Effects of Heterogeneity in a Fish School Model on Avoiding Obstacles

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Abstract

It is commonly known that fish schools can avoid obstacles. We investigated whether the personalities of the fish enable tha fish school to avoid obstacles. The personalities of fish can be interpreted as heterogeneity among fish.

We employed a fish school model. Through intensive simulations based on parameters obtained by tank experiments, it was shown that (1)the heterogeneity of a fish school enables the fish to avoid obstacles, and (2)the heterogeneity of the parameters that control interactions is especially effective for this cooperative behavior.

1 Introduction

Fish schools can avoid obstacles. Do the personalities of the fish reflect on this cooperative behavior? Intuitively, the answer to this question is negative.

To investigate the above question, we employ a fish school model that has been well verified[1]. This model describes the movements of each fish in a fish school, and consists of three differential forces acting on each fish and many parameters. The parameters have been presumed and verified through real tank experiments.

The personalities of fish can be interpreted as heterogeneity among fish because personalities can be defined as differences among individuals. In the above model, for instance, a fish school is called homogeneous, if the individuals in the school have the same parameters, and otherwise, it is called heterogeneous. Naturally, each real fish is expressed by different parameters that have been obtained in the above tank experiments. A simulation based on this fish school model enables us to compare homogeneous fish schools and heterogeneous fish schools because we can create a fish school based on the same single fish parameters. We would like to emphasize that this is the only way to investigate whether heterogeneity is the cause of avoiding obstacles.

From the above understanding, we would like to investigate whether the heterogeneity of a fish school enables a fish school to avoid obstacles. In addition to this, the parameters of the model can be separated into three distinct categories. Hence we would also like to investigate which categories' heterogeneity is effective for this cooperative behavior.

This paper is organized as follows. Section 2 starts with a fish school model description. Section 3 explains experiments using an obstacle. Section 4 discusses the results, and Section 5 concludes the paper.

2 Fish School Model

We employ a fish school model that has been well verified[1]. This model is a physical model that consists of differential forces and parameters. The following shows those forces and parameters.

2.1 Mathematical Model

The motion of a fish is assumed to be restricted within a two-dimensional space. Let the position and the velocity of fish i be x_i and v_i, respectively, where $x_i, v_i \in R^2$. Then the motions of N_f fish in a school are described by

$$\left.\begin{array}{lcl} \dot{x}_i & = & v_i \\ m\dot{v}_i & = & F_{i1} + F_{i2} + F_{i3} \\ i & = & 1, 2, \ldots N_f \end{array}\right\} \quad (1)$$

where m is the mean mass of the fish. F_{i1}, F_{i2} and F_{i3} are the forces that cause the motion of fish i. They are explained as follows.

Each fish has a characteristic of swimming forward at its own favorite speed (called the characteristic velocity) when other causes do not exist to alter the motion of the fish. This characteristic is expressed by

$$F_{i1} = -a_i^1(||v_i|| - a_i^2)(||v_i|| - a_i^3)v_i, \quad (2)$$

where a_i^1, a_i^2 and a_i^3 are parameters, $||v_i||$ is v_i's norm, and $a_i^2 < a_i^3$. We call F_{i1} the propulsive force.

Each fish keeps itself in a school on the basis of interactions among its neighbors. By information exchanges, the fish adjusts its speed and direction to match those of nearby neighbors. This characteristic is given by

$$F_{i2} = \sum_{j=1}^{N_f} b_i(r_{ij})\frac{x_j - x_i}{r_{ij}} + \sum_{j=1}^{M_i} c_i(r_{ij})\frac{v_j - v_i}{M_i} \quad (3)$$

$$b_i(r_{ij}) = \begin{cases} \frac{(k_{b_i}^2 - k_{b_i}^1)r_{ij}}{\alpha_{i1}} + k_{b_i}^1 & \text{for } 0 < r_{ij} \le \alpha_{i1} \\ k_{b_i}^2 & \text{for } \alpha_{i1} < r_{ij} \le \alpha_2 \\ 0 & \text{for } r_{ij} > \alpha_2 \end{cases} \quad (4)$$

$$c_i(r_{ij}) = \begin{cases} k_{c_i} & \text{for } 0 < r_{ij} \leq \delta \\ 0 & \text{for } r_{ij} > \delta, \end{cases} \tag{5}$$

where $k^1_{b_i}$, $k^2_{b_i}$, k_{c_i}, α_{i1} and δ are parameters, α_2 is a constant, and $r_{ij} = ||x_j - x_i||$. The first term of (3) is an interactive force to keep a proper distance between neighboring fish. The second term is a schooling force to make the velocity of each fish uniform. In (3), M_i is the number of fish, whose r_{ij} is less than the distance δ.

Each fish has the ability to perceive environmental variations and to acquire information from the environment by using its eyes and lateral lines. Then the fish adjusts its own action according to the environment. In this model, the walls of a box-shaped obstacle give an environmental effect to the movement of the fish. When a fish swims into the obstable, it often moves along the wall, stays inside and then goes out of the obstacle, but never strikes against it even if the fish approaches it very closely. Consequently, fish act both attractively and repulsively with respect to the wall. This characteristic is expressed by

$$F_{i3} = k^+_{w_i} \sum_{l=1}^{L} f^+_{wil} + k^-_{w_i} \sum_{l=1}^{L} f^-_{wil} \tag{6}$$

$$f^+_{wil} = \begin{cases} v_{il} \frac{d^+ - d_{il}}{d^+} e_l & \text{for } v_{il} > 0 \text{ and } d_{il} < d^+ \\ 0 & \text{otherwise} \end{cases} \tag{7}$$

$$f^-_{wil} = \begin{cases} v_{il} \frac{d^- - d_{il}}{d^-} e_l & \text{for } v_{il} < 0 \text{ and } d_{il} < d^- \\ 0 & \text{otherwise,} \end{cases} \tag{8}$$

where L is the number of the wall sides. The unit vector e_l is normal to wall l, and v_{il} is the velocity component normal to wall l, given by $v_{il} = -e_l^T v_i$. The quantity d_{il} means the distance from fish i to wall l.

In (6), the first and the second term are called the repulsive and the attractive forces from the wall, respectively. The parameters k^+_{wi} and k^-_{wi} are their coefficients. The repulsive force acts on fish i when it approaches the wall, i.e, $v_{il} > 0$ and the attractive force acts on fish i when it goes away from the wall, i.e, $v_{il} < 0$.

2.2 Observed Parameters

The experiment in the tank showed the parameters of Bitterling[2]. These parameters are shown in Table 1.

In this table, i means the number of fish, hence five fish's parameters are shown. The explanation of other parameters have already been shown in Section 2.1. Naturally, each fish has a different set of parameter values. Therefore, this fish school is heterogeneous.

These parameters are separated into three categories, according to the equations that each parameter belongs to. First is F_1's parameters. These are a^1, a^2 and a^3. Second is F_2's parameters. These are k^1_b, k^2_b, k_c and α_1. Third is F_3's parameters. These are k^+_w and k^-_w.

3 Experiment

3.1 Obstacle

In experiments, we analyze how fish avoid an obstacle. Figure 1 shows the obstacle. The obstacle is a square without one side. One side is thirty cm long.

It is difficult to define a *general* obstacle. Hence this obstacle is just one example. But avoiding the box-shaped obstacle can be considered as a typical avoiding behavior[1].

At the beginning of the experiment, all fish are put into the obstacle and swim to the bottom. Formations at the beginning are randomly decided each time.

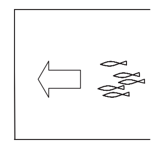

Figure 1: Obstacle

3.2 Procedure

One fish school consists of five fish, and it is put into the obstacle thirty times. An avoidance by a fish is defined as the position where the fish traverses the imaginary side of the obstacle. In each trial, if all of the fish avoid the obstacle, the trial is successful. Each trial is held for 300 seconds.

3.3 Fish Combinations

3.3.1 Experiment without Parameter Change

We wish to investigate whether homogeneous fish schools can escape from the obstacle or not. There are five available homogeneous fish schools. In Table 1, there are five different fish. A homogeneous fish school can be made by choosing one fish and copying it. A homogeneous fish school made from No. 1 is called No. 1 Homo. Other homogeneous fish schools are named in the same way.

As a comparison to these experiments, heterogeneous fish are also investigated. This fish school consists of fish from No. 1 to No. 5, and called Hetero.

3.3.2 Experiment with Parameter Change

Here, we wish to investigate whether heterogeneity, which results from some category of parameters, affects the escape or not. As mentioned before, there are three categories, which are F_1's, F_2's and F_3's parameters. Therefore these categories should be experimented separately.

The experiment for the F_1 parameters is called the experiment with F_1 parameter change. In this experiment, different values of F_1 parameters are set. Heterogeneous

[1]Whether fish want to avoid the obstacle or not does not matter. What we would like to analyze is what kind of fish school avoids the obstacle.

Table 1: Parameters of Bitterling

i	a_i^1 (g · sec/cm^2)	a_i^2 (cm/sec)	a_i^3 (cm/sec)	k_{bi}^1 (g · sec/cm^2)	k_{bi}^2 (g · sec/cm^2)	k_{ci} (g/sec)	α_{i1} (cm)	k_{wi}^+ (g/sec)	k_{wi}^- (g/sec)
1	-0.00366	11.9	35.0	-6.20	4.20	1.57	8.47	10.6	3.19
2	-0.00275	11.0	38.4	-6.40	4.38	1.31	8.44	13.1	2.90
3	-0.00330	10.9	37.9	-4.40	3.11	1.49	8.35	7.3	3.58
4	-0.00180	10.6	46.4	-5.60	2.57	1.30	9.64	19.8	3.91
5	-0.00122	10.4	53.9	-6.90	4.02	1.46	8.88	13.8	3.17

$m = 2.58\text{g}$, $\delta = \alpha_2 = 50\text{cm}$, $d^+ = 5\text{cm}$, $d^- = 20\text{cm}$

fish schools are made from the fish schools shown in Section 3.3.1. One is, for example, a heterogeneous fish school based on No. 1 Homo. The F_1 parameters of the fish are overwritten by the F_1 parameters of fish from No. 1 to No. 5. This is called No. 1 based F_1 Hetero. Other F_1 heterogeneous fish schools can be made in the same way. In addition, fish schools that have heterogeneity in F_2 and F_3 can be made similarly.

3.4 Result

3.4.1 Experiment without Parameter Change

Table 2 shows the result of the experiment without parameter change. This table shows the type of fish schools and the number of successful escapes in thirty trials. Hetero escapes 18 times. But no homogeneous fish school can escape from the obstacle even once.

Table 2: Result of Experiment without Parameter Change

Fish School	Escape Success (in 30 trials)
No. 1 Homo	0
No. 2 Homo	0
No. 3 Homo	0
No. 4 Homo	0
No. 5 Homo	0
Hetero	18

3.4.2 Experiments with Parameter Change

Tables 3, 4 and 5 show results of experiments with parameter change. These tables also show the type of fish schools and the number of successful escapes in thirty trials.

Fish schools in experiments with F_1 and F_3 parameter change cannot escape from the obstacle even once. On the other hand, fish schools with the experiment F_2 parameter change can escape many times through dispersion.

Table 3: Result of Experiment with F_1 Parameter Change

Fish School	Escape Success (in 30 trials)
No. 1 based F_1 Hetero	0
No. 2 based F_1 Hetero	0
No. 3 based F_1 Hetero	0
No. 4 based F_1 Hetero	0
No. 5 based F_1 Hetero	0

Table 4: Result of Experiment with F_2 Parameter Change

Fish School	Escape Success (in 30 trials)
No. 1 based F_2 Hetero	12
No. 2 based F_2 Hetero	3
No. 3 based F_2 Hetero	12
No. 4 based F_2 Hetero	9
No. 5 based F_2 Hetero	12

4 Discussion

In the result of the experiment without parameter change, only Hetero was able to escape (Table 2). This result supports our hypothesis that heterogeneity in a fish school enables the fish school to avoid obstacles.

Based on the above discussion, it is natural to investigate what kind of heterogeneity is effective. Therefore we separate the parameters of the model into three categories.

In the result of the experiment with F_1 parameter change, no fish school can escape (Table 3). Similarly, in the result of the experiment with F_3 parameter change, no fish school can escape (Table 5). On the other hand, in the result of the experiment with F_2 parameter change, all of the fish schools can escape at least once. This shows that heterogeneity in the F_2 parameters is effective compared to other parameters. More generally, heterogeneity of the parameters that control interactions is effective, because F_2 parameters control interactions.

These results agree with the past result that fish schools have to interact with each other first to escape from an

Table 5: Result of Experiment with F_3 Parameter Change

Fish School	Escape Success (in 30 trials)
No. 1 based F_3 Hetero	0
No. 2 based F_3 Hetero	0
No. 3 based F_3 Hetero	0
No. 4 based F_3 Hetero	0
No. 5 based F_3 Hetero	0

obstacle[2]. If heterogeneity in the F_2 parameters is necessary to avoid the obstacle, it is natural that no fish school can escape in the experiment with F_1 and F_3, because in these experiments, there is no heterogeneity in F_2 parameters.

The reason why heterogeneity in the F_2 parameters is necessary should be supposed. F_2 parameters are separated into two groups, the k_b^1 and k_b^2 group and the k_c group. k_b^1 and k_b^2 control the distance between neighboring fish. k_c control the schooling force. To avoid the obstacle, fish have to turn around. That requires the fish to interact with other fish. If the interaction is imperfect, the fish will get stuck. This is because several fish that try to move along the wall will swim in two different directions in a corner. There are two ways to avoid this phenomenon. First is heterogeneity in the schooling force. The fish that have a weaker schooling force than others pull the school in their own direction, and avert the deadlock. Second is heterogeneity in the distance between neighboring fish. Homogeneous distances make an even formation. This causes the same number of fish to try to swim in two different directions along the walls, get stuck easily. On the other hand, heterogeneous distances make an uneven formation. This causes a different number of fish to try to swim in two different directions along the walls, so they do not get stuck easily.

This paper assumes that a fish school gathers. Indeed, there are fish that do not gather, and these fish may not get stuck in obstacles. But what we want to discuss here is how a fish school avoids obstacles without breaking up its group. Therefore, the result of this paper may help studies of multi-agent systems moving in formations.

5 Conclusion

We investigated whether the personalities of fish enable a fish school to avoid obstacles. The personalities of fish can be interpreted as heterogeneity among fish.

We employed a fish school model. Through intensive simulations based on parameters obtained by tank experiments, it was shown that (1)the heterogeneity of a fish school enables the school to avoid obstacles, and (2)the heterogeneity of parameters that control interactions is especially effective for that cooperative behavior.

Acknowledgement

This research was conducted as part of 'Research on Human Communication' with funding from the National Institute of Information and Communications Technology.

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