Joint Mind Modeling for Explanation Generation in Complex Human-Robot Collaborative Tasks

Xiaofeng Gao\textsuperscript{1*}, Ran Gong\textsuperscript{1*}, Yizhou Zhao\textsuperscript{1}, Shu Wang\textsuperscript{1}, Tianmin Shu\textsuperscript{2}, Song-Chun Zhu\textsuperscript{1}

University of California, Los Angeles, USA\textsuperscript{1}
Massachusetts Institute of Technology\textsuperscript{2}
Motivation

• Humans can work towards a common goal even though one doesn’t know the exact details of the task
• Communication is necessary for coordination
• Efficient communication comes from inferring other’s belief, desire, or intention
Collaborative Cooking Game

Task Example:
making apple juice with 3 apples

A Task Plan:
- Take each apple from the basket
- Put it onto chopping board and cut it
- Put it into a juicer
- Use the juicer
- Pour the juice into a bowl
- Deliver the juice

Sub-tasks dependency

For better task performance, how should the robot coordinate with non-expert users?
For task allocation, we minimize the amount of time for the slower agent to finish the task, with respect to variables:

- Binary decision variable \( x \): whether to assign a “task” to an agent \( v \)
- Continuous timing variable \( t \): the time that a certain atomic action is performed
- Constraint: generated based on causal and temporal structure of task

\[
\min_{x,t} \quad \max_{v \in V} \quad \sum_{i,j,k} x_{i,j,k}^v T_{i,j,k}^v \\
\text{subject to} \quad x \in X_{\text{feasible}}, \quad t \in T_{\text{feasible}}.
\]
Explanation framework

- Planning
  - To get an initial joint plan
- Inference
- Explanation
- Re-planning
  - To comply with suboptimal user behaviors

Algorithm 1: Planning and explanation generation

1. while Task not finished do
2.   if Replan needed then
3.     Collect state information from the game;
4.     Collect predicted human intentions from the last time step;
5.     Call DP planner;
6.     Obtain a new sequence of sub-tasks from planner and re-organize AoG based on it;
7.     Parse AoG through checking pre-conditions and post-effects against the current environment state information;
8.     Find out the next atomic action to execute based on parsing result;
9.     Predict human intentions by equation (6);
10.    Measure the difference between predicted intention and expected human actions;
11.    Generate an explanation if the difference > τ;
Human mental model inference

- Bayesian inference of user subtasks

\[ \hat{p}g^h = \arg \max_{pg^h} p(pg^h|D_T, G) \]
\[ \propto p(pg^h|G, D_{T-1})p(d_T|pg^h, G) \]

- We consider communication history \( m \) and observed user action \( a_{obs}^h \) independently in the likelihood

\[ p(d|pg^h, G) = p(a_{obs}^h|pg^h, G)p(m_r|pg^h, G), \]
\[ p(a_{obs}^h|pg^h, G) = \sum_{a_{samp}^h} p(a_{samp}^h|pg^h)p(a_{obs}^h|a_{samp}^h) \]

likelihood of sampled trajectory

Similarity between partially observed trajectory and sampled trajectory
Inferring human intention/plan based on observations

• Sampled trajectories

• Observed Trajectories

Based on the distance between $a^h_{obs}$ and $a^h_{samp}$, a reasonable prediction of user’s action would be “taking the bowl”
Explanation generation

Explanation content: How much to say
• By modeling user’s task plan $pg^{UinM}$, the machine can give detailed explanations to improve the task performance, i.e. the machine can communicate the current subtasks and atomic actions of both agents.

Explanation timing: When to say
• By modeling user’s task plan $pg^{UinM}$ during collaboration, the machine can generate explanations at a more appropriate time, i.e. when the expected user subtasks are different from the inferred subtasks.
Example: make apple juice with 3 apples
**Experiment Procedure**

**Control**
- **Introduction**: An introduction of the experiment. Showing an explanation template.

**Heuristics**
- **Familiarization**: Asking users to finish a simple task to help them get familiar with the control.
- **Testing**: No Explanation
  - Explain when there is no detected user action
  - Explanation generated by the algorithm at the proposed timing.

**Mind Modeling**
- **Evaluation**: Post experiment survey

N=27, non-expert users
Experiment Result on 2 Hypotheses

H1: Using explanations generated by the proposed algorithm would lead to more fluent teamwork
   • Task completion time

H2: Participants under different testing conditions would have different levels of perceptions of explanations, indicated by the subjective measures
   • Efficiency
   • Helpfulness

• Confirmed H1 and H2
• Take-away Message: with proper communication between human and machine, both the task performance and user’s perception about the machine can be improved.

*: p < .05
**: p < .01
Limitations and future work

• Task and environment
  • Shared workspace
  • Diverse strategies
• Balanced roles for the human and machine
• Explanation content
  • Identify the problem
  • Tailored to the user’s need

“Robots Make Bavarian Breakfast Together.” IEEE Spectrum
Any questions?

For more information, contact Xiaofeng Gao (xfgao@ucla.edu).