Spatial sorting and collective motion in mixed shoals of fish

Markus Eriksson
Abstract

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Shoaling behaviour arises when fish respond to the movements and positions of nearby neighbours. The dynamic patterns of shoaling fish has been studied by the Mathematical department in Uppsala University. In this project experimental data collected for groups with two sizes of fish are analysed. An existing model was modified to reproduce the dynamic patterns in the fish shoal, this was done by comparing visual and statistical properties from the simulations with experimental observations. By analysing the impact of the parameters in the model it was found out that introducing limitations in the vision of the smaller fish are essential to be able to reproduce the behaviour of the mixed sized fish shoal. The limitations in the vision are speculated to be a representation of physiological limitations in the coordination of mechano-sensoric activities and visual information.
Popular Scientific Summary

If you have experienced the fascinating appearance of flocking birds, complex ant networks or shoaling fish you can get an idea of what the scientists in the field of Collective behaviour are working with. Collective behaviour is a relatively new and growing study field which goal is to understand and reproduce the complex patterns seen in different groups of individuals. By learning the rules that determine the complex and often efficient behaviour we would be able to apply it to human developed systems, such as robots or to the infrastructure in cities.

In this project the interaction rules that determines the behaviour of a shoal with two sizes of fish are investigated. This was done by the help of experiments and a model developed at the Mathematical Department in Uppsala University. In the experiment groups of fifty fish were recorded when they were confined into a circular tank. By modifying the existing model and adjusting the model parameters accordingly the result from the simulations showed that it was possibly to reproduce the behaviour seen in the experiments.

The results from these simulations gave the insight that limitations in the vision field of the smaller sized fish in the model were needed to receive the same kind of behaviour as observed in the experiment. These vision limitations could be a representation of the younger and smaller sized fish not having fully developed central neuron system, which reduces their ability to coordinate in a shoal.
Acknowledgements

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1 Introduction

When individuals in a group respond to each others movements and positions, a cooperative complex motion arises. This type of behaviour is called collective motion [1, 2]. One of the main goals in the research of collective motion is to understand and make classification of the interaction rules leading to the flocking behaviour that can be observed in groups of different species [3, 4]. The fish is an animals that can be modelled by implementing a set of simple behavioral rules and when each individual follows those rules complex patterns emerges [5, 6]. The study of the shoaling dynamics are of special interest since fish is a convenient animal to use in experiments and modelling. By learning more about the shoaling dynamics it would be possible to get a better insight in the collective motion of other systems of individuals. The research group lead by D.J.T. Sumpter at the Mathematics Department in Uppsala University have been working on the study of collective animal behaviour with a focus on on the shoaling behaviour of fish. In an experiment different amounts and sizes of the fish species Pacific blue eyes was confined in a shallow circular tank and filmed from above. By analysing the videos they found that the shoaling behaviour of groups with only big sized fish, groups with only small sized fish and groups with mixed sized fish behave differently from each other. The group with only big sized fish tend to move cohesively, with high speed close to the wall. The group with only small sized fish tend to move with less cohesiveness, with low speed and distributed all over the tank. For the group of mixed sized fish the big sized fish had the same behaviour as in the case with only big sized fish while the small sized fish changed their behaviour to move with more cohesiveness and going in the same angular direction as the big sized fish but closer to the center of the tank. The observations indicate that the small sized fish tries to adapt to the motion of the big sized fish. By implementing a computer based model the research team could reproduced the behaviour of the groups with only big sized fish and small sized fish. In this project it was my task to reproduce the collective motion of the group with mixed sized fish, by modifying the model and tuning the parameters in a qualitative manner so the same behaviour seen in the experiments could be received and make quantitative interpretations of the results.
2 Material and methods

2.1 Experimental setup and data collection

The fish species used in the experiment was Pacific blue eyes, *Pseudomugil signifer*. Groups of 50 fish were used with two different sizes of the fish, small sized fish with the body length 7.5 mm and big sized fish with the body length 20 mm. The fractions of big sized fish in the mixed sized groups were 0.2, 0.3 and 0.4, i.e. the fraction is 0.2 when 20% of fish in a group are big sized fish. The fish were confined into a large (760 mm in diameter) shallow circular arena and recorded from above. The camera used was a Logitech C615. Each video had the duration of 15 to 20 minutes, recorded with the frame rate of 15 frames per second. In total, ten experimental trials were filmed and the videos were compressed to AVI-format. The tracking software DIDSON [7] was used to convert the position of the fish in the videos into MAT-file format with the X-coordinate, Y-coordinate, ID-number and with the corresponding time step. The pixel-to-mm ratio was 1.4755. The classification of the fish size was done by manually picking out which ID-numbers corresponded to big sized fish and small sized fish.

2.2 Data processing

The videos were examined visually to analyse specific spatial patterns of the fish so that the model parameters could be tuned and the statistical collections from the experiment could be validated. MATLAB was used to analyse the experimental data by visualizing the tracking data of the fish and calculating the statistical properties of the shoals. The tracking data contained approximately 30% errors that were caused by a too coarse resolution in the recording of the videos which lead to inconsistencies when the fish were swimming close to each other, some of the time steps were not tracked for some fish and the ID-numbering of the fish changed owner from time to time, therefore the data had to be processed to make the tracking data consistent. The first approach to solve the inconsistencies were to use parts of trajectories with consistent identities. The result was realistic plots but with too few time frames to be used to do quantitative interpretations. Then the approach was changed to implementing a filter algorithm that tracked the fish until they did an unrealistically large change in position, the result was that the majority of the time frames contained small sized fish since the big sized fish had higher probability to make a large change in position and the simulation was to no use. The final approach was to manually do the classification for each time frame for the fish size for one of the videos, this resulted in consistent plots with large enough number of frames to be used to do statistical analysis of the simulations.

2.3 Statistics collection

From the tracking data the velocities of each fish can be calculated based on two subsequent positions. The positions and velocities could be used to calculate the radial density distribution $g(r)$, the polar order parameter $\varphi(r)$ and the angular order parameter $L(r)$. The statistics were calculated by dividing the tank into ten circular shells, with the shell radius 38, 76, ..., 380 mm, where each fish could be positioned in one of shells at each time step. The normalized density $g(r)$ quantifies the distribution of fish across the tank in radial direction and was calculated as in [8].
Figure 1: Figure demonstrating three circular shells. \( \mathbf{r}_i \) is the position vector from the center of the tank to the center of the fish \( i \) and \( r \) is the half-shell-width.

\[
g(r) = \frac{1}{\pi r^2} \frac{1}{N(r)} \left( \sum_{i=1}^{N(r)} \delta(r - |\mathbf{r}_i|) \right)
\]

(1)

where \( \delta \) is the Dirac delta function, \( |\mathbf{r}_i| \) is the euclidean distance from the center of the tank to the fish \( i \), \( r \) is the half-shell-width, \( <..> \) stands for the ensemble average and \( N(r) \) is the amount of fish inside the circular shell given by \( r \). The angular order parameter is a scale free measurement of the sum of the angular momenta of the fish, it is the degree of rotation of the group about the centre of the tank and takes a value in the interval \([0,1]\). The angular order parameter \( L(r) \) is calculated as in [6]

\[
L(r) = \frac{1}{\sum_{i=1}^{N(r)} |\mathbf{r}_i| |\mathbf{v}_i|} \left( \sum_{i=1}^{N(r)} \mathbf{r}_i \times \mathbf{v}_i \right)
\]

(2)

and is calculated for every shell. \( \mathbf{v}_i \) is the velocity and \( \mathbf{r}_i \) is the position of the fish. The polar order parameter \( \varphi(r) \) is a measurement of how strong the alignment within a group is, it is calculated as in [6]

\[
\varphi(r) = \frac{\sum_{i=1}^{N(r)} \mathbf{v}_i}{\sum_{j=1}^{N(r)} |\mathbf{v}_j|}
\]

(3)

and is calculated for every shell. The nearest-neighbour distance was calculated by

\[
NN_i = \min_{i \neq j} r_{ij}
\]

(4)

where \( r_{ij} \) is the euclidean distance between fish \( i \) and \( j \).
3 Model

3.1 Interaction rules

In the model the fish are moving with a constant propulsion speed and the direction of motion is calculated by obeying interaction rules on the surrounding neighbours, with some random perturbation added.

![Zones of interactions](image)

Figure 2: Zones of interactions. Each zone starts from the center of the fish $i$. $v_i$ is the velocity of fish $i$, $R_r$ is the radius of the repulsion zone, $\beta$ is the blind angle and $R_a$ is the radius of the alignment zone.

The interaction rules are that for each time step

- The fish repulse from their neighbours that are positioned inside their repulsion zone that has the radius $R_r$, to avoid collision.

- If the fish does not have any neighbours inside their repulsion zone but there are neighbours inside the zone of alignment, that has the radius $R_a$, it aligns with the average direction of motion of the fish inside the alignment zone.

- If some neighbours of the fish are in the area of the blind angle, defined by the angle $\beta$, the focal fish will not align with those neighbours.

- If there are no fish inside the zone of repulsion or in the alignment zone the fish will continue their movement unaffected by other fish.

The velocity was calculated as in [8]

$$ v_i(t) = v_0 \hat{u}_i(t) R_1(\xi_i(t)) R_2(\omega_i(t)) $$

(5)

where

$$ \hat{u}_i(t) = -\sum_{j \neq i}^{n_r} \frac{r_{ij}(t)}{\sum_{j \neq i}^{n_r} r_{ij}(t)} $$

(6)

or

$$ \hat{u}_i(t) = \sum_{j=1}^{n_a} \frac{v_j(t)}{\sum_{j=1}^{n_a} v_j(t)} $$

(7)
Equation (6) is used for repulsion interactions and equation (7) is used for alignment interactions [6]. \( \hat{u} \) is the unit vector of the direction of motion. \( v_0 \) is the speed of the fish, which is a fixed value in this model. \( r_{ij} \) is the euclidean distance between the fish \( i \) and the fish \( j \). \( R_1 \) is a rotation matrix which is used to calculate the angular noise where \( \xi_i(t) \) is a random number in the interval \(-\pi \) to \( \pi \) used to rotate fish \( i \). \( R_2 \) is a rotation matrix which is used to calculate the influence the wall has on the fish, where \( \omega_i(t) \) is the turning rate the fish \( i \) will change the direction of motion with. The definition of the rotation matrix is

\[
R(\theta) = \begin{bmatrix}
\cos(\theta) & -\sin(\theta) \\
\sin(\theta) & \cos(\theta)
\end{bmatrix}
\]

where \( \theta \) is the turning angle.

### 3.2 Initial conditions and position updating

The time integration and the statistical collection in the model was implemented by using the program language FORTRAN and compiled with a GFortran compiler. MATLAB was used to visualize the movement and plotting the statistical properties. The simulations were carried out in a circular shaped cell with the radius 380 pixels and integrated for 50 000 time steps at each run. The fish were initially positioned with a random uniform distribution in the cell with random uniformly distributed directions. At each time step positions of all fish were streamed along to their new direction by using the equation

\[
r_i(t + 1) = r_i(t) + \Delta t v_i(t)
\]

where the time unit \( \Delta t \) was set to one and the velocity was calculated by equation (5).

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \eta_{\text{big}} )</td>
<td>0.1</td>
<td>Noise parameter for the big sized fish.</td>
</tr>
<tr>
<td>( \eta_{\text{small}} )</td>
<td>0.0 to 1.0</td>
<td>Noise parameter for the small sized fish.</td>
</tr>
<tr>
<td>( R_{a,\text{big}} )</td>
<td>96</td>
<td>Alignment zone radius for the big sized fish.</td>
</tr>
<tr>
<td>( R_{a,\text{small}} )</td>
<td>30.0, 51.9 or 92.3</td>
<td>Alignment zone radius for the small sized fish.</td>
</tr>
<tr>
<td>( v_{0,\text{big}} )</td>
<td>10</td>
<td>Speed of the big sized fish.</td>
</tr>
<tr>
<td>( v_{0,\text{small}} )</td>
<td>1 to 9</td>
<td>Speed of the small sized fish.</td>
</tr>
<tr>
<td>( \beta_{\text{big}} )</td>
<td>0 rad</td>
<td>Blind angle for the big sized fish.</td>
</tr>
<tr>
<td>( \beta_{\text{small}} )</td>
<td>0 to 2( \pi ) rad</td>
<td>Blind angle for the small sized fish.</td>
</tr>
<tr>
<td>( R_r )</td>
<td>10</td>
<td>Repulsion zone radius.</td>
</tr>
<tr>
<td>( \text{fraction} )</td>
<td>0.0 to 1.0</td>
<td>Fraction of big sized fish.</td>
</tr>
</tbody>
</table>

In Table 1 the parameters used in the model are stated, some of the parameters are tuned within a range specified in the table for different simulations to get motion patterns similar to those observed in the experiment. The repulsion zone radius and alignment zone radius parameter values were estimated experimentally.

### 3.3 Boundary condition

The boundary condition is modeled as a repulsion from the wall and is calculated as in [11]
where $\alpha_i$ is the angle between the direction of motion of the fish $i$ and the normal to the point of impact on the wall and $d_i$ is the euclidean distance from fish $i$ to the point of impact on the wall. $\omega_i$ is the turning rate with which the fish $i$ will change direction of motion due to the wall repulsion when time integrating by equation (5). These parameters can be seen in figure 3.

Figure 3: Parameters used to calculate the wall influence on the fish $i$ in the model

3.4 Angular noise

To get realistic fish movement behavior the angular noise has to influence the fish when the direction of motion is integrated. If noise is to weak the fish will move with a unrealistic robotic behaviour while under influence of strong noise the fish will move with a random in-cohesive behaviour. The angular noise is calculated by using the Gaussian distributed probability density function

$$P(\xi_i(t)) = e^{-\xi_i^2(t)/2\eta^2} / \sqrt{2\xi_i(t)\eta}$$

where $\eta$ is the noise parameter that is a value chosen between zero and one to tune how big the influence of angular noise is when integrating the direction of motion in equation 5. For each simulation a different initial seed was used in the random number generator function calls to avoid repeated motion patterns.

3.5 Modification of the model

To be able to use the existing model modifications had to be made to support mixed sized group where fish had different properties. The following modifications were made to the existing model

- Introduced a fraction variable for different ID-numbers of the fish to correspond to a big sized fish or small sized fish, which made it possible to distinguish the different properties.
- Implemented the support for the big sized fish and the small sized fish to move with different constant speeds.
- Implemented the support for the big sized fish and the small sized fish to have different alignment zone radius.
• Implemented the support for the big sized fish and the small sized fish to interact with different blind angles.

• Implemented an independent control over the noise parameter $\eta$ for small and large fish.

• Implemented the support for the statistical collection to do separate calculations for the big sized fish and the small sized fish.

• Introduced shell statistics where statistical collection could be done to see radial distance dependencies, with separate calculations for the big sized fish and the small sized fish.

The parameters in the modified model had to be tuned to achieve similarity in statistical behaviour. This was done by iteratively changing one parameter at a time and comparing the visualization of the result and the statistical collection from the simulations with the videos and the statistical collection from the experiment.
4 Results and discussion

4.1 Experimental results

The results from the experiment are calculations made on the tracking data from three of the videos. One video of the mixed sized group where the fraction of big sized fish was 0.4, one video of the group containing only big sized fish and one video of the group containing only small sized fish.

(a) Group of mixed sized fish  (b) Group of big sized fish  (c) Group of small sized fish

Figure 4: Snapshots of the observation of the three different videos recorded in the experiment, with an overlay of the tracked data visualized by blue dots for big sized fish and red dots for small sized fish.

In figure 4 the typical movement behaviour of the three different groups are seen. In the group of mixed sized fish the big sized fish are moving cohesively positioned close to the wall of the tank while the small sized fish are moving with some cohesiveness positioned close to the center of the tank. In the group with only big sized fish the group is moving cohesively close to the wall of the tank. In the group with only small sized fish the group is moving with little cohesiveness and the fish are positioned all over the tank.

Figure 5: Statistics from the experiment on the mixed sized group: (a) Normalized density distribution, (b) polar order parameter and (c) angular order parameter as a functions of radial distance.

In figure 5 the statistics from the experiment on the mixed sized group is seen. The normalized density distribution shows that the big sized fish is distributed close to the wall of the tank, with a density distribution peak at the radial distance 670 mm, and
that the small sized fish are distributed close to the center of the tank, with a density distribution peak at the center of the tank. The polar order parameter shows that big sized fish has increasing polar order as the radial distance is increasing, with a polar order peak at the radial distance 680 mm, and that the small sized fish has decreasing polar order as the radial distance is increasing, with a polar order peak at the radial distance 340 mm. The angular order parameter shows that big sized fish has increasing angular order as the radial distance is increasing, with a angular order peak at the radial distance 680 mm, and that the small sized fish has a peak at the radial distance 420 mm.

Figure 6: Statistics from the experiment on the unmixed group with big sized fish and on the unmixed group with small sized fish: (a) Normalized density distribution, (b) polar order parameter and (c) angular order parameter as a functions of radial distance.

In figure 6 the statistics from the experiments on the group with big sized fish and the group with small sized fish, calculated at separate occasions, are seen. The normalized density distribution shows that the density distribution of big sized fish is increasing as the radial distance is increasing and the density distribution of the small sized fish is decreasing as the radial distance is increasing. The polar order parameter shows that big sized fish has increasing polar order as the radial distance is increasing, with a polar order peak at the radial distance 500 mm, and that the small sized fish has decreasing polar order for big radial distances, with a polar order peak at the radial distance 600 mm. The angular order parameter shows that the big sized fish has increasing angular order as the radial distance is increasing, with a angular order peak at the radial distance 525 mm, and the small sized fish has low angular order for all radial distances, but has a angular order peak at the radial distance 680 mm. Comparing these results for the unmixed group with small sized fish to the group with mixed sized fish, seen in figure 5, it is seen that the group with unmixed small sized fish is distributed at bigger radial distances, the polar order is increased for radial distances close to the wall of the tank, the polar order is decreased for radial distances close to the center of the tank and the total angular order is decreased. The statistical properties for the big sized fish are similar in the group with mixed sized fish and the group with unmixed big sized fish.

In figure 7 the absolute velocity probability distribution from the experiment is seen. Comparing the group of mixed sized fish with the groups of unmixed sized fish it is seen that the small sized fish are faster in the mixed group case, while the speed of big sized fish are smaller. The speed distribution for small sized fish has bigger peak and slope in the unmixed group compared to the mixed group.

In figure 8 the nearest-neighbour distance distribution is seen, calculated by equation 4. It is seen that in the mixed sized group the nearest-neighbour distance distributions are
more skewed than in the unmixed group. The peaks and the slopes of the distributions in the unmixed group are smaller than in the mixed sized group.

### 4.2 Model results

The parameters for small sized fish were adjusted in the simulations, to simulate the movement behaviour seen in the experimental observations of the group with mixed sized fish. The parameters for the big sized fish are fixed since their experimentally observed moving patterns for the mixed and unmixed case were closely resembled. In figure 9 the curves for different values of the alignment zone radius for small sized fish is seen. For the big sized fish the statistical properties are unaffected by the parameter tuning and the peaks are located at the radial distance 600 for the normalized density distribution, at the radial distance 550 for the polar order and at the radial distance 680 for the angular order. For the small sized fish all three statistical properties have the highest value when the alignment zone radius for small sized fish is set to 92.3, except for radial distances bigger than 400 in the normalized density distribution case. These results are the preferred ones since the goal is to reproduce the observed experimental properties. The density distribution peaks for the small sized fish at the center of the tank, the polar order peaks at the radial distance 250 and the angular order peaks at the
Figure 9: Tuning of the small sized fish alignment zone radius parameter in the model: (a) Normalized density distribution, (b) polar order parameter and (c) angular order parameter as a functions of radial distance. The continuous lines are small sized fish and the dashed lines are big sized fish. With the parameters set to $\eta_{\text{big}} = 0.1$, $\eta_{\text{small}} = 0.2$, $R_{a,\text{big}} = 92.3$, $v_{0,\text{big}} = 10$, $v_{0,\text{small}} = 4$, $\beta_{\text{big}} = 0$ rad $\beta_{\text{small}} = 0.93$ rad, $R_r = 10$ and $\text{fraction} = 0.4$.

radial distance 340.

Figure 10: Tuning of the small sized fish blind angle [$\text{rad}$] parameter in the model: (a) Normalized density distribution, (b) polar order parameter and (c) angular order parameter as a functions of radial distance. The continuous lines are small sized fish and the dashed lines are big sized fish. With the parameters set to $\eta_{\text{big}} = 0.1$, $\eta_{\text{small}} = 0.2$, $R_{a,\text{big}} = 92.3$, $R_{a,\text{small}} = 92.3$, $v_{0,\text{big}} = 10$, $v_{0,\text{small}} = 4$, $\beta_{\text{big}} = 0$ rad, $R_r = 10$ and $\text{fraction} = 0.4$.

In figure 10 the curves for different values of the blind angle for the small sized fish are presented. It is seen that setting the blind angle for small sized fish to 0 rad gives statistics that are similar to the statistics of the big sized fish. Setting the blind angle for the small sized fish to 0.93 rad gives the density distribution with the small sized fish located closest to the center of the tank, it also gives the lowest value of the polar order and the angular order at radial distances close to the wall. For the big sized fish the statistical properties are unchanged and the peaks are located at the same positions as in figure 9.

In figure 11 the curves for different values of the noise parameter for small sized fish is seen. It is seen that setting the noise parameter for small sized fish to 0.1 or 0.05 the highest values on the statistical properties close to the center of the tank for the small
sized fish are received, for those values the density distribution is peaking at the radial
distance 180, the polar order is peaking at the radial distance 260 and the angular order
is peaking at the radial distance 350. For the big sized fish the statistical properties are
unchanged and the peaks are located at the same positions as in figure 9.

In figure 12 the statistics from the simulations of the case with unmixed groups of big sized
fish and a small sized fish are seen. The parameters were set to $\eta_{\text{big}} = 0.1$, $\eta_{\text{small}} = 0.2$, $R_{a,\text{big}} = 92.3$, $R_{a,\text{small}} = 92.3$, $v_{0,\text{big}} = 10$, $v_{0,\text{small}} = 4$, $\beta_{\text{big}} = 0$ rad $\beta_{\text{small}} = 0.93$ rad, $R_r = 10$ and $\text{fraction} = 0.4$. Those parameters were chosen to reproduce the spatial
patterns and statistical properties observed in the experiment with groups of mixed sized
fish. It is seen that the small sized fish are evenly distributed in the tank while the big
sized fish are distributed close to the wall of the tank with a density distribution peak
at the radial distance 600. The small sized fish has a polar order parameter peaks at
the radial distance 300 and the big sized fish has a polar order parameter peaks at the
radial distance 500. The small sized fish angular order parameter is increasing as the
radial distance is increasing and for the big sized fish the angular order parameter peaks at the radial distance 510. Comparing the simulations of the group with mixed sized fish and the unmixed groups it is seen that the movement behaviour of the big sized fish are similar in both cases but the movement behaviour of the small sized fish are changed, one of the biggest changes in the behaviour for the small sized fish are that they are distributed closer to the center of the tank in the group with mixed sized fish.

Figure 13: Nearest-neighbour distance distribution from the model. With the parameters set to \( \eta_{\text{big}} = 0.1, \eta_{\text{small}} = 0.2, R_{a,\text{big}} = 92.3, R_{a,\text{small}} = 92.3, v_0,\text{big} = 10, v_0,\text{small} = 4, \beta_{\text{big}} = 0 \text{ rad}, \beta_{\text{small}} = 0.93 \text{ rad}, R_r = 10 \text{ and fraction} = 0.4. \)

In figure 13 the nearest-neighbour distance distribution is seen, calculated by equation 4. It is seen that in the mixed sized group the nearest-neighbour distance distribution for the small sized fish is more skewed than in the unmixed group. The peak of the distribution for the small sized fish in the mixed sized group is bigger than in the unmixed group.

**4.3 Comparison of positional data**

Some of the comparison made between the visualization of the simulations and the videos from the experiment with tracking data is in this section presented through snapshots.

In figure 14 snapshots from the experiment and the model for the group with mixed sized fish are seen. In the figure the similarities in the collective motion is observed, the big sized fish tend to move cohesively distributed close to the wall of the tank while the small sized fish tend to move cohesively distributed close to the center of the tank and following the angular movement of the big sized fish.

In figure 15 snapshots from the experiment and the model for the group with big sized fish is seen. In the figure the similarities in the collective motion is observed, the big sized fish tend to move cohesively positioned close to the wall.

In figure 16 the snapshots from the experiment and the model for the groups with small sized fish is seen. In the figure the similarities in the collective motion is seen, the small sized fish tend to move with little cohesiveness and distributed all over the tank.
Figure 14: Snapshots of the group with mixed sized fish. Blue circles shows big sized fish and red circles shows small sized fish.

Figure 15: Snapshots of the big sized group.

4.4 Conclusions and future work

The collective motion and spatial sorting in the group with mixed sized fish observed in the experiment was successfully reproduced by the modified model. The results show both qualitatively and quantitatively that a simple self-propelled particle model can be used to simulate the collective motion of the group with mixed sized fish. The results from figure 8 and figure 4 suggest that the aggregation within small sized fish and big sized fish subgroups in the mixed sized group is stronger than in the unmixed group, this
Behaviours has been reproduced in the simulations seen in figure 13. The parameters that make the dynamics in the model similar to experimental observations are the alignment zone of the small sized fish, the noise parameter for the small sized fish and the blind angle for the small sized fish. Introducing a blind angle is essential in order to reproduce the behaviour of small sized fish within a mixed group. From the tested values on the blind angle for small sized fish the value 0.93 rad was the optimal, which is seen in figure 10. The biological properties of fish bodies give them limited vision directly behind them. In mathematical models, these limitations are traditionally introduced in a form of blind angle [9]. In a broader sense, it can be speculated that the blind angle can be also used as a representation of the physiological limitation on a level of coordination of mechano-sensoric activities and visual information [10]. The younger small sized fish may not yet fully developed their neuron and muscular system and therefore cannot respond fast to changing environment or support large swimming speeds. From a physical point of view the blind angle allows to tune a degree of anisotropy of interactions between the individuals in the system. If the blind angle is equal to zero the interactions are fully isotropic which corresponds to fish with more developed central nervous systems. If the blind angle is increased more limitations are imposed which corresponds to fish with less developed central nervous systems. Lower level of mechanical activity can be simulated by assigning the fish lower propulsion speeds.

Improvements that could be made to give more reliable results is to use a camera and/or tracking software that tracks the fish with more consistency, this would make it possible to more effectively use tracking data from the videos. The tuning of the parameters could be done more precise if an automatic parameter fitting algorithm was implemented with a optimized time-integrator.
References


