Effects of burst-and-coast duty cycle on collective behavior in a fish school model

Jan Anžur, Maks Popovič, and Anže Hočevar

Collective behaviour course research seminar report

November 16, 2025

Iztok Lebar Bajec | izredni professor | mentor

Burst-and-coast swimming is a common mode of locomotion among fish. Its asynchronous decision making process significantly affects interactions between fish and collective behavior within a school. Our project expands upon a paper that modeled burst-and-coast swimming and studied its long-term collective behaviour, but modeled the burst phase as an instantaneous impulse. We intend to investigate the effects of this simplification on collective behavior as well as the effects of intermittent movement and asynchronous decision making in general by varying the duty cycle and number of decisions per burst.

Collective behavior | Burst-and-coast | Fish school model

Introduction

The behavior of individual fish in a group is strongly influenced by social interaction, resulting in collective behaviors such as swarming, schooling and milling. These behaviors have been extensively studied [1, 2] and reproduced using continuous motion models.

However, continuous motion is not the typical mode of locomotion for many species of fish. Instead, many species use burst-and-coast swimming [3] where movement is composed of two cyclical phases: the burst phase, during which the fish decides on a direction (based on the aforementioned social interactions) and rapidly accelerates towards it; and the coast phase, during which the fish passively glides and does not actively attempt to change its speed or heading outside of deceleration due to drag. The ratio between the duration of the burst phase and the total durations of the both phases is known as the duty cycle [4].

We build upon a paper [5] which models the behavior of *Hemigrammus rhodostomus* using agents that implement burst-and-coast swimming and analyzes the long-term collective behavior of large groups of such agents. In its implementation, the paper makes several simplifications, one of which is modeling the burst phase as an instantaneous event due to its short duration compared to the coast phase [6], which is equivalent to a duty cycle of 0%. We will introduce additional parameters to model a non-zero duty cycle and study its effects on the collective behavior.

Related work. [7] researched the effect of perturbations on the behavior of schools of fish based on the burst-and-coast model. The perturbations were modeled as a slight modification of the attraction and alignment strength of a subset of fish in the population. Their findings showed that larger groups of fish (N = 100) are much more sensitive to perturbations than smaller groups (N = 25 or 50) across most combinations of attraction and alignment strength.

The paper we're expanding upon is based on an earlier research paper [6] that also tackles the burst-and-coast model on the same species of fish. This paper used raw data, obtained from capturing the movement of fish in enclosed tanks using a digital camera, along with domain knowledge about the specific species of fish, to construct equations that govern the movement of fish during the kick and glide phases. They also separated the drives of avoiding the wall of the tank and interacting with another (neighboring) fish.

Methods

We will first replicate the results of the original paper [5], then extend the model by introducing parameters to model a non-zero duty cycle. We will then rerun the experiments with different values for the duty cycle and evaluate how it affects the collective behavior using objective metrics.

Model Description. The original burst–coast model consists of a repeated cycle:

1. **Heading selection:** Before each burst, the fish computes a combination of attraction and alignment values based on selected neighbors.

2. **Burst phase (kick):** The fish updates its heading and samples a random kick time and length.

3. **Coast phase:** The fish now moves along a straight path for the duration and length of its kick, with an exponentially velocity.

4. **Repeat:** Once the fish reaches the end of its coast phase, it immediately selects a new heading and begins a new burst.

Proposed extension. We will introduce two parameters to model a detailed duty cycle:

- $\omega \in [0, 1]$: The ratio between the duration of the burst phase and the total duration of both phases.
- $n_\omega \in \mathbb{N}$: The amount of decision instants within the burst phase. Increasing this value will approximate a continuous decision making process within the burst phase.

In the initial model, $\omega = 0$ and $n_\omega = 1$. Instead of an immediate impulse at the start of a burst, a fish's velocity linearly increases for a duration determined by ω. The acceleration is set so that the velocity at the end of a burst phase would be the same as the velocity at that time if ω were 0 and the usual exponential delay was applied from the start. The burst phase is also evenly split into n_ω sub-phases, where the start of each sub-phase represents a decision point for the desired direction of the fish. Similarly to velocity between the start and the end of the entire burst phase, the heading of the fish is linearly interpolated between each sub-phase. This means that by increasing n_ω, we can get a (biologically inaccurate) model that arbitrarily approximates a continuous motion model, which allows us to study the effects of a limited decision making process on collective behavior.

Simulation Implementation. The simulation will be implemented in Python using:

- **NumPy** for array-based state storage,
- **Numba** for the inner simulation loop,
- **Matplotlib** for figures, and
- **Pygame** or a similar library for real-time visualization.

Evaluation Metrics. The original model uses three metrics to evaluate its behavior. The first one is *Group Dispersion*, representing the average square of distance from the barycenter (i.e., how much the fish are spread out in space). The second one is *Group Polarization*, which is the measure of how varied the headings of different fish are. Lastly, the *Milling Index* quantifies the degree of how much the fish are swimming around a barycenter in a circular fashion. We will use the exact same metrics as the original paper with the aim of producing comparable results:

Group Dispersion:

$$D(t) = \sqrt{\frac{1}{N}\sum_{i=1}^{N} \|\mathbf{u}_i(t) - \mathbf{u}_B(t)\|^2}$$

where $\mathbf{u}_i(t)$ refers to position of fish i at time step t, $\mathbf{u}_B(t)$ refers to position of barycentre and N refers to the number of fish.

Group Polarization:

$$P(t) = \left\| \frac{1}{N}\sum_{i=1}^{N} \frac{v_i(t)}{\|v_i(t)\|} \right\|$$

where $\mathbf{v}_i(t)$ refers to the velocity vector of fish i at time step t.

Milling Index:

$$M = \left| \frac{1}{N}\sum_{i=1}^{N} \sin\left(\bar{\theta}_w^i(t)\right) \right|.$$

where $\bar{\theta}_w^i = \bar{\phi}_i - \bar{\theta}_i$ and $\bar{\phi}_i$ is the angle of the fish's heading and $\bar{\theta}_i$ is the angle of the fish's position, both with respect to the barycentre as the coordinate origin.

These metrics allow for classification of ordered schooling, milling, swarming, and disordered phases.

Results

N/A

Discussion

N/A

CONTRIBUTIONS. N/A

Bibliography

1. Lopez U, Gautrais J, Couzin ID, Theraulaz G (2012) From behavioural analyses to models of collective motion in fish schools. *Interface focus* 2(6):693–707.
2. Filella A, Nadal F, Sire C, Kanso E, Eloy C (2018) Model of collective fish behavior with hydrodynamic interactions. *Physical review letters* 120(19):198101.
3. Kramer DL, McLaughlin RL (2001) The Behavioral Ecology of Intermittent Locomotion. *American Zoologist* 41(2):137–153.
4. Chao LM, Couzin ID, Li L (2024) On turning maneuverability in self-propelled burst-and-coast swimming. *Physics of Fluids* 36(11):111918.
5. Wang W et al. (2025) Collective phases and long-term dynamics in a fish school model with burst-and-coast swimming. *Royal Society Open Science* 12(5):240885.
6. Calovi DS et al. (2018) Disentangling and modeling interactions in fish with burst-and-coast swimming reveal distinct alignment and attraction behaviors. *PLOS Computational Biology* 14(1):e1005933. Publisher: Public Library of Science.
7. Lin G, Escobedo R, Han Z, Sire C, Theraulaz G (2025) Group size and social interactions' strength determine collective response to perturbation in a model of burst-and-coast swimming fish. *bioRxiv* pp. 2025–07.