

Social Feedback For Robotic Collaboration

EMILY WU
PROFESSOR STEFANIE TELLEX
PROFESSOR JEFF HUANG
BROWN UNIVERSITY
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Abstract

Robotic collaboration requires not just communication from the human to the robot, but also from the robot to the human. We call this robot-to-human communication *social feedback*. In order to flexibly and intelligently generate social feedback, we describe a Partially Observable Markov Decision Process that incorporates the human's belief about the robot's intent. We then engineer a system that can respond in near-real time that is supplemented with a multithreaded interaction model that allows for more responsive human-robot interactions. Initial evaluation in simulation shows that our social feedback model results in improved length of interaction and accuracy.

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1 Introduction

Collaboration is a process that relies heavily on communication for its success. When humans collaborate, this communication is both obvious and implicit—we not only instruct and request aid from each other, but we also tacitly monitor our partners for signs of approval and understanding while producing these signals ourselves. However, in robotics, many of these vital components of successful communication are missing or lost. The absence of these signals likely account for numerous failures in human-robot collaborative tasks. In order to give robots these missing communicative skills, we employ *social feedback* signals to provide human-like communication to both inform the human participant of the robot’s state and request information from the participant.

Feedback refers to the responses that are received by an agent when it takes some action. These feedback responses inform the agent about the success or failure of its actions. *Social feedback* therefore refers to social signals that convey this information. These can be explicit signals, such as “I want this object”, or implicit signals, like a perplexed expression. When humans interact with another human, they use this feedback to improve the flow and clarity of the collaboration, which in turn improves its success. For my thesis work, I have developed a framework that describes how robotic agent should likewise generate social feedback for its human partner in human-collaborative tasks, and show that it improves the speed and accuracy of human-robot interaction.

In this work, we address the object delivery task. In this task, a set of objects are laid out on a table within the robot’s reach. A human participant requests an object from the robot using speech and gesture (pointing). The robot must interpret the human’s speech and gesture and deliver the requested object to the human. The task then repeats with the remaining objects on the table. This task is achievable without social feedback; the robot need only wait until enough information is given and then deliver the correct object. However, we will show that by adding social feedback actions, such as asking questions, looking at objects, and pointing at objects, we will achieve better accuracy and speed as well as improved user experience.

We will solve this problem by formulating it as a Partially Observable Markov Decision Process (POMDP)[Kaelbling and Lozano-Perez, 2010], which will allow us to dynamically and flexibly determine how to choose social feedback actions. First, we will describe a two agent model and use this to motivate the construction of a POMDP. The crucial improvement we make over existing robot interaction models is that we maintain a state variable that tracks the human’s interpretations of the actions the robot takes. We will next discuss how we solved this POMDP and other measures we took to allow our system to respond dynamically and fluidly.

As an initial evaluation, we run our model in simulation to showcase improved speed and accuracy in the object delivery task.

2 Related Work

This work is primarily built off of Eldon [2015], which describes a system for incremental speech and gesture recognition in an object-delivery domain. In Wu et al. [2015], Eldon [2015] is expanded into a POMDP model and allowed to ask yes-no actions. In this work, we generalize the idea of the affect of robot’s actions on humans state within a POMDP framework.

Work demonstrating the importance of social feedback in human-human communication has been done in the field of psycholinguistics. In Clark and Krych [2004], one human (labeled the builder) builds a Lego model according to instructions given by another human (labeled the director). In the feedback-free trials, the director’s instructions were prerecorded, and the resulting models were very inaccurate (in fact no model was completely correct). In the feedback trials, errors were reduced by a factor of eight. Our goal is to enable a robot to collaborate with a human in this way.

Other work with collaborative robots exists, for example, Foster et al. [2012] have done research with a bartending robot. This robot follows a rule-based state estimator, and delivers drinks from fixed positions behind the bar to multiple users based on their speech and torso position. We expand the scope of the problem: we do not use a rule-based state planner, our items are not in fixed positions, and our gesture model uses pointing instead of torso position.

In Bohus and Horvitz [2014], a robotic building guide directs guests to find specific rooms. Our project addresses a similar domain, requiring the interpretation of users’ requests, but differs in the task and the type of communication necessary to accomplish that task.

Other work involving robotic object delivery also exists. Some approaches have no social feedback and will either deliver the wrong item or do nothing if given a request it does not understand [Tellex et al., 2011, Matuszek et al., 2012, Tellex et al., 2012, Misra et al., 2014]. Language only feedback models also exist [Chai et al., 2014,

MacMahon et al., 2006, Tellex et al., 2011, Matuszek et al., 2012, Guadarrama et al., 2014, Hewlett et al., 2011, Misra et al., 2014], and several gesture only models [Waldherr et al., 2000, Marge et al., 2011].

Matuszek et al. [2014] shows promising work in fusing language and complex gesture to understand references to multiple objects at once. We build off this work by including social feedback.

In the field of computational linguistics, previous work exists in resolving referring expressions incrementally, such as Schlangen et al. [2009], Zender et al. [2008], Gieselmann [2004]. Other work in that community also incorporates gesture, and/or eye gaze [Kennington et al., 2013, 2015], but the given work does not incrementally update gesture along with speech. Chai et al. [2011] provides work towards resolving referring expressions in a different domain, but does not address the task of acting on the results of these referring expressions. In Kruijff et al. [2008], they propose a system for planning to ask for clarifications, which covers a wide scope of knowledge failures. In this work, we are interested only in a small subset of these clarifications, and address the problem of how and when these clarifications should be used in a concrete human-robot collaboration task.

POMDP approaches to dialog [Young et al., 2013] are quite common, but treat dialog as a discrete, turn-taking interaction. The Dialog State Tracking Challenge [Williams et al., 2013] a notable driving force for computer dialog understanding, treats dialog in this turn-based way. Our model is also based off a turn-based interaction, but we provide a systems solution to allow our model to behave more incrementally.

Interactive POMDPs (I-POMDPs) [Gmytrasiewicz and Doshi, 2005] describe a multi-agent POMDP that allows agents to anticipate each other’s actions by forming beliefs over action and observation histories. This work attempts to accomplish the same, but makes more specialized assumptions that allow for a more tractable state space.

Alternative approaches to POMDPs include cognitive architectures such as SOAR [Laird, 2012] or DIARC [Schermerhorn et al., 2006]. By taking a probabilistic approach, we can seamlessly fuse information from multiple sources and explicitly reason about the robot’s uncertainty when choosing actions.

3 Technical Approach

3.1 POMDP Overview

Partially Observable Markov Decision Processes (POMDPs) are used to model Markov Decision Processes where the true state is not known. Instead, the agent receives observations that are generated by the true state, and must infer what the true state is from the observations. Thus, the agent maintains a belief over true states which is updated as it receives new observations. The agent must then use this belief state to determine which action to take to maximize its expected value of the reward over time. This splits the POMDP into two main components, a state estimator and a policy generator.

State Estimator The state estimator is given an initial belief and uses Bayesian mathematics to update its belief over time. In order to perform this update, the state estimator has a model of how the hidden states emit observations as well as how the state evolves in response to actions performed by the robot. The first model is described by the observation function and the second by the transition function.

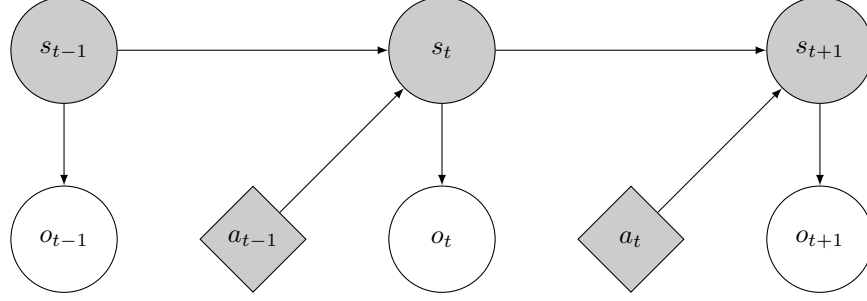
Policy Generator The policy generator is the means by which actions are chosen by the agent. Specifically, the policy generator should choose actions that maximize the agent’s expected reward over time. The reward for taking a particular action in a state is given by a reward function. These state-action pairs are called policies, and are generated by a POMDP Solver. Generally, POMDPs are solved by converting to their equivalent belief-MDP, which is an MDP where the state is distribution over the POMDP’s hidden states, a belief. In subsequent sections we will refer to this belief over states as b .

Formally, a POMDP is defined as a tuple $\{S, A, T, R, \Omega, O\}$, where :

- $s \in S$ is a hidden state.
- $a \in A$ is an action that an agent takes.
- $T : S \times A \times S \rightarrow [0, 1]$ is a transition function that returns the value $p(s'|s, a)$, the probability of transitioning to state $s' \in S$ from state $s \in S$ when taking action $a \in A$.
- $R : S \times A \rightarrow \mathbb{R}$ is a reward function that returns the reward for taking action $a \in A$ in state $s \in S$.
- $o \in \Omega$ is an observation.

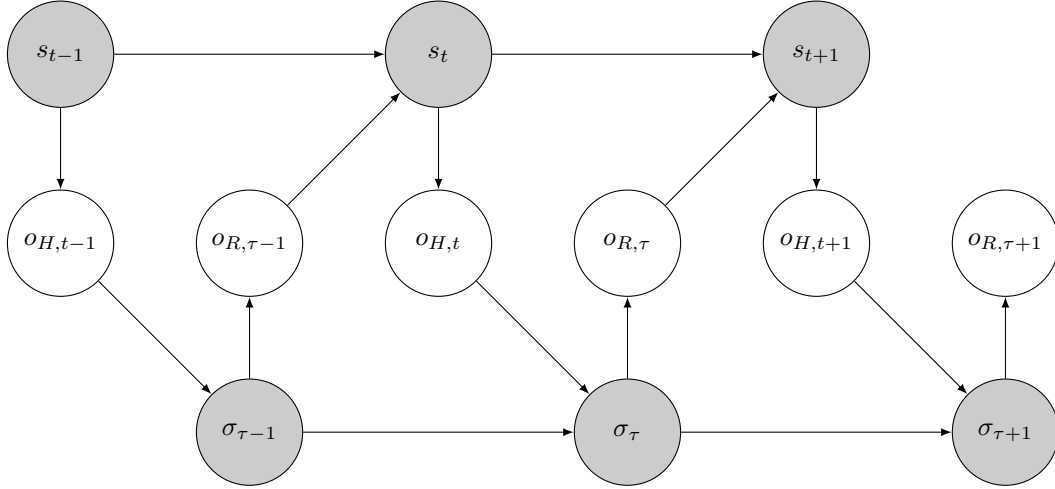
- $O : S \times A \times O \rightarrow [0, 1]$ is an observation function that returns the value of $p(o|s, a)$, the probability of observing observation $o \in O$ when action $a \in A$ transitions into $s \in S$.

A typical bayesian network for a POMDP is as follows.¹



3.2 Model Description

To model this human-robot interactive task, we will use a POMDP. To motivate the construction of our model, consider the following two-agent Bayesian network.



In the above model, we represent human states s_t , robot states σ_τ , and observations generated by the robot $o_{R,t}$ and by the human $o_{H,t}$. Observe that the structure of this model resembles two POMDPs combined together at their actions and observations. The lower POMDP is the POMDP from the human's perspective: the robot has some hidden states s_t , which the human observes by means of $o_{R,t}$. The human takes actions $o_{H,\tau-1}$ to influence the robot's state s_t . The upper POMDP is likewise the a POMDP that models the robot's process: the human's state σ_τ is hidden from the robot, and the robot must infer it from observations $o_{H,t}$. When the robot takes action $o_{R,t}$, it affects the human's state σ_τ . Crucially, each agent treats the other agent's action as an observation that influences their belief about the other agent's hidden state. Thus, the human's actions affect the robot's belief about the human's state, which is what we call b as defined above. Importantly, the reverse is also true: the robot's actions affect the human's belief about what the robot's hidden state is. We will call the human's belief over the robot's hidden state β .

In the following section we will use this dual structure to inform the construction of our POMDP as applied to our object delivery domain.

3.3 POMDP Definition

We define our object-delivery POMDP as a tuple $\{S, A, T, R, \Omega, O\}$:

¹In this model, we have omitted the dependency between an action and the observation that results from the next state. In the POMDP discussed in this paper, we will not use this dependency for any action. Rather, the affect of the actions on the resulting state variable are encapsulated fully by the resulting transition in the state.

- Each $s \in S$ is a tuple of $\langle \iota, \beta, \mathcal{I} \rangle$
 - \mathcal{I} is the set of all objects that the robot can deliver. Each object is parameterized by a name, a unigram vocabulary, and a position; for example: a red bowl would be represented $\langle \text{redBowl}, [\text{red}, \text{red}, \text{bowl}, \text{bowl}, \text{plastic}], (1.0, 2.0, 0.0) \rangle$. We assume the set of all objects is known.
 - $\iota \in \mathcal{I}$ is the object the human desires. This is a hidden variable.
 - β is a distribution over the robot’s hidden states, as defined above. In this domain, the robot state σ represents which object the robot will hand the human, or which object the robot believes the human wants. Specifically, $\beta_t(\iota_t) = p(\iota_t | a_{1:t-1})$. While this variable is technically unknown, make some assumptions about the transition functions and initialization to allow us to know β ’s exact value.

Since our state is composed of both hidden and known states, it resembles a Mixed Observability MDP [Ong et al., 2010], and we leverage the computational benefits of having both hidden and known states.

- The set of actions A consists of both social and non-social actions. Non-social actions are **pick(i)** (picking up and delivering an object i) and **wait**. Social actions are **point(x)**, pointing at a location x ; **look(x)**, looking at a location x ; **say(p)**, informing the human that the robot believes the desired object has property p . p is an element of some object’s vocabulary.
- $T(s, a, s') = p(s' | s, a)$. We make the assumption that the human’s desired object ι does not change unless the robot picks up object ι . The set of all objects \mathcal{I} transitions to $\mathcal{I} \setminus \{i\}$ when the robot chooses action **pick(i)**. For each action in A , we define a “reverse observation function” that describes our assumptions about how the human imagines the robot generates actions (which the human sees as observations) given a hidden robot state σ . This is gone into further detail in section 3.3.2.
- $R(s, a, s')$ returns a numeric reward from transitioning from s to s' by taking action a . In this domain, we incentivize our robot to pick the correct object by giving it a +10 reward if it delivers the correct object and a -50 reward for picking the incorrect object. We also give negative rewards for taking various actions: **wait** receives a -1 reward (to incentivize the robot to finish the task quickly); **look(x)** receives a reward of -2; **say(p)** receives a reward of -3; **point(x)** receives a reward of -4. These additional penalties for social actions reflect the penalty for “bothering the user”, as well as the time it takes to execute these actions. These reward values were chosen experimentally to result in a high rate of pick accuracy.
- Observation $o \in \Omega$ represents an observation generated by the human. These are tuples of language and gesture: $\langle l, g \rangle$. Language utterance l is represented by a string of any number of words, obtained by transcribing microphone input using webkit’s speech recognition API through google chrome. A gesture g is represented by a vector from the participant’s shoulder to their wrist, and all gestures are interpreted as a straight-armed point. This vector is obtained using the Kinect’s tracking software.
- $O(o, s, a) = p(o | s, a)$ describes the probability of seeing an observation o from the human given their state s and the robot’s last action a (though we do not make use of this last parameter). We choose an observation function that reflects that the human is an agent attempting to communicate which object they desire to the robot, and thus chooses to generate observations that are more likely to result in the robot delivering the correct object. This is gone into more detail in section 3.3.1

3.3.1 Observation Function

According to our double-agent model, the human emits observations as though it were an agent interacting with our robotic agent. Thus, we choose an observation model that depends on the human’s belief about the robot’s state, β . Specifically, the human will choose an action according to the its estimate that the robot will hand them that object. In order to define this function, we will first have to define a base-level observation function.

Base-Level Observation Function The base level observation function describes the probability of an observation conditioned only on the object: $p(o | \iota)$. For our object delivery domain, we will define two base-level observations, one for language and one for gesture.

Speech Model: Language is interpreted according to a smoothed unigram speech model. An utterance l is broken down into individual words, $w \in l$:

$$p(l|\iota) = \prod_{w \in l} p(w|\iota) = \prod_{w \in l} \frac{\text{count}(w, \iota.\text{vocab}) + \alpha}{|\iota.\text{vocab}| + \alpha|\text{words}|} \quad (1)$$

where $\text{count}(w, \iota.\text{vocab})$ is the number of times word w appears in ι 's vocabulary. α is a smoothing value chosen to be 0.05. $|\text{words}|$ is the total number of words in all object vocabularies.

Gesture Model: All gestures are interpreted as a straight armed point. These pointing gestures are selected from a normal distribution centered at the object's location.

Define the angle between the vector defined by the pointing gesture and the vector from the human's arm to the object ι to be θ_ι . The probability of a particular gesture is then

$$p(g|\iota) = \mathcal{N}(\theta_\iota|0, v) \quad (2)$$

where v is a hand-tuned variance.

Posterior Observation Function We will use the base-level observation functions defined above to define a posterior observation that considers the effects of the base level observation function. Specifically, the human chooses an action proportional the probability that the robot will hand them the desired object ι if the human had chosen that action. This action the robot then receives as an observation.

$$p(o|s) = p(o|\iota, \beta) \triangleq \eta p_\beta(\iota|o) \quad (3)$$

$$= \eta \frac{p(o|\iota)p(\iota)}{\sum_{\iota'} p(o|\iota')p(\iota')} \quad (4)$$

Next, we will use we will set $p(\iota) = \beta(\iota)$. $p(\iota)$ describes the robot's belief in ι . This value is represented in the robot's belief-state vector, b . But since the human does not know b , it uses its estimate of b , β . Our new expression is

$$p(o|s) = \eta \frac{p(o|\iota)\beta(\iota)}{\sum_{\iota'} p(o|\iota')\beta(\iota')}$$

Using β as a prior for our observation function incentivizes the robot to take actions that modify β in such a way that increase the probability of useful observations, while in turn decreasing the probability of getting observations that tell the robot things it already knows. This result falls out of our assumption that the human is more likely to provide observations that communicate its intentions to the robot well.² For a worked example in a toy domain, see the appendix.

Modification for Object Delivery Domain In the object delivery domain, we have both speech and gesture, which we assume are conditionally independent given the state.

$$p(o|s) = p(l|s)p(g|s)$$

In addition, it is possible to observe no speech or no gesture input. Let L be a random variable that is 1 if the agent receives a language observation and 0 otherwise. Similarly, let G be a random variable that is 1 if the agent receives a gesture observation and 1 otherwise. For all states s :

$$\begin{aligned} p(L = 1|s) &= c_L \\ p(L = 0|s) &= 1 - c_L \end{aligned}$$

$$\begin{aligned} p(G = 1|s) &= c_G \\ p(G = 0|s) &= 1 - c_G \end{aligned}$$

²It is perhaps more accurate to say that the human does not pick proportional to the probability, but picks the action with the greatest probability of $p_\beta(\iota|o)$, though this deterministic observation function would lead to irregularities when faced with real human users who do not pick perfectly. Using a softmax function with a tuned temperature parameter would serve to compromise between a deterministic max and a weaker "proportional to probability".

where c_L and c_G are constant values less than 1.

For each of language and gesture, we will use their own posterior observation function. Combined with the probability to receive a null speech or null gesture observation, the full expression is as follows:

$$p(o|s) = \eta p(l|s)p(g|s) = \eta p(L|s) \left[\frac{p(l|\iota)\beta(\iota)}{\sum_{\iota'} p(l|\iota')\beta(\iota')} \right]^L \cdot p(G|s) \left[\frac{p(g|\iota)\beta(\iota)}{\sum_{\iota'} p(g|\iota')\beta(\iota')} \right]^G$$

3.3.2 Transition Function

We make the assumption that every component of our state transitions conditionally independent of the other components given the previous state. In addition, each state variable depends only on its previous value and the action taken.

$$p(\iota_{t+1}, \beta_{t+1}, \mathcal{I}_{t+1} | \iota_t, \beta_t, \mathcal{I}_t, a_t) = p(\iota_{t+1} | \iota_t, a_t) p(\beta_{t+1} | \beta_t, a_t) p(\mathcal{I}_{t+1} | \mathcal{I}_t, a_t)$$

Object Transition Function As previously stated, we assume the object the human desires does not change unless its desired object is picked up. If the desired object is picked, it transitions uniformly at random between the remaining objects.

If a_t is `pick(ι_t)`,

$$p(\iota_{t+1} | \iota_t, a_t = \text{pick}(\iota_t)) = \begin{cases} 1/(|\mathcal{I}| - 1) & \text{if } \iota_{t+1} \in \mathcal{I} \text{ and } \iota_{t+1} \neq \iota_t \\ 0 & \text{otherwise} \end{cases} \quad (5)$$

If a_t is any other action:

$$p(\iota_{t+1} | \iota_t, a_t) = \begin{cases} 1 & \text{if } \iota_{t+1} = \iota_t \\ 0 & \text{otherwise} \end{cases} \quad (6)$$

Object Set Transition Function The set of objects \mathcal{I} changes only when an object is picked up. The picked object is removed from the set.

If a_t is a `pick(i)` action:

$$p(\mathcal{I}_{t+1} | \mathcal{I}_t, a_t = \text{pick}(i)) = \begin{cases} 1 & \text{if } \mathcal{I}_{t+1} = |\mathcal{I}_t| \setminus \{i\} \\ 0 & \text{otherwise} \end{cases} \quad (7)$$

If a_t is any other action:

$$p(\mathcal{I}_{t+1} | \mathcal{I}_t, a_t) = \begin{cases} 1 & \text{if } \mathcal{I}_t = \mathcal{I}_{t+1} \\ 0 & \text{otherwise} \end{cases} \quad (8)$$

Belief Transition Function The human's belief about which object the robot will hand over, β_t , is informed by the actions the robot takes. In the same way the robot's belief state b is a summary of all the observations the robot has made **cite that Littman paper**, β_t is a summary of all observations the human has made of the robot's actions, and reflects the human's estimate about the robot's true state. We therefore update β_t according to Bayesian probabilities the same way. The following is a standard Markovian update:

For a particular state ι_t , its probability after t observations is given as follows:

$$p(\iota_{t+1} | o_{1:t+1}) = p(o_{t+1} | \iota_{t+1}) \sum_{\iota_t} p(\iota_{t+1} | \iota_t) p(\iota_t | o_{1:t}) \quad (9)$$

Recall that β is a distribution over states (objects) ι_t , so we can use this rule to write an update for each entry of β .

$$\begin{aligned} \beta_{t+1}(\iota_{t+1}) &= p(\iota_{t+1} | a_{1:t}) = p(a_t | \iota_{t+1}) \sum_{\iota_t} p(\iota_{t+1} | \iota_t) p(\iota_t | a_{1:t-1}) \\ &= p(a_t | \iota_{t+1}) \sum_{\iota_t} p(\iota_{t+1} | \iota_t) \beta_t(\iota_t) \end{aligned}$$

This requires us to specify $p(a_t|\iota_{t+1})$. Recall that actions are operating as observations from the perspective of the human, making this expression a *reverse observation function*. We must provide a reverse observation function for each action. These will often be very similar the base-level observations described in Section 3.3.1, though adapted slightly to suit being performed by a Baxter robot. See the appendix for details.

We can rewrite our element-wise update for the whole β vector using a matrix multiplication:

$$b_{t+1} = A_t T b_t$$

where A_t is a matrix representing the reverse observation function $p(a_t|\iota_t)$ and T is a matrix representing the transition function $p(\iota_{t+1}|\iota_t)$. If the set of items $\iota = \{\iota_1, \iota_2, \dots, \iota_n\}$,

$$A_t = \begin{bmatrix} p(a_t|\iota_1) & 0 & \dots & 0 \\ 0 & p(a_t|\iota_2) & \dots & 0 \\ \vdots & \vdots & \ddots & \dots \\ 0 & 0 & \dots & p(a_t|\iota_n) \end{bmatrix} \quad (10)$$

$$T = \begin{bmatrix} p(\iota_1|\iota_1) & p(\iota_1|\iota_2) & \dots & p(\iota_1|\iota_n) \\ p(\iota_2|\iota_1) & p(\iota_2|\iota_2) & \dots & p(\iota_2|\iota_n) \\ \vdots & \vdots & \ddots & \dots \\ p(\iota_n|\iota_1) & p(\iota_n|\iota_2) & \dots & p(\iota_n|\iota_n) \end{bmatrix} \quad (11)$$

This gives us a deterministic transition function for β :

$$p(\beta_{t+1}|\beta_t, a_t) = \begin{cases} 1 & \text{if } \beta_{t+1} = A_t T \beta_t \\ 0 & \text{otherwise} \end{cases} \quad (12)$$

If we assume that β_0 begins as the uniform distribution over objects, we can now calculate β_t for any given time step deterministically. However, there are many assumptions that were made, and there is additional expressiveness that can be used by allowing for non-deterministic updates to β . However, we lead the exploration of this space for future work.

3.4 Policy Generation

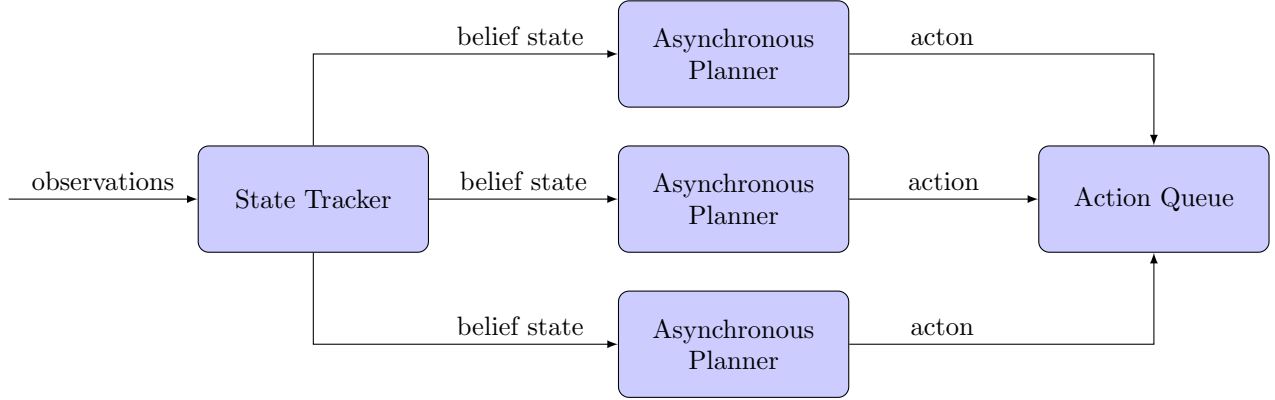
It is possible to calculate an optimal policy to solve our POMDP, however, due its size, doing so is intractable. Moreover, we would like to solve our POMDP add speeds suitable for interaction. Fortunately, approximate solutions exist which allow us to trade off accuracy for computational time. In this paper, we use the Partially Observable Sparse Sampling (POSS) algorithm [Gopalan et al., 2016], which uses Monte-Carlo Tree Search [?] and Upper Confidence Bound exploration ? to derive a policy for our POMDP. In order to improve the accuracy of the planner, we also provide a heuristic for the random rollouts that prevents the rollouts from selecting pick actions that are unlikely to pick the correct objects.

3.5 Incremental System Design

Interactive systems that involve speech often make an assumption that the interaction can be split neatly into turns: first one speaker provides a complete utterance, and then the other. This is often not the case, and it is a subtle matter to determine when one turn is completed and the other agent can begin to speak. As a consequence, many systems involving dialogue, including earlier iterations of this project, do not “hear” utterances or gestures while the agent is speaking or acting. Any speech or gestures the human made while the robot was executing its action were dropped and never incorporated into the robot’s belief about the state. An additional problem was that while the robot was planning its next action, it would also not incorporate any observations made. This was a significant affect, as it could take up to 10 seconds of planning for the robot to make its next move. As a consequence, most observations would be dropped unless we incorporated a system of turn-taking where we waiting a set amount of time for the human to provide any speech and gesture input.

While turn-taking is an adequate solution for dialogue-only systems, full fledged interaction is more continuous. Even when speaking in a turn-like manner, agents give signals back and forward to signal their understanding and also provide corrections and interruptions.

In order to create more fluid interactions, we employ a multithreaded solution that separates the state estimation, planning, and executions of actions. This allows our robot to simultaneously track the human’s belief, plan its next move, and interact with the human.



State Tracker The state tracker incorporates observations from the human at a very high rate, allowing the tracker to always have access to the most up-to-date state estimation. However, our domain description requires the robot to choose an action between each consecutive observation. We address this by feeding the model a `wait` action unless the planning thread has provided a action that has not yet been integrated, in which case we use that action. This also requires minimal dependency between actions and observations, which our model avoids.

Asynchronous Planner A separate thread runs the planning code. Planning can take several seconds, during which the robot is not only idle, but also deaf and blind. Running the planning code on a separate thread allows the robot to continue observing and interacting with the human while the robot plans its next move. In addition, we can use several planning threads at once, with separate policies to control the robot’s face, arms, head angle, etc. In our work, we use one thread to plan for the POMDP domain described above, and another to animate the Baxter’s face to show an facial expression of increasing confusion with the entropy of the belief state.

Action Queue The planning threads push their actions onto a queue which executes them one by one, allowing the planning threads to resume planning if the actions they produce take some time to execute. An additional advantage is that this allows the robot to be constantly acting, with minimal idle time.

4 Evaluation

4.1 Sample Interactions

4.2 User Studies

5 Future Work

The next order of work will be to run user-studies with human participants to compare to efficacy of this system compared to the system without social feedback.

Other areas for further exploration can be found by removing many of the assumptions made in this paper. For example, the set of objects on the table was assumed to be known. Attempting to learn from the human more about the set of objects, such as their vocabularies and location, would be an interesting expansion.

Use of the β variable can be expanded to include uncertainty over the value of β_t , allowing for ambiguity in how the human interprets the robot’s action. In the same vein, additional modes of interaction from both the robot and human can be explored.

The object delivery domain can also be abstracted to a domain where the goal is not to determine which object the human wants, but the human’s intent in general. This system of tracking the human’s belief about the robot’s communicated intent can be widely applied to other human-robot interaction tasks.

6 Acknowledgements

7 Appendix

7.1 Posterior Observation Function: Toy Example

In order to demonstrate and motivate the posterior observation function, we will define a toy domain. In this toy domain, the states are the following: $\{AA, AB, BA, BB\}$ as well as β , which is a distribution over these states. The observations are $\{A_-, \neg A, B_-, \neg B\}$, which mean “the first character is an A”, “the second character is an A”, “the first character is B”, “and the second character is a B” respectively. These observations are provided by the human. The agent can take actions CX which is informing the human that the agent believes the Xth character is a C, as well as “picking” the object or waiting. In our toy domain, for the base level observation, the human always gives truthful observations, and has equal probability of generating an observation pertaining to a particular character. We will see how this affects the POMDP observation function, which incorporates β .

Consider the following situation:

Initially both b , the robot’s belief about the human’s desired object and β , the human’s belief about the robot’s belief, are uniform. The true state is AA .

t	b	β	a	o
0	[0.25, 0.25, 0.25, 0.25]	[0.25, 0.25, 0.25, 0.25]		

The robot then receives an observation A_- . The new beliefs are:

t	b	β	a	o
0	[0.25, 0.25, 0.25, 0.25]	[0.25, 0.25, 0.25, 0.25]		
1	[0.50, 0.50, 0, 0]	[0.25, 0.25, 0.25, 0.25]		A_-

Next, the robot can choose to take an action. If it chooses to wait, this is the resulting state

t	b	β	a	o
0	[0.25, 0.25, 0.25, 0.25]	[0.25, 0.25, 0.25, 0.25]		
1	[0.50, 0.50, 0, 0]	[0.25, 0.25, 0.25, 0.25]		A_-
2	[0.50, 0.50, 0, 0]	[0.25, 0.25, 0.25, 0.25]	wait	

Examine the probabilities of each observation.

$$\begin{aligned}
 p(A_-|AA, \beta) &= \frac{p(A_-)\beta(AA)}{p(A_-)\beta(AA) + p(A_-)\beta(AB) + p(A_-)\beta(BA) + p(A_-)\beta(BB)} \\
 &= \frac{0.5 * 0.25}{0.5 * 0.25 + 0.5 * 0.25 + 0 + 0} \\
 &= 0.5
 \end{aligned}$$

$$\begin{aligned}
 p(\neg A|AA, \beta) &= \frac{p(\neg A)\beta(AA)}{p(\neg A)\beta(AA) + p(\neg A)\beta(AB) + p(\neg A)\beta(BA) + p(\neg A)\beta(BB)} \\
 &= \frac{0.5 * 0.25}{0.5 * 0.25 + 0 + 0.5 * 0.25 + 0} \\
 &= 0.5
 \end{aligned}$$

The probabilities of all other actions are 0, since we only give truthful observations.

Notice that this situation is not ideal. The agent has equal probabilities of receiving either observation, even though the agent already knows that the first character is an A. Now, consider what would happen if the robot chose the action $A0$. We would get the following belief states:

t	b	β	a	o
0	[0.25, 0.25, 0.25, 0.25]	[0.25, 0.25, 0.25, 0.25]		
1	[0.50, 0.50, 0, 0]	[0.25, 0.25, 0.25, 0.25]		A_-
2	[0.50, 0.50, 0, 0]	[0.5, 0.5, 0, 0]	$A0$	

If we examine the probabilities again:

$$\begin{aligned}
p(A_-|AA, \beta) &\propto \frac{p(A_-)\beta(AA)}{p(A_-)\beta(AA) + p(A_-)\beta(AB) + p(A_-)\beta(BA) + p(A_-)\beta(BB)} \\
&\propto \frac{0.5 * 0.5}{0.5 * 0.5 + 0.5 * 0.5 + 0 + 0} \\
&\propto 0.5 \\
&= \frac{1}{3}
\end{aligned}$$

$$\begin{aligned}
p(\neg A|AA, \beta) &\propto \frac{p(\neg A)\beta(AA)}{p(\neg A)\beta(AA) + p(\neg A)\beta(AB) + p(\neg A)\beta(BA) + p(\neg A)\beta(BB)} \\
&\propto \frac{0.5 * 0.5}{0.5 * 0.5 + 0 + 0 + 0} \\
&\propto 1 \\
&= \frac{2}{3}
\end{aligned}$$

Now, we are more likely to get the observation $\neg A$, which is more useful to us than the observation A_- , since it gives us the information we need to pick the correct object, AA . This provides an incentive for the robot to choose an action that conveys something about its current state of belief over doing nothing.

7.2 Reverse Observation Functions

We define a reverse observation function for each action the robot can take. These define how β is updated when a robot takes an action.

For **look(x)** actions, we define an angle ϕ_l to be the angle between a vector from the robot’s face to the location x and the vector from the robot’s face to the location of object ι_{t+1} . We assume this angle is chosen from a normal distribution centered at 0 with a hand tuned variance, v_l .

$$p(a_t = \text{look}(\mathbf{x})|\iota_{t+1}) = \mathcal{N}(\phi_l|0, v_l)$$

For **point(x)** actions, we define an angle ϕ_p to be the angle between the vector from Baxter’s wrist to location x and the vector from Baxter’s wrist joint to the object ι_{t+1} . This gesture is chosen according to a normal distribution with hand-tuned variance v_p .

$$p(a_t = \text{point}(\mathbf{x})|\iota_{t+1}) = \mathcal{N}(\phi_p|0, v_p)$$

Actions **say(p)** take the form of a statement “I believe that the object you want is p ”, where p is some property from the some object’s vocabulary. The probability of this action given some ι is identical to the speech model for the human, given in section 3.3.1.

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