking, and obstacle avoidance. In obstacle avoidance approach, birds fly through simulated environment and avoid static objects if it experiences force field from the surface of the obstacles. There are no predator-prey interactions in this model.

Tu and Terzopoulos [15, 17, 36] developed an artificial fish with eight behavior routines: avoiding static obstacle, avoiding other fish, eating food, mating, leaving, wandering, escaping, and schooling. They developed a relatively simple fish escape behavior model. Prey fish form school when a predator appears in distance. As the predator comes near the fish school, the prey

fish choose an escape routine relative to the predator's position and orientation or sometimes the fish school disperses. The predator chases the prey fish if the distance and angle cost is minimal.

Satoi, et al. [16] proposed a unified motion planner to generate various fish swimming styles. However, this method can only generate relatively simple escape behavior and obstacle avoidance behavior. Wang, et al. [37] and Li, et al. [38] proposed different dynamics models to simulate insect swarm behavior. Both models are based on insect motion capture data, but neither model addresses insects' interactions with predators. Therefore, these models cannot be easily adapted to fish animation. The escape maneuvers exhibited by a school of fish cannot be easily generated by the existing flocking models. In addition, most existing methods focus on the interactions within the group but do not effectively address the complex interactions between a school of prey fish and predator fish, as shown by many biological studies.

## **1.2 Prey Selection Model Overview**

To address how a predator fish, choose its target prey fish that is isolated and peripheral in school, a method is designed and implemented in the 3D world. This proposed method based on the related biological research, tries to simulate the hunting behavior of predator fish and more realistic target selection. The most isolated and peripheral prey fish among large network of fish school are the ones that are easily targeted by the predator. Therefore, isolated peripheral value is determined for each prey fish in fish school and the prey fish with highest isolated peripheral value is the target for predator. This value is based on three factors: vulnerability ( $V_n$ ), average neighbor distance ( $AND_n$ ) and prey distance ( $PD_n$ ). The vulnerability factor in three-dimensional world is determined using graph theory property vulnerability. The visibility factor ( $E_n$ ) is another important factor that aid to determine isolated peripheral fish as the predator has visibility for only some of fish in the school because of its field of view.

This method is implemented and simulated by using 3D models for predator and prey fish school in the Unity. The simulations are realistic, visually appealing in 3D space and can be comparable with the live footage of predator attacking prey fish school in nature.

### **1.3 Prey Fish School Escape Maneuvers Model Overview**

To simulate the escape maneuvers exhibited by a school of fish, a fish school escape behavior model for twelve fish escape maneuvers identified in biological studies: compact, avoid, fast avoid, skitter, fountain, flash, ball, split, join, herd, vacuole, and hourglass is developed in Unity 3D Game engine. This behavior animation model can free an animator from dealing with the low-level animations and can generate complex escape maneuvers, prey-predator interactions with just a few clicks and adjusting parameters. In addition, the transitions based on biological observations from one pattern to another are added to the finite state machine. Unlike previous work on insect behavior animation [37, 38], the developed animation is based on biological observations and does not need any motion capture data. With the state machine and relatively few system parameters, the system is stable, predictable, and easy to tune, which represent important properties for animators.

To simulate prey escape behavior patterns, modeling a prey fish's perception is necessary as their behavior is based on the perception of the predator and dynamic environment. In nature, a prey fish gathers information through its eyes and lateral line organs. Therefore, vision and lateral perception models are constructed which is largely based on biological research but made with simplifications and assumptions.

Overall, escape behavior received little attention in the previous works. In most of them, only the relatively simple avoid maneuver is simulated. My work is an attempt to address this issue and goal is to simulate a variety of biologically realistic escape maneuvers in a school of fish. The main

difference between the proposed model and these two insect swarm models [37, 38] is that the developed model depends on human-generated, high-level biological observations, not on motion capture data. While data-driven models provide more accurate low-level simulation, the built observation-driven models can simulate a wider variety of high-level behavior patterns, such as the escape maneuvers described in this thesis. The simulation results of the escape maneuvers are realistic and comparable to the real footage.

A fish school modifier plug-in for 3D graphics tool Blender is also developed with user interface where the animator can play with the parameters of the escape maneuvers. Each escape maneuver of fish school has its pattern related specific parameters. The escape maneuvers behaviors are the same which are modeled for the unity except prey fish cannot decide which maneuver to exhibit and the plug in has the most commonly used maneuvers (compact, fountain, flash, split, and join). The animator can decide and select the maneuver on the required keyframe.

## 2 RELATED WORK

### 2.1 Prey Selection

Many researchers performed analysis on selection of target prey [39-42] and provided predator model to choose prey either nearest, center or peripheral.

#### *2.1.1 Nishimura's Prey Selection Model*

Nishimura [39] proposed a mathematical model for a predator to choose prey from school of fish in two dimensional-space. The author has introduced priority functions to select nearest, peripheral and split prey fish. Priority numbers are assigned to the prey fish and the predator chooses the prey depending on these priority numbers. Generally, the prey with highest priority number is targeted for a certain amount of time. These priority functions are defined with respect to relative distance, direction and velocity of prey fish in school. The nearest prey priority function

is the priority number obtained based on the distance between the prey fish and the predator which is given below.

$$p_i = -|r_i - r_a|, \quad (2.1) [39]$$

where  $p_i$  is the priority number assigned to the  $i_{th}$  prey fish,  $r_i$  is the prey fish's position and  $r_a$  is the predator position.

The second priority function peripheral victim strategy has a complicated mathematical form that computes distance between each fish position and a point where point is the intersection of a circle of group radius and the line between predator and center of mass of prey. The priority function is given below

$$p_i = - \left| \vec{r}_i^g - \beta M_{j \neq i}(|\vec{r}_i^g|) \frac{\vec{r}_a^g}{|\vec{r}_a^g|} \right|, \quad (2.2) [39]$$

where  $M_{j \neq i}$  is the average,  $\vec{r}_i^g = r_i - G$ ,  $G$  is the center of mass of the prey group and  $\beta$  is a constant parameter.

Split victim priority function calculates the average distance between each fish to other individuals in a group, larger distance indicates the more isolation which is given below.

$$p_i = M_{j \neq i}(|\vec{r}_j - \vec{r}_i|), \quad (2.3) [39]$$

The result of this function gives the average distance between prey fish  $i$  and prey fish  $j$  and larger value indicates the more separation of prey fish  $i$  from the group.

### **2.1.2 Tu and Terzopoulos's Prey Selection Model**

Tu, et al. [17] modeled the predator intention generator in three-dimensional space. In this model, predator chases prey fish if the cost is minimal in terms of distance between prey-predator,

predator turning cost and factor of being prey in a school. The cost obtained for chasing prey fish  $k$  is given by

$$C_k = d_k(1 + \beta_1 S_k + \beta_2 E_k/\pi) \quad (2.4) [15]$$

where  $d_k$  indicates the distance between center of the body of prey fish  $k$  and predator mouth,  $S_k$  is 1 if prey  $k$  is in school of fish else 0.  $E_k$  is the turning cost for the predator towards the prey fish  $k$ ,  $\beta_1$  and  $\beta_2$  are the varying weights. However, fish being isolated and peripheral were not handled in the cost. Prey fish being isolated and peripheral are the two major factors that influence the predator's selection of prey to attack.

## 2.2 Fish School Escape Maneuvers

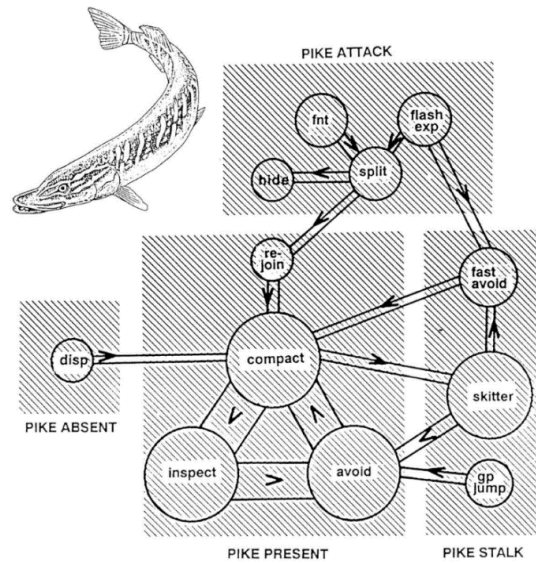
### 2.2.1 Related Work in Biology

*Fish perception.* Partridge and Pitcher [32] conducted detailed experiments and reported the qualitative analyses of the effects with blindfolding and lateralis section on the school of fish. Lateral line system plays an important part in allowing prey fish to detect water movements such as those generated by stationary objects in flowing water or from the movements of other animals such as swimming fish. The same system allows prey to detect water movements that differ in frequency, speed, shape and direction generated by hunting predators. Lateral line reacts to the vibrations or force created by the predator and can know roughly the movement of whole the school through the lateral line. Fish uses lateral line only when the school is stable and there is no external perturbation around the school. School structure and dynamics depend upon both senses, with vision primarily important for the maintenance of position and the lateral line primarily important for monitoring the swimming speed and the direction of travel.

*Fish School Escape Maneuvers.* There have been a lot of research on fish school escape behavior [24, 44, 45 and 46] in biology and ecology. Instead of giving an extensive review of this

complicated subject, background information about the biological foundation for my thesis work is provided.

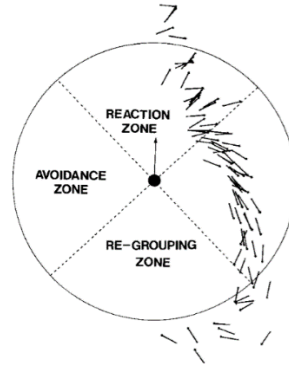
Magurran [26] conducted an experiment to analyze the predator attack and the anti-predator mechanism exhibited by school of fish to escape from the predator. Various tactics ranging from confusion effect to the flash expansion are exhibited by fish schools to protect from the predator. The typical patterns exhibited by fish school in the predator presence and predator attack are compact, inspection, avoid, fountain and flash. The compact, inspection and avoid maneuvers are exhibited by prey fish school during predator presence in the environment of the school. Compact school maneuver was polarized and densely packed within the range of 0.5-2 body lengths. During inspection behavior, a group of prey fish approached the predator within 4-6 body lengths paused and then moved away. Avoid maneuver is exhibited at two intensities: compression near to the predator and moving away from the predator to the distance approximately 1.3m (observed from the experiments) and is perhaps the most common escape maneuver. The author also summarized the transition among escape behaviors as shown in Figure 2.1 [26]. In this sequence of predator evasion tactics, initially inspection takes place when predator is present in the environment but not in hunting state. If the predator enters stalk state, the escape tactics like skittering, fast avoids and group jumps are exhibited, in the predator attacks, fountain and flash maneuvers are displayed. A very detailed analysis on fountain and flash patterns are given by Hall et al. [44] and Romey et al. [45] respectively. Fountain maneuver is exhibited when a predator attacks from behind a school of fish. The fish school splits up and then rejoin behind the predator. During the split, the prey fish increase speed and swim towards the predator's tail, and the predator cannot easily make a sharp turn to catch them. Based on Hall et al. [44], this maneuver is likely to



*Figure 2.1 Sequence analysis of predator evasion tactics*

be a function of the predator's speed, the prey detection time of the approaching predator, and the speed of the prey fish. When a predator attacks, a prey fish turns its path away from the threat and takes an angle between 0 to 45 degrees. When the predator leaves the fish school, the prey fish change into the regrouping status and generally the fish at angle 135 degrees turns back into the original position (Figure 2.2 [44]). The flash escape maneuver is the last response when a school of fish got exhausted with all the other escape maneuvers. Therefore, this maneuver is triggered by a predator's final attack [16, 47, and 48]. A detailed analysis on the flash expansion in beetles is given by Romey et al. [45]. This expansion starts with a fast startle response and then the beetles move away from the group in random directions, although it is not clear from the observations whether the beetles move away from the group centroid, or the original position, or some other point. The beetles rapidly increase their speed while moving away and then decrease their speed while turning back. All the described tactics are displayed randomly so the predator cannot predict which maneuver is displayed next. However, there are many chances that school splits at the





*Figure 2.2 Fountain Behavior model*

predator chase and attack leading to isolated fish which are vulnerable to get caught. Fish do not send any warning call about the danger of the predator [26, 49]. However, information transfer is done through visual signals. The fish that react first are transmitter fish and the fish which receive information and act accordingly are the receiver fish.

Pitcher and Wyche [24] conducted a similar experiment in an outdoor tank with 250 sand-eels and observed patterns exhibited by the fish school when predator fish introduced in the tank. Among the maneuvers observed by the Pitcher and Wyche [24], ball pattern is the first pattern exhibited when the predator is introduced into the tank. The stationary compact ball persisted for few seconds and later it transitioned to the compact maneuver. The prey fish school ball can be tight or loosely coupled. Most of the time the school remained in a tight ball and spent less time in exhibiting other anti-predator maneuvers (split, hourglass, vacuole, bend, dive, herd and fountain). The vacuole maneuver is displayed when the predator attacked through the school like a zip fastener. The vacuole shape is generally in an elliptical cross section. With the successive attacks, the predator can successfully split the school. School often split into two or more subgroups when they cannot stick together at the time of predator attacks, encountered with the obstacle or if the school travels faster, jerkily in opposite directions. This split maneuver is displayed either as a

direct response to the predator or as an intermediate response for the fountain, vacuole and hourglass maneuvers. These splits are less structured and amorphous schools. The splits generally last for 10 seconds or longer [25]. The school reforms whenever possible [21, 24, 50, and 51] that is the two or more subgroups join when they come in closer range. Then the new direction is followed by the subgroups and this new direction is the resultant vector directions of the subgroups [24]. The leading fish of the two subgroups join smoothly onto the new direction whereas the last fish take large ill-coordinated turns to the new direction creating a confusion zone. Hourglass maneuver exhibited when the predator constricted at the center of the school [24] and fish on either side of the school turn in the same direction to move away from the predator, however, this maneuver is less dominant when compared with the other maneuvers [52]. Herd maneuver is exhibited at the time of predator chase. This maneuver can be merged into other maneuvers like vacuole and hourglass [52].

Fish school often encounter with the decisions to make in movement. For instance, the decision can be which direction to turn when confronted by a predator. The investigation in [53] reported that fish in school used consensus decision-making method to follow a fish model. Consensus decision-making is the collective decision made by the group members by using information from multiple sources to reach to correct conclusion. One of the findings of this method is that larger the fish group more accurate the decision is.

### ***2.2.2 Related Work in Computer Graphics***

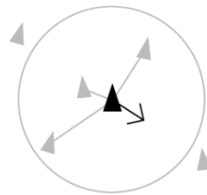
*Reynolds Model.* Craig Reynolds proposed the first flock model with three basic rules to simulate flocks graphically. This simulation model is developed as an alternate approach to scripting path model for each bird. Each individual is given with the behavior rules that are made by the local perception of the environment and the laws of physics. After embedding correct

behavior into a given model, the next step is to create simulated flock by creating instances of the given model and allowing them to interact. The aggregate motion of each individual and their interactions results in flock motion.

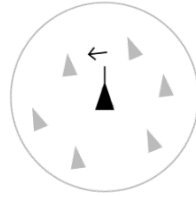
The behavior rules defined by this model are collision avoidance, velocity matching and flock centering. These three rules are applied in the decreasing order of precedence. Collision avoidance rule (Figure 2.3 [10]) ensures individual models not running into each other and is based on the relative position of the models.

Velocity matching (Figure 2.4 [10]) rule is designed to move the group together. Velocity is a vector quantity with speed and direction. Each model in the group travels with the same velocity. The velocity matching and collision avoidance rules are complementary to each other. The velocity matching rule is based on the velocity unlike the position in collision avoidance.

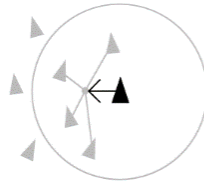
Flock centering rule (Figure 2.5 [10]) is the urge of each model to be at the center of the group (nearest neighbors) so that group model is maintained. The model deep inside the flock is surrounded by all other models in each direction. The urge for the model to be in center is less and models at the boundary has greater urge to be at the center as they are surrounded by other models in a limited direction. This rule has more importance when the flock encountered with an obstacle. If the flock faces an obstacle, it does not disintegrate, because as long as the individual model stays close to its nearby neighbors, the model does not care if the rest of the flock turns in other directions.



*Figure 2.3 Collision avoidance*



*Figure 2.4 Velocity matching*



*Figure 2.5 Flock centering*

Flock model is an elaboration of particles system. Particles system is used to generate fire, smoke clouds and waves. This system has collection of many individual particles with their own behavior and state. They have independent color, speed and each particle is a dot like structure. However, in flock model, each individual is a complex structure with orientation. The geometric flight of each model is described in forward direction that is local positive z axis. In addition to that, there are other translations mixed about the local x and y axes. In animation, the motion is incremented once per each frame. The author has used each model local co-ordinate system to represent motion with respect to position and orientation. The left/right axis is denoted by X co-ordinate, up/down is Y axis and forward/back is Z axis.

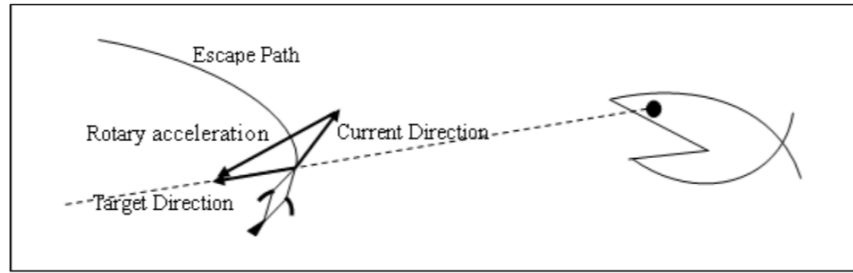
Later, many flock models were proposed based on these rules with variations in methodology and factors like velocity and position. For example, Charnell [54] defined these three basic rules with different terms (attract/repel/comfort) and used a different methodology that is individuals attract, repel and comfort based on directional light intensities.

*Agent-based simulation.* Agent-based simulation method [55] is another approach that can be used for fish school simulation, avoidance and escape. In this approach, fish receives information through visual perception. The author defined the cluster motion with Reynolds rules flock centering, velocity matching, and collision avoidance. These three rules decide the swimming motion for a fish. The direction for each fish is updated by the following equation

$$Direction = lastDirection * \lambda1 + d1 * \lambda2 + d2 * \lambda3 + d3 * \lambda4 \quad (2.5) [55]$$

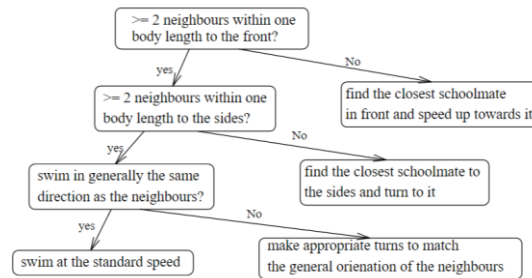
where  $d1$ ,  $d2$ ,  $d3$  are three rules and  $\lambda1$ ,  $\lambda2$ ,  $\lambda3$  and  $\lambda4$  are regular parameters. The author has proposed a bounding box algorithm to avoid static obstacles which is composed of collision detection and avoiding algorithm. In collision detection, a sorted ray queue is maintained for the direction of fish. If the first object is an obstruction and is within collision range distance, then the collision is detected. After detection of an obstacle, the fish may turn to opposite either by rotating clockwise direction or anti-clockwise direction based on the vector direction between fish and the obstacle. The author has described the fish escape motion (Figure 2.6 [55]) in terms of direction and speed. Each fish chooses the opposite direction to danger which is known as target direction to escape. The rotatory acceleration is the angle between the current direction and target direction. The speed of each fish increases until it reaches its upper limit and starts decreasing to reach the lower limit once it moves of the danger.

*Tu, et al. model.* Tu, et al. [15] extended Craig Reynolds' flock behavior model to model mathematical algorithms for autonomous agent's movement, individual behavior and complex group behaviors in the physical world. The authors have modeled artificial fish with two sensors: a vision sensor and a temperature sensor. These sensors provide information about the dynamic environment. An object is considered seen if any of the body parts enters in the view volume of an



*Figure 2.6 Fish escape scenario using agent-based simulation method*

artificial fish and is not fully occluded even if it is behind some opaque object. This artificial fish receives geometry, material property, illumination, position and velocity from the vision sensor. In addition, the authors have demonstrated the intention and behavioral generator model for artificial fish. The artificial fish receives intention from intention generator and sensory information based on the behavior routine selected. The typical intention generator generates an urge to eat, wander, avoid, school, escape, and mate. The behavior routines include avoiding-static-obstacle, avoiding-fish, eating food, mating, leaving, wandering, escaping, and schooling. If the school is encountered with the obstacle, the school splits into two groups and joins again after the obstacle is cleared. The schooling routine behavior for prey fish is given below (Figure 2.7 [15]). A relatively simple fish escape behavior is modeled. The prey fish form school when a predator appears in distance. As the predator comes near the fish school, the fish school disperses and choose an escape routine relative to the predator's position and orientation.



*Figure 2.7 Schooling behavior routine*

*Satoi, et al. model.* Satoi, et al. [16] modeled different sizes and skeletal structures for fish and proposed a unified motion planner approach to generate various swimming styles. The school behavior is largely based on Reynolds' model, and escape maneuvers seems to be a variation of the obstacle avoidance behavior. A constraint of collision is added to the virtual fish if it is in a school and a constraint of escape or avoid (move in opposite direction) is added if the school of fish encounters a predator. The acceleration vector for the fish to move in opposite direction to a predator is given below.

$$a_E = \begin{cases} \frac{d_0}{\|d_0\|} K_E (1 - \frac{\|d_0\|}{D_{safety}}), & \text{if } \|d_0\| < D_{safety} \\ 0, & \text{otherwise} \end{cases} \quad (2.6) [16]$$

where  $d_0$  is the vector from the predator to artificial fish,  $K_E$  is the degree of avoidance,  $D_{safety}$  is the threshold distance to exhibit the avoidance.

*3D Graphic Tools.* Particles system is the most common technique used in computer graphics to simulate behavioral systems. This system simulates the complex movement of objects or certain patterns exhibited by the flock of birds or group of humans. The flock of birds or group of humans are not just simple particles but a complex system with individual behaviors and interaction among them. Maya, Blender and 3ds Max [56] are some of the full-fledged graphics tools which contain particles system to simulate the group behaviors.

*Maya.* In Maya, one way to create flock of birds is through emitter. This emitter system has different components like the number of particles, speed and the type of emitter. The other way is to use dynamics. For instance, to create a school of fish moving together, first create a curve to define the path for fish school to move along and then use *create curve flow* with altering respective components.

*Blender.* Similar to Maya, particles system in Blender is used to create group behaviors with the different components to be modified by the user. For instance, the number of particles,

velocity and life time of the particles can be set according to the pattern required by the user. There is a special tab called Boids which provides UI to create flock of birds and different components to choose as shown in Figure 2.8 [8].

Plug-ins are the other most commonly used to implement distributed behavioral model. For example, *Flock Modifier* plugin for Cinema4D is developed to implement flocking and swarming system as a particle modifier. Similar to particles system, an emitter is created to generate the flock. The components like *neighbor range*, *center flock* and *match flock velocity* for the flock can be altered. In addition to these, path specification, collision avoidance and flash pattern can be achieved through *flock target* and *flock repeller*.

*Mash* [57]. is another plugin developed for Maya to create complicated procedural animation. This plugin can create flock behaviors and has the components to alter the rules. The components are *separation strength*, *alignment strength*, and *cohesion strength*. The path animation for the flock can be defined using *mash flight shape locator*.

Using these plugins or techniques different flock simulations can be created. However, specific patterns are not flexible to create with the components provided. It takes great effort to

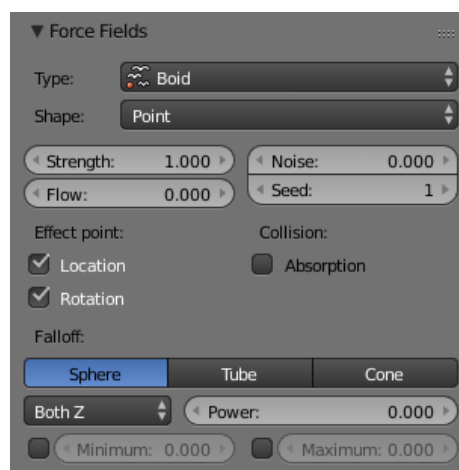


Figure 2.8 UI for a Boid force field



create patterns like flash, fountain that look realistic. Therefore, a fish school modifier plug-in is developed to address these issues. This plug-in can be used to create specific patterns related to the fish school and simulate prey-predator interactions with the given components.

### 3 PREDATOR-PREY PERCEPTION AND INTERACTION MODELS

#### 3.1 Predator Perception Model

Vision is an important sensory system for fish, therefore, it is established as the major source of information in interactions. Figure 3.1 illustrates the fish vision with a field of view of 300 degrees wide and blind angle of 60 degrees behind it [58, 59]. It covers a 300-degree spherical angle extending to an effective length that is perception length. Perception length ( $L$ ) is the maximum distance a fish can possibly see and is a pre-defined value (Table 1.1). An object is visible if any part of it enters this view and is in the range of perception length. An object is not invisible if any other object is present in-between and obstructing its view (Figure 3.2). Let  $P$  is the forward vector of prey\_fish\_1 and  $Q$  is the direction vector from prey\_fish\_1 to predator. Then the view angle ( $\alpha$ ) is determined by

$$\alpha = \cos^{-1}((P \cdot Q) / \|P\| \|Q\|) \text{ where } 0 \leq \alpha \leq 300 \quad (3.1)$$

The view angle of prey\_fish\_2 is interrupted by the body of prey\_fish\_1 resulting in the loss of information about the visibility of predator even the predator is in the range of perception length. The above discussed parameters provide fish with visual information that is object visibility ( $V$ ) and distance to object ( $D$ ). If the  $\alpha$  is in the range  $0 \leq \alpha \leq 300$  and  $L$  is in the range of pre-defined value,  $V = 1$  else  $V = 0$ . The distance ( $D_{ij}$ ) between two objects is determined from the position

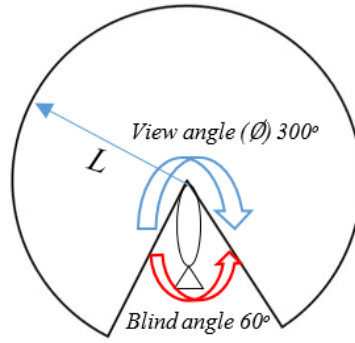


Figure 3.1 Visibility of Fish

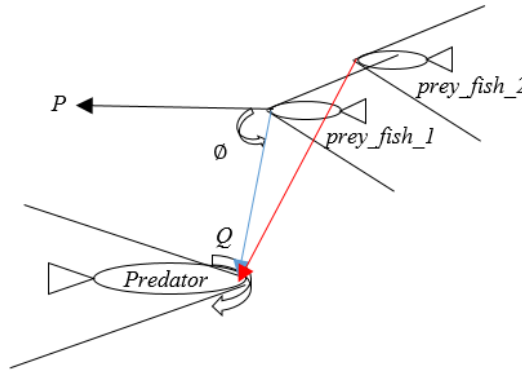


Figure 3.2 View angle of prey fish\_2 is occluded by prey fish\_1

values in three-dimensional world,  $P1(x_i, y_i, z_i)$  is the position of object 1 and  $P2(x_j, y_j, z_j)$  is the position of object 2.

$$D_{ij} = |P2(x_j, y_j, z_j) - P1(x_i, y_i, z_i)| \quad (3.2)$$

The other sensory organ lateral line runs through the body of fish and it is used in a wide range for intra and inter specific behaviors like schooling and prey/predator interactions. However, this perception is not considered in the predator model as the predator is single fish and there is no need to sense the vibrations of the neighbor fish. Instead, vision perception is used in prey selection.

### 3.2 Prey Selection Model

In nature, the large complex schools visually attract a predator and the predator selects the target first before it decides to swim. In this proposed model, predator targets the isolated peripheral fish among the large network of fish school. The isolated peripheral value ( $IP_n$ ) is calculated (Equation 3.3) for each prey fish  $n$  in fish school by determining four normalized factors: vulnerability ( $V_n$ ), average neighbor distance ( $AND_n$ ), prey distance ( $PD_n$ ) and visibility factor ( $E_n$ ). If the prey is in predator's field of view then  $E_n$  is set to one, otherwise zero. The  $IP_n$  for each prey fish in a school is expressed as below.

$$IP_n = E_n * (\alpha * V_n + \beta * AND_n + \gamma * PD_n) \quad (3.3)$$

*Vulnerability Factor (V).* The vulnerability factor contributes to a major part in determining the isolated peripheral fish in 3D space. This factor is defined for tree graphs and analyzes the structural properties of graphs. It chooses leader positions to transfer information or signals efficiently to all the other nodes in the network and also identifies vulnerable nodes at the time of failure attacks on nodes or edges. In the graph, the leaf nodes, identified with high vulnerability values are the peripheral nodes. If the fish school is considered as a complete graph of a complex network with tree generated from the complete graph, then vulnerability property can be leveraged to find the peripheral fish. To generate a tree from the graph, the minimum spanning tree would be the best choice because of the minimum total weighting for its edges to achieve group model (flock centering). The definition of vulnerability factor and determination of vulnerability value for a tree graph (node one) is given below (Figure 3.3).

*Definition.* Let  $G$  be a tree graph,  $i$  be the node and  $e_{ij}$  is the number of edges in the path connecting  $i, j$  nodes. The vulnerability value for a node  $i$  is given by [60]

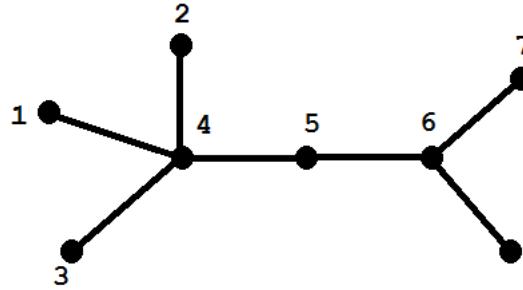


Figure 3.3 Graph with vulnerable nodes 1, 2, 3, and 7

$$V(i) = \sum_{j \in G} e_{ij} \quad (3.4)$$

Example:  $V(1): e_{12} + e_{13} + e_{14} + e_{15} + e_{16} + e_{17} + e_{18} = 2 + 2 + 1 + 2 + 3 + 4 + 4 = 18$

*Average Neighbor Distance Factor (AND).* The average neighbor distance factor is defined as the average of the distances between fish and its neighbor fish in a tree. The greater average distance indicates that the fish is far from its neighborhood. This factor plays a significant role in choosing more isolated when two peripheral fishes have the same vulnerable value. For instance, in a tree graph, two leaf nodes with the same parent node will end up having the same vulnerability factor.

*Prey Distance Factor (PD).* The prey distance factor is the inverse of distance between predator's position and prey's position in 3D space. The vulnerable and isolated nodes determined from the above two factors are distributed all over 3D space. It is more likely that, in nature, predator attacks nearest prey and this prey distance factor will help in determining the most isolated peripheral prey fish closer to the predator's field of view.

### 3.3 Predator Behavior Model

In this section, how to simulate the behavior of a predator fish is discussed. In attacking a prey fish school, the predator fish has two main tasks: disorganizing the fish school structure and feeding on the isolated individuals [27]. In the proposed behavior model, only the first task is considered for interactions that is disrupting the fish school structure.

A predator fish's behavior is modelled with a finite state machine that contains three states: *predator\_Presence* ( $P_S$ ), *predator\_Chase* ( $P_C$ ) and *predator\_Attack* ( $P_A$ ). The predator fish changes from one state to another without any pre-conditions and its new position ( $P_{np}$ ) is updated every frame using Equation (3.5). Its direction  $Di$  is the vector that points from the predator's current position ( $P_p$ ) to the goal position ( $G_P$ ) as shown in Equation (3.6).

$$P_{np} = P_p + S_P * \Delta t * \widehat{Di} \quad (3.5)$$

$$Di = P_p - G_P \quad (3.6)$$

where  $S_P$  is the speed of the predator,  $\Delta t$  is the time between two frames and the goal position ( $G_P$ ) is chosen based on the state the predator is in (*predator\_Presence*, *predator\_Chase* and *predator\_Attack*).

In *predator\_Presence* ( $P_S$ ) state, the goal position is a random 3D position that maintains a distance greater than the minimum approach distance ( $M_{AD}$ , as defined in Table 1.1 ) to a prey fish school ( $D_{PC} > M_{AD}$ ). The distance ( $D_{PC}$ ) to the prey fish school is determined as the distance from the predator's position ( $P_p$ ) to the prey fish school's centroid ( $G_c$ ).

In *predator\_Chase* ( $P_C$ ) state, the predator always chases the prey fish school from the back. Therefore, the predator's goal position is always directed towards a prey fish located at the back of the school while maintaining a distance  $M_{AD}$  ( $D_{PC} = M_{AD}$ ) with the prey fish school. This prey fish is termed as the back-prey fish. The back-prey fish ( $f_b$ ) (Figure 3.4) is the fish with the largest

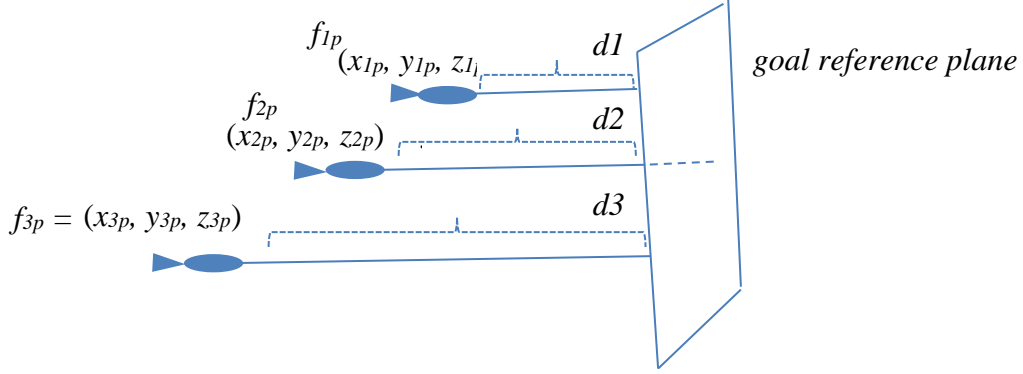


Figure 3.4 Back-prey fish ( $f_B$ ) is at position  $f_{3p} (x_{3p}, y_{3p}, z_{3p})$ .

perpendicular distance to a plane (goal reference plane). The goal reference plane is orthogonal to all the planes formed by connecting the centroid of the prey fish school ( $G_c$ ), goal position of prey fish school ( $G_{pr}$ ) and with each prey fish positions ( $f_{ip}$ ). The goal position of the prey fish school ( $G_{pr}$ ) is a random 3D point that gives the direction for the prey fish school to move in 3D world.

In *predator\_Attack* ( $P_A$ ) state, the predator attacks the prey fish school either at their centroid or at the peripheral. The peripheral attack has six possibilities: *attack\_front*, *attack\_back*, *attack\_top*, *attack\_bottom*, *attack\_left*, and *attack\_right*. The predator's goal position is determined with respect to these six states. For example, *attack\_back* means the predator will attack a group of peripheral back-fish nearest to the predator, their average center is the goal position for the predator fish, and the predator maintains a distance of less than  $M_{AD}$  ( $D_{PC} < M_{AD}$ ) with the prey fish school.

### 3.4 Prey Perception Model

A prey fish's behavior depends on its perception. The proposed prey perception model is based on the work of Partridge and Pitcher [32], who conducted detailed experiments and analysed the effects with blindfolding and lateralis section on school of fish. This perception model has three ways of receiving information: visual, lateral, and prey-to-prey communication system. I have

improved the perception model by adding communication factors discussed in detail in *Prey-to-prey Communication System*.

### **3.4.1 Visual Perception**

The prey perception model is similar to the predator visual perception model (Equation 3.1), prey fish has a vision with a field of view of 300 degrees' spherical angle and a blind angle of 60 degrees [61]. This visual perception model provides information about the vision ( $V=0$  indicates not visible or 1 indicates visible). It also provides additional information about nearest neighbor distance ( $NND$ ), fear of predator ( $Fe_f$ ), and direction to move ( $Di$ ) for each prey fish.

### **3.4.2 Lateral Perception**

In general, swimming fish generate ripples that can be detected by other fish's lateral perception system. The lateral line organs run through the body of a fish and are used in a wide range of tasks, such as schooling and prey/predator interactions [32]. In the lateral perception model for prey fish, information about neighbor's speed  $S$  and the predator's ripple force ( $F_{iR}$ ) are sensed by each prey fish through lateral perception. For instance, when a predator approaches a school of prey fish, its presence is perceived through the ripple force. The ripple force ( $F_{iR}$ ) among the prey fish is ignored because it is negligible with respect to the predator. The prey fish closer to the predator tend to perceive stronger force sooner than the prey fish that are farther from the predator [44].

### **3.4.3 Prey-to-prey Communication System**

Prey-to-prey communication system is used in situations where some of the prey fish in school cannot see the predator or do not experience the predator's ripple force ( $F_{iR}$ ). Prey fish who see the predator or experience ripple force first are called leaders. They communicate the values of  $S$ ,  $NND$ , and  $Di$  to the nearest neighbors (followers) who further send them 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. If the information is received, communication factor  $R_i$  is set to 1 for the follower fish. Otherwise, it is set to 0. The average information transfer ( $I_T$ ) in the fish school is calculated as below

$$I_T = \sum R_i / n \quad (3.7)$$

where  $n$  is the number of followers,  $I_T = 1$  if all the followers in the fish school receive the information.

The perception factors vision ( $V$ ,  $NND$ ,  $Di$ ), lateral ( $S$  and  $F_{iR}$ ), and communication ( $I_T$ ) act as triggers and pre-conditions (Figure 3.5) for prey fish behavior that are discussed in detail in *Prey fish escape maneuver behavior models*.

### 3.5 Prey Fish Escape Behavior State Machine Model

The prey fish behavior is determined by a finite state machine (Figure 3.5). The proposed state machine consists of a set of escape maneuvers, with the transitions from one maneuver (state) to other (state) based on certain input conditions such as visual, lateral, and communication factors. The transitions among these escape behaviors are based on the biological studies [24, 25, 27, and 61]. For example, when a predator is detected, the prey fish may form the shape of a *ball* [24]. If the predator attacks, the prey fish use the *Split* maneuver and then regroup into a *compact* school or break down completely [25]. Prey fish school may exhibit the *vacuole* maneuver if they are large enough, otherwise they may use the *hourglass* maneuver when attacked [27]. The *Herd* pattern is observed when they are chased by a predator [27]. The *Fountain* maneuver is preceded by the *herd* maneuver when a predator attack [27]. This proposed state machine also incorporates the rules proposed by Reynolds [1]: separation, alignment, and cohesion. For example, in the



fountain maneuver, when the fish school split and move in an arc shape, the fish in the individual sub-groups follow Reynolds' rules, which drive the fish to school again.

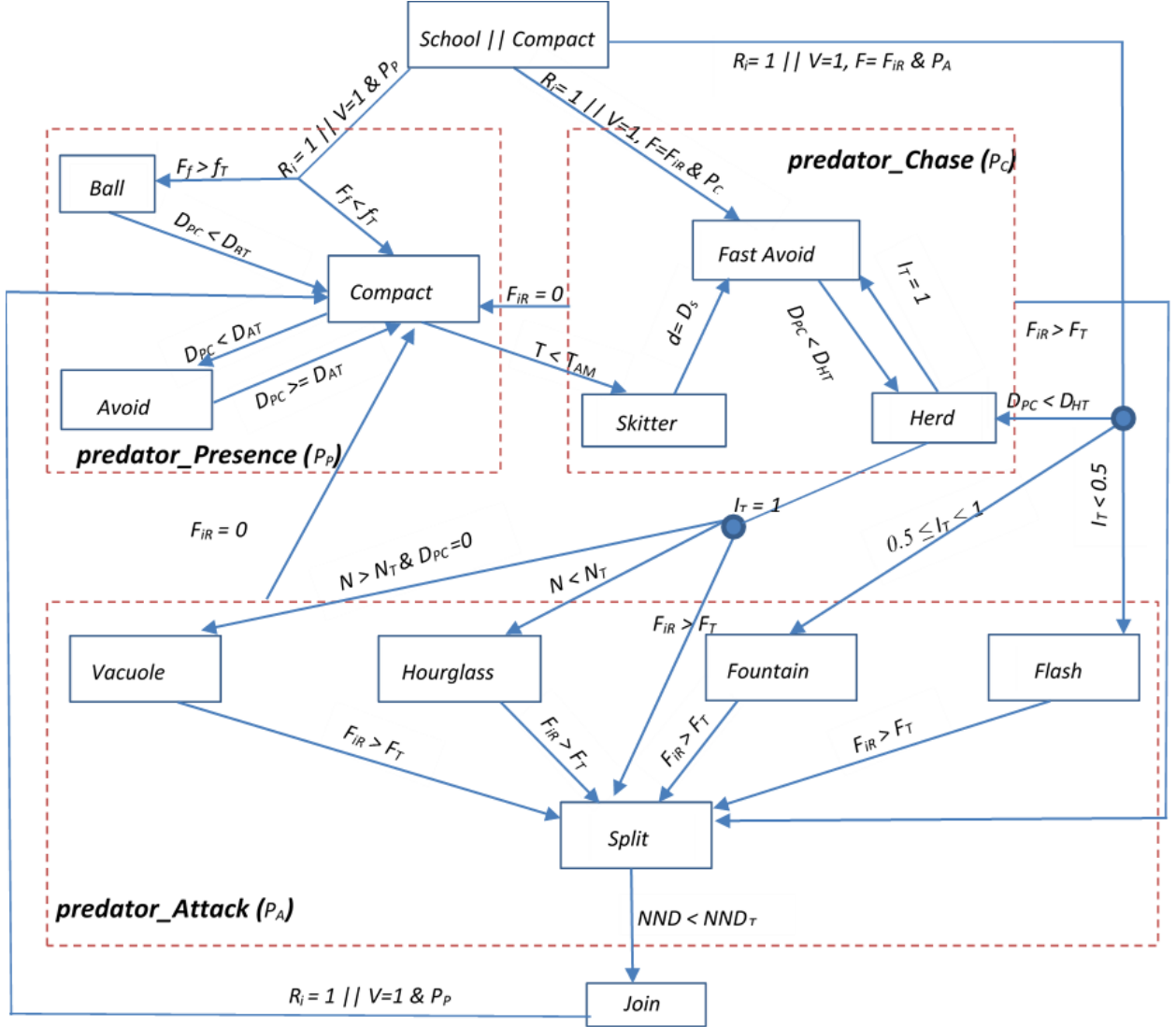


Figure 3.5 Prey fish escape behavior state machine model. The variables are described in Table 1.1.

The escape maneuvers in the state machine are grouped based on three predator states (*predator\_Presence*, *predator\_Chase* and *predator\_Attack*). Details on each escape maneuver are discussed in section *Prey fish escape maneuver behavior models* section. Here is an overview.

In the *predator\_Presence* ( $P_P$ ) state of predator, the vision ( $V=1$ ) or communication ( $R_i$ ) and fear factors ( $F_{ef}$ ) trigger the prey fish school to form either a *ball* or *compact* pattern. If the fear factor is greater than the threshold ( $F_{ef} > F_{et}$ ), as defined in Table 1.1, they use *ball* maneuver. The *ball* maneuver persists until the predator reaches the *ball*. If the predator is within a threshold distance ( $D_{PC} < D_{BT}$ ), the *ball* disperses into the *compact* maneuver. ( $D_{BT}$  is defined in Table 1.1). The *compact* maneuver can be triggered by either the vision or communication system. In the case of a communication-based trigger, a few prey fish sense the predator ( $V=1$ ) first and then communicate the speed and direction to the followers and move into the *compact* state. The *compact* maneuver is maintained as long as the distance to the predator is above the threshold ( $D_{AT}$ , as defined in Table 1.1). Otherwise, the fish school enter the *avoid* maneuver. This *avoid* state can transit back to the *compact* state if the prey fish school move away from the predator until the distance ( $D_{PC}$ ) is greater than the threshold avoid distance ( $D_{AT}$ ).

In the *predator\_Chase* ( $P_C$ ) state, vision, communication, or lateral factors ( $V$ ,  $R_i$ , and  $F_{iR}$ ) can trigger the prey fish school to exhibit *fast avoid* maneuver. The *fast avoid* maneuver is sometimes preceded by the *skitter* maneuver and followed by the *herd* maneuver. If the *compact* school is suddenly chased by the predator and do not have enough time ( $T < T_{AM}$ , as defined in Table 1.1) to directly avoid the predator, the prey fish school first exhibit *skitter* where each prey fish skitters for a certain distance (skitter distance  $d = D_s$ , as defined in Table 1.1), and then the *skitter* maneuver changes to the *fast avoid* maneuver. The transition from *fast avoid* to *herd* maneuver occurs if the predator approaches the prey fish school with less than the herd distance ( $D_{PC} < D_H$  as defined in Table 1.1), and the fish school will go back to the *fast avoid* if the information is transferred among all the followers in the prey school ( $I_T = 1$ ). The *herd* state is also reached from the *predator\_Attack* state and can be merged into the *predator\_Attack* escape maneuvers.

In the *predator\_Attack* state ( $P_A$ ), the visual, lateral, and communication factors trigger the *flash*, *fountain*, *split*, *vacuole*, and *hourglass* maneuvers. The *flash* maneuver is exhibited if  $I_T < 0.5$  (the direction to move away from the predator and the speed information is transferred to fewer than half of the total followers in the prey school, and leaders senses the predator either by visual perception or lateral perception). The prey fish school display the *fountain* maneuver by splitting the fish school into two opposite directions if  $I_T$  is in the range (0.5, 1). The *vacuole* or *hourglass* maneuver -- always preceded by the *herd* maneuver -- is exhibited when all the follower fish receive information ( $I_T = 1$ ). The *vacuole* maneuver is exhibited only when the number of fish ( $N$ ) is greater than the threshold number ( $N_T$ , as defined in Table 1.1) and  $D_{PC}$  is zero.

All these escape maneuvers in  $P_C$  and  $P_A$  states will transit to the *split* maneuver if the predator's ripple force is greater than its respective state's threshold force ( $F_{iR} > F_T$ , as defined in Table 1.1) or transit to the *compact* state if  $F_{iR}$  reaches zero. The split sub-groups can *join* and form a school again if any of the fish in the sub-groups are within threshold nearest neighbor distance ( $NND < NND_T$ ).

### 3.6 Prey Fish Escape Maneuver Behavior Models

#### 3.6.1 Compact Maneuver.

In the *compact* maneuver, the prey fish form a densely packed school (with low nearest neighbor distance  $NND$ ). This maneuver is categorized under *predator\_Presence* ( $P_p$ ).

*Pre-States.* A prey fish enters the *compact maneuver* either from the escape maneuvers (*ball*, *avoid*), in  $P_p$  with respective pre-conditions (Figure 3.5), or from maneuvers in *predator\_Chase*. Or they can move into *compact* from *school* or *join*.

*Compact.* This maneuver is composed of two states: *alert\_Compact* and *reaction\_Compact*. In the *alert\_Compact* state, the leaders enter the *communicate* sub-state, transfer the information

about the new nearest neighbor distance ( $NND_N$ , Equation (3.8)) to the followers, and move to the *reaction\_Compact* state as shown in Figure 3.6. After the follower fish receive the information ( $R_i = 1$ ), they move to the *reaction\_Compact* state. Some prey fish are designated to be leaders in this maneuver if the predator is visible to them ( $V = 1$ ). The leaders start exhibiting compactness earlier than their followers.

$$NND_N = NND_C / f_d \quad (3.8)$$

where  $NND_C$  is the current nearest neighbor distance of the fish school and  $f_d$  is the distance factor that varies with respect to the maneuver.

In the *reaction\_Compact* state, all the prey fish *school* together with the determined  $NND_N$ , and with the same speed and direction as the *school* maneuver.

*Post-States.* All the other escape maneuver states can be reached from the *compact* maneuver state.

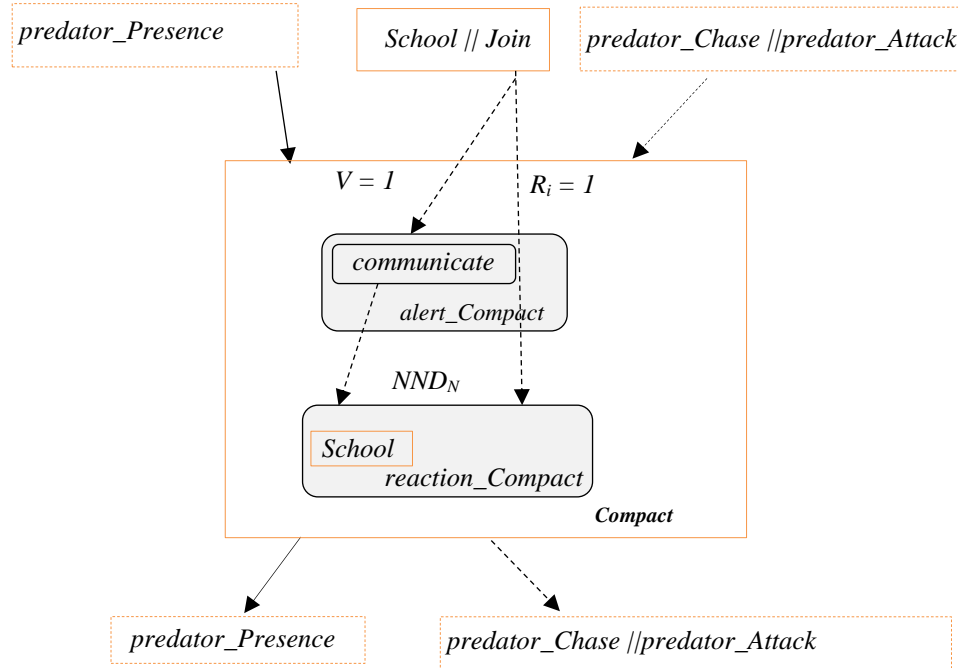


Figure 3.6 Compact maneuver state machine behavior model.

### 3.6.2 Avoid Maneuver

In the *avoid* maneuver, a prey fish swim away from a predator until it reaches a distance greater than  $D_{AT}$  (defined in Table 1.1) from the predator. The state machine for the *avoid* maneuver (Figure 3.7) is similar to that of the *compact* maneuver. In addition to exhibiting the compactness, the prey fish alter the course of their direction to avoid the predator.

*Pre-States.* A prey fish enters the *avoid* maneuver either from the *compact* or *skitter* with respective to pre-conditions (Figure 3.5). The other possibility is to enter from the *herd* state. The predator is in either *predator\_Presence* or *predator\_Chase*.

*Avoid.* In the *alert\_Avoid* state, the leaders *communicate* the new direction  $Di_N$  (opposite to the predator) to the followers. The followers reach the *reaction\_Avoid* state after the leaders, and then they school together with  $Di_N$ .

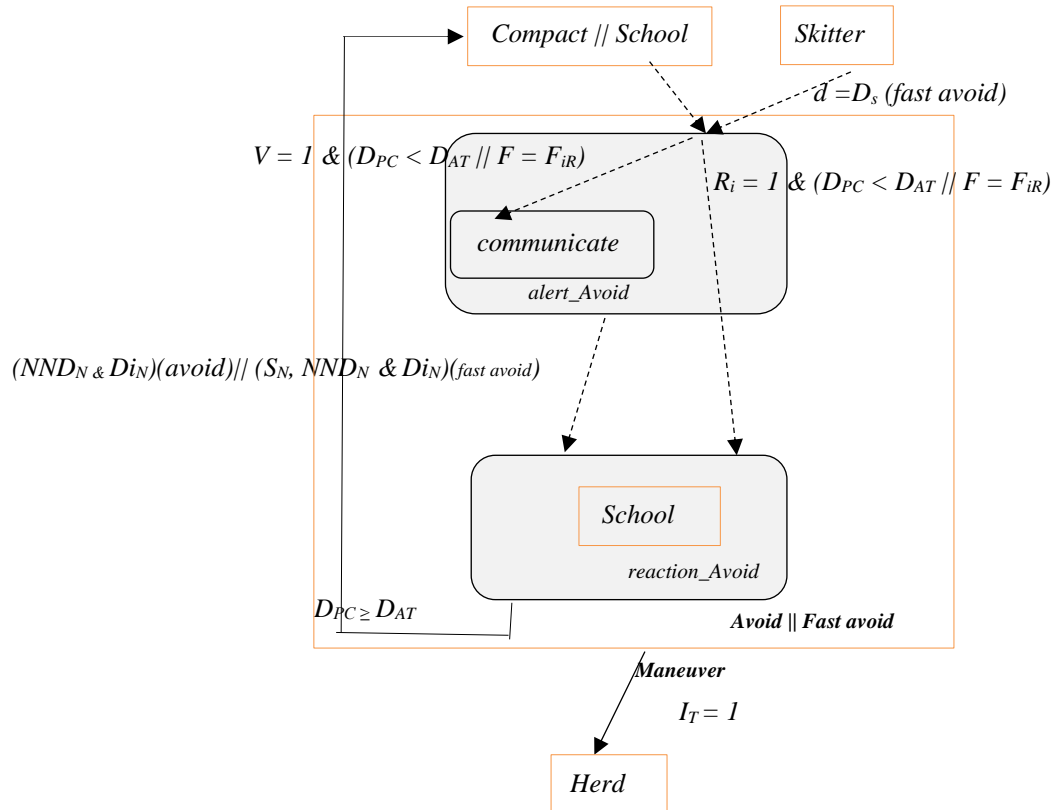


Figure 3.7 Avoid maneuver state machine behavior model.

*Fast avoid* is similar to the *avoid maneuver*. The only difference is that the prey fish move away from the predator with much greater speed (Equation (3.9)) than the normal *avoid* behavior due to the ripple force ( $F_{iR}$ ) from the predator (*predator\_Chase*). This new speed and new direction are communicated by the leaders to the followers before reaching the *reaction\_Avoid* state.

$$S_N = S_C * f_s \quad (3.9)$$

where  $S_C$  is the current speed of the fish school,  $S_N$  is the new speed of the fish school,  $f_s$  is the speed factor that varies with respect to the maneuver.

*Post-States.* As soon as the prey fish school move away from the predator, they enter the *compact* state with the condition  $D_{PC} \geq D_{AT}$  (Figure 3.5). Another possible transition is to the *herd* state. Prey fish school may switch back and forth between the *fast avoid* and *herd* states at the time of *predator\_Chase*.

### 3.6.3 Ball Maneuver

In ball maneuver, prey fish form a compact ball and rotate around a center. This maneuver is exhibited under *predator\_Presence*.

*Pre-States.* The prey fish form a ball shape either from the *compact* or *school* state.

*Ball.* In *alert\_Ball* state, a global center ( $G_B$ ) is generated for prey fish school. This global center is located either to the left or right of the school centroid ( $G_c$ ). Later they move into the reaction state (*reaction\_Ball*).

The *reaction\_Ball* state is divided into two sub-states: *reach\_targetPosition* and *rotate\_Around*. In *reach\_targetPosition* sub-state (Figure 3.8), each prey fish reaches the global center ( $G_B$ ) generated in *alert\_Ball* and adjusts its position to avoid collision with the neighbors. After the *reach\_targetPosition* sub-state, the fish move into the *rotate\_Around* sub-state. In this sub-state, each fish rotates around a center ( $G_B$ ) with a speed  $S_N$  (Equation (3.9)). All these motions

result in a ball shape and the position of each prey fish in the ball is updated using polar coordinates in Equation (3.10).

$$f_{ip} = (r \cos \theta \sin \phi, \quad r \sin \theta \sin \phi, \quad r \cos \phi) \quad (3.10)$$

$$\text{where } r \in (0, r_x), \theta \in [0, 2\pi) \text{ and } \phi \in [0, \pi]$$

parameter  $r_x$  depends on the number of fish. The fish ball is composed of multiple layers, and the number of fish ( $n$ ) on each layer is given below.

$$n = 4\pi r_i^2 / (C_1 * BL) \quad (3.11)$$

where  $r_i$  is the radius,  $C_1$  is a constant, and  $BL$  is the body length of prey fish.

*Post-States.* The *ball* maneuver disperses after the predator is away for a distance greater than the ball threshold ( $D_{BT}$ ) defined in Table 1.1. The only possible state after the *ball* state is the *compact* state.

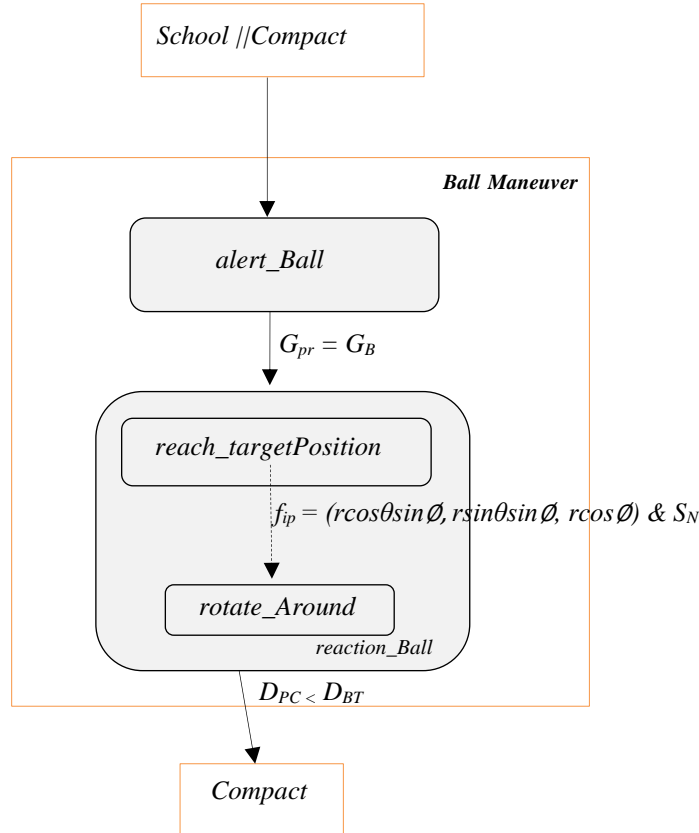


Figure 3.8 Ball maneuver state machine behavior model.

### 3.6.4 Herd Maneuver

In the *herd* maneuver, prey fish find themselves ahead of the predator and move radially forward, forming a scalloped rear edge. This maneuver is exhibited in the *predator\_Chase*.

*Pre-States.* Prey fish enter the *herd* state either from the *compact* state or the *fast avoid*, with the pre-conditions defined in Figure 3.5.

*Herd.* In this *alert\_Herd* state, the leaders and followers are designated based on their positions with respect to the predator. The back-prey fish ( $f_{iB}$ ) within the herd radius range  $H_R$  (defined in Table 1.1) are the leaders, who communicate the speed ( $S_{iN}$ ) to the front fish (followers  $f_{iF}$ ) and then move to the *reaction\_Herd* state. The leaders then go to *move\_radially* and *compact* sub-states. The followers enter the *reaction\_Herd* state and move directly into the *compact* sub-state after they receive the information from the leaders (Figure 3.9).

In *move\_radially* sub-state, back-prey fish move radially forward in the directions as shown in Figure 3.10. These directions are determined based on the angle ( $\beta$ ), which is determined by the predator's direction vector and the vector joining the predator and prey fish positions. For instance, the fish that fall between the angles 0 to 45 move straight, and the fish that fall between the angles 45 and 90 move slightly to the right. The speed ( $S_{iN}$ ) for each prey fish varies based on the ripple force from the predator. The front-prey fish speeds are slower than the back-prey fish speeds (Equation 3.12). They move radially forward until their *NNDs* are less than the collision threshold ( $C_T$  defined in Table 1.1). The overall direction is to move away from the predator in the three-dimensional environment.

$$S_N = S_C * f_s \quad (3.12)$$

$$S_{iN} = S_N / d_{iP}$$



where  $S_C$  is the current speed of the fish school,  $f_s$  is the speed factor that varies with respect to the maneuver and  $d_{iP}$  is the distance from fish  $i$  to the predator.

*Post-States.* The *herd* state can transit to other patterns like *vacuole* and *hourglass* with the post-conditions defined in Figure 3.5. They may also transit from *herd* to *compact* and *avoid*. When attacked by a predator with  $F_{iR} > F_T$ , the fish school transit from the *herd* state to the *split* state because they cannot stay together any more.

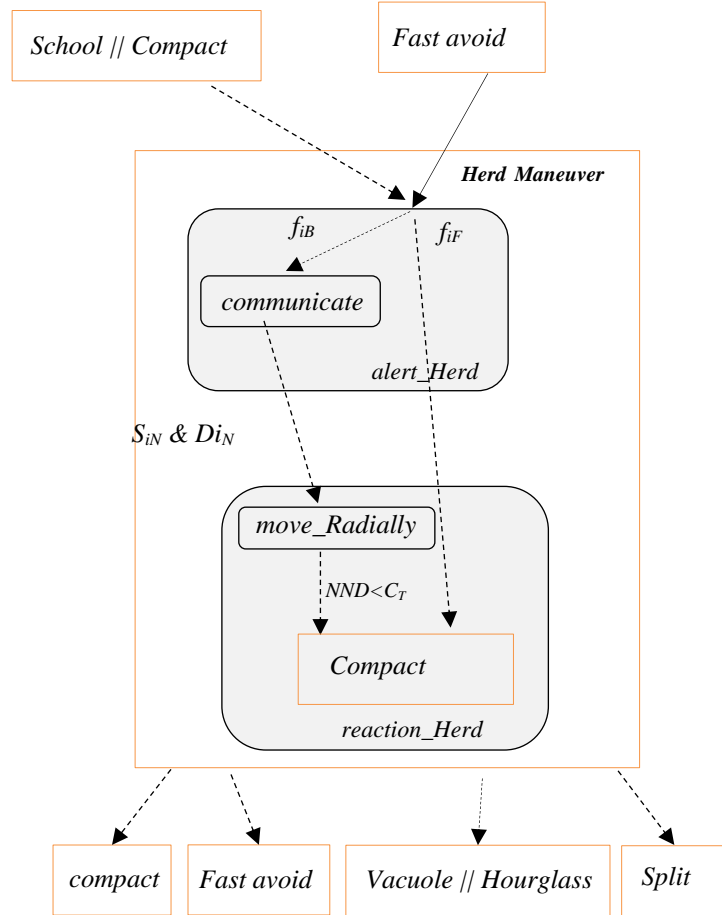


Figure 3.9 Herd maneuver state machine behavior model

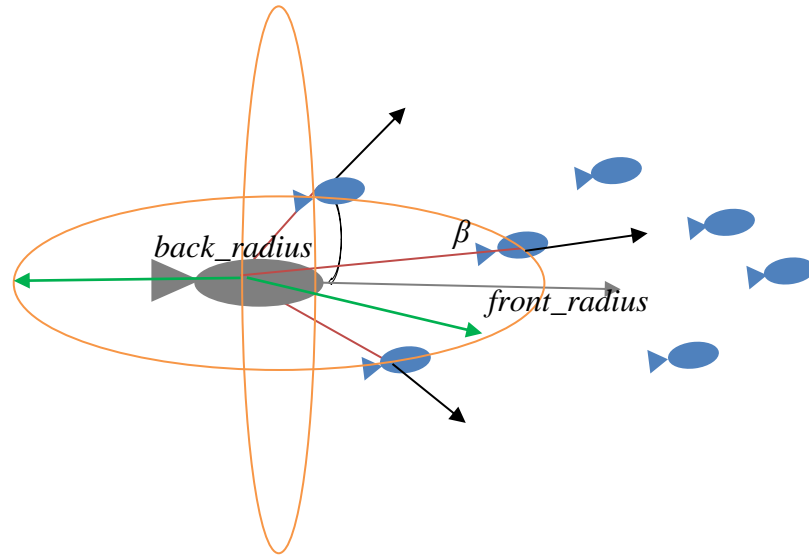


Figure 3.10 Prey fish fall in the sphere radius (herd radius range  $H_R$ ) are categorized based on angle ( $\beta$ ), from which the direction (black arrows) of radial movement for each prey fish is determined.

### 3.6.5 Vacuole Maneuver

In the *vacuole* maneuver, the prey fish school encloses the predator when the predator moves rapidly through the fish school. The resulting formation looks like a vacuole (elliptical form).

*Pre-States.* The herd maneuver discussed above can be extended into the vacuole maneuver (Figure 3.5).

*Vacuole.* In the *alert\_Vacuole* state, the prey fish that fall in the *back\_radius* (Figure 3.10) (fish behind the predator ( $f_{ibehPred}$ )) move to the *surround* sub-state within the *reaction\_Vacuole* state, while the other fish move to the *compact* state with speed  $S_N$  (Figure 3.11). In the *surround* sub-state, the prey fish ( $f_{ibehPred}$ ) enclose the predator. That is, the prey fish on the left and right move towards the centroid with varying speed  $S_{iN}$  (Equation 3.12) until they reach the threshold collision distance  $NND > C_T$ , and then they school along with the predator and rest of the prey fish ( $f_{ibehPred}$ ) with the same speed as in the *herd* state in the original direction.

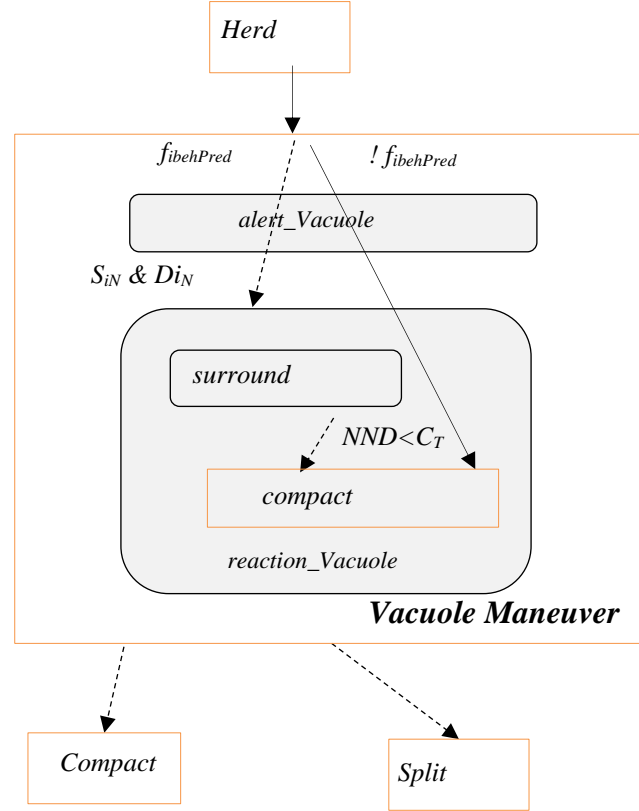


Figure 3.11 Vacuole maneuver state machine behavior model.

*Post-States.* After the *vacuole* state, the prey fish enter the *compact* state. If the predator attacks (with  $>F_{iR}$ ), they exit the *vacuole* state and enter *split*.

### 3.6.6 Fountain Maneuver

In the *fountain maneuver* state, the prey fish increase speed, divide, turn around (in a semi-circle), and join behind the predator. The predator is in *predator\_Attack* state and may attack at any side of prey fish school.

*Pre-States.* The *fountain* state is reached either from the *school* or *compact* state with pre-conditions defined in Figure 3.5.

*Fountain.* In the *alert\_Fountain* state, the school is divided into two halves (right and left). Gravity centers ( $G_{ic}$ ) are generated for each prey fish to rotate around and exhibit the *fountain*

pattern (Figure 3.12). In 3D world, the right and left subgroups are determined by creating a simplified 2D local axis on the  $PG$ - $PG^\perp$  plane (Figure 3.13), as the third dimension (y-vertical axis) is not required to determine the left or right positions of the prey fish. The  $PG$ -axis is the line joining the predator position ( $P_p$ ) and prey school centroid ( $G_c$ ), and  $PG^\perp$ -axis is perpendicular to the  $PG$ -axis passing through the centroid  $G_c$ . To determine which side of the  $PG$ -axis that each prey fish should fall (right or left), project the goal position ( $G_{pr}$ ) to the  $PG^\perp$ -axis ( $goal\_intercept$ ), and then find out which side this point falls with respect to  $PG$ -axis, which is determined by checking  $intercept\_Direction$  (Equation 3.13)  $> 0$  or  $< 0$ .

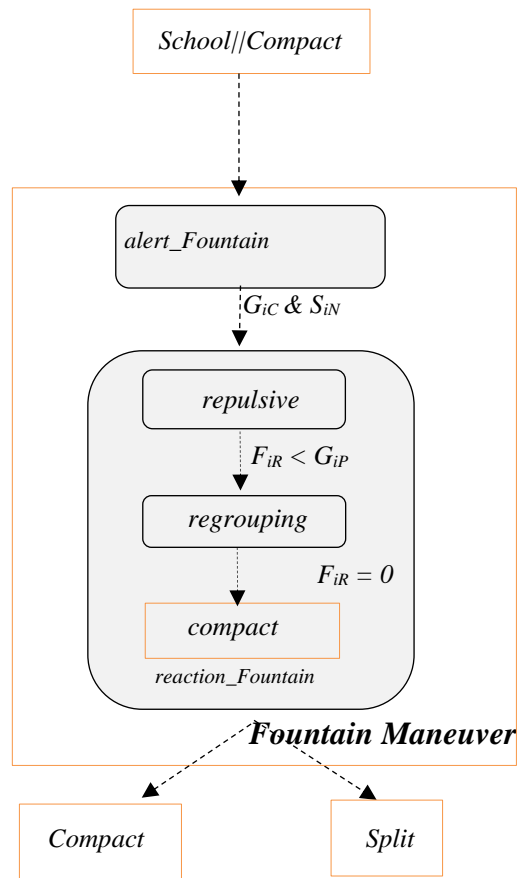


Figure 3.12 Fountain maneuver state machine behavior model

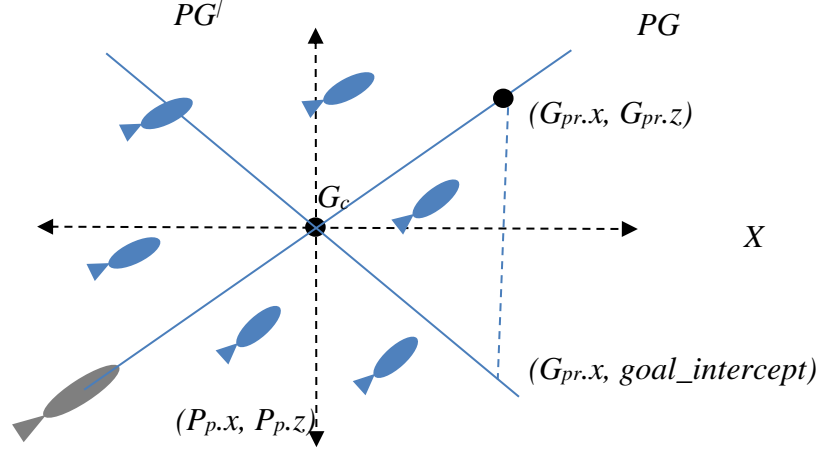


Figure 3.13 Determining left and right fish.

The equation for calculating *intercept\_Direction* is shown below.

$$\begin{aligned} \text{intercept\_Direction} = & (\text{goal\_intercept.x} \\ & - P_{p.x}) * (G_{pr.z} - P_{p.z}) - (\text{goal\_intercept.z} - P_{p.z}) * (G_{pr.x} - P_{p.x}) \end{aligned} \quad (3.13)$$

Similarly, by checking *fish\_Direction* > 0 or <0, we can determine which side a prey fish (*f<sub>iP</sub>*) falls with respect to PG-axis. Based on *intercept\_Direction*, *fish\_Direction*, and the direction of the prey school, we can determine whether a prey fish falls on the right side or left side of PG-axis. For instance, if *intercept\_Direction* and *fish\_Direction* have the same sign (>0 or <0), then they are on the same side of the PG axis.

In the *reaction\_Fountain* state, the ripple force  $F_{iR}$  pushes away the two subgroups into opposite directions (*repulsive* sub-state) and the  $G_{iC}$  generated (in *alert\_Fountain* state) for each prey fish acts as gravity pulling force ( $G_{iP}$ ). The two opposite forces (gravity pulling force and predator ripple force) rotate each fish in an arc shape. The prey fish that are closer to the predator experience greater ripple force  $F_{iR}$  and are pushed away by stronger forces ( $F_{iR}$ ). As a result, their

curved paths have larger radii. As the predator moves away,  $F_{iR}$  decreases and  $G_{iP}$  increases, and the prey fish rejoin behind the predator (*regrouping* sub-state) and move into the *compact* pattern. In these sub-states (*repulsive* and *regrouping*), the prey fish react with accelerated speed determined in Equation 3.12.

*Post-States.* From the *fountain* maneuver, the prey fish enter the *compact* state. If the predator attacks (with  $>F_{iR}$ ), the prey fish exit the *fountain* state and enter *split*.

### 3.6.7 Hourglass Maneuver.

In the *hourglass* maneuver, part of the fish school is compressed, forming an hourglass shape. The predator is in *predator\_Attack* state and generally attacks at the back of the prey fish school.

*Pre-States.* Similar to the *vacuole* maneuver, the *herd* maneuver can be extended into the *hourglass* maneuver. That is, after the *herd* maneuver, the prey fish school is compressed at the center. With the prey fish turning around in the same direction to move away from the predator, an hourglass shape is formed.

*Hourglass.* There are two steps in the *hourglass maneuver*: depression formation (*herd* maneuver) and turn around in the same direction (Figure 3.14).

In *alert\_Hourglass* state, prey fish form three groups: left, center and right as shown in Figure 3.15. The leader group is on the left, and the direction ( $Di$ ) is sent (*communicated*) to the other two follower groups. After that, the leader group move into the *reaction\_Hourglass* state. After receiving the information, the followers move into the *reaction\_Hourglass* state.

In the *reaction\_Hourglass* state, the predator ripple force ( $F_{iR}$ ) makes the leaders turnaround (new  $Di$ ) from the predator with speed  $S_{iN}$  (Equation 3.12), and then the followers follow the leaders by turning towards them with a large radius in *turn\_Around* sub-state. The more

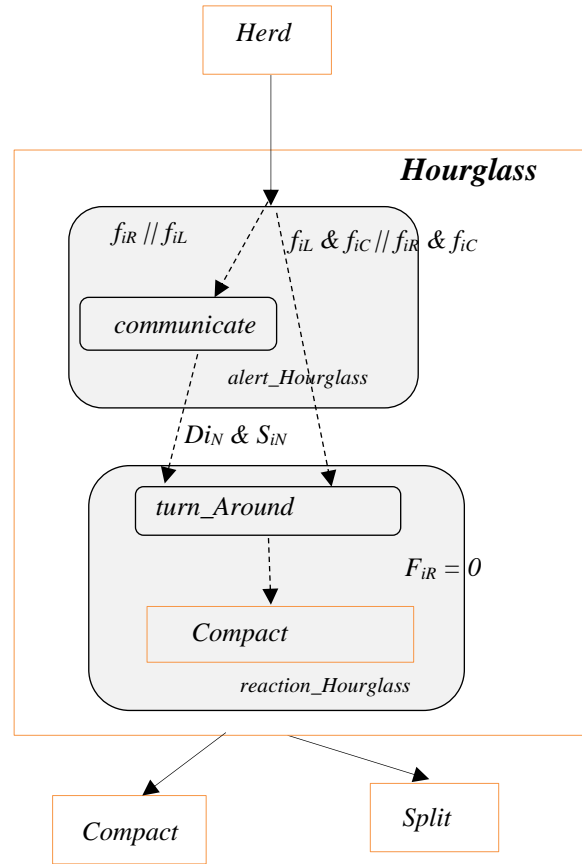


Figure 3.14 Hourglass maneuver state machine behavior model

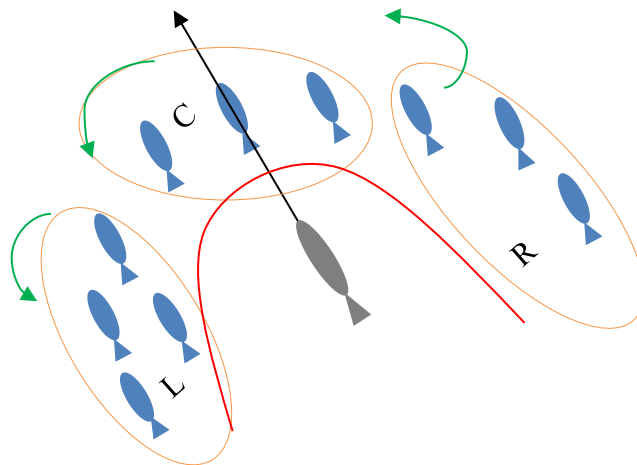


Figure 3.15 Prey fish are categorized into left (L), center (C) and right (R) subgroups with respect to the direction vector of the predator. The red curve indicates the depression formed by the herd maneuver.

the distance a prey fish is from the predator's direction vector, the larger the turning radius is for the prey fish. The speed varies for each prey fish with respect to the intensity  $F_{iR}$ . Finally, all of them move into the *compact* sub-state.

*Post-states.* After the *hourglass* state, the prey fish school enter the *compact* state. If the predator attacks (with  $>F_{iR}$ ), the *hourglass* shape disperses, and the fish school enters *split* state.

### 3.6.8 Flash Maneuver

In the *flash* maneuver, the prey school explode and all the fish move in random directions. A few seconds later they form the school again. The predator is in *predator\_Attack* state and generally attacks at any side of prey fish school.

*Pre-States.* The *flash* state can be reached either from the *school* or *compact* state with pre-conditions defined in Figure 3.5.

*Flash.* In the *alert\_Flash* state (Figure 3.16), a direction is generated for each prey fish to move. Each prey fish's direction is calculated based on its horizontal escape angle ( $xz$  plane) and the vertical escape angle ( $y$ ) and the equations for these angles are shown below.

$$\alpha_h = C_2 * Sp_i \quad (3.14)$$

where  $\alpha_h$  is a horizontal escape angle,  $C_2$  is a constant,  $Sp_i$  is  $(z_c - z_{ip} / x_c - x_{ip})$ .

$$\alpha_v = C_3 \left( \frac{r_v}{d_{vi}} \right) \quad (3.15)$$

where  $\alpha_v$  is a vertical escape angle,  $C_3$  is a constant,  $r_v = y_m - y_n$ ,  $y_m$  is the  $y$  co-ordinate of the top most prey fish;  $y_n$ , is the  $y$  co-ordinate of the bottom most prey fish,  $d_{vi} = y_c - y_{ip}$ . A prey fish rotates either clockwise or counterclockwise based on the direction of  $\alpha_h$  and  $\alpha_v$ .



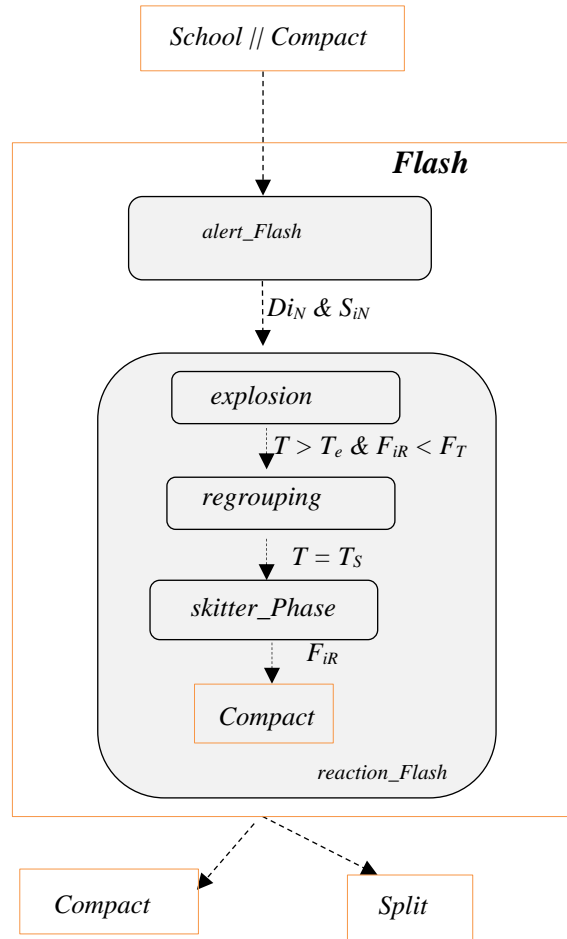


Figure 3.16 Flash maneuver state machine behavior model

In *reaction\_Flash* state, *explosion* sub-state, each prey fish moves very quickly (Equation 3.12) along its own path by rotating with the angles discussed above. The *Regrouping* sub-state is triggered after explosion time  $T_e$  (defined in Table 1.1) has passed. In this sub-state, the ripple force decreases as the predator moves away from the fish school and each prey fish turns back (with same speed from previous sub-state) towards its original position. On reaching their approximate original positions, they enter the *skitter* phase and startle for few seconds ( $T_s$ ) in random directions (this phase is a *skitter* maneuver), and then move to the *Compact* state (Figure 3.6). The *skitter* can also be a part of *predator\_Chase* state when the prey school is suddenly chased.

*Post-states.* After the *flash* state, the prey fish form the *compact* pattern.

### 3.6.9 Split Maneuver

In the *split* maneuver, the prey fish school split into sub-groups and each sub-group move in opposite or different directions.

*Pre-States.* *Split* can be a part of many escape maneuvers. For instance, if the *fountain* pattern cannot hold under attack, the fish school may split.

*Split.* The *alert\_Split* state is divided into two sub-states: *subgroup\_Form* and *communicate* (Figure 3.17). In *subgroup\_Form*, sub-groups are formed. The sub-groups are formed based on the number of leaders (number of leaders = number of sub-groups). The prey fish near the predator at the time of attack are designated as leaders ( $f_{iLd}$ ) and the number of leaders is random. The rest of the prey fish (followers  $f_{iFd}$ ) are grouped into these sub-groups based on the follower prey fish's distance to the leader ( $L_{dR}$ , as defined in Table 1.1). After the sub-groups are formed, the leaders move into the *communicate* sub-state and send the direction information to the followers in their respective sub-groups. The directions are determined based on the predator's direction as shown in Figure 3.18.

In the *reaction\_Split* state, the fish in the different sub-groups move into the *school\_subGroup* sub-state with varying speeds  $S_{iN}$  (Equation 3.12) and directions ( $D_{iN}$ ). In this sub-state, these sub-groups form individual schools and move away from the predator in the opposite directions.

*Post-states.* After the *split* pattern, the fish school *join* together.

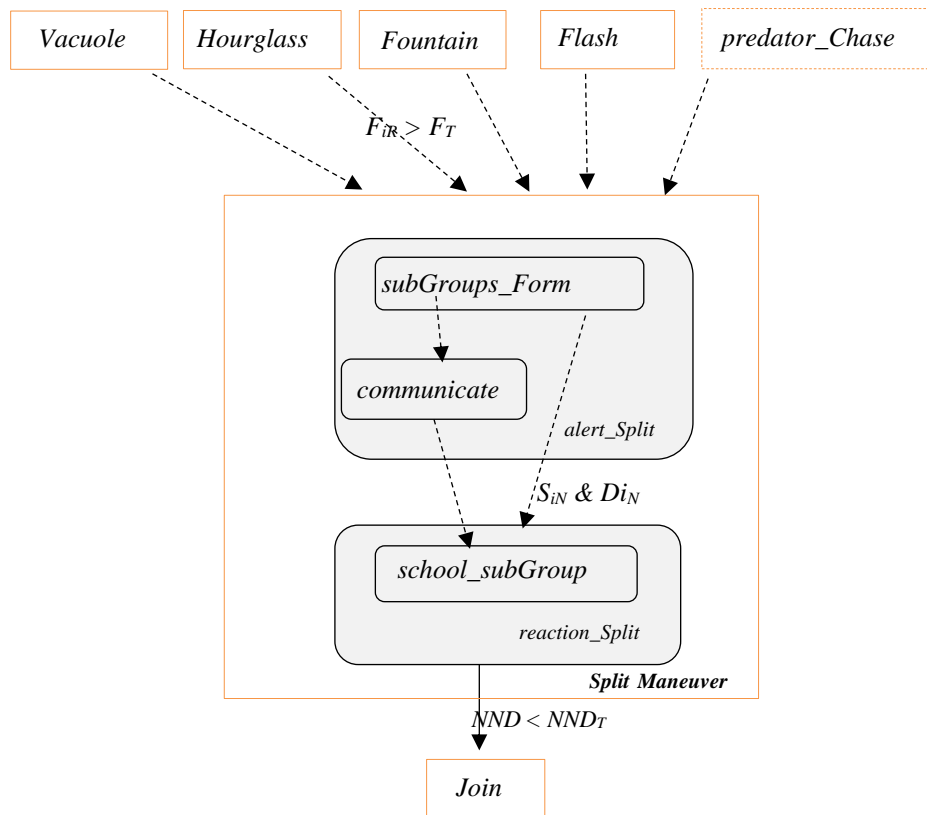


Figure 3.17 Split maneuver state machine behavior model

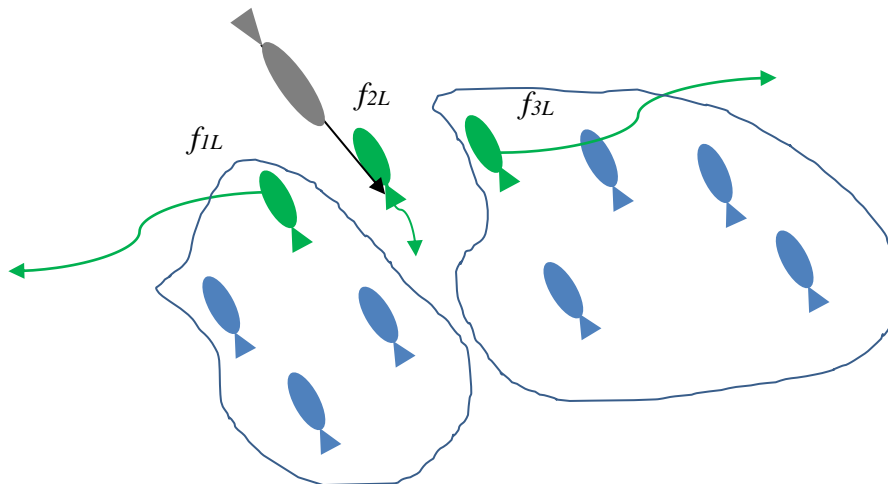


Figure 3.18 This figure shows the leaders ( $f_{iL}$ , green) with three sub-groups. The green arrows indicate the directions for the sub-groups to move away from the predator

### 3.6.10 Join Maneuver.

In the *Join* maneuver, the separated groups in a fish school rejoin. In this process, there will be a confusion zone at the intersection at first, and later they *school* together.

*Pre-States.* The prey fish enter the *join* maneuver after the *split* maneuver, if the predator is not present.

*Join.* In the *alert\_Join* state, the prey fish in each sub-group are grouped into front and back groups and move to the *reaction\_Join* state (Figure 3.19). In the *reaction\_Join* state, the leaders (at the front  $f_{iF}$ ) move in the direction (Equation (3.16)) determined from the  $n$  sub-group's goal direction ( $\hat{G}_{iSG}$ ) to form a school (*school\_Reform*).

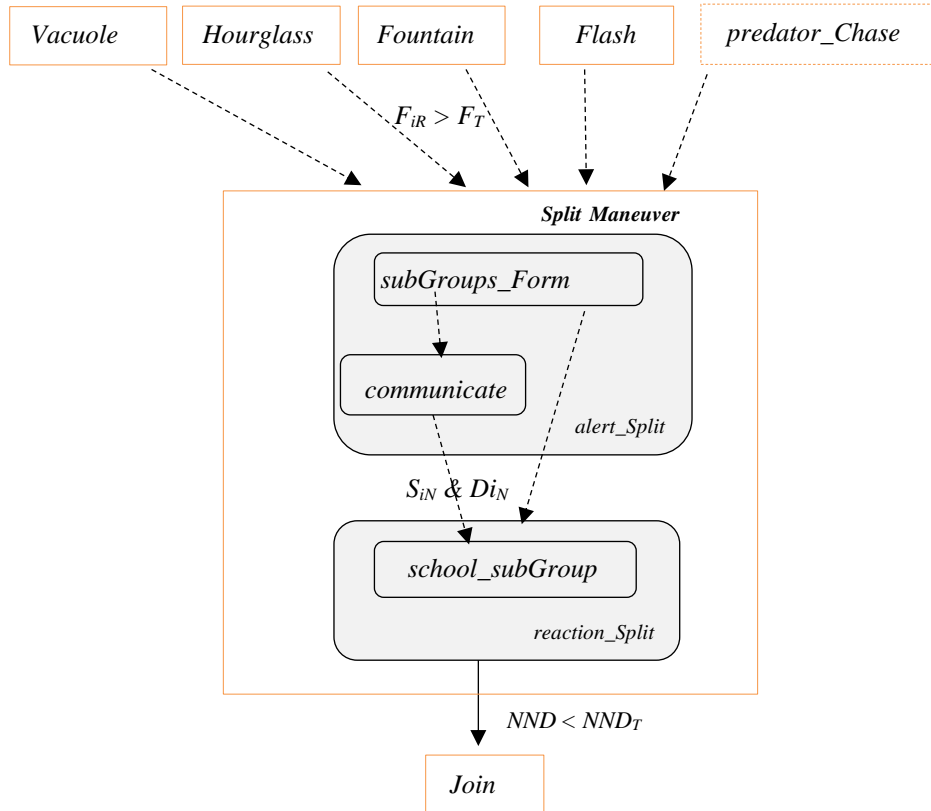


Figure 3.19 Join maneuver state machine behavior model

$$Di_N = \sum_{i=1}^n \hat{G}_{isG} \quad (3.16)$$

The back-prey fish ( $f_{iB}$ ) receive this direction information with a time delay. This time delay depends on the distance from its respective sub-group's centroid ( $D_{ic}$ ). These fish briefly get into the *confusion* sub-state, jiggle for a moment and move to the *school\_Reform* sub-state with varying speed (Equation 3.12) and new goal direction (Equation (3.16)).

*Post-states.* After the *join* state, the prey fish enter the *compact* state.

### 3.7 Fish School Modifier Plug-in

Fish school modifier plug-in allows animator to choose the patterns *school* (*compact-avoid*), *flash*, *fountain*, *join*, and *split*. Each pattern has the parameters specific to it. *Compact* and *avoid* patterns are embedded in *school* that is altering parameters appropriately yield *compact* or *avoid* patterns.

*School Pattern.* *School* has the parameters *neighbor distance*, *speed* and *avoid* (Figure 3.20) where reducing the *neighbor distance* yields the *compact* pattern and changing the *avoid* parameter from 0 to 1 exhibit the *avoid* pattern.

*Flash pattern.* *Flash* pattern has the parameters *explosion time* and *speed*. Explosion time value determines how long the flash explosion lasts before forming back to the *school*. *Speed* of the flash animation can also be altered.

*Fountain pattern.* *Fountain* pattern has the parameters *neighbor distance*, *force* and *speed*. The change of *neighbor distance* yields compact fountain pattern. The *force* parameter is used to increase or decrease the repel from predator that is increase in *force* parameter creates a wide spread out of *fountain* pattern.

*Join pattern.* *Join* has the parameters *confusionZone*, *neighbor distance* and *speed*. The *confusionZone* parameter can be altered to increase or decrease the confusion created at joining of two subgroups that is animation of fish skitter can be seen. *Neighbor distance* and *speed* can be defined for the *school* formed after join.

The simulations are taken from the perspective of the predator and prey fish. The first set of simulations and observations are made on how the predator selected the prey fish based on the discussed model (Section 3.2 *Prey Selection Model*). The second set of observations are made on how the prey fish reacted to predator presence, chase and attack (Section 3.5, 3.6). in 3D world using Unity. The third set of observations are made on fish school modifier plug-in which is developed in Blender using Python with the system properties mentioned above. The models used for simulation are the 3D objects of Blender tool like cone. The simulations are taken for the group of 3D objects ranging from 20 to 200.

#### **4.1 Simulating a Predator Fish Attacking a School of Prey Fish**

Each simulation starts with a predator, prey fish school positioned at random. When predator enters fish school zone, predator selects isolated peripheral target and starts chasing it. I have run the simulations for each individual factors discussed in equation 3.3 and all together to understand the importance of each factor role in the selection of isolated peripheral prey in fish school and the results are provided (Figure 4.1 and Figure 4.2).

Figure 4.1a, shows the fish school wandering in 3D space. When a predator enters the fish school zone, a minimum spanning tree is generated with each prey fish as a vertex position occupying in three-dimensional space and edges connecting fish (Figure 4.1b). In the 3D world, the view can be very deceiving, and each view has a different isolated peripheral fish. In figure 4.1a, fish 11 seems like isolated peripheral fish, if viewed in one angle, when viewed from other perspective fish 6 and 7 look like isolated peripheral fish. To figure out isolated peripheral fish in the 3D world, all the factors described in the mathematical model with weightage given to each of them is to be determined. In figure 4.1a, fish 6 is the most isolated fish as it has the highest average

neighbor distance factor (0.4), followed by fish 11(0.3305) and fish 7 (0.3131). In figure 4.1b, fish with id 1, 9, 6, 3 and 11 are peripheral fish, among them fish 6 is identified as the most vulnerable with highest vulnerability factor 0.4 followed by fish 3 (0.34) and 11 (0.34). Therefore, from the values, fish 6 has the highest average neighbor distance and vulnerability factors followed by fish 3 and 11. Even though fish 11 (0.1462) has the higher prey distance factor compared to fish 6 (0.0671), adding prey distance factor to the mathematical model did not yield the fish 11 to be the isolated peripheral but effectively fish 11 moved to second in order. The weights for the factors are  $\alpha$  (0.4),  $\beta$  (0.4) and  $\gamma$  (0.2) which are determined based on the experimental results.

The simulations that are taken with the 3D models from Unity asset store are realistic and visually appealing. These results in 3D space can be comparable with prey selection by predator in nature. The predator attack on isolated peripheral fish in fish school (Figure 4.2) can be comparable with the live footage image as shown in Figure 4.3 [62].

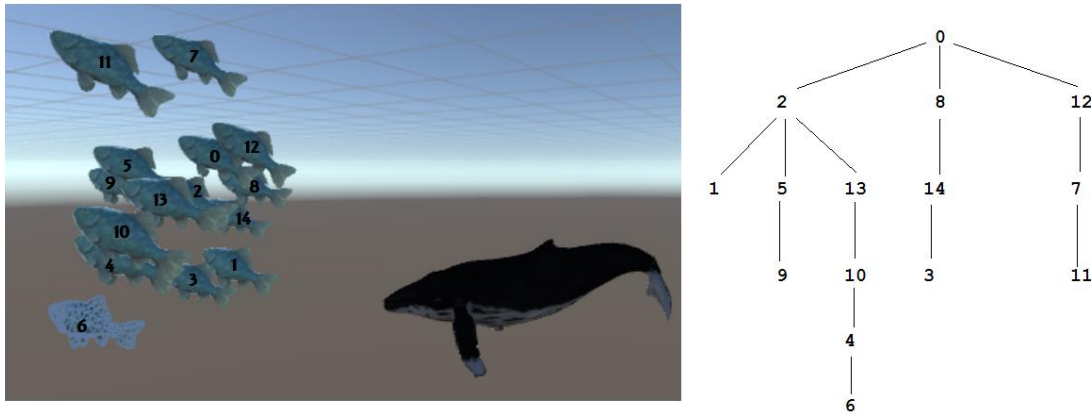


Figure 4.1 a. Fish school with isolated peripheral fish (id '6'), b. Minimum spanning tree structure



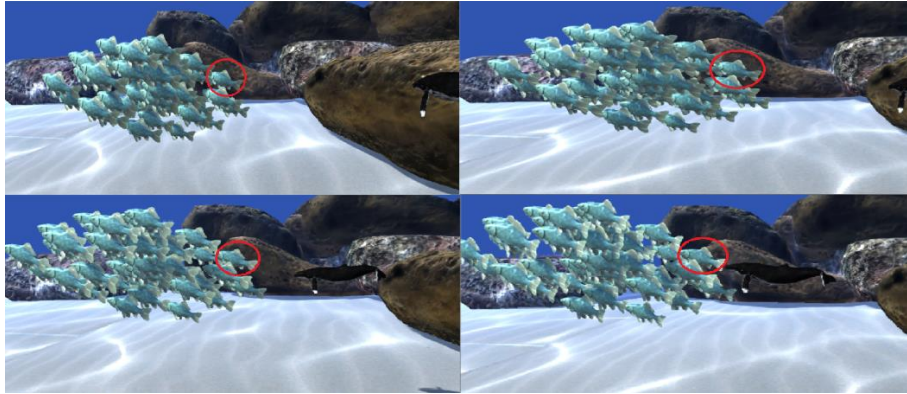


Figure 4.2 Simulation of predator chasing isolated peripheral fish with group size 50 in successive frames (red oval indicates the isolated peripheral prey)



Figure 4.3 Live footage of predator attacking peripheral fish in fish school

## 4.2 Animating Escape Maneuvers for a School of Fish

The simulations of prey reaction to predator is taken for two cases. In the first simulation, the predator transits among the states of *predator\_Presence* ( $P_s$ ), *predator\_Chase* ( $P_c$ ), or *predator\_Attack* ( $P_A$ ) while the prey fish school are in one of the following escape maneuvers: *ball*, *compact*, *avoid*, *skitter*, *fountain*, *flash*, *split*, or *join*. In the second simulation, the predator is in the *predator\_Attack* state and the prey fish school reacts with *herd* and *hourglass* maneuvers. The key parameter values recorded at the time of simulations is given in Table 1.1.

Table 1.1 Values for the key parameters

Key parameters	Value
Threshold nearest neighbor distance ( $NND_T$ )	4.0
Speed ( $S$ )	0.15
Perception length ( $L$ )	10.0
Threshold force ( $F_T$ )	5
Skitter Distance ( $D_s$ )	0.02
Threshold avoid distance ( $D_{AT}$ )	2
Fear threshold ( $fe_T$ )	1
Minimum Approach Distance ( $M_{AD}$ )	1
Threshold number of fish ( $N_T$ )	150
Explosion time ( $T_e$ )	0.4
Time to execute avoid maneuver ( $T_{AM}$ )	2
Startle time ( $T_s$ )	0.7
Leader distance ( $L_d$ )	2.0
Herd distance ( $D_H$ )	0.9
Herd radius range ( $H_R$ )	0.5
Ball threshold distance ( $D_{BT}$ )	2.5
Explosion time ( $T_e$ )	0.09
Predator ripple force in $P_C$ ( $F_{iR}$ )	5
Predator ripple force in $P_A$ ( $F_{iR}$ )	10
Threshold force for $P_C$ ( $F_T$ )	10
Threshold force for $P_A$ ( $F_T$ )	15
Collision threshold ( $C_T$ )	0.05
Startle time ( $T_s$ )	0.01
Leader distance range ( $L_{dR}$ )	1
Constant ( $C_1$ )	2
Constant ( $C_2$ )	(-355.06, 43.3)
Constant ( $C_3$ )	(-350, 45)

**4.2.1 Prey Fish Escape Behavior Scenario 1-  $P_S$ : (Ball  $\rightarrow$  Compact  $\rightarrow$  Avoid)  $\rightarrow P_C$ :  
(Skitter // Fast avoid)  $\rightarrow P_A$ : (Fountain // Flash // Split  $\rightarrow$  Join)**

The simulation starts with the predator in the tank and the fear and visual factors as trigger events ( $V = 1$  &  $F_f = 1$ ), then the prey school forms the *ball* maneuver. Figure 4.4 shows that each prey fish in the *reaction\_Ball* state rotates around the global center with varying speed (ranges from 0.11f to 0.17f). Speed is varied for each fish in the *ball* maneuver in order to make it look more realistic. This formation lasts for a few seconds (3s) until the predator is within a distance of  $D_{BT} = 2.5$ , and then the fish school enter the *compact* maneuver. Next, the predator approaches the prey school ( $D_{PC} < 2$ ). The fish school respond with the *avoid* maneuver and move away from the predator until  $D_{PC} > 2$ .

In the second stage, the predator moves into the state  $P_C$ . In response to the predator chase, the prey fish school exhibit the *skitter* maneuver (Figure 4.5) with a startle time of 0.01s and then move away from the predator (*fast avoid*).

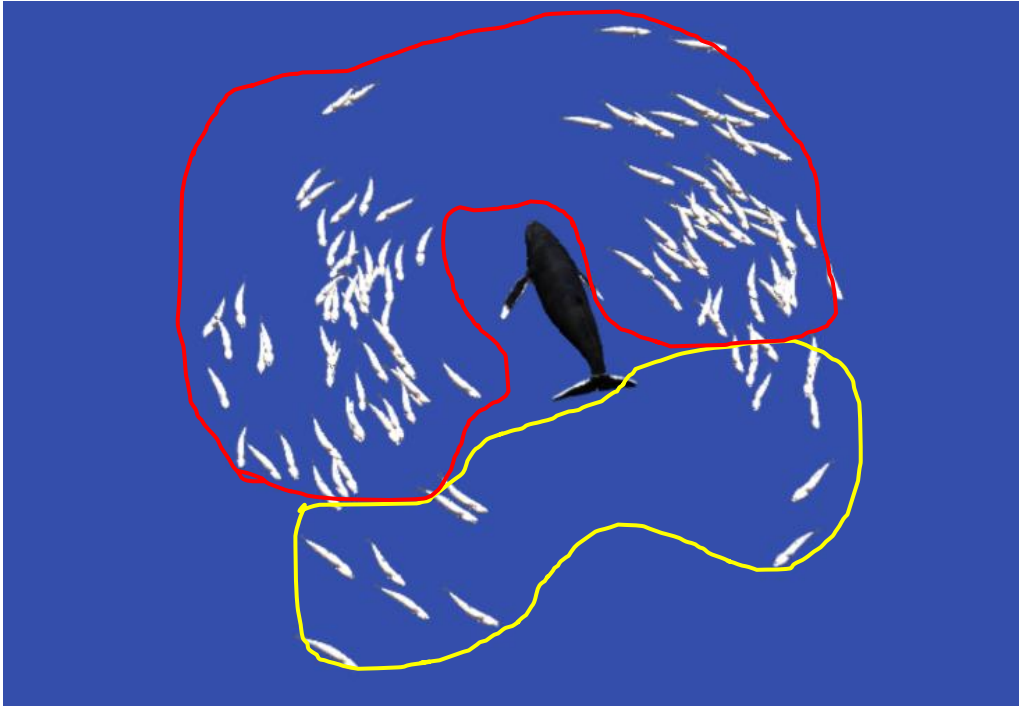


Figure 4.4 Ball maneuver (The prey fish are in the rotate\_Around sub-state.)



Figure 4.5 Skitter maneuver (The prey fish are in the skitter phase with startle time 0.01s.)

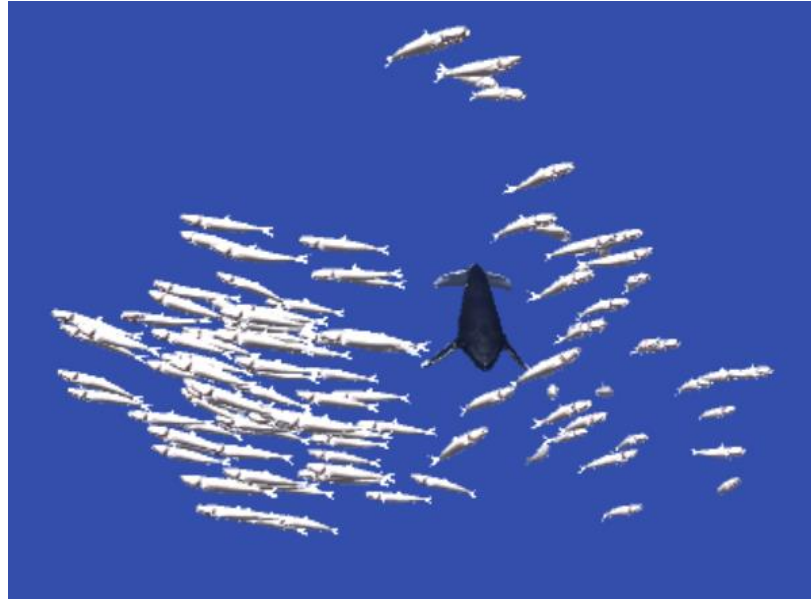
The third stage (*predator\_Attack*) includes three attacks: *attack\_back*, *attack\_bottom*, and *attack\_right*. In response to the first attack *attack\_back*, the prey fish school respond with the escape maneuver *fountain*. Figure 4.6 shows the *fountain* maneuver, with the fish in red circle in the *repulsive* sub-state and the fish in the yellow circle in the *regrouping* sub-state. In response to the second attack (*attack\_bottom* sub-state), the prey fish school enter the *flash* maneuver (Figure 4.7). In the third attempt ( *attack\_right* sub-state), the predator attacks with the ripple force  $F_{iR} > 15f$ , causing the prey fish school to *split* (Figure 4.8). Later, when the subgroups are within  $NND_T = 4$ , the prey fish school regroup through the *Join* maneuver (Figure 4.9).



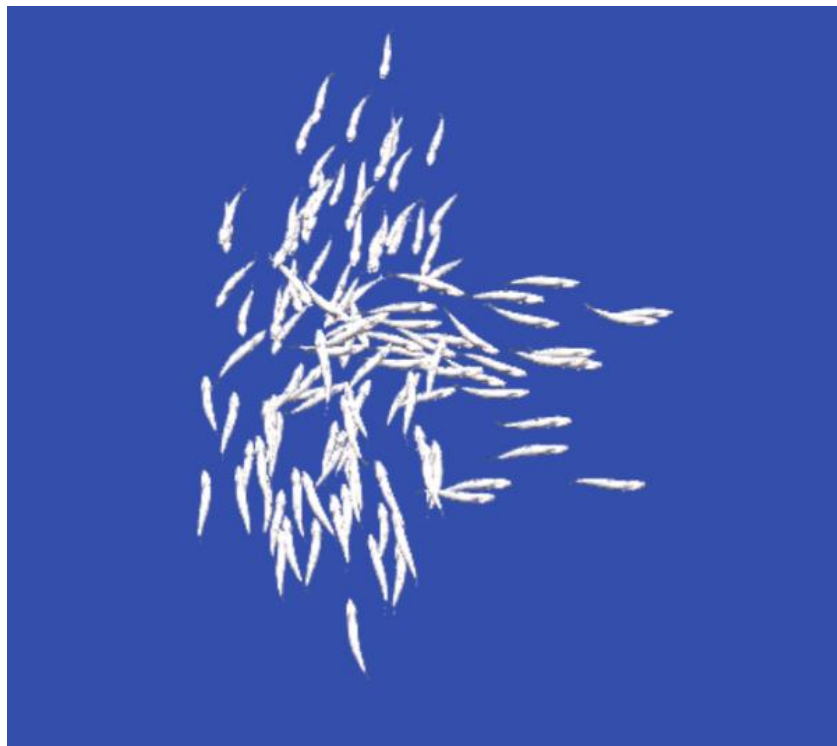
*Figure 4.6 Fountain maneuver (The prey fish are in the repulsive sub-state (red) and some prey fish are in the regrouping sub-state (yellow).)*



*Figure 4.7 Flash maneuver (The prey fish are in explosion sub-state for a period of 0.09s.)*



*Figure 4.8 Split maneuver (The prey fish formed into two sub-groups.)*



*Figure 4.9 Join maneuver with back fish (orange) in the confusion sub-state.*

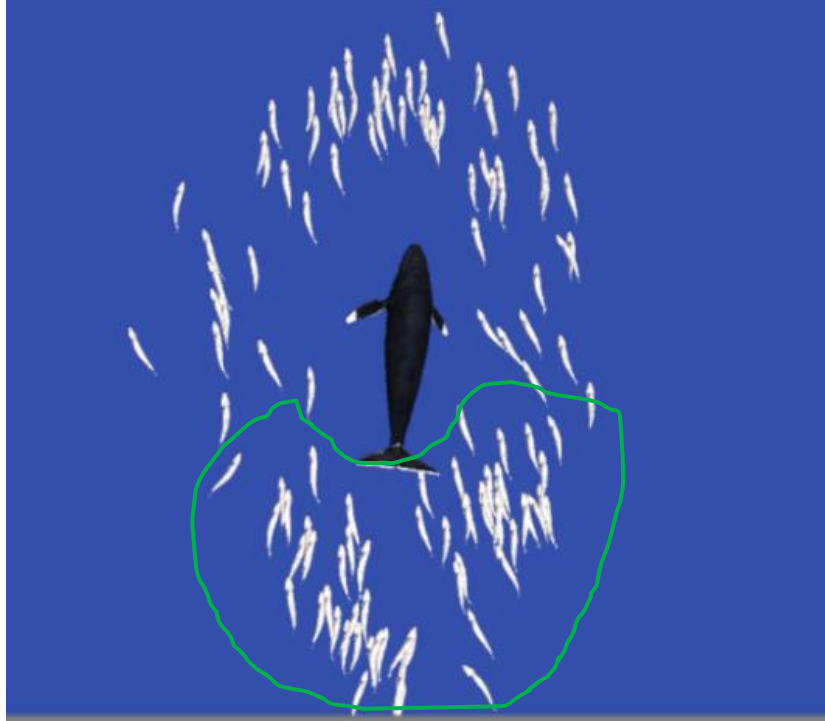
#### 4.2.2 Prey Fish Escape Behavior Scenario 2: $P_A: \text{Herd} \rightarrow \text{Vacuole} \parallel \text{Hourglass}$

In the second scenario, the simulation starts with the predator in *predator\_Attack* (*attack\_back*) state. In response to this attack, the prey fish school exhibit the *herd* maneuver (Figure 4.10), which is then extended into the *vacuole* maneuver (Figure 4.11). In response to the predator's second attack attempt, the prey school exhibit the *hourglass* maneuver (Figure 4.12).



Figure 4.10 Herd maneuver (The prey fish are in the *move\_Radially* sub-state, forming a depression.)





*Figure 4.11 Vacuum maneuver (The back fish are in the surround sub-state.)*



*Figure 4.12 Hourglass maneuver (The prey fish are in the turn\_Around sub-state.)*



### 4.2.3 Escape Maneuvers User Interface (UI)

We have developed an escape maneuver editor interface (Figure 4.13) that allows users to edit the key parameters defined in Table 1.1. The key parameters for each maneuver are discussed in the section *Prey fish escape maneuver behavior models*. For instance, in Figure 4.13, the *herd* maneuver is selected, and the UI presents the default properties such as fish school size, speed, neighbor distance, and herd radius range ( $H_R$ ).

### 4.2.4 Validation

While crowd simulation can be evaluated with qualitative or quantitative methods [63], it is common to evaluate crowd simulations by qualitative methods, which include demonstrating the general realistic “look-and-feel” of the simulation or comparing simulated crowds with videos or images of real crowds. Quantitative methods including statistical analysis of the crowd simulation. Some data-driven approaches compare individual character’s movement with those in

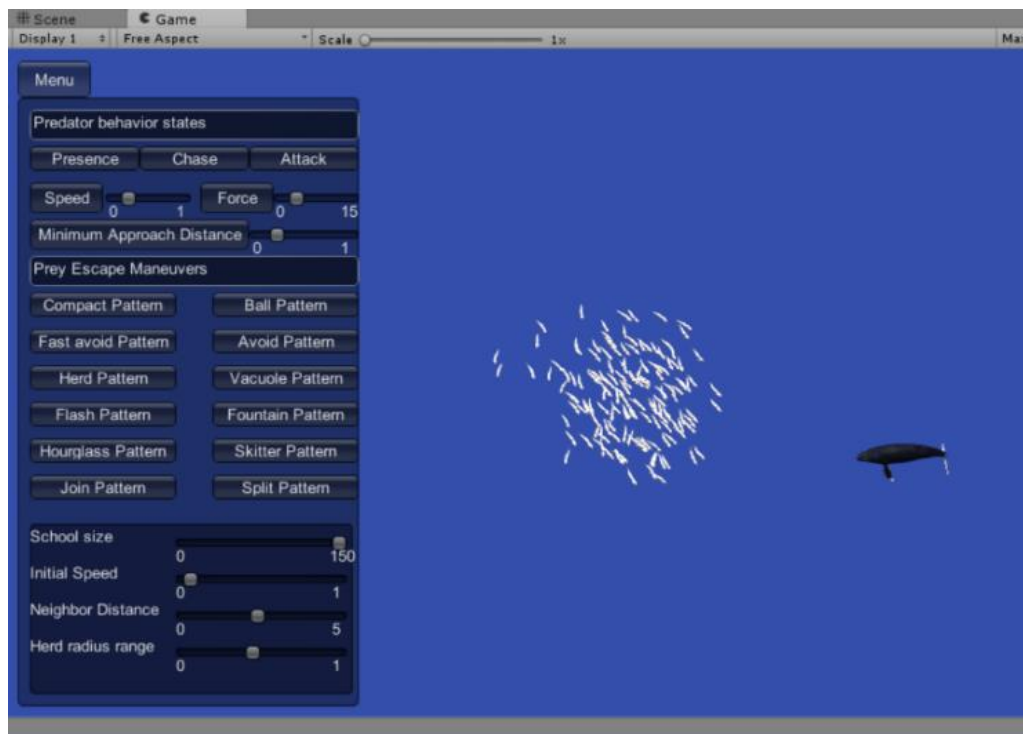


Figure 4.13 User Interface.

real video footage. In some data driven simulations, real-world motion capture data is used to simulate insect swarms.

The proposed work is validated with qualitative methods and the simulations are compared with videos of real-world predator and prey fish school interactions in the public domain, and the simulation is visually comparable with the real footage. More importantly, the proposed predator fish behavior and prey fish escape behavior models are based on published biological research papers, which were based on field observations of live fish. Although the experiments are not conducted with real fish to compare the simulations, the proposed models are built on solid biological studies and field observations.

### **4.3 Fish school modifier plug-in**

In this simulation, the predator path is manually adjusted while the fish school patterns are chosen from the UI and parameters are adjusted.

#### ***4.3.1 Set the Path for Prey Fish School***

The path for fish school is created by using goal marker. Set the keyframes for goal marker along the timeline. Fish school will follow this goal marker and a simulation of fish school following certain path can be seen in Figure 4.14. To create the visual of predator following the prey fish and attacking them, a curve is created, and predator is attached to the curve resulting in the predator following the path of a curve.

#### ***4.3.2 Fine Tune Predator Animation and Prey Fish Escape Pattern Parameters***

After keyframing the required patterns (Figure 4.15), respective pattern parameters can be adjusted. For instance, for *flash* pattern *explosion time*, for *compact* pattern *speed* and *neighbor distance*. The simulation screen shots taken after the fine tune are shown in Figure 4.16.

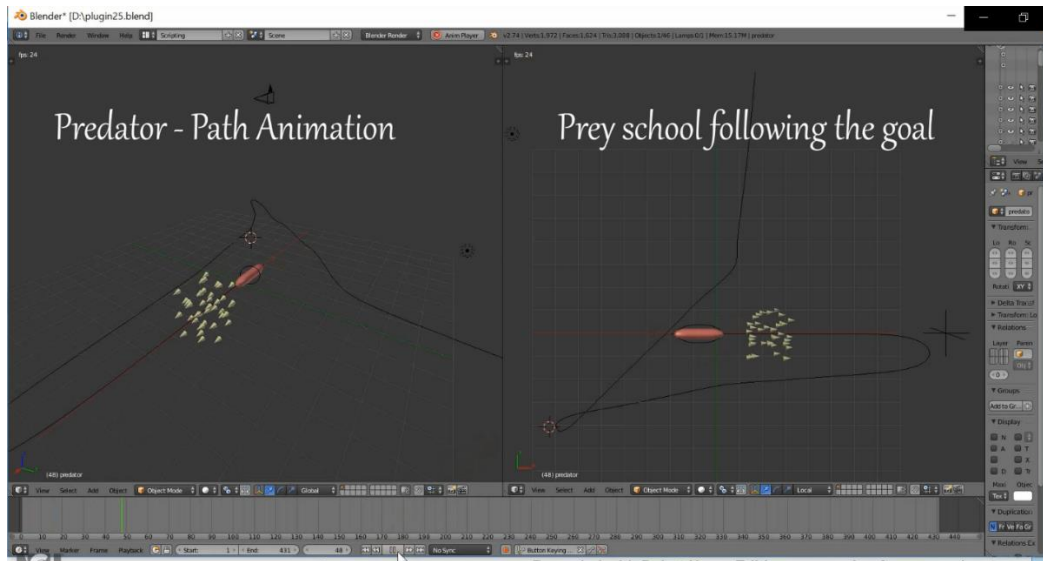


Figure 4.14 Fish school modifier (plug-in) for Blender. Path is set for both prey fish school and predator.

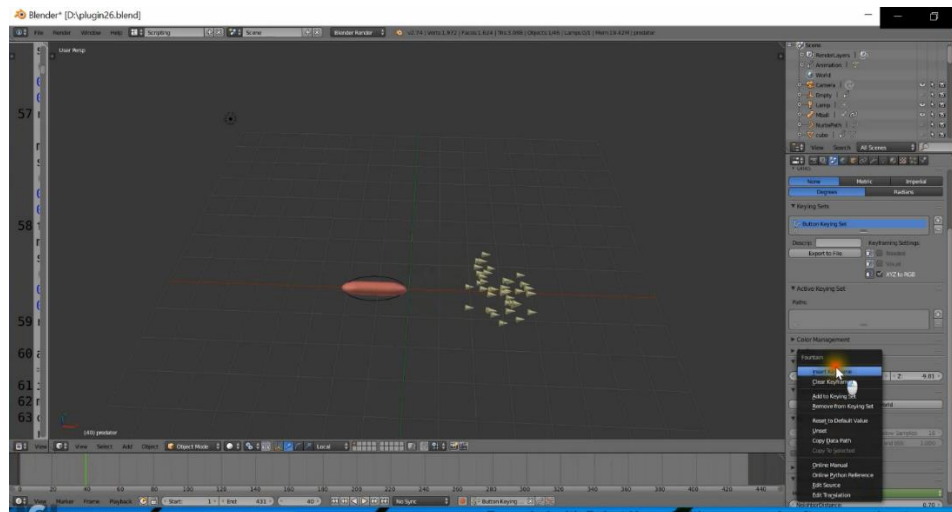


Figure 4.15 Fish school modifier (plug-in) for Blender. Keyframing the patterns for prey fish

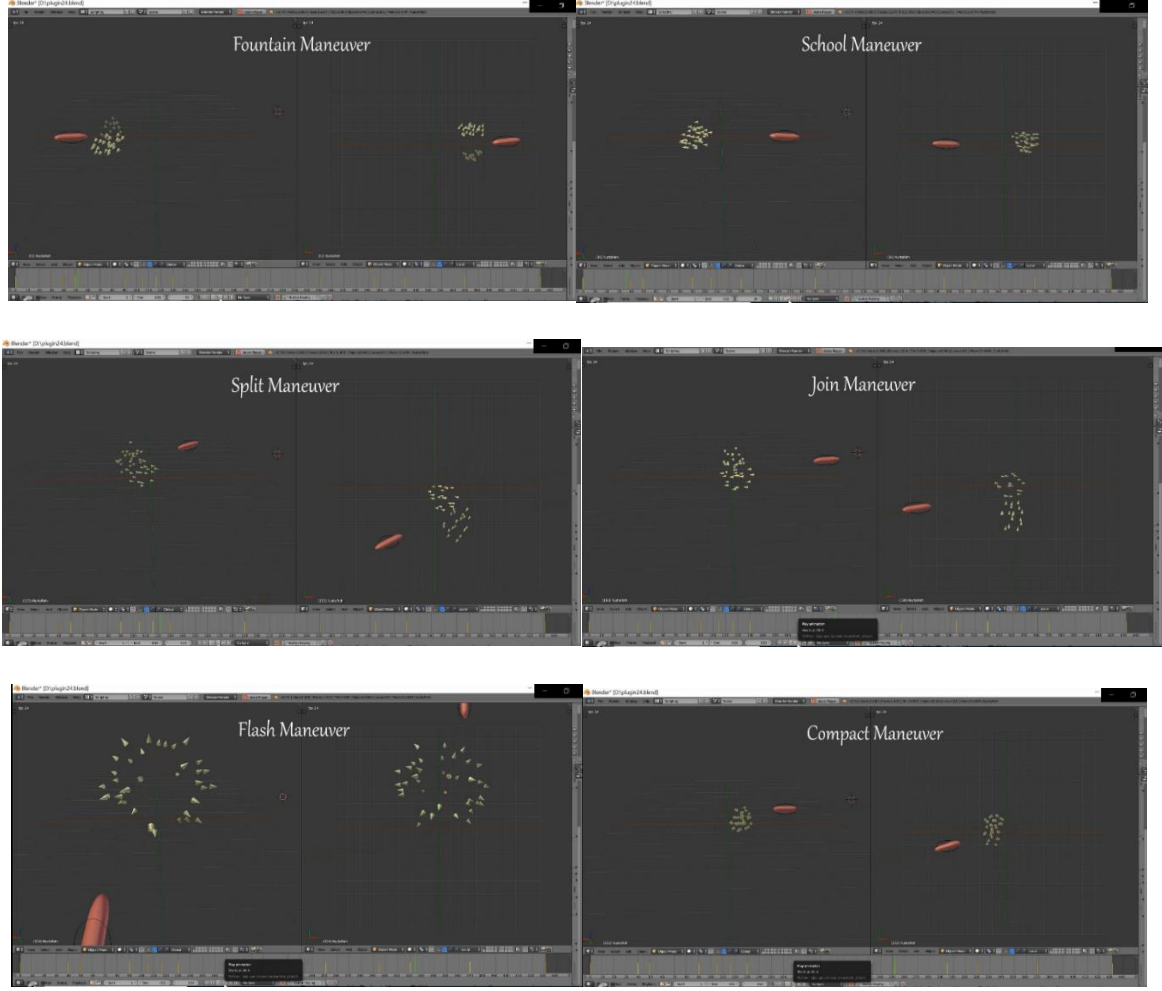


Figure 4.16 Fish school modifier (plug-in) for Blender. Keyed patterns after fine tune in the sequence fountain, school, split, join, flash and compact.

## 5 CONCLUSION AND FUTURE RESEARCH

In this work, a theory is formulated to find isolated peripheral fish in fish school at the time of predatory attacks and a state machine model is provided for the prey fish to exhibit escape behavior patterns. The simulations are realistic and can be comparable with prey selection in nature.

Animating a school of prey fish escaping a predator is not trivial because the prey fish school use a wide variety of escape maneuvers. Creating such maneuvers manually can be very time consuming and previous research has not sufficiently addressed this issue. Therefore, a prey fish escape behavior state machine model that can simulate twelve escape patterns identified in

biological research: compact, avoid, ball, skitter, fast avoid, fountain, flash, split, join, herd, vacuole, and hourglass is modeled.

This behavior model can help reduce the workload of animators by automatically simulating prey fish escape maneuvers in reaction to the behavior of a predator fish, allowing animators to focus on animating the predator fish. If necessary, an animator can adjust the prey fish school behavior on a higher level by modifying a state machine and a small set of system parameters. The simulations of the fish escape maneuvers taken using the proposed theory are realistic and comparable to the real footage.

A top-down approach is adopted in which a state machine governs the transition among different escape maneuvers. The set of escape behavior is restricted to the ones specified in the finite state machine. To add a new behavior, the state machine must be modified. Perhaps it is more appealing to build a dynamic system to generate a wide variety of emergent behavior through a set of system parameters. However, the current understanding of fish behavior is not sufficient to build such a dynamic system. Previous attempts in building such dynamic systems can only simulate a small set of behavior. Such dynamic systems are also more difficult to tune and control. The proposed method may feel scripted, but it has its benefits. It is stable, predictable, and gives animators a great deal of control over the fish escape behavior.

In addition, fish school modifier plug-in is also developed which is an easy and flexible tool that provides different patterns to choose and set key in 3D graphics tool Blender. The complex animations can be created just by choosing the pattern from the UI rather than scripting individual path for each fish.

The current model does not support multiple predator attacks on fish school. In future, support for multiple predators attacking a school of fish simultaneously can be added. The breakage of fish

schools can also be further investigated with the application of graph theory properties to test for realistic results. In addition, more prey fish maneuvers can be added and build better user interfaces for animators to adjust the fish school behavior.

## APPENDICES

### Appendix A: Escape Maneuvers

#### *Appendix A.1 Ball Maneuver*

This maneuver is exhibited by fish school when they are intimidated by a predator. They form a compact stationary ball like pattern with low nearest neighbor distance (Figure A.1 [64]). This ball is also known as bait ball which is a tightly packed spherical formation about a common center. This ball pattern is displayed when they are threatened by a predator either as a last-ditch defensive measure or at the start when predator is first observed in the environment. These behaviors are observed in sardines and the ball can be around 10-20 meters in diameter and the ball can be extended to a depth of 10 meters. This ball pattern can be lasted for few minutes that range from 10 to 30 minutes. However, this maneuver mechanism can attract large number of predators in return and can undermine the defensive nature of fish school with predator counter measures [65].



*Figure A.1 Ball pattern*

### ***Appendix A.2 Avoid Maneuver***

Avoid is the most common and important maneuver adopted by the fish school as an anti-predator defense. The avoid maneuver is simply to avoid or alter the course of predator. There is little change in the shape or size of a fish school. There will be a reduction in the neighbor distance in the region nearest to the predator and at the end they move away from predator around 1.3 m to 2 m [25]. This avoid maneuver is first initiated by the prey fish that are near to the predator while the rest will follow. The number of fishes which initiate the avoid maneuver is important. For instance, if the maneuver is initiated by few of them (four of prey fish school), the rest does not follow instead they make the initiators tend to be in a major school. Fast avoid is exhibited at a greater speed to normal avoid which is less frequent.

### ***Appendix A.3 Herd Maneuver***

Herd maneuver is observed when the predator is just behind the fish school. Like the avoid maneuver there is a little compression at the place where the predator is close to the fish school, resulting in a 'v' shape or a scalloped shape at the rear end of the school (Figure A.2 [66]). This pattern is exhibited by the prey school when predator is chasing from back in the same direction. The prey fish maintain a minimum distance with the predator while displaying this maneuver and positional changes occur for each individual in the prey school.





*Figure A.2 Herd Maneuver*

#### ***Appendix A.4 Vacuole Maneuver***

In the vacuole maneuver, a predator is surrounded by a gap (Figure A.3 [67]) in the prey school. This maneuver is observed in school of hundreds of fish that encounter predators or threatening objects and has the tendency to obey its neighbors. The vacuole pattern is sequenced in three steps. First, the predator tries to penetrate through the school, second the prey school creates a gap and finally they surround the predator. Generally, the first step occurs more frequent as the predator has higher speed relative to fish school therefore it does not stay too long surrounded by the prey school.



*Figure A.3 Vacuole Maneuver*

### ***Appendix A.5 Hourglass Maneuver***

Hourglass maneuver occurs when the fish school is constrained at the center by the predator. When school has no tendency to split, the depressed part of the school connects two groups at the edges like a bridge. Prey fish stream across the bridge and has the greater velocity and neighbor distance when compared to the fish at the either end of bridge.

### ***Appendix A.6 Fountain Maneuver***

Fountain maneuver occurs when a predator approach from behind. This maneuver is widely studied by researchers [68-70]. Each individual fish increases speed relative to predator, divides, swim towards the predator back and finally reforms into school. This maneuver is a result of a strike at the center of fish school by the predator. However, this maneuver has a major cost associated with it as fish are more vulnerable to capture when they split to turn back towards predator (Figure A.4 [71]).



*Figure A.4 Fountain Maneuver*

### *Appendix A.7 Split Maneuver*

Split maneuver occurs when a school of fish is compressed against predator or an obstacle. Split is also observed when the two extremes in school head in opposite directions. Predator attempt to split the school and feed on isolated prey. After split they either form school again or they might be broken down completely. Split can be part of other maneuvers. If fountain pattern cannot withstand by the prey school, they result in split. Similarly, when herd turn to opposite direction from each other the school splits into two subgroups (Figure A.5 [72]).



*Figure A.5 Split Maneuver*

### ***Appendix A.8 Flash Maneuver***

Flash expansion usually occurs when a school of fish is directly attacked by a predator. This maneuver is observed by many researchers [24, 67 and 69]. In this maneuver, the prey school explodes with all of them moving in different directions from the center (Figure A.6 [73]). After moving to certain distance, the school reassemble after few seconds. Sometimes prey fish may take longer time to reassemble. This maneuver has a major cost associated to it that is if prey gets isolated while exhibiting the maneuver then there is greater chance of being caught by the predator. This maneuver is majorly seen in small fish school as in large fish schools it is not possible for all the prey fish to be aware of the predator attacks.



*Figure A.6 Flash Maneuver*

### ***Appendix A.9 Compact Maneuver***

In the compact maneuver, the school of fish move closer to each other, polarized and densely packed within the range of 0.5-2 body lengths. When the prey school observe the predator, each fish in school immediately gets alert and move closer to its neighbor fish.

## **Appendix B Algorithms for Prey Fish Escape Maneuvers**

### **Appendix B.1 Compact-Avoid Maneuver**

*Predator state.* The predator is in the *predator\_Presence* state.

*Algorithm.* Compact-Avoid Maneuver

*Input.* prey\_School

*Output.* Compact-Avoid\_Maneuver

Begin

1. //visual trigger of predator presence-*alert state*
2. if  $V=1$  &  $P_S$  then
3. //reaction state
4. for each fish  $f_i$  in prey\_School do
5.  $NND_N = NND_C / f_d$  //reduce nearest neighbor distance
6.  $S_N = S_C * f_s$  //increase speed
7.  $Di = G_c - (-P_p)$  //direction opposite to predator position
8. end for each
9. end if

End

### **Appendix B.2 Ball Maneuver**

*Predator state.* The predator is in the *predator\_Presence* state.

*Algorithm.* Ball Maneuver

*Input.* prey\_School

*Output.* Ball\_Maneuver

Begin

1. //visual and fear factor triggers of predator presence-*alert state*
2. if  $V=1$  &  $F_f$  &  $P_S$  then
3. //reaction state
4.  $radius\_Ball$ =default initial value
5. loop=true;
6. do
7.  $r = radius\_Ball + \text{random\_Value}$
8.  $n = 4 \pi (r)^2 / (BL * c_1)$
9. if  $(N - n \leq 0)$  //N- number of fishes
10.  $n = N$
11.  $N=0$
12. else
13.  $N=N - n$
14. end if

```

15. initialize thetaArray[]
16. initialize phiArray[]
17. while  $n > 0$ 
18.    $n - -$ 
19.    $\theta = \text{Random}(0, 2 * \pi)$ 
20.    $\emptyset = \text{Random}(0, \pi)$ 
21.   //checking for duplicate pair of random values
22.   while (thetaArray.contains( $\theta$ ) and
           phiArray.contains( $\emptyset$ ) and
           thetaArray.position( $\theta$ ) == phiArray.position( $\emptyset$ ))
23.      $\theta = \text{Random}(0, 2 * \pi)$ 
24.      $\emptyset = \text{Random}(0, \pi)$ 
25.   end while
26.   thetaArray.push( $\theta$ )
27.   phiArray.push( $\emptyset$ )
28.    $f_{iP} = (r \cos \theta \sin \emptyset, r \sin \theta \sin \emptyset, r \cos \emptyset)$ 
29. end while
30. if ( $N < 0$ )
31.   loop = false
32. while(loop) //end of do while
33. //rotate around a common center (random goal position)
34. for each fish  $f_i$  in prey_School do
35.    $S_N = S_C * f_s$ 
36.   rotateAround( $G_{pr}$ )
37. end for each
38. end if
End

```

### ***Appendix B.3 Herd, Vacuole, and Hourglass Maneuvers***

*Predator state.* The predator is in the *predator\_Chase* state for *herd* and *predator\_Attack* for *hourglass* and *vacuole*.

*Algorithm.* Herd Maneuver, Vacuole Maneuver or Hourglass Maneuvers

*Input.* *prey\_School*

*Output.* Herd\_Maneuver, Vacuole\_Maneuver or Hourglass Maneuvers

Begin

1. if  $D_{PC} < M_{AD}$ ,  $V = 1$ ,  $F = F_{iR}$  &  $P_C$  then //alert state  
//reaction state for herd maneuver
2. for each fish  $f_i$  in *prey\_School* do
3.  $\beta = \text{Vector3.Angle}(\overrightarrow{f_i P}, \overrightarrow{G_c P})$

```

4.   if ( $D_{ifP} < \text{front\_radius}$ )
5.       if ( $0 < \beta < 45$  or  $0 > \beta > -45$ )
6.            $S_{iN} = S_i * f_s$ 
7.       else if ( $45 < \beta < 90$ )
8.            $f_{iP} = \text{transform.right};$ 
9.       else if ( $-45 > \beta > -90$ )
10.           $f_{iP} = -\text{transform.right};$ 
11.      end if
12.      //vacuole_reaction
13.  (if  $I_T=1$ ,  $D_{PC} = 0$ ,  $P_A$ , and herd_reaction)
14.  else if ( $D_{iP} > \text{back\_radius}$ )
15.      if ( $135 < \beta < 180$  or  $-135 > \beta > -180$ )
16.           $S_{iN} = S_i * f_s$ 
17.      else if ( $90 < \beta < 135$ )
18.           $f_{iP} = -\text{transform.right};$ 
19.      else if ( $-90 > \beta > -135$ )
20.           $f_{iP} = \text{transform.right};$ 
21.      end if
22.  end if
23.  end for each
24.  //hourglass_reaction
25.  (if  $I_T=1$ , &  $P_A$ , and herd_reaction and not vacuole_reaction)
26.  if ( $D_{PC} < \text{start\_HourG}$ )
27.      if ( $D_{PC} > \text{hourglass\_Treshhold}$ )
28.          hour_Direction = Random (left, right) (i.e., -1 or 1)
29.          for each fish  $f_i$  in prey_School do
30.              if (hour_Direction *  $\beta > 0$ )
31.                  transform ( $f_i$ , in hour_Direction)
32.              else
33.                  rotate ( $f_i$ , with larger radius)
34.              end if
35.          end for each
36.      end if
37.  end if
38.  //end hourglass maneuver
End

```

#### **Appendix B.4 Fountain Maneuver**

Predator state. The predator is in the *predator\_attack* state.

*Algorithm.* Fountain Maneuver

*Input.* prey\_School

*Output.* Fountain\_Maneuver

Begin

1. if  $F_{iR} > F_T$  &  $P_A$ , then //alert state
2.     //Reaction state
3.      $intercept\_Direction = (goal\_intercept.x - P_p.x) * (G_{pr.z} - P_p.z) - (goal\_intercept.z - P_p.z) * (G_{pr.x} - P_p.x)$
4.     for each fish  $f_i$  in prey\_School do
5.          $time\_Delay (D_{iP} / c)$  // stall the below calculation for fish  $i$  about  $D_{iP} / c$  seconds,  $c$  is constant determined from the simulations
6.          $fish\_Direction = (((f_{iP}.x - P_p.x) * (G_{pr.z} - P_p.z)) - ((f_{iP}.z - P_p.z) * (G_{pr.x} - P_p.x)))$
7.         if ( $intercept\_Direction == fish\_Direction$ )
8.              $start\_rotateAround (f_{iP})$
9.              $S_{iP} = f_s / D_{iP}$  //assign speed based on distance to predator
10.         else
11.              $start\_rotateAround (-f_{iP})$
12.              $S_{iP} = f_s / D_{iP}$
13.         end for each
14.     else
15.          $stop\_Rotate (f_{iP})$
16.     prey\_School ( $P_p$ ) form school with predator position as goal position
17. end if

End

### **Appendix B.5 Flash Maneuver**

Predator state. The predator is in the *predator\_Attack*.

*Algorithm.* Flash Maneuver

*Input.* prey\_School

*Output.* Flash\_Maneuver

Begin

1. if  $I_T = 0$ ,  $F = F_{iR}$  &  $P_A$ , //alert state
2.     for each fish  $f_i$  in prey\_School do //reaction state
3.         if ( $D_{PC} < c$ ) //  $c$  is constant determined at the time of simulations
4.              $prey\_Horizontal = C_2 * Sp_i$  //  $C_2$  defined in Table 1.1
5.              $prey\_Vertical = C_3 (\frac{r_v}{d_{vi}})$  //  $C_3$  defined in Table 1.1
6.             if ( $f_i$  above  $G_c$  in vertical axis)
7.                  $sign = 1$ ;
8.             else



```

9.         sign= -1
10.     end if
11.     switch(prey_Vertical) {
12.         case prey_Vertical< constant1:
13.             vertical_Rotation= sign* alpha1;
14.         case prey_Vertical< constant2:
15.             vertical_Rotation= sign* alpha2;
16.         case prey_Vertical< constant3:
17.             vertical_Rotation= sign* alpha3;
18.         .....
19.     end switch
20.     switch(prey_Horizontal) {
21.         case prey_Horizontal between 0 to10:
22.             horizontal_Rotation= sign* beta1;
23.         case prey_Horizontal between 10 to20:
24.             horizontal_Rotation= sign* beta2;
25.         case prey_Horizontal between 20 to30:
26.             horizontal_Rotation= sign* beta3;
27.         .....
28.         case prey_Horizontal between 350 to360:
29.             horizontal_Rotation= sign* beta36;
30.     end switch
31. end for each
32. else if  $I_T=0$ ,  $F_{iR} < F_T$ ,  $T > T_e$  &  $P_A$ 
33.     rotate ( $f_{iP}$ , vertical_Rotation, horizontal_Rotation)
34.     translate (d) //translate for distance d
35.     startle ( $T_s$ ) //Skitter_Maneuver
36.     prey_School( $f_{iP}$ ) //form school
37. end if
End

```

### ***Appendix B.6 Split Maneuver***

Predator state. The predator is in the *predator\_Attack* state. The *predator\_Attack* aims at the prey school centroid from any direction (*attack\_top*, *attack\_bottom*, *attack\_left*, *attack\_right*, *attack\_front*, and *attack\_back*).

*Algorithm.* Split Maneuver

*Input.* prey\_School

*Output.* Split\_Maneuver (sub-groups)

Begin

18. if  $F_{iR} > F_T$  &  $P_A$ , then //alert state
19. //Reaction state

```

20.  $intercept\_Direction = (goal\_intercept.x - P_p.x) * (G_{pr.z} - P_p.z) - (goal\_intercept.z - P_p.z) * (G_{pr.x} - P_p.x)$ 
21. if ( $G_{pr} \in Q1$ ) // quadrant 1
22.     sign = 1
23. else if ( $G_{pr} \in Q4$ ) // quadrant 4
24.     sign = -1
25. else if ( $G_{pr} \in Q2$ ) // quadrant 2
26.     sign = -1
27. else if ( $G_{pr} \in Q3$ ) // quadrant 3
28.     sign = 1
29. for each fish  $f_i$  in prey_School do
30.      $time\_Delay (D_{iP} / c)$  // stall the below calculation for fish  $i$ 
        about  $D_{iP} / c$  seconds,  $c$  is constant determined from the simulations
31.      $fish\_Direction = (((f_{iP}.x - P_p.x) * (G_{pr.z} - P_p.z)) - ((f_{iP}.z - P_p.z) * (G_{pr.x} - P_p.x))$ 
32.     if ( $intercept\_Direction == fish\_Direction$ )
33.          $f_{iP} = (sign) * f_i.transform.right$ 
34.          $S_{iP} = f_i / D_{iP}$  //assign speed based on distance to predator
35.     else
36.          $f_{iP} = -(sign) * f_i.transform.right$ 
37.          $S_{iP} = f_i / D_{iP}$ 
38.     end for each
39. else
40.     prey_School( $f_i$ ) //form school
41. end if
End

```

### Appendix B.7 Join Maneuver

Predator state. Predator can be in any of the states: *predator\_Presence*, *predator\_Chase* or *predator\_Attack*.

*Algorithm.* Join Maneuver

*Input.* prey\_School\_1, prey\_School\_2 //subgroups

*Output.* Join\_Maneuver

Begin

1. //alert state
2. if ( $NND < NND_T$ ) // if any of the fish are at  $NND_T$
3. for each fish  $f_i$  in prey\_School do //reaction state
4. if ( $f_i \in prey\_school\_1$ )
5. if ( $f_i$  is leader)
6.  $Di = \sum \hat{G}_{isG}$

```

7.      else
8.          //c is constant determined from the simulations
9.          time_Delay ( $D_{ic}/c$ )
10.          $Di = \sum \hat{G}_{isG}$ 
11.     else if ( $f_i \in \text{prey\_school\_2}$ )
12.         if ( $f_i$  is leader)
13.              $Di = \sum \hat{G}_{isG}$ 
14.         else
15.             time_Delay ( $D_{ic}/c$ )
16.              $Di = \sum \hat{G}_{isG}$ 
17.         end for each
18.     end if
End

```

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