Evolutionary Design and Experimental Validation of a Flexible Caudal Fin for Robotic Fish

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Biomutualism

Bio-inspiration

Material properties
  - Passive
  - Flexibility

Robotic Fish
  - Evolutionary robotics
Design Process

- Mathematical Models
- Physics-Based Simulation
- Fabrication and Evaluation
- Material Properties
- Optimization
- Rapid Prototyping

Feedback
Study Overview

- Optimize Caudal Fin
  - Dimensions
  - Flexibility

- Physically Validate
  - Stable velocity
  - Improve simulation
Applications

Ecological Monitoring

Harbor Surveillance
Biological Studies

Elicit a response

- ex. robot as predator
  - Predator inspection
- ex. robot as leader
  - Schooling
Outline

- Introduction
- Evolution Park
- This Study
  - Only Flexibility
  - Flexibility + Dimensions
- Conclusion
Evolution Park

- NSP-Sponsored testbed
- Cross department collaboration
- Facilities
  - Robot grab-bag
  - Compute cluster
  - 4,500 gallon test tank
  - Rapid prototyping 3D printer
3D Printer

Objet Connex350

Prints multiple material
Young’s Modulus

- (Modulus of elasticity)
- Material property
- Higher value $\Rightarrow$ higher stiffness
- Lower value $\Rightarrow$ higher flexibility

~ 0.01 GPa
~ 10 GPa
~ 100 GPa
Printed Robotic Fish
Printed Robotic Fish

- Printed parts
  - body
  - gears
  - fins

- Electronics
  - Arduino
  - Servo
  - LiPo battery
Outline

- Introduction
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Study Parameters

- Fixed control
  - 30° amplitude
  - 0.9 Hz frequency
- Flexible, rectangular caudal fin
- Swims on the surface
Mathematical Model

Hydrodynamics

Net Hydro Force

Net Drag Force

Instantaneous Hydro Force

Flexibility

Wang et. al. 2011, 2012
Caudal Fin Example
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Optimize Only Flexibility

Optimization target
- Maximal average velocity

Hill-climber
- 30 runs
- 100 candidates tested

Evolution
- 30 runs
- 100 individuals
- 100 generations
Physical Validation

- Stable velocity
- Seven trials
  - Remove best
  - Remove worst
  - Compute average
Experimental Comparison

Model Prediction

Simulation Results

3D Printed Materials

Improved Model
Outline

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Optimization
Dimensions and Flexibility

- Evolve
  - flexibility
  - fin dimensions
- Maximal average velocity
Optimization
Dimensions and Flexibility

- Maximal flexibility for every set of dimensions

- Constraints
  - $\text{Length}_{\text{max}} = 14 \text{ cm}$
  - $\text{Length}_{\text{min}} = 4 \text{ cm}$
  - $\text{Modulus}_{\text{max}} = 50 \text{ GPa}$
Conclusion

- For Evolutionary Computation
  - Models can approximate flexible materials
  - Models can approximate hydrodynamics
  - Multi-material 3D printers can fabricate evolved flexible solutions

- EC results can help improve the modeling process

- Design process can be repeated for other environments
Future Directions

- Energy consumption
- Morphology
  - Expand models
  - Non-rectangular fins
- Complex tasks
  - Speed, maneuverability
  - Higher level → waypoint following
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Big Picture

- Robotics
  - Underwater Vehicle
    - System
      - Optimization
        - Us
          - Industrial
          - Search and Rescue
            - Sensor Node
          - Propeller
          - Paired Fin
            - Caudal Fin
          - Strategy
          - Control
            - Morphology
          - Guess and Check
          - Gradient Climbing
            - Evolutionary Computation
Mathematical Model

- Aquatic environment
- Reality gap
- Model accuracy
- Elongated-body theory

\[
\vec{f}(\tau) = \begin{pmatrix} f_X(\tau) \\ f_Y(\tau) \end{pmatrix} = -m \frac{d}{dt}(v_{\perp} \hat{n}), \quad (1)
\]

\[
\vec{F}_L = \begin{pmatrix} F_{L_X} \\ F_{L_Y} \end{pmatrix} = \left[ -\frac{1}{2} m v_{\perp}^2 \hat{m} + m v_{\parallel} v_{\perp} \hat{n} \right]_{\tau=L}, \quad (2)
\]

\[
K_s = \frac{Edh^3}{12l}, \quad (3)
\]
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Future Directions

Efficiency
- Power usage
- Mechanical work
- Performance

Coevolution
- Control
- Morphology
- Complex tasks

Multi-Objective