Control and Implementation of Highly Maneuverable Motions for Bioinspired Robotic Fish

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Outline

- Fish locomotion and bionics
- Biomimetic robotic fish control
  - Highly efficient locomotion
  - Highly maneuverable locomotion
- Summary

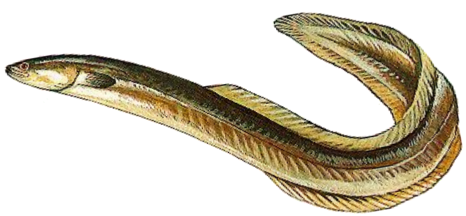
Fish Locomotion

Propulsive Speed

- Swordfish: 28 m/s
- Common Ships: ≤20 m/s

Propulsive efficiency

- Thunniform fish: ≥90%
- Screw propeller: 40%~60%

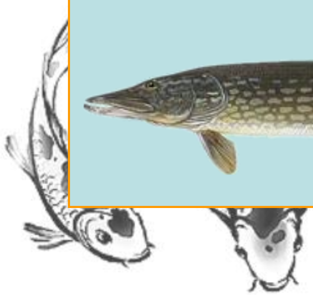


Turning radius

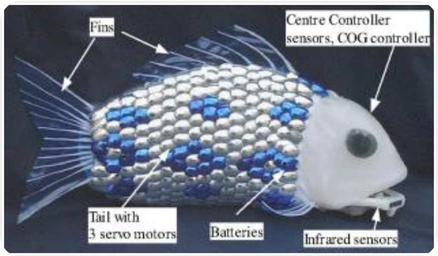
- Fish: 0.1~0.3 Body length
- Ship: 3.0~5.0 Body length

Acceleration

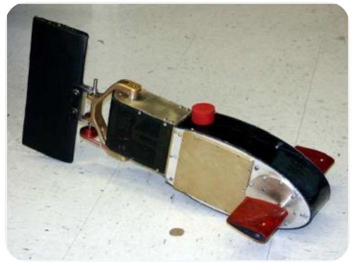
- Northern pike: ~25 g
- Common ship: gradually



Existing robotic fish



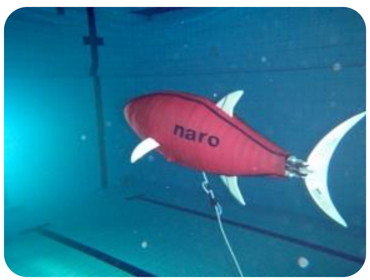
Essex Univ.
（2004）



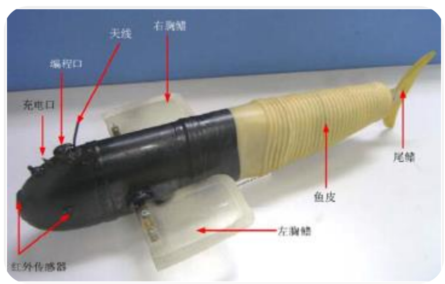
Washington Univ.
（2007）

Beihang Univ.
（2007）

Boston Engineering Co. Ltd（2008）



ETH Zurich
（2009）

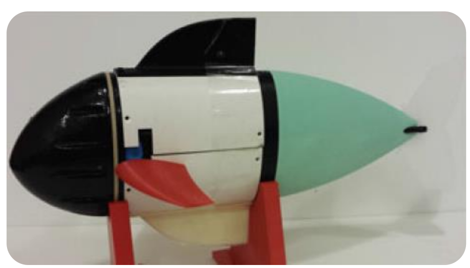


CASIA
（2010）

European SHOAL
（2012）

Michigan State Univ.
（2012）

MIT
（2014）

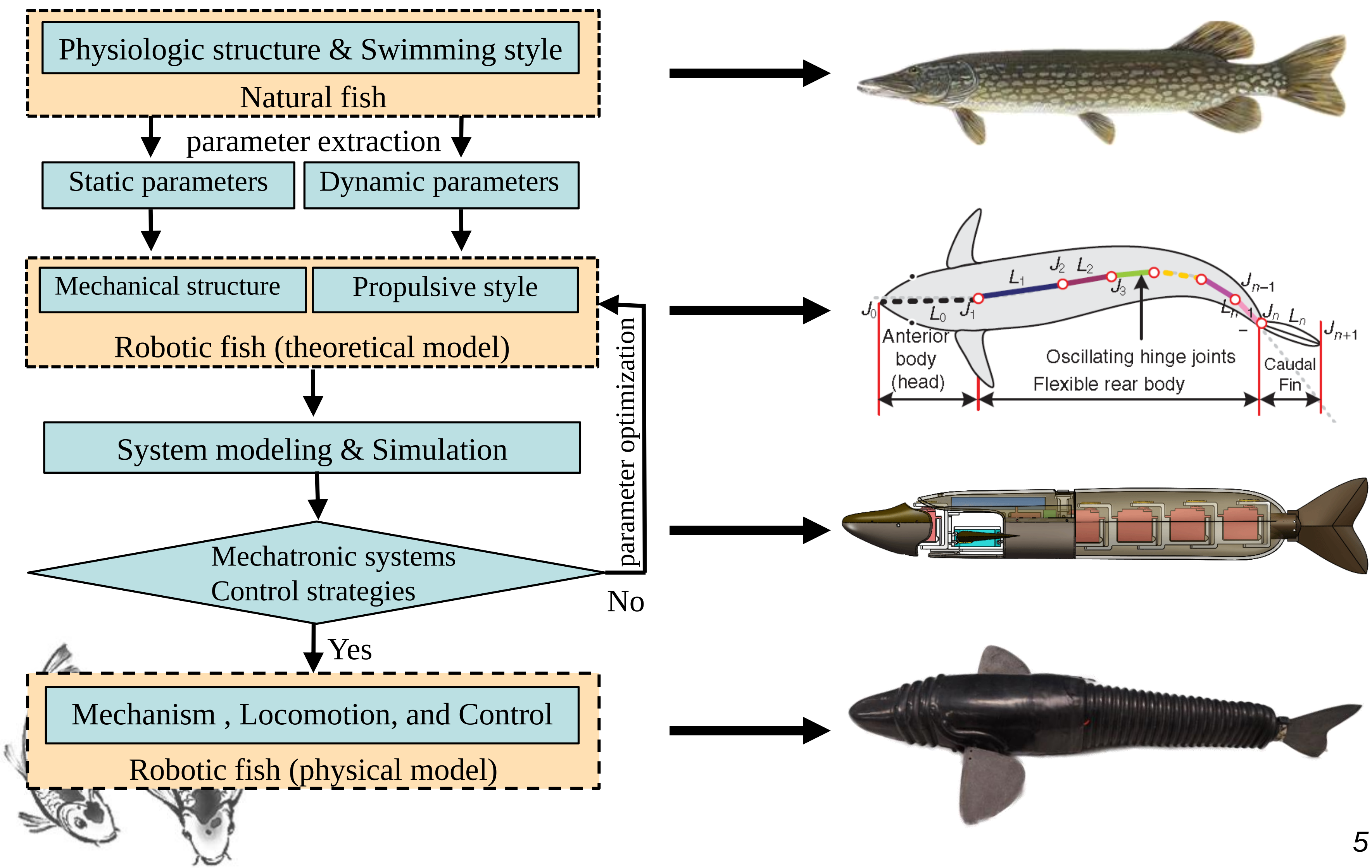


MIT
（2016）

Peking Univ.
（2008）

CASIA
（2010）

Research technical route



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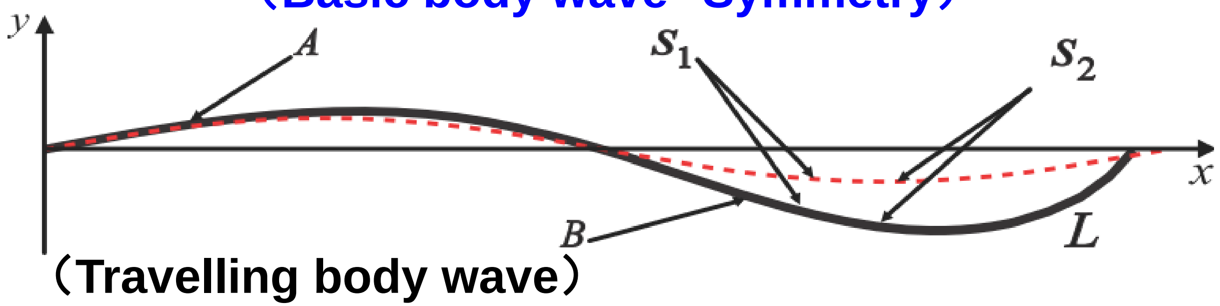
Biomimetic robotic fish control

1. Highly efficient locomotion

- ¤ Basic body wave
- ¤ Travelling body wave
- ¤ Kinematic analysis in swimming gaits
- ¤ Dynamic analysis in fishlike swimming

Highly efficient locomotion



- Ensure the center of mass of the robotic fish to be fixed on the axis along the swimming direction.
- Ensure the resultant of the lateral forces is nearly zero when swimming.

→ **Basic body wave equations**

Basic body wave equations

$$\begin{cases} \rho_0 = \sup_{s\in[0,L]} \rho(s) \\ r_{base} = \{x(s,t), y(s,t)\} \end{cases}$$

Linear density

Morphology

Travelling body wave equations

$$\begin{cases} r_{body} = \{X(s,t), Y(s,t)\} \\ Y(s,t) = \dfrac{\rho_0}{\rho(s)} y(s,t) \\ X(s,t) = \int_0^s \sqrt{1 - \left(\dfrac{\partial Y(u,t)}{\partial u}\right)^2} du \end{cases}$$

Highly efficient locomotion

Small-amplitude slender-body theory

Basic body wave $r_{base} = \sin(kx + \omega t)$

Linear density $\rho = \rho_0 / (c_1 x + c_2 x^2)$ **Here** $s \approx x$

$$\rho(s)Y(s,t) = \rho_0(s)y(s,t)$$

$$y_{body}(x,t) = [c_1 x + c_2 x^2][\sin(kx + \omega t)]$$

the typical travelling body wave equations proposed by *Lighthill* (a famous hydrodynamicist)

Highly efficient locomotion

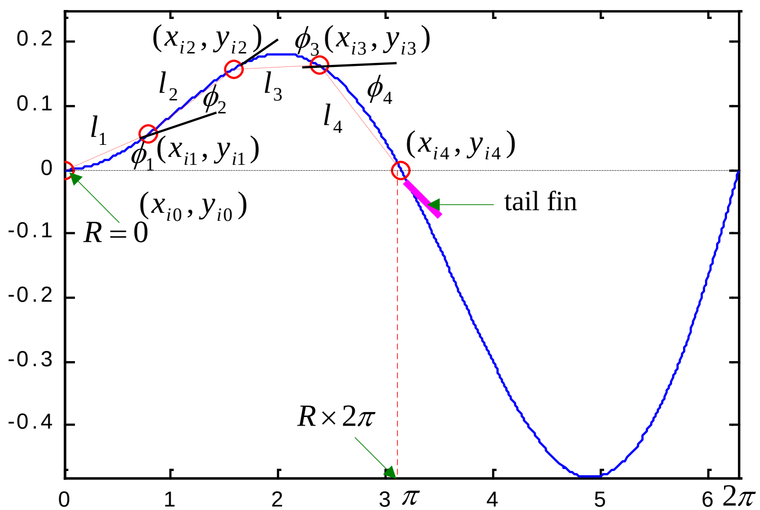
◻ Kinematic analysis

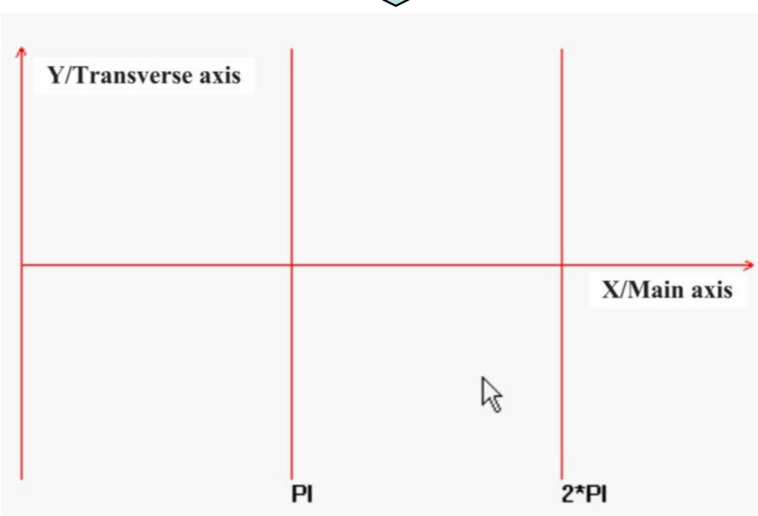
- **Travelling body wave equations**

$$y_{body}(x,t)=[c_1x+c_2x^2][\sin(kx+\omega t)]$$

- **Discrete equations**

$$\begin{cases}(x_{i,j}-x_{i,j-1})^2+(y_{i,j}-y_{i,j-1})^2=l_j^{\ 2}\\ y_{i,j}=(c_1x_{ij}+c_2x_{ij}^{\ 2})\sin(kx_{ij}-\frac{2\pi}{M}i)\end{cases}$$

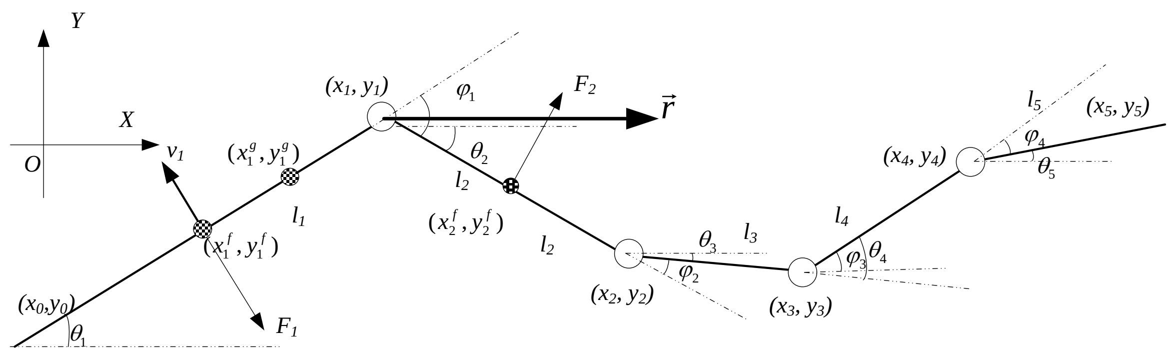




Highly efficient locomotion

Dynamic analysis

- **Coordinate systems**



- **Lagrangian equations**

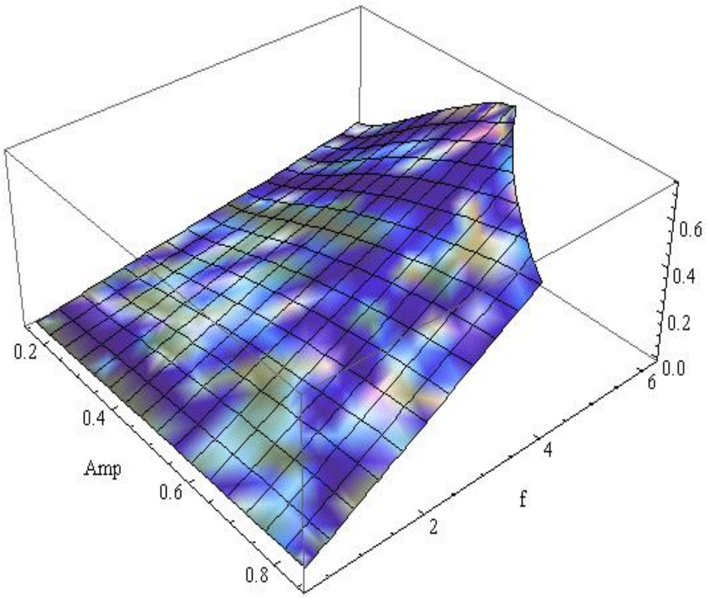
$$
\begin{aligned}
L = {} & \frac{1}{2}m_1\left(\dot{X}+(l_1-l_1^g)\left(\dot{\Theta}-\dot{\varphi}\right)\sin\left(\Theta-\varphi\right)\right)^2 \\
& +\frac{1}{2}m_2\left(\dot{X}+l_2^g\dot{\Theta}\sin\Theta\right)^2+\frac{1}{2}I_1\left(\dot{\Theta}-\dot{\varphi}\right)^2 \\
& +\frac{1}{2}m_1\left(\dot{Y}-\left(l_1-l_1^g\right)\left(\dot{\Theta}-\dot{\varphi}\right)\cos\left(\Theta-\varphi\right)\right)^2 \\
& +\frac{1}{2}m_2\left(Y-l_2^g\dot{\Theta}\cos\Theta\right)^2+\frac{1}{2}I_2\dot{\Theta}^2 \\
& +\sum_{i=3}^{N}\frac{1}{2}m_i\left[\frac{d}{dt}\left(X+\sum_{j=2}^{i-1}l_j\cos\theta_j+l_i^g\cos\theta_i\right)\right]^2 \\
& +\sum_{i=3}^{N}\frac{1}{2}m_i\left[\frac{d}{dt}\left(Y+\sum_{j=2}^{i-1}l_j\sin\theta_j+l_i^g\sin\theta_i\right)\right]^2 \\
& +\sum_{i=3}^{N}\frac{1}{2}I_i\left[{}_i\frac{d}{dt}\left(\Theta+\sum_{j=2}^{N-1}\varphi_j\right)\right]^2+E
\end{aligned}
$$

Highly efficient locomotion

Dynamic analysis

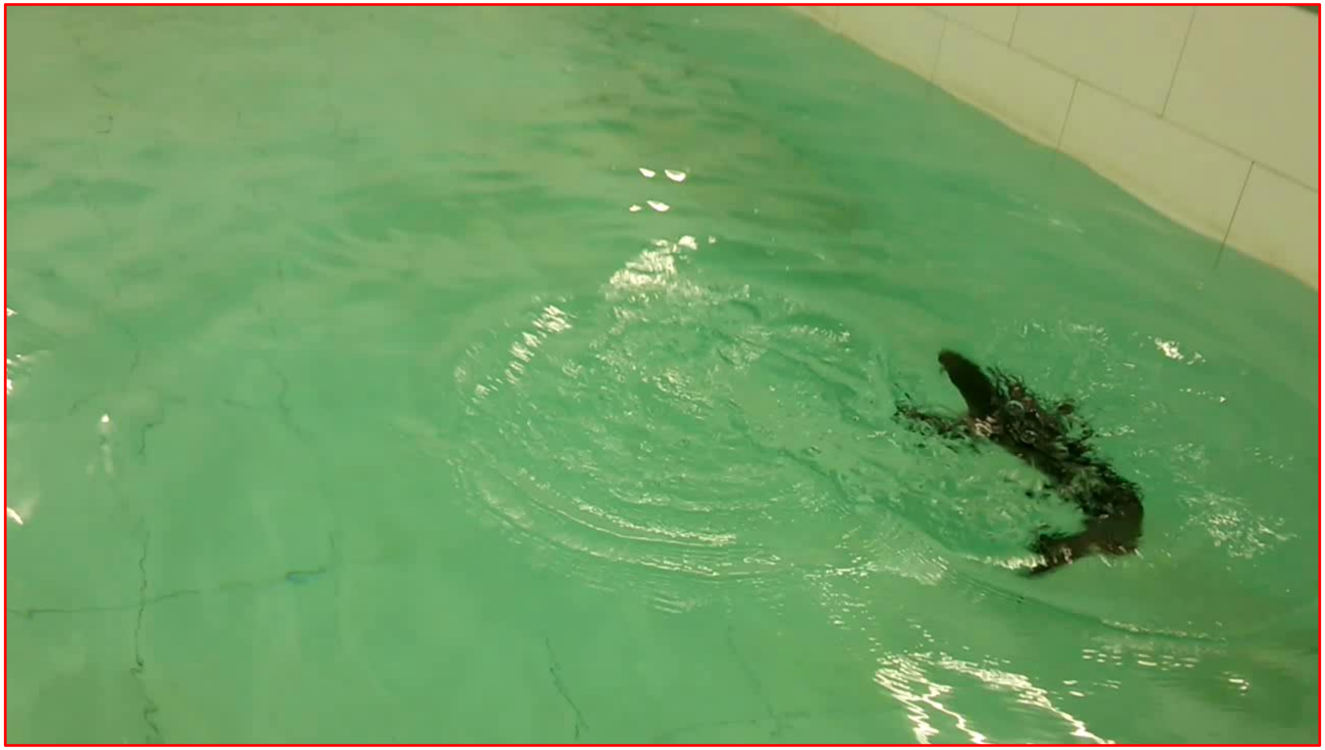
- **Forces and moments on the robotic fish**

$$
\begin{cases}
F_X = \dfrac{d}{dt}\dfrac{\partial L}{\partial \dot{X}} - \dfrac{\partial L}{\partial X} = \sum_{i=1}^{N} F_i^x + \left(F_1^= + F_f\right)\cos\theta_1 \\
F_Y = \dfrac{d}{dt}\dfrac{\partial L}{\partial \dot{Y}} - \dfrac{\partial L}{\partial Y} = \sum_{i=1}^{N} F_i^y + \left(F_1^= + F_f\right)\sin\theta_1 \\
M_\Theta = \dfrac{d}{dt}\dfrac{\partial L}{\partial \dot{\Theta}} - \dfrac{\partial L}{\partial \Theta} = \sum_{i=1}^{N}\left[-F_i^x(y_i^f - Y)\right] + \sum_{i=1}^{N} F_i^y(x_i^f - X)
\end{cases}
$$



Propulsive speed with varying amplitudes and frequencies

Highly efficient locomotion



Swimming number ($Sw = U/fl$)

Our robotic fish	Typical robotic fish (*iSplash-II*)	Real fish (Carp)
0.61	0.58	0.7

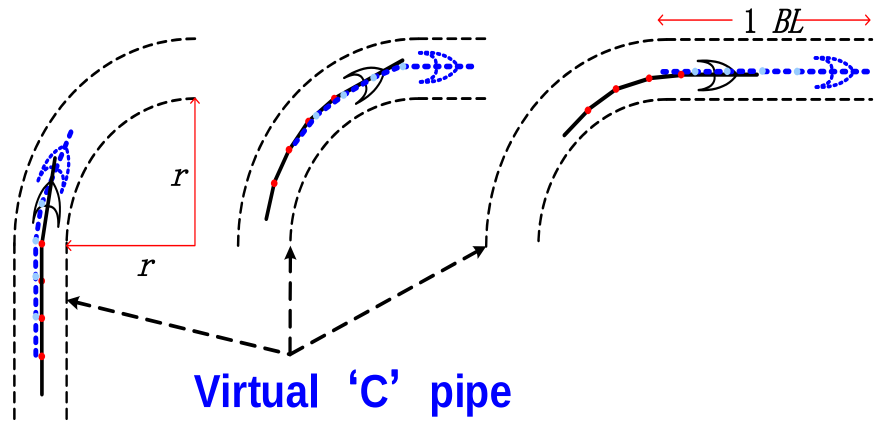
Biomimetic robotic fish control

2. Highly maneuverable locomotion

- ¤ **Turning characteristics of real fish**
- ¤ **Dynamic trajectory tracking strategy**
- ¤ **Control for frontfilp and backflip**

Highly maneuverable locomotion

Turning characteristics of real fish



Biological phenomenon:

- Fish always maintain their posterior bodies pass through the same point (a virtual 'C' pipe) in space when turning.

Highly maneuverable locomotion

Dynamic trajectory tracking (DTT)

$$\begin{cases} F_n = mV^2 / r' = m\omega^2 r' \\ M_s = m\dot{\omega} r'^2 \end{cases}$$

$$r' = \frac{mV^2}{\alpha V^2 \sin\theta_0 - F_t \sin\frac{\theta_0}{2}}$$

$$|\alpha_i| = \frac{|\dot{J}_{i+1} - \dot{J}_{i-1} - \mathcal{R}_{\alpha_{i-1}}(\overrightarrow{J_{i-1}J_{i+1}})|}{l_i}$$

- In addition to provide enough centripetal force, the posterior body should move in a virtual 'C' pipe based on the feedback information.

Experimental results

Items	Our robotic fish	Reported in the literature
Turning angle	220°	120°
Average turning rate	460°/s (peak 670°/s)	150°/s

Experimental results

➢Multimodal locomotion test (bionic)

Forward swimming in BCF

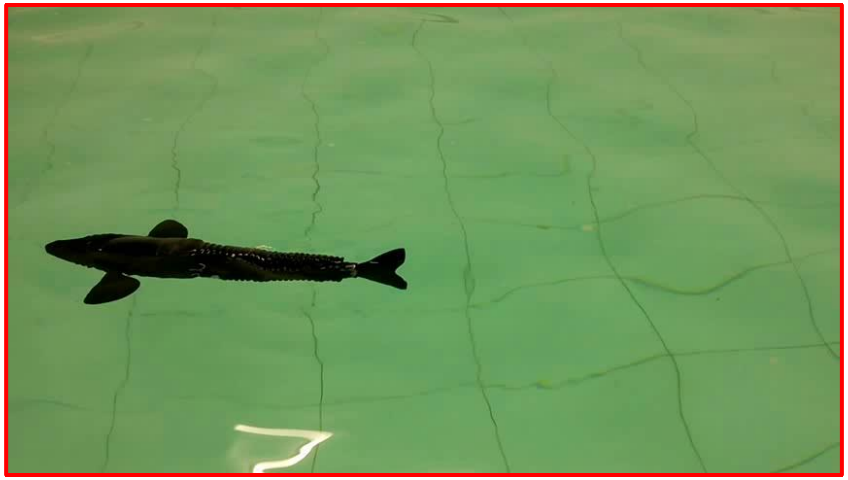
Rhythmic turning

Forward swimming in MPF (Flapping)

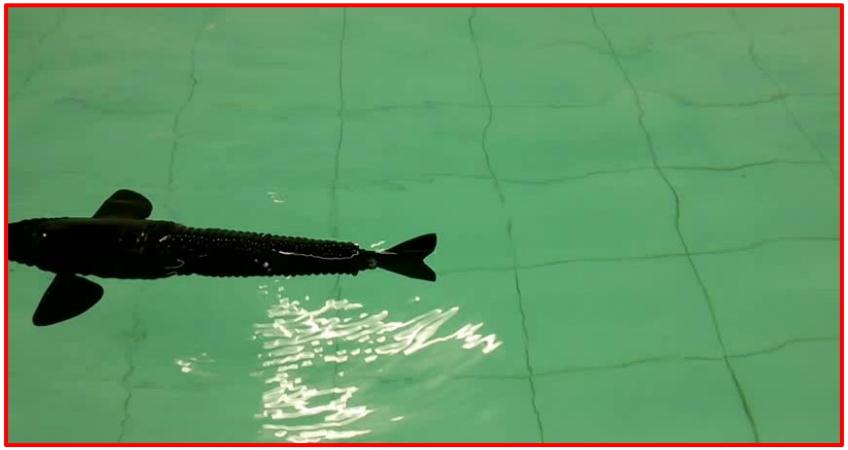
Diving and surfacing

Experimental results

➢ **Multimodal locomotion test (non-bionic)**



Backward swimming in BCF



Backward swimming in MPF

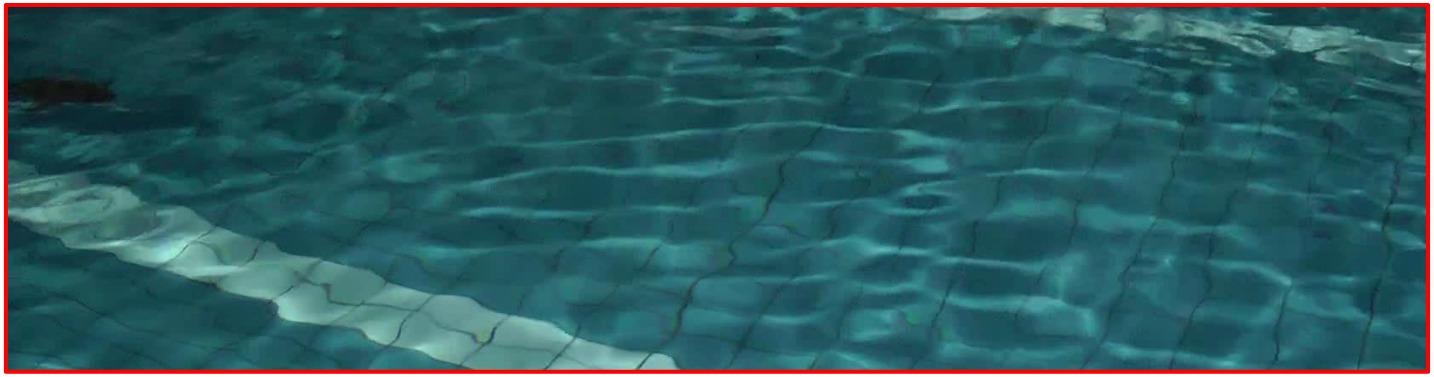
Experimental results

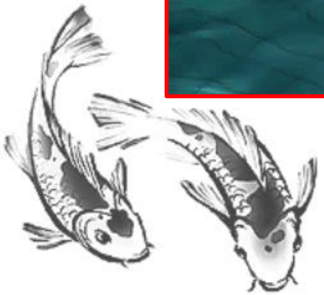
➢ **High-maneuverability swimming test**

Fast turning (90º)

Large-range turning (360º)

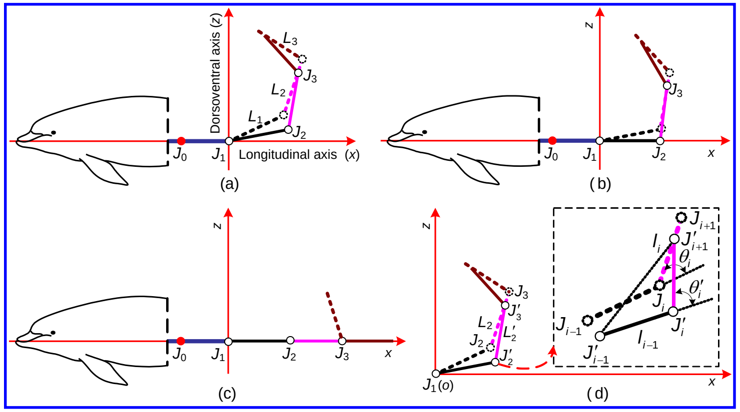
A flip in pitching style





Large-range rolling (360º)

Highly maneuverable locomotion



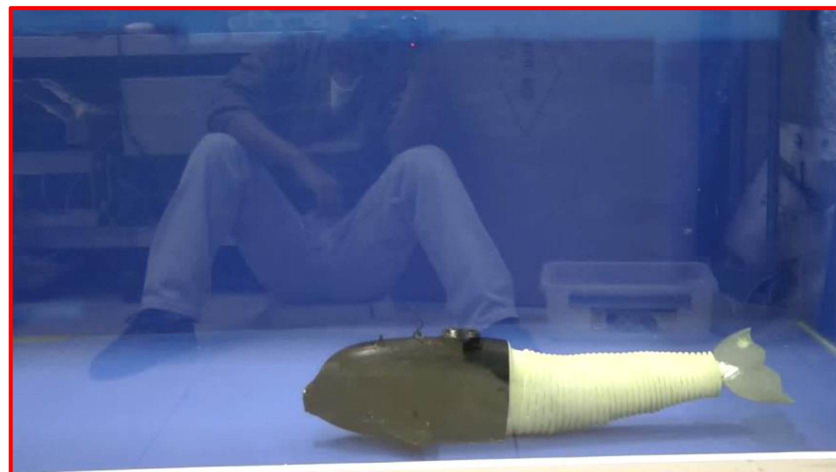
- **High maneuvers control in the vertical plane for a robotic dolphin**

$$J_D\ddot{\theta} = M_{F'} + M_{f'} + M_G$$

$$M_{F'} = \begin{cases} -\frac{1}{8}\rho\dot{\psi}^2\left\{W_pC_cL_p^4 + W_cC_F[(L_p+L_c)^4 - L_p^4]\right\} & t\in[t_0, t_0+t_{\text{tuck}}] \\ 0 & t > t_0 + t_{\text{tuck}} \end{cases}$$

$$M_G = \begin{cases} mgd_0 t\cos(\dot{\theta})/t_{\text{tuck}}, & t\in[t_0, t_0+t_{\text{tuck}}] \\ mgd_0\cos(\dot{\theta}), & t > t_0 + t_{\text{tuck}} \end{cases}$$

$$M_{f'} = \begin{cases} -\frac{1}{8}sign(\dot{\theta})\dot{\theta}^2\rho W_aC_cL_a^4 & t\in[t_0, t_0+t_{\text{tuck}}] \\ -\frac{1}{16}sign(\dot{\theta})\dot{\theta}^2\rho(W_aC_cL_a^4 - 2W_cC_FL_p^4) & t > t_0 + t_{\text{tuck}} \end{cases}$$



Frontflip and backflip of a robotic dolphin

Highly maneuverable locomotion

- The developed dolphin robot realized several leaping motions, and attained a marked speed as high as 2.93 BL/s (2.11 m/s).

One-shot leap

Two continuous leaps

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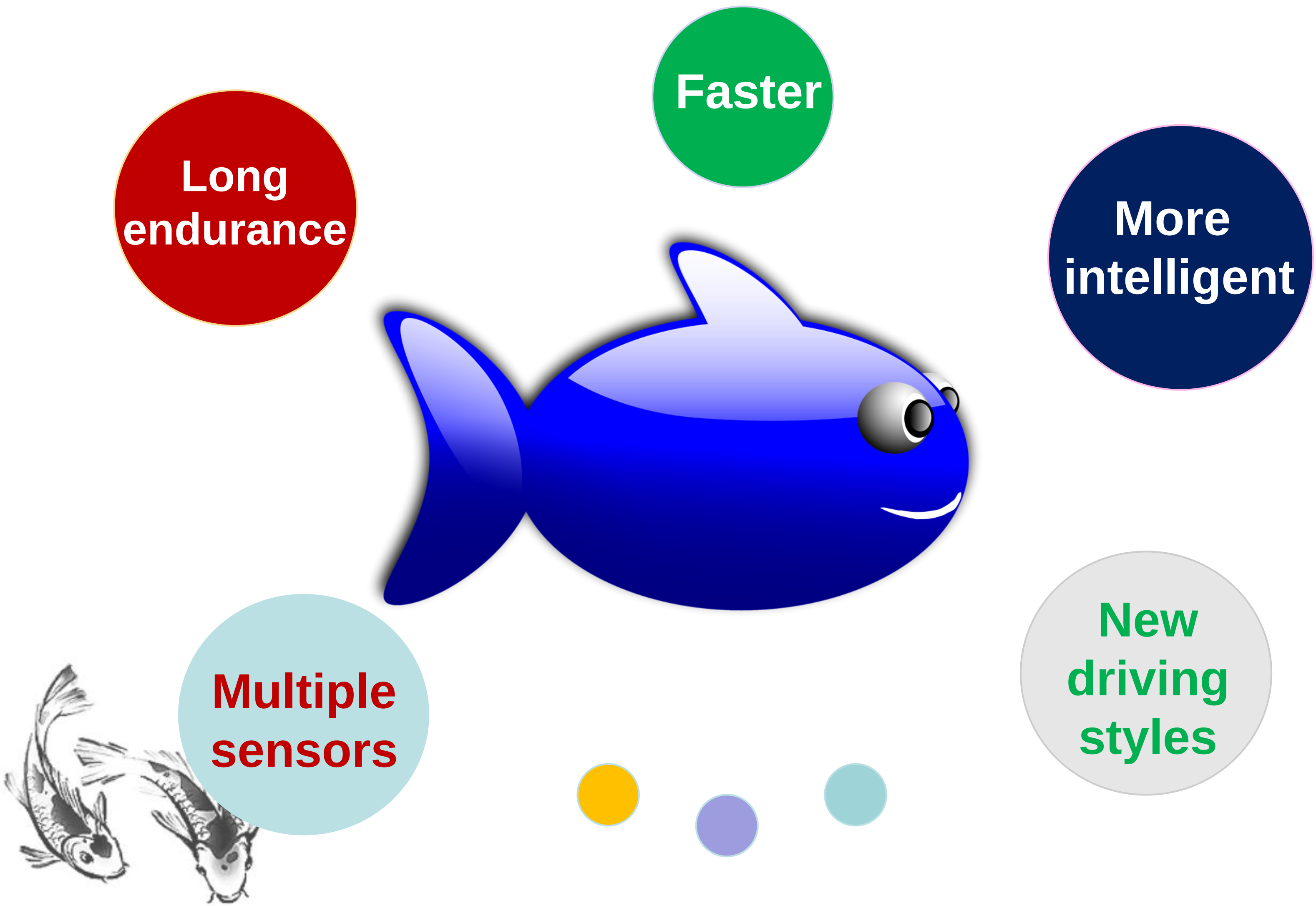
Summary

1. A novel basic body wave theory is proposed to design the practical travelling body wave for a robotic fish.
2. Highly efficient locomotion are realized through swimming gaits optimization, kinematic and dynamic analysis.
3. A dynamic trajectory tracking strategy based on a virtual ‘C’ pipe is proposed according to the observation and analysis in turning of real fish.
4. A variety of high maneuvers are successfully implemented, such as fast C-start, frontflip, backflip and leaping out of the water, etc.

Future work


Faster
Long endurance
More intelligent
Multiple sensors
New driving styles