Motivation

Goal: *Improve Autonomous Robot Control*

• Evolve adaptive control:
  – changes to a *control* signal
  – changes in the *environment*
  – changes in dynamics (*morphology*)

• *Not behaviors*
Motivation : Robotic Fish

Industrial

Biological
Outline

Robotic Fish Design
Adaptive Control
Velocity Study
Flow Tank Application
Future Work
Small Robotic Fish

• Stickleback size
  – robot : 7 cm
  – real : 4 to 6 cm

• Electrical components
  – 32-bit ARM μ-controller
  – 3-axis accelerometer
  – 3-axis gyroscope
  – 2 light sensors
  – 2.4 GHz wireless
  – magnetic motor
  – 1 hour battery life
  – NOT tethered
Design Process

Robot Prototype
Design Process

Robot Prototype

Dynamic Modeling

[Wang 2012, Clark 2012]
Design Process

Robot Prototype

Dynamic Modeling

Parameter Identification
Design Process

Robot Prototype
Dynamic Modeling
Parameter Identification
Control Design

Control System
- $r$: desired system output
- $y$: actual system output
- $e$: system output error
- $u$: control signal

![Diagram](image.png)
Design Process

Robot Prototype
  ↓
Dynamic Modeling
  ↓
Parameter Identification
  ↓
Control Design
  ↓
Simulation

[Clark 2013]
Design Process

Robot Prototype
↓
Dynamic Modeling
↓
Parameter Identification
↓
Control Design
↓
Simulation
↓
Physical Experiments
Design Process

Robot Prototype
  ↓
Dynamic Modeling
  ↓
Parameter Identification
  ↓
Control Design
  ↓
Simulation
  ↓
Physical Experiments

Repeat to refine
  – reduce modeling error
  – improve parameter estimates
  – model noisy sensors

Repeat for new robot
  – different parameters
  – different sensors
Outline

Robotic Fish Design

Adaptive Control

Velocity Study

Flow Tank Application

Future Work
Adaptive Control: MRAC
Model-Free Adaptive Control
Model-Free Adaptive Control
Adaptive Neural Network

Network Activation
- feed-forward network
- propagated error
- sigmoid activation

Network Update
- minimize error

\[ E_s(t) = \frac{1}{2} e(t)^2 \]
Adaptive Neural Network

\[
\Delta w_{ij}(n) \propto \frac{\partial E_s}{\partial w_{ij}} ,
\]

\[
= \frac{\partial E_s}{\partial y} \frac{\partial y}{\partial w_{ij}},
\]

\[
= \frac{\partial E_s}{\partial y} \frac{\partial y}{\partial u} \frac{\partial u}{\partial w_{ij}},
\]

\[
= \frac{\partial E_s}{\partial y} \frac{\partial y}{\partial u} \frac{\partial u}{\partial o} \frac{\partial o}{\partial w_{ij}},
\]

\[
= \frac{\partial E_s}{\partial y} \frac{\partial y}{\partial u} \frac{\partial u}{\partial o} \frac{\partial o}{\partial q} \frac{\partial q}{\partial w_{ij}},
\]

\[
= \frac{\partial E_s}{\partial y} \frac{\partial y}{\partial u} \frac{\partial u}{\partial o} \frac{\partial o}{\partial q} \frac{\partial q}{\partial p} \frac{\partial p}{\partial w_{ij}}.
\]

\[
\Delta h_j(n) \propto \frac{\partial E_s}{\partial h_j} ,
\]

\[
= \frac{\partial E_s}{\partial y} \frac{\partial y}{\partial h_j},
\]

\[
= \frac{\partial E_s}{\partial y} \frac{\partial y}{\partial u} \frac{\partial u}{\partial h_j},
\]

\[
= \frac{\partial E_s}{\partial y} \frac{\partial y}{\partial u} \frac{\partial u}{\partial o} \frac{\partial o}{\partial h_j},
\]

\[
= \frac{\partial E_s}{\partial y} \frac{\partial y}{\partial u} \frac{\partial u}{\partial o} \frac{\partial o}{\partial q} \frac{\partial q}{\partial h_j},
\]

\[
= \frac{\partial E_s}{\partial y} \frac{\partial y}{\partial u} \frac{\partial u}{\partial o} \frac{\partial o}{\partial q} \frac{\partial q}{\partial p} \frac{\partial p}{\partial h_j}.
\]

\[
= -\eta K_c S_f(n) e(n) q_j(n) (1 - q_j(n)) E_i(n) \sum_{k=1}^{N} h_k(n),
\]
Parameters

Network values
- hidden layer bias
- hidden layer bias weights
- output layer bias
- output layer bias weight

Learning Values
- learning rate

Network topology
- number of input nodes
- number of hidden nodes

Control values
- gain
- error bounds
- activation period
Outline

Robotic Fish Design
Adaptive Control
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Simulation Study

Swim at a given (changing) speed

Adapt to:

- different control signals
- changing fin flexibilities
- changing fin lengths

Evaluation

- simulate for 60 seconds with a varying control signal
- fitness = mean absolute error
Un-tuned Parameters
Single Trial Evolution
Multi-trial Evolution

<table>
<thead>
<tr>
<th>Name</th>
<th>Flexibility</th>
<th>Length</th>
</tr>
</thead>
<tbody>
<tr>
<td>sim1</td>
<td>100%</td>
<td>100%</td>
</tr>
<tr>
<td>sim2</td>
<td>200%</td>
<td>100%</td>
</tr>
<tr>
<td>sim3</td>
<td>50%</td>
<td>100%</td>
</tr>
<tr>
<td>sim4</td>
<td>100%</td>
<td>110%</td>
</tr>
<tr>
<td>sim5</td>
<td>200%</td>
<td>110%</td>
</tr>
<tr>
<td>sim6</td>
<td>50%</td>
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</tr>
<tr>
<td>sim7</td>
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</tr>
<tr>
<td>sim8</td>
<td>200%</td>
<td>90%</td>
</tr>
<tr>
<td>sim9</td>
<td>50%</td>
<td>90%</td>
</tr>
</tbody>
</table>
Multi-trial Evolution
Changing Dynamics

9 Evaluations, low-limits (best replicate): 10% stiffness

Speed vs Frequency

Control signal: $u$

Motor angle

Speed (cm/s)

Time (s)

Frequency (Hz)

Motor angle

Frequency (Hz)

Motor angle

Frequency (Hz)

Motor angle

Frequency (Hz)
Outline

Robotic Fish Design

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Station Keeping

Video of new fish
SISO to MIMO

\[ r_1 + e_1 \xrightarrow{MFA\ Controller} u_1 \xrightarrow{(frequency)} y_1 \]

\[ r_2 + e_2 \xrightarrow{MFA\ Controller} u_2 \xrightarrow{(bias)} y_2 \]

\[ (x\ acceleration) \]

\[ (y\ acceleration) \]

\[ (IMU\ x-axis) \]

\[ (IMU\ y-axis) \]
SISO to MIMO

Anthony J. Clark | ALIFE 2014 : EPS Workshop
Outline

Robotic Fish Design
Adaptive Control
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Flow Tank Application
Future Work
Future Work: High-level Control

• Higher level control
  – FSM
  – ANN
Future Work: Failure

• When MFA fails
  – the error signal gets to high
  – combine with Self-modeling

[Rose 2013, Bongard 2006]
Conclusions

• Increase adaptability of autonomous robots
  – control signals, morphology, noise

• Decrease modeling effort
  – evolve online/onboard

• Help cross the reality gap in traditional ER
  – handle disparity between simulation and reality

• Requires higher-level control for behaviors
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Thank You

Questions?

Robotic Fish Design  Adaptive Control  Velocity Study  Flow Tank Application  Future Work
References


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


• [Rose 2013] : *Just Keep Swimming: Accounting for Uncertainty in Self-Modeling Aquatic Robots*