Interactive Hierarchical Brain-Computer Interfacing: Uncertainty-Based Interaction between Human and Robots

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Outline

• Hierarchical BCIs
• Uncertainty-based interactive hierarchical BCIs
Traditional BCIs for Robotic Control

• Trade-off between cognitive load and scalability

High-level control paradigm: more robotic autonomy
  - low cognitive load
  but
  - coarse-grained control

Low-level control paradigm: Finer-grained moment-by-moment control
  - High-flexibility
  but
  - higher-cognitive load
Hierarchical BCIs Phase I: Train

**User intention:** “Go to kitchen”

**EEG command:** “Learn GO_TO_KITCHEN skill”

**Available high-level control commands:**
- GO_TO_KITCHEN

**Robot “learns” a position-based navigation skill**

**User notices robot reached goal**
Hierarchical BCIs Phase II: Test

User intention: “Go to kitchen”

EEG command: “GO_TO_KITCHEN”

Available commands: “GO_TO_KITCHEN”

Robot goes to kitchen
Methods: BCI

- Current system uses SSVEP (but not limited to)
  - TFT monitor with refresh rate of 60Hz.
  - Three options: 12 Hz, 15 Hz, and 20 Hz
  - Asynchronous BCI paradigm (e.g., motor imagery) could be a more natural interface

- Classification
  - data collection (4s), refractory periods (2s)
  - classification using frequency domain features
Methods: Robot Learning

- Learning “high-level” control commands on-the-fly from “low-level” control demonstration traces.
  - function approximator, e.g., RBF Neural Network, or Gaussian Process Regression
  - training data: position based traces from “low-level” control demonstrations
  - output of function approximator produces sequence of control commands until goal-state is reached
  - one function approximator for each high-level control command
Methods:
Hierarchical
Adaptive Menu
Experimental Setup
Results

Navigation traces and policy

- User
- Robot
- User Endpoint
- Robot Goal
- Learned Policy
## Results

<table>
<thead>
<tr>
<th></th>
<th>Low-level BCI</th>
<th>Hierarchical BCI</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Mean among four subjects (std)</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Number of selections made</td>
<td>20 (7)</td>
<td>5 (2)</td>
</tr>
<tr>
<td>Task completion time (s)</td>
<td>220 (67)</td>
<td>112 (25)</td>
</tr>
<tr>
<td>Navigation only time (s)</td>
<td>124 (37)</td>
<td>73 (19)</td>
</tr>
<tr>
<td><strong>Mean of three trials from best subject (std)</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Number of selections made</td>
<td>15 (5)</td>
<td>4 (1)</td>
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<tr>
<td>Task completion time (s)</td>
<td>141 (42)</td>
<td>85 (4)</td>
</tr>
<tr>
<td>Navigation only time (s)</td>
<td>99 (30)</td>
<td>74 (9)</td>
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<tr>
<td><strong>Minimum (std)</strong></td>
<td></td>
<td></td>
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<tr>
<td>Number of selections made</td>
<td>8</td>
<td>4</td>
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<tr>
<td>Task completion time (s)</td>
<td>91</td>
<td>75</td>
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<tr>
<td>Navigation only time (s)</td>
<td>59</td>
<td>58</td>
</tr>
</tbody>
</table>

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Interactive Hierarchical BCIs

- Unreliable “high-level” skills due to incomplete, or insufficient training data
- Example:

Q: What happens if the robot starts from location “A”?
Uncertainty-based Interaction

- High-uncertainty region: Ask for user guidance
  - User gives additional “low-level” control commands to help robot finish the high-level command.

- Low-uncertainty region: Take control from user, autonomously finish an issued high-level command.
  - Relieves the user from engaging in low-level control.
Methods: Robot Learning

- Gaussian Process (GP) function approximator
  - Output of GP: <mean, variance>
  - Variance used as “uncertainty-metric”
Methods:
Interactive
Hierarchical
Adaptive Menu
Result

Train Mode: Go to location B

- RedStar: Goal position
- GreenDot: Start position
- BlueLine: User demonstration trace

Learned confidence map

- BlackArea: High-uncertainty region
- WhiteArea: Low-uncertainty region
Result

Test: High-level command
“Go to location B”

Immediately switches to user demonstration mode due to high-uncertainty!
(blue line trace)

Once the user drives the robot to low-uncertainty region, BCI takes control from user.
(black dotted line)

Red Star: Goal position
Green Dot: Start position
Blue Line: User demonstration trace
Black Dotted Line: Autonomous robot navigation trace
Result

*Updated confidence map after incorporating more data*

Black Area: Highly uncertain region
White Area: Less uncertain region
Comparison

Learned confidence map before update

Updated confidence map after incorporating more data
Conclusion

• Hierarchical BCI
  - Combines advantages of fine-grained and high-level autonomous control paradigms.
  - Learns high-level commands on-the-fly from user demonstrations with “low-level” control.

• Uncertainty-based interactive hierarchical BCIs
  - Interaction based on “uncertainty-metric” makes BCI more reliable and robust while remaining adaptive to user’s needs
  - Ability to handle uncertainty opens the door to practical real-world BCIs
Towards Practical Hierarchical BCIs
Acknowledgments

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