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

Anthony J. Clark, Jared M. Moore, Jianxun Wang, Xiaobo Tan and Philip K. McKinley

BEACON Center for the Study of Evolution in Action
Michigan State University
East Lansing, Michigan, USA 48823
ajc@msu.edu

Biomutualism

Bio-inspiration

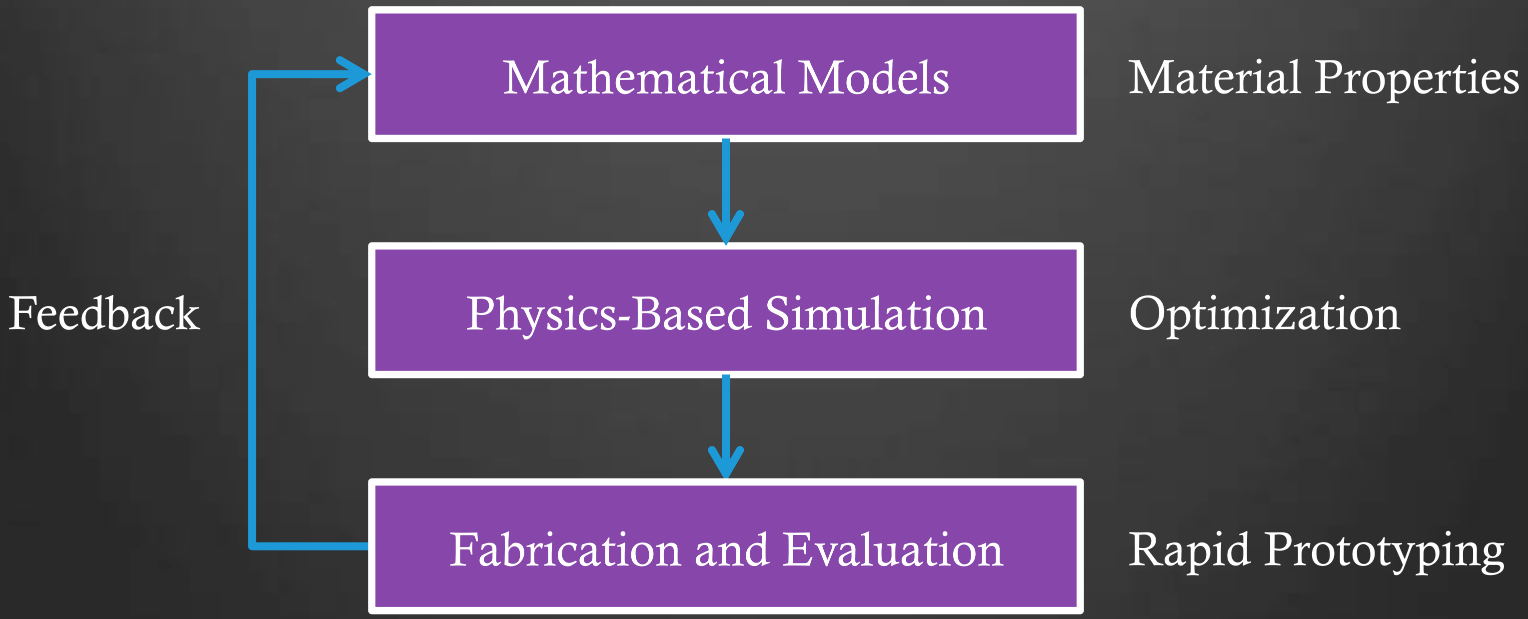
Material properties

- Passive
- Flexibility

Robotic Fish

- Evolutionary robotics

Design Process



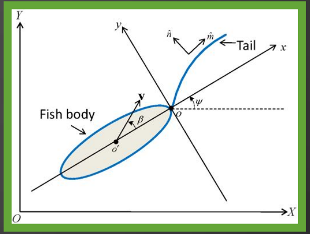
Study Overview

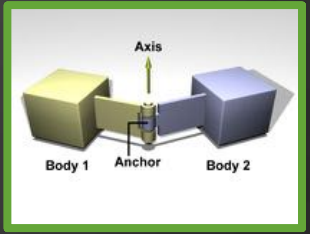
- Optimize Caudal Fin
  - Dimensions
  - Flexibility
- Physically Validate
  - Stable velocity
  - Improve simulation

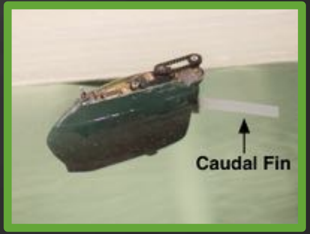
Model

Simulation

Reality

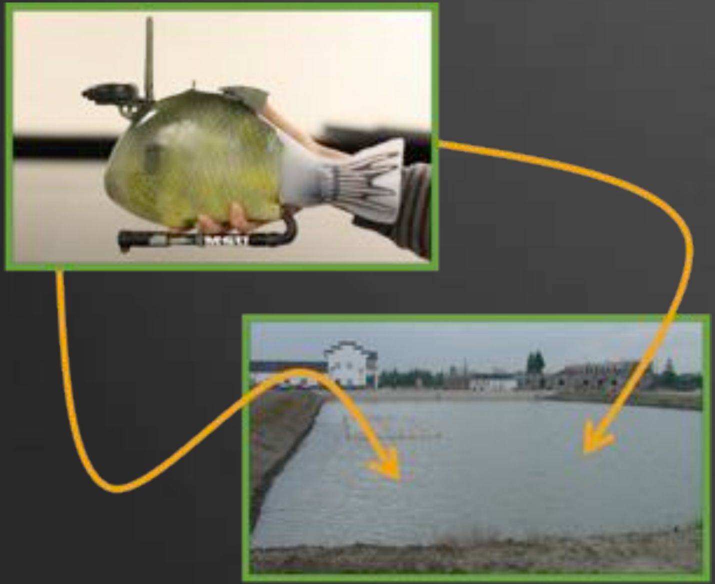






Applications

Ecological Monitoring

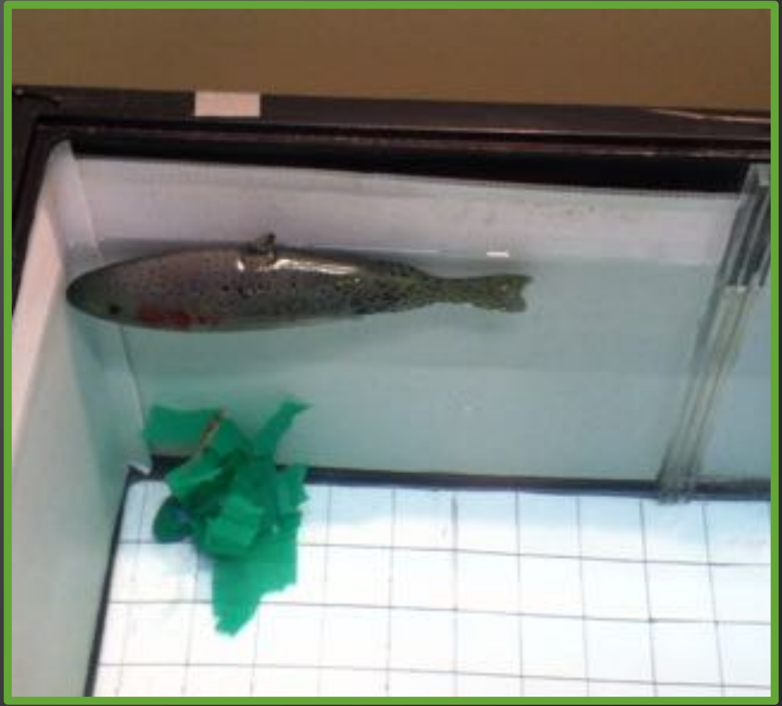


Harbor Surveillance

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

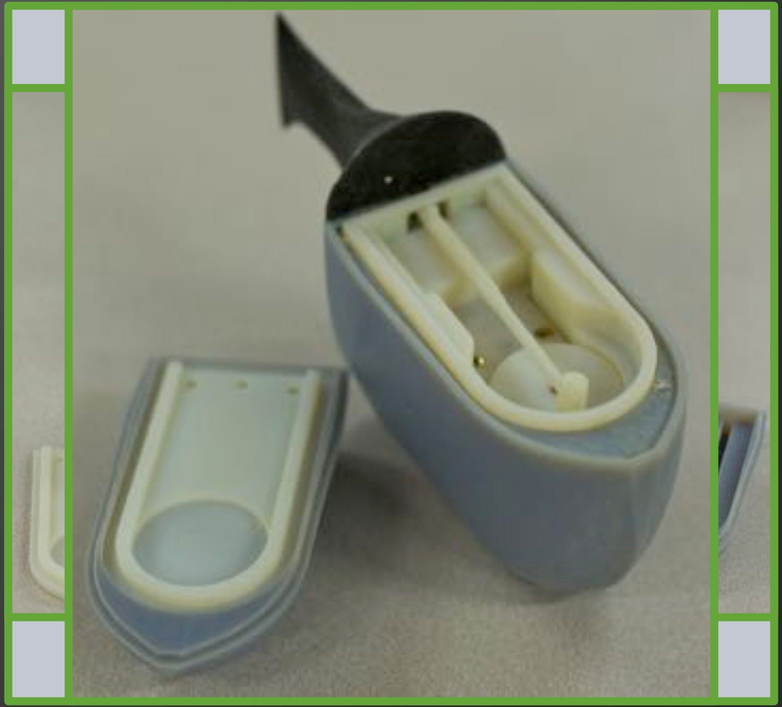
Evolution Park

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

3D Printer

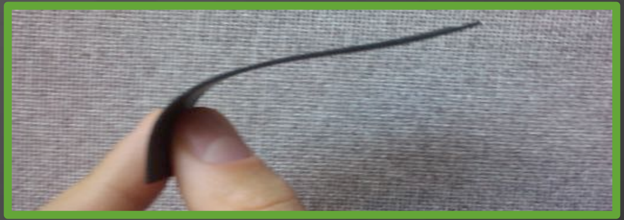
Objet Connex350

Prints multiple material



Young's Modulus

- (Modulus of elasticity)
- Material property
- Higher value → higher stiffness
- Lower value → higher flexibility

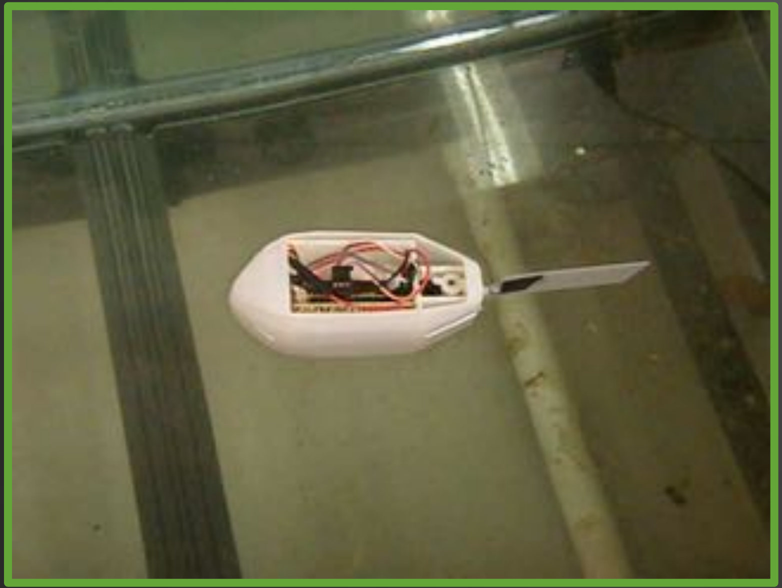


~ 0.01 GPa

~ 10 GPa

~ 100 GPa

Printed Robotic Fish



Printed Robotic Fish

- Printed parts
  - body
  - gears
  - fins
- Electronics
  - Arduino
  - Servo
  - LiPo battery

Outline

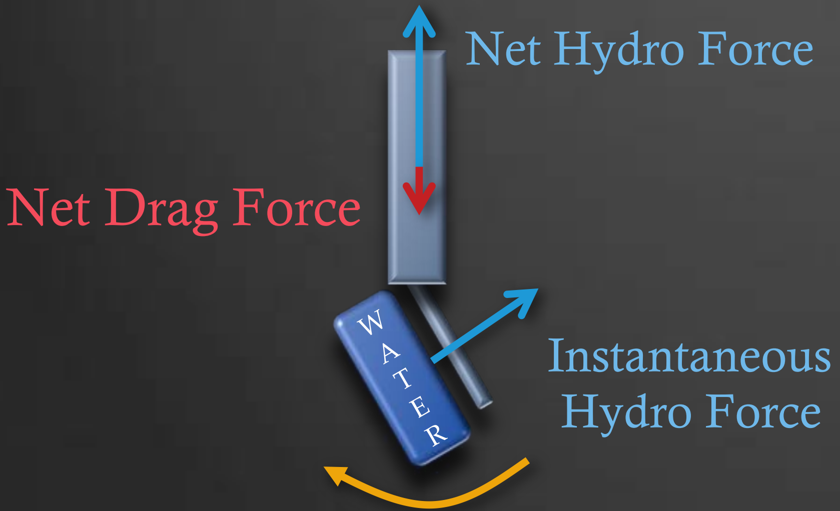
- Introduction
- Evolution Park
- **This Study**
  - Only Flexibility
  - Flexibility + Dimensions
- Conclusion

Study Parameters

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

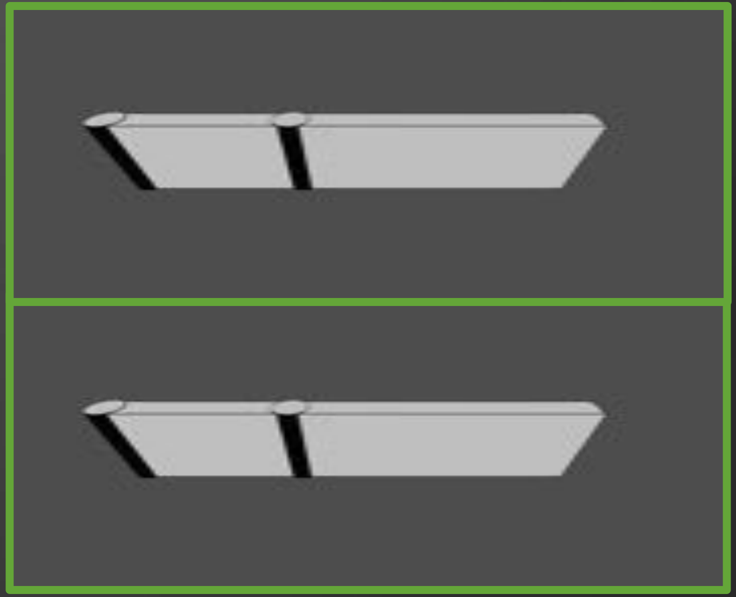
Mathematical Model

Hydrodynamics

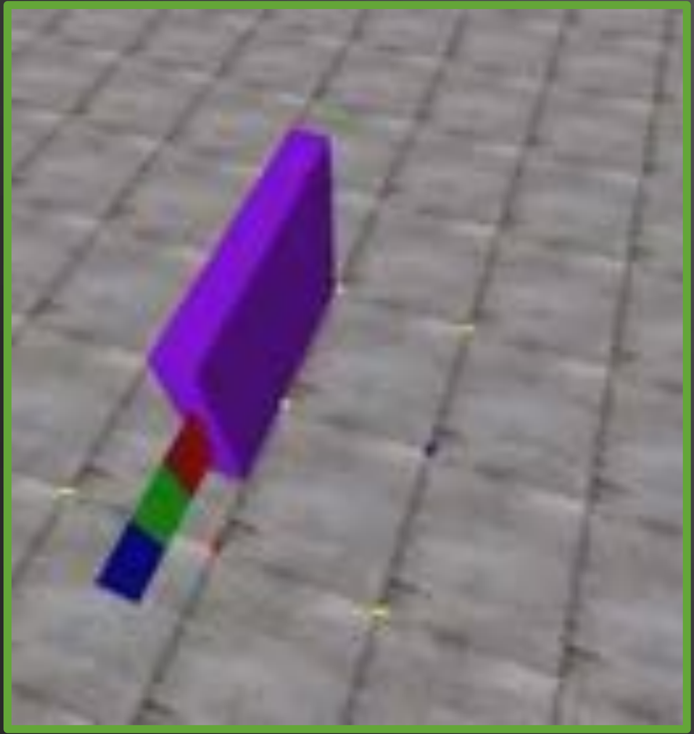


Wang et. al. 2011, 2012

Flexibility



Caudal Fin Example



Outline

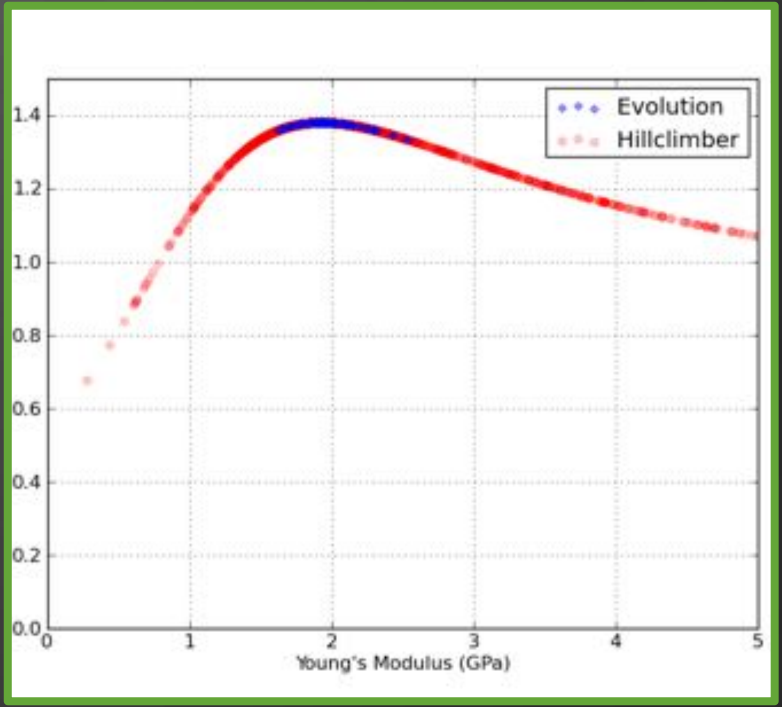
- Introduction
- Evolution Park
- This Study
  - **Only Flexibility**
  - Flexibility + Dimensions
- Conclusion

Optimize Only Flexibility

Optimization target
- Maximal average velocity

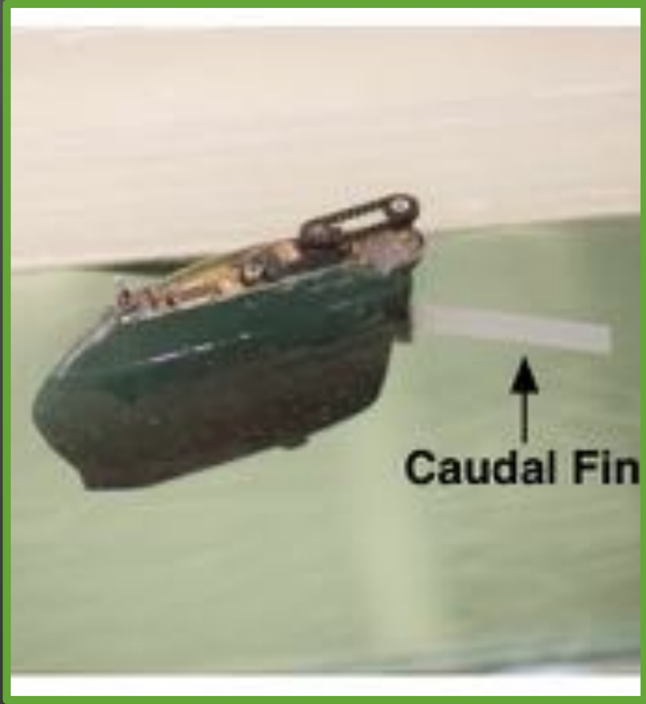
Hill-climber
- 30 runs
- 100 candidates tested

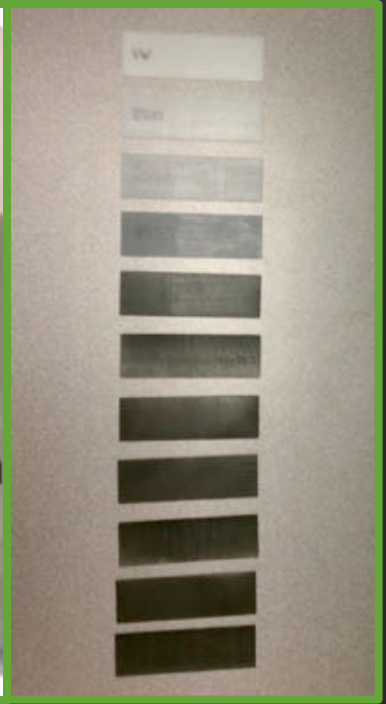
Evolution
- 30 runs
- 100 individuals
- 100 generations



Physical Validation

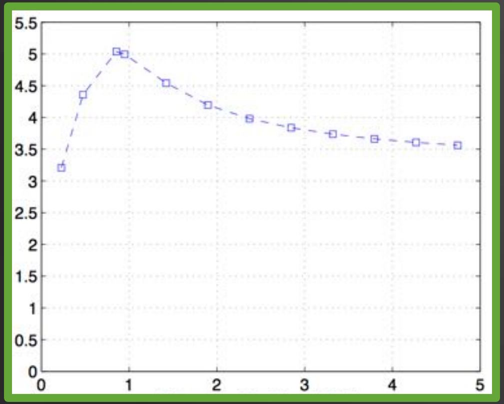
- Stable velocity
- Seven trials
  - Remove best
  - Remove worst
  - Compute average



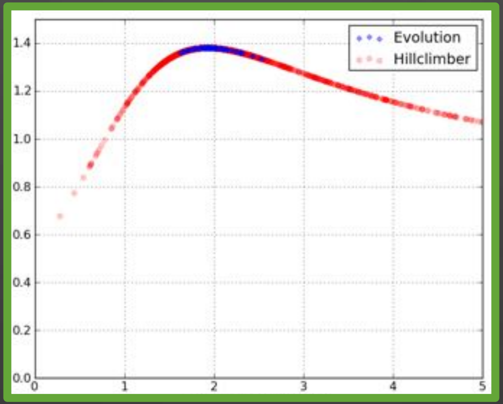


Experimental Comparison

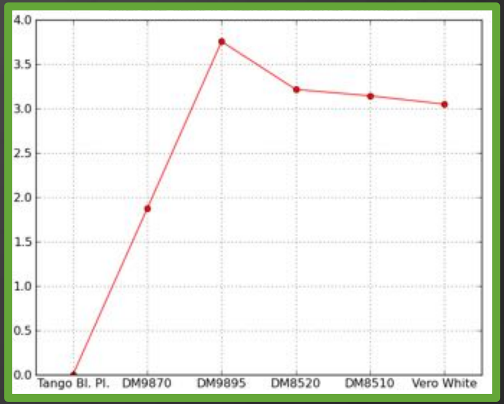
Model Prediction



Simulation Results



3D Printed Materials



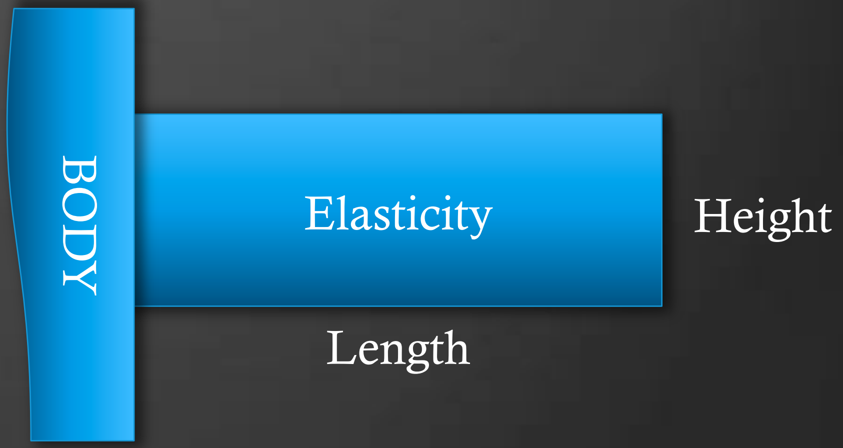
Improved Model

Outline

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

Optimization
Dimensions and Flexibility

- Evolve
  - flexibility
  - fin dimensions
- Maximal average velocity



Optimization
Dimensions and Flexibility

- Maximal flexibility for every set of dimensions
- Constraints
  - $Length_{max}$ = 14 cm
  - $Length_{min}$ = 4 cm
  - $Modulus_{max}$ = 50 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

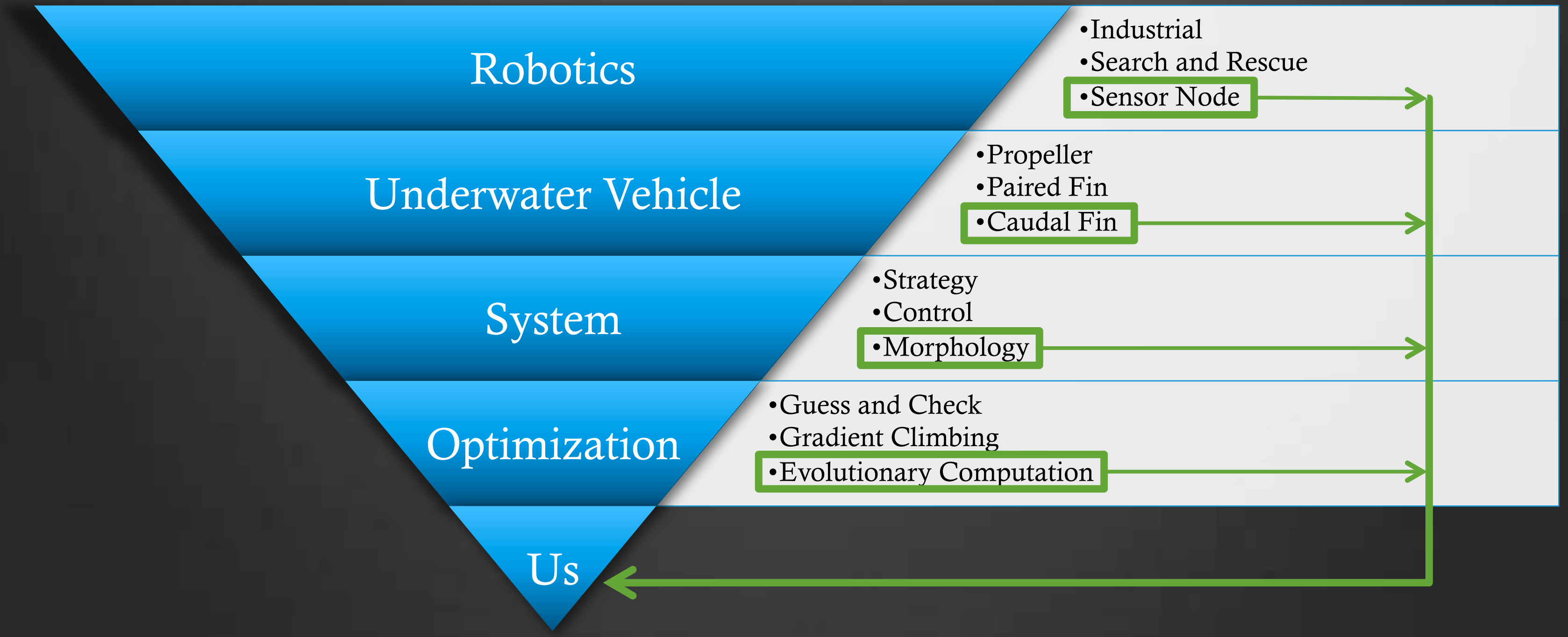
Acknowledgements

- Professor Janette Boughman
  - Dr. Jason Keagy
  - Dr. Liliana Lettieri
- Members of
  - The SENS Laboratory
  - The Smart Microsystems Laboratory
  - The DevoLab
  - The BEACON Center

National Science Foundation grants
CNS-1059373, CNS-0915855, DBI-0939454, CCF-0820220, IIS-0916720, ECCS-1050236, ECCS-1029683, CNS-0751155.
U.S. Army Grant W911NF-08-1-0495.

thank you

Big Picture


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

Mathematical Model

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

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

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

$$K_s = \frac{Edh^3}{12l}, \quad (3)$$

Outline

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

Future Directions

Efficiency

Power usage

Mechanical work

Performance

Coevolution

Control

Morphology

Complex tasks

→ Multi-Objective ←