Simulating the Bubble Net Hunting Behaviour of Humpback Whales: The BNH-Whale Algorithm

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Abstract. We describe the BNH-Whale algorithm, which simulates a method of catching schooling fish employed by humpback whales called bubble net hunting. When this method is used, the fish are herded into a net of bubbles created by one or more whales. Modified flocking algorithms are used to guide whale and fish behaviour, with a relatively complex algorithm being used by the whales to trap and consume fish.

1 Introduction

We describe the BNH-Whale algorithm, which simulates and visualizes the bubble net hunting behaviour of humpback whales (*Megaptera novaeangliae*) in real-time by using a wide variety of information about the characteristics of these whales and their prey. Briefly, *bubble net hunting* (BNH) refers to a hunting strategy employed by humpback whales, in which one or more whales swim around a school of fish and release bubbles (which the fish avoid) while other whales herd the fish up into the area enclosed by the "net" of bubbles [1]. Here we describe only the hypothesized models of decision making and action used by whales, although we have also devised models for fish and the environment. This work is of interest to Artificial Intelligence researchers as a case study that simulates a non-human intelligence. We propose a specific form of decision making that the whales could be using to guide their behaviour. The observed success of the simulated whales in capturing their simulated prey provides evidence that this form of decision making is actually employed.

The BNH-Whale algorithm is intended to aid biologists in evaluating their theories about BNH. Simulating BNH is valuable because observation in the field is expensive, often has poor visibility, and can potentially disrupt normal hunting behaviour. In particular, a simulation may provide insight into events occurring inside the bubble net, which are difficult to observe in nature.

2 Background

Relevant background concerns whale characteristics and behaviour reported by biologists and representations and algorithms developed for simulating and animating large numbers of thinking creatures in real time.

Biological Background: Humpback whales are a *rare enemy* to their target fish, i.e., these whales are not the primary predators of the fish [1]. The predator response of the fish is effective against predators targeting a single fish, but the whales take advantage of this response for bulk feeding. The maneuverability of slower, smaller prey is far higher than that of the faster, larger predators. At certain predator-prey length ratios, when prey is around 10 to 100 times smaller, higher maneuverability allows the small prey to avoid being caught by a direct whole body attack while still being fast enough to avoid filter feeding [2]. Some schooling fish, such as herring, fall into such a ratio for humpback whales. It is at these predator-prey length ratios where alternative methods such as BNH are employed to allow the predator to capture the prey.

Various strategies are used by whales to hunt individually and in groups called *pods*. Individual whales look for natural clumps of fish and lunge to feed [3]. One hunting strategy used by pods is *corralling*, whereby whales herd fish into better positions for consumption [3]. BNH is a form of coralling; it motivates fish to move into a compact formation, which permits easier feeding [4].

Detailed observations suggest BNH requires at least two whales working together [1]. Pod sizes for BNH range from two to twenty whales, but the mean size is 7.4 whales [1]. It is speculated that whales communicate during feeding [1]. Each whale in the pod has a role. At least one whale, here called a *bubble blower*, stays close to the surface to form a cylindrical net of bubbles, called a *bubble net*. The other whales, here called *prey herders*, herd the school of fish towards the net and circle the school. Since many fish in coastal waters tend to stay closer to the sea floor than to the surface, the BNH strategy is apparently more effective when the whales herd the school towards the bubble net from below. This net aids in trapping the fish by motivating them to form a compact sphere called a *bait ball*, a last ditch defensive maneuver to avoid predators [5].

When the net is complete with the fish trapped inside, the whales perform a vertical lunges towards the center. In some instances of BNH, the whales take turns lunging; in others, they all lunge at the same time [3]. The choice between these techniques likely depends on school size, pod size, and circling radius [4].

AI Decision Making: To provide an accurate model of the decision making behaviour of the whales and fish, decision making should be simulated in each organism. However, faster execution is produced if single decisions affect multiple whales and fish. Making wise choices between such local and global decisions is necessary to achieve an effective balance between the accuracy of the simulation and its speed [7]. We use local decision making for the whales, since they are relatively few in number.

Previous simulations of whale feeding behaviour have focused on lunge feeding [8, 9]. These particular simulations lack animation and focus on the forces involved with lunging. The mechanics of the lunge are used to calculate energy expenditure and the effectiveness of lunge feeding. An earlier simulation program uses data collected from tags attached to whales to visualize their movement [10]. It does not generate the motion of the whale, but it does give insight into the dynamics of the whale's maneuvers.

Table 1. Meanings of symbols used in equations.

α	some vector value	h_i	a humpback whale
β	depth function	$\hat{\jmath}$	unit vector pointing up
c	some constant	λ	height of school, bottom to top
c_{fh}	distance between a fish and a whale	m	mass
c_{hh}	distance between two whales	P	a preference
d	distance function	p	position
δ	horizontal span of school	r	radius
E_i	fish eaten by whale h_i	Δt	time interval
F_T	the target school	u	unit vector function
γ	hunting location	v	velocity
H	a set of humpback whales	x, y, z	location or vector components

A simulation for BNH behaviour needs to model artificial fish as well as whales. The most widely known algorithm for controlling groups of objects is flocking [11]. This algorithm approximates the schooling behaviour of fish, and has been used to simulate schooling behaviour in other studies [12].

Fish and their environment have been modelled by previous researchers with varying degrees of fidelity, including detailed models of the muscles used by fish for movement, their senses, their learning algorithms, and the physics of the water involved [13]. However, our simulation requires 50,000+ entities and uses simpler models in order to run at real-time speeds.

3 The BNH-Whale Algorithm

We now describe the BNH-Whale algorithm, which is used by the simulated whales when hunting fish using the BNH method. Symbols used in equations are defined in the Table 1. The algorithm, which is shown in Fig. 1, is executed for each whale at each time step. When animation is enabled, each time step results in a frame of the animation being displayed. In the whale behaviour model, communication with and perception of other whales are handled separately. Communication is permitted among all whales, but perception is restricted to only the neighbours of a whale. It is assumed that the whales use communication to decide when to start blowing bubbles and whose turn it is to lunge. Perception refers to checking whether it is time to lunge: the whales begin to lunge when the center of the target school is above all of the whales or sufficiently close to the surface. When determining which whale is to lunge, the simulated whales communicate a level of hunger, and a hierarchy settles whose turn it is when multiple whales are equally hungry.

To identify a target school for the whales, we use a single global calculation (since the whales in a pod are near to each and therefore likely perceive similar things). The ocean is divided into grid cells using *spatial hashing*, a technique often used to improve computational efficiency in flock and crowd simulations [14]. The fish in each cell are stored in a list. Tthe target school is found by first

1. If there is no current target school, identify a target school and obtains its position, width, and height
2. Perform message passing between whales in order to:
   (a) If circling, arrange location in circle with other whales (by role)
   (b) Ensure that all bubble blowers are ready before beginning to blow bubbles
   (c) Determine whose turn it is to lunge (if they are taking turns lunging)
3. If not close to target school, calculate hunting position
   (a) Increase depth while traveling
   (b) Bubble blowers may start forming an approach curtain before reaching the school
4. If close to school, determine hunting location
   (a) If bubble blower, calculate depth using Equation 3
   (b) If prey herder, calculate depth using Equation 4
   (c) Calculate the circling radius and position further along circle
5. If it is time to lunge
   (a) If taking turns, only the selected whale lunges
   (b) If not taking turns, all whales lunge together towards the target school center
6. Update velocity based on separate, momentum, and hunting location preferences

Fig. 1. BNH-Whale algorithm used to model whale behaviour.

identifying the grid cell containing the most fish.Then from nearby grid cells are added to the school, as long as the density of the fish in the next neighbouring cells is sufficiently high. The center of the target school is calculated by averaging the positions of all fish in it. The width (δ) of the target school is calculated as the maximum horizontal distance between any two fish in the school along either the x or z axis, and the height (λ) of the target school is calculated as the maximum vertical distance between any two fish in the school.

The whales are guided by flocking behaviour with three factors: separation, momentum, and hunting location. Separation ($P_{1,i}$) is a vector representing the preference of whale h_i to avoid other whales up to a defined distance c_{hh}.

$$\text{Separation: } P_{1,i} = \sum_{h_n \in H} \left(\left(c_{hh} - d\left(h_i, h_n\right) \right) / c_{hh} \right)^2 u\left(p\left(h_i\right) - p\left(h_n\right) \right) \quad (1)$$

Momentum ($P_{2,i}$) reflects the preference for continuing with the same velocity.

$$\text{Momentum: } P_{2,i} = m(h_i) * v(h_i) \quad (2)$$

The *hunting location* (γ) for a whale is the location it wants to be with respect to its target school of fish. This location depends on the role of the whale and its the distance from the school. If it is a bubble blower and far from the school, the hunting location is the nearest location at the starting depth for blowing bubbles and at its circling radius from the center of the school. If it is a prey herder and far from the school, its hunting location is below the school at a smaller circling radius. If a whale is at its circling radius from the school, its hunting location is further along the circle.

While circling, the depth of a bubble blower is based on the depth of the school and is calculated using Equation 3 [1]; this choice of depth causes the bubbles to arrive at the surface at the same time as or before the fish arrive. Thus, the fish are unable to escape by swimming over the net.

$$\gamma_y = 6.380 * \log\big(p_y(F_T)\big) - 2.686 \tag{3}$$

The depth of a prey herder is calculated using Equation 4 to be just below the bottom of the school and within the distance required to startle the fish.

$$\gamma_y = p_y(F_T) - 0.5 * \lambda - c_{\text{height fraction}} * c_{fh} \tag{4}$$

The circling radius of a bubble blower depends on both the *horizontal span* (greatest horizontal width in any direction) of the school [4] and how close a whale must be to startle a fish. Equation 5 is used to find the preliminary radius.

$$r_{\text{pre}} = 0.5 * \delta + c_{\text{width fraction}} * c_{fh} \tag{5}$$

The circling radius of a bubble blower also depends on its depth because the bubbles spread out more at the surface when they are emitted at greater depths [1]. Additionally, in the cases where the target school is located below the bubble net, the radius is increased to simplify the task of the prey herders. Thus, the circling radius r is the preliminary radius multiplied by a factor that depends on the depths of the bubble blower and school and the maximum allowed depth of a bubble blower using Equation 6.

$$r = \beta\big(\gamma_y, p_y(F_T), c_{\text{maxDepth}}\big) * r_{\text{pre}} \tag{6}$$

The circling radius of a prey herder is found similarly with a different β function.

Circling behaviour is produced by first finding the *outward vector*, which is a unit vector pointing from the target school to the whale (Equation 7).

$$\alpha_{xz} = u_{xz}\big(p_{xz}(h_i) - p_{xz}(F_T)\big) \tag{7}$$

By multiplying the outward vector by the circling radius, a location on the circle is obtained, and then by adding an offset perpendicular to the outward vector and the y axis using Equation 8, a location further along on the circle is found.

$$\gamma_{xz} = p_{xz}(F_T) + r * \alpha_{xz} + c * \alpha_{xz} \times \hat{\jmath} \tag{8}$$

Hunting location $P_{3,i} = \gamma$ is found by combining depth γ_y and horizontal γ_{xz}.

4 Conclusions

The BNH-Whale algorithm is designed to simulate the bubble net hunting behaviour of humpback whales. It simulates the herding maneuvers executed by whales in 3D and the escape behaviour of the fish. Future research could measure the effectiveness of the method by measuring the number of fish caught. It could also include further aspects of bubble net hunting such as the fatiguing of fish, varied sizes of fish and whales, modelling of the sound used to provoke the startle reflex in the fish [6], and improving the model of the bubbles to incorporate fluid dynamics. The simulation could also be designed to be GPU based.

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