Data-Driven Models for Zebrafish Motion
IDP kick-off

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Introduction

Collaboration with Couzin Lab (Max Plank Institute for Ornithology/University of Konstanz)

Advisers: Dr. Jacob Davidson (Konstanz), Nicola Rieke (CAMP)

Supervisor: Prof. Dr. Nassir Navab

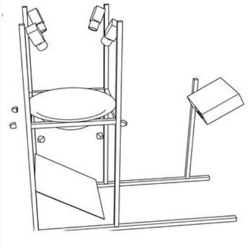
Idea:

- Compare three data-driven models for motion of juvenile zebrafish
- Model should capture motion of fish observed in experiments with **real fish** (not tracking an individual fish)

Example **use case**: controlling a fish in a virtual reality environment

Real and Virtual Zebrafish

A juvenile zebrafish



Virtual reality for zebrafish

VR-paper and image source[1]

[1] *Virtual reality for freely moving animals*, Nature Methods, 2017, Stowers JR, Hofbauer M, Bastien R, Griessner J, Higgins P, Farooqui S, Fischer RM, Nowikovsky K, Haubensak W, Couzin ID, Tessmar-Raible K.

Zebrafish: Burst-and-coast Motion

Example of zebrafish motion

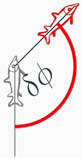
Modelling Fish Motion

Data: Roughly **100k kicks** from 10 experiments with 2 fish swimming, each for 1h

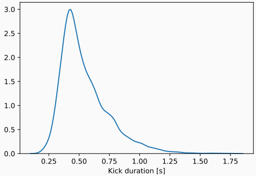
Videos already annotated, use trajectories (no tracking needed)

Segmentation into kicks as pre-processing step

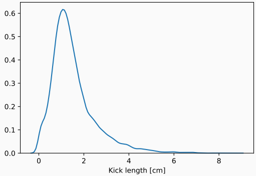
Model **for each** fish: Map wall distance/angle and neighbor distance/angle to heading change $\delta\phi$



Heading change



Kick duration



Kick length

First Model: Force Based (Calovi et al[2])

1. Discrete model, model heading change $\delta\phi$ for kicks
2. Decision process only uses **current status**
3. Force based, stochastic model
4. Symmetry constraints

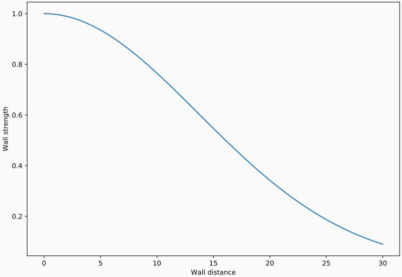
Full model:

$$\begin{aligned}\delta\phi &= \delta\phi_r(r_w) + \delta\phi_w(r_w, \theta_w) + \delta\phi_{\mathrm{Att}}(d, \psi, \Delta\phi) + \delta\phi_{\mathrm{Ali}}(d, \psi, \Delta\phi) \\ &= \text{noise} + \text{wall avoidance} + \text{attraction} + \text{alignment}\end{aligned}$$

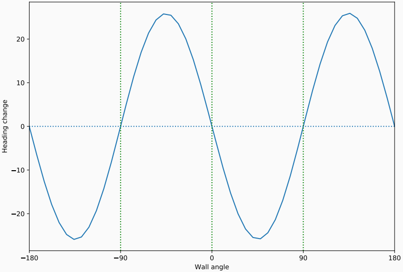
with: r_w distance to wall, θ_w angle towards wall,
d distance between both fish, ψ viewing angle and $\Delta\phi$ relative angle

[2] *Disentangling and modeling interactions in fish with burst-and-coast swimming*, arXiv, 2017, Calovi, D.S., Litchinko, A., Lecheval, V., Lopez, U., Escudero, A.P., Chaté, H., Sire, C. and Theraulaz, G.

Calovi - (Preliminary) Wall Fit



$f(r_w)$

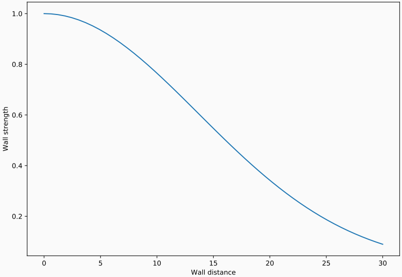


$O(\theta_w)$

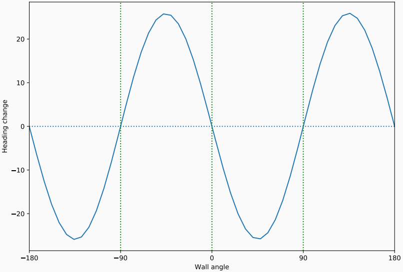
$$\delta\phi_w(r_w, \theta_w) = f(r_w) O_w(\theta_w)$$
$$f(r_w) = \exp\left(-(r_w/l_w)^2\right)$$
$$O(\theta_w) = (a_1 \sin(\theta_w) + a_2 \sin(2\theta_w))\,(1 + b_1 \cos(\theta_w) + b_2 \cos(2\theta_w))$$

r_w distance to wall, θ_w angle towards wall

Calovi - (Preliminary) Wall Fit



$f(r_w)$



$O(\theta_w)$

Stable fixed points

-90° and 90°

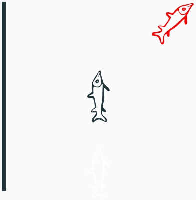
Unstable fixed points

0°, -180° and 180°

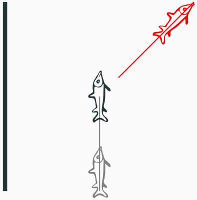
Calovi - First simulation

First simulation for wall model

Second model: Spatio-Temporal Receptive Field



No memory: Only current position, etc.



Memory: Current position and trace

- Drop assumption that kick is influenced only by current surroundings
- Inspired by computational neuroscience
- Approximate reaction to social forces by **weighted sum** over past environment influences (e.g. distances, angles)
- Linear model with memory

Third Model: Neural Network

Some evidence[3] for non-linear effects in collective animal motion

Idea: Approximate reaction to social influences with a neural network

Time series data, strong autocorrelation

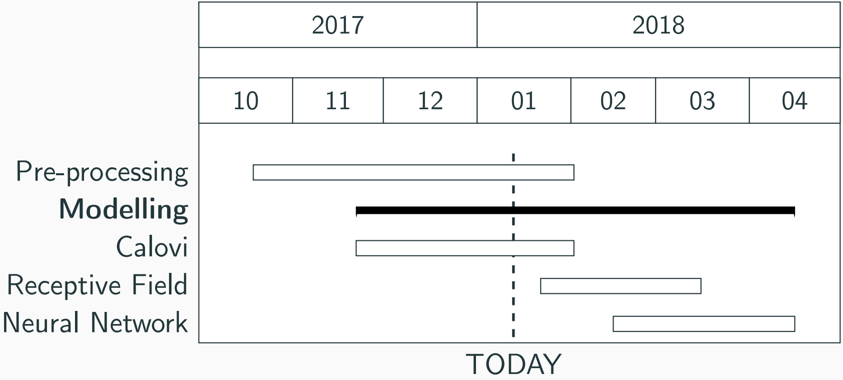
Use models such as **recurrent neural networks** (e.g. LSTM, GRU) or causal convolutional networks

Highly non-linear model with memory

[3] *Inferring the structure and dynamics of interactions in schooling fish*, Proceedings of the National Academy of Sciences, 2011, Katz, Y., Tunstrøm, K., Ioannou, C. C., Huepe, C., and Couzin, I. D.

Summary and timeline

- Calovi: Linear model without memory
- Spatio-Temporal Receptive Field: Linear model with memory
- Neural Network: Non-linear model with memory



Appendix

Calovi - Only wall

Consider no social component:

$$\delta\phi = \delta\phi_r(r_w) + \delta\phi_w(r_w, \theta_w)$$

Symmetry for wall influence:

$$\delta\phi_w(r_w, -\theta_w) = -\delta\phi_w(r_w, \theta_w)$$

Split into force term $f(r_w)$ and odd function $O_r(\theta_w)$

$$\delta\phi_w(r_w, \theta_w) = f(r_w) O_w(\theta_w)$$

$$f(r_w) = \exp\left(-(r_w/l_w)^2\right)$$

$$O(\theta_w) = \left(a_1 \sin(\theta_w) + a_2 \sin(2\theta_w)\right)\left(1 + b_1 \cos(\theta_w) + b_2 \cos(2\theta_w)\right)$$