Morphing Airfoils with Four Morphing Parameters

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Outline

- Morphing Air Vehicles
- Q-Learning
- Morphing Airfoil
- Results
- Conclusions
- Challenges
Morphing Aircraft

- Mutli-role platform
- Changes state substantially
  - Adapt to diverse mission profiles
- Provides superior system capability only possible with reconfiguration
- Geometric changes on the order of 50%

NextGen & Barron Associates
How to Achieve Morphing?

- Historically
  - Variable geometry
    - e.g. B-1 Lancer and Grumman F-14 Tomcat
- Traditional
  - Design set of configurations
  - Design control laws from one to another
  - Or use morphing in lieu of control effectors
- Non-traditional
  - Use machine learning
    - Learns most configurations
    - Learns path from one to another
Previous Morphing Research

**Cornell (collaborator)**
- Garcia & Lipson
  - Morphing dynamical model and simulation that incorporates aerodynamic and structural effects
  - Validated with experimental data
  - Basic morphing parameters (incidence angle, dihedral angle)

**Maryland**
- Hubbard
  - Actuating a flapping wing structure with SMA’s
  - Structure, material, distribution of actuators

**Florida**
- Lind
  - Morphing flight demonstrator vehicle
  - Basic morphing parameters (dihedral angle, sweep angle)
  - $H_\infty$ control
Previous Morphing Research

*at Texas A&M University*

- **Smart Aircraft**
  - 2 independent morphing degrees-of-freedom
  - Actor-critic, then Q-learning
  - Function Approximation

- **Morphing Airfoil**
  - 2 interdependent morphing degrees-of-freedom
  - Goal based on aerodynamic and structural requirements
  - Q-learning

- **Morphing Wing**
  - In development
Research Overview

- **Approach**
  - Reinforcement Learning

- **Key Issue**
  - 4 morphing parameters

- **Solution**
  - Modify discretization and reward function to promote good convergence

- **Benefit**
  - Important step to learning shape changing of full morphing aircraft
Scope

- Airfoil
- 4 Morphing Degrees-of-Freedom
  - $\rightarrow$ 4 learning states
- CFD Model
  - Doublet panel method
- Q-learning
- MatLab R2007b
- Monte Carlo Success Rate
- Requirement Performance
Reinforcement Learning

- Reinforcement Learning Problem
  - Agent interacts with environment and makes decisions
    - Environment states, $s$
    - Possible action, $a$
    - Future state, $s'$
    - Reward, $r$
  - Track previous states, or
  - Retain current state information only
    - Markov Decision Process

- Generate policy
  - Mapping of states to “best possible” actions
    $\pi : S \rightarrow A$
Q-Learning

- Off-policy Method
  - Learned action-value function, $Q$, directly approximates the optimal solution, $Q^*$
    - Independent of the policy being followed
  
  $$Q(s_t, a_t) \leftarrow Q(s_t, a_t) + \alpha \left[ r_{t+1} + \gamma \max_a Q(s_{t+1}, a_{t+1}) - Q(s_t, a_t) \right]$$

- Policy determines state-action pairs
- Convergence to optimal behavior
  - Continual update of pairs
Q-Learning Algorithm - Pseudocode

Q-Learning()
Initialize $Q(s,a)$ arbitrarily
Repeat (for each episode):
  Initialize $s$
  Repeat (for each step of episode):
    Choose $a$ from $s$ using policy derived from $Q(s,a)$
    // (e.g., $\epsilon$-greedy policy)
    Take action $a$, observe $r, s'$
    $Q(s,a) \leftarrow Q(s,a) + \alpha[r + \gamma \max_a Q(s',a') - Q(s,a)]$
    $s \leftarrow s'$
  until $s$ is terminal
return $Q(s,a)$
State Space Discretization

- Challenging to Learn on Continuous Domain
- Common Solution – Discretizing Action and/or State Space
  - Reduces space to a finite number of state-action pairs the agent must visit
- “Curse of Dimensionality”
  - Number of state-action pairs increases exponentially as the number of state variables increase
Pseudogrid for Learning

\[ x_2 \]

\[ x_1 \]

\[ h_{x_2} \]

\[ h_{x_2} \]

\[ h_{x_2} \]

\[ h_{x_2} \]

\[ h_{x_1} \]

\[ h_{x_1} \]

\[ h_{x_1} \]

\[ h_{x_1} \]
4 dof Morphing Airfoil

- Morphing Parameters
  - Thickness
  - Camber
  - Location of maximum camber
  - Airfoil angle-of-attack

- Goals
  - $c_l \geq 0.4$
  - $c_l = 0.0 \pm 0.05$
  - $c_l = 0.2 \pm 0.05$
  - $c_l = -0.2 \pm 0.05$

- Airfoil must “fly” through a series of flight conditions that require one of the above goals.
  - 3 examples with different initial conditions
Problem Setup

- 10000 episodes
- 1000 action steps allowed per episode
- ‘Flight’ simulation
  - 200 steps long
  - Goal changes every 50 steps

Photo by Russ Hansen
Monte Carlo Simulations

- Test Each Saved Action-Value Function
- 1000 Trials per Function
- Policy:
  - Probability of random action: 5%
  - Probability of greedy action: 95%

<table>
<thead>
<tr>
<th>State</th>
<th>$h_{x_i}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thickness (%)</td>
<td>1.0</td>
</tr>
<tr>
<td>Camber (%)</td>
<td>1.0</td>
</tr>
<tr>
<td>Location of Max Camber</td>
<td>0.1</td>
</tr>
<tr>
<td>Angle-of-attack (deg)</td>
<td>1.0</td>
</tr>
</tbody>
</table>
Monte Carlo Results

a) $c_l \geq 0.4$

b) $c_l = 0.0 \pm 0.05$

c) $c_l = -0.2 \pm 0.05$

d) $c_l = 0.2 \pm 0.05$
4 dof Morphing Airfoil: Lift Coefficient Goals
4 dof Morphing Airfoil: States
Conclusions

- 92% - 96% success rate for all goals
- Discretizing state space is a promising candidate for handling inherently continuous state space of morphing airfoil problem
- Changes in camber and angle-of-attack dominate agent’s efforts
  - Can reduce complexity of problem by setting the other states to constant values
Challenges and Open Problems

- Model Complexity
  - Morphing wing
- SMA Dynamics and Control Policy
- Adaptive-Reinforcement Learning Control
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Questions?
V^\pi (s) = R(s) + \gamma \sum_{s'} P(s'|s, \pi(s)) V^\pi (s')