Balancing Performance and Efficiency in a Robotic Fish with Evolutionary Multiobjective Optimization

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Motivations

Optimize Robotic Fish with Flexible Fins

Optimize for
– performance AND
– efficiency

While matching flexibility with control settings
Robotic Fish

**Biomimetic Robots**

Compared with other aquatic robots
- Smaller in size
- More maneuverable

Actuation
- less complex
- fewer moving parts
Robotic Fish

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**Challenges**

Complex environment
- turbulence

Flexible components
- changing performance

Limited supervision
- poor communication
Applications
This Paper

- **Maximize** efficiency
  - focus of several recent studies [Low 2010, Park 2012]
  - important due to lack of supervision
  - remain operational as long as possible

- **Maximize** average velocity

- **Constraints**
  - maximum power exerted by the motor
  - ratio of length to width for the caudal fin
Search Space

Pareto-optimal
- best solutions

Dominated
- sub-optimal solutions

Infeasible
- violate constraints

Impossible
- unachievable

This study: NSGA-II [Deb 2000]
Computational Evolution

• Fin characteristics
  – flexibility
  – length
  – height
• Control parameters
  – sinusoidal amplitude
  – sinusoidal frequency

• Why evolutionary multiobjective optimization?
  – fewer evaluations and more effective than parameter sweep
  – avoid local optima
Flexible Fins
3D Printing Composite Fins
Efficient Simulation

MATLAB / Simulink

Hydrodynamics
- developed by Wang et al. [Wang 2012, Clark 2012]
- faster and less accurate compared to CFD

Flexibility
- rigid bodies
- torsion springs (can be converted to Young’s modulus values)
Evolutionary Optimization

Task: quick and efficiently forward swimming

- Evolve
  - fin flexibility
  - fin dimensions
  - sinusoidal control parameters

- NSGA-II parameters
  - 200 individuals in the population
  - 500 generations for convergence
  - 20 replicate experiments
Final Combined Pareto-Front

• Efficiency
  – 35 to 40 percent
  – similar to values found in other studies

• Velocity
  – 4.8 to 5.8 cm/s
Caudal Fin Length

Length vs Speed

Length vs Efficiency
Discussion

Guidelines
1. Flexible fins are more efficient
2. Length-height ratio of 3-to-1
3. Fin length ½ the length of the body
4. Increase speed by increasing amplitude

Choosing a single Pareto-optimal value is specific to the task given to the robotic fish.
- example: robotic fish needs to operate for 1 hour
- choose the fastest solution that is within the bounds for efficiency
Physical Trials

![Combined Pareto-Front Graph](image)

<table>
<thead>
<tr>
<th>Label</th>
<th>Simulation (cm/s)</th>
<th>Reality (cm/s)</th>
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</thead>
<tbody>
<tr>
<td>Fin1</td>
<td>5.17</td>
<td>7.43</td>
</tr>
<tr>
<td>Fin2</td>
<td>5.39</td>
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<td>Fin3</td>
<td>5.62</td>
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</tr>
<tr>
<td>Fin4</td>
<td>4.97</td>
<td>4.90</td>
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</tbody>
</table>
Physical Results

Reality gap
  – different dynamics
  – printing fins
  – noisier control

Pareto-front clustering
  – all are good solutions
  – tight clustering between solutions
Summary

In this study we,

– optimized a robotic fish for two objectives
  • objectives: speed and efficiency
  • evolved parameters: fin morphology and control
– we found a set of guidelines for designing robotic fish of similar builds
– however, physical results are somewhat inconclusive and will need to be expanded
Ongoing Research

How can we improve the transferability of evolved individuals?
   – cross the reality gap through adaptive control

How can we get better generality during evolution?
   – operate under different control conditions
   – more complex tasks

How advantageous are more complex fins?
   – include non-rectangular fins
   – include non-uniform flexibility fins
Thank You

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References


[Clark 2012] : *Evolutionary design and experimental validation of a flexible caudal fin for robotic fish.*


Park [2012] : *Kinematic condition for maximizing the thrust of a robotic fish using a compliant caudal fin.*