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Using Simulations to Model Shared Mental Models

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Introduction

Good team members seem to have the ability to simulate what others on the team will do in different situations. Team researchers have long studied what makes an effective team. Their methodology has been to examine how high and low performing teams accomplish team-related tasks. They have suggested that a good team-member has three knowledge components (Cannon-Bowers, Salas, & Converse, 1993):

(1) Knowledge of own capabilities [meta-knowledge],
(2) Knowledge of the task, and
(3) Knowledge about the capabilities of their teammates.

Most researchers have suggested that these three components are deeply inter-related; without any one of these, a person is not a good team member. However, without a computational theory, these claims can be difficult to examine empirically.

The focus of this paper is the third component, the cognitive modeling done of a teammate's cognitive processes. This shared understanding of teammates is frequently called a shared mental model (Mathieu, Heffner, Goodwin, Salas, & Cannon-Bowers, 2000). We start with the premise that humans use themselves as an initial model of their teammate, and then refine it as the team (and individuals within the team) gains experience. Our primary research goal is to create a computational theory of teamwork by modeling the individuals within the team so that we can eventually build plausible robots for teamwork and human-robot interaction.

Method

To explore teamwork at the individual level, we implemented a simple cognitive model of shared mental models in a desk-top simulation of a robotic member of a team. The scenario used to test the value of the robot cognitively modeling a teammate was a two-agent security guard force made up of one human and one robotic agent, patrolling a warehouse with two separated guard stations. They begin in positions approximately across the warehouse from each other and move around the perimeter. When an alarm sounds, they must "man" the two security stations as soon as possible. The performance measure was simply the time (in steps) it takes for the team to fill both stations after the alarm sounds.

We used ACT-R (Anderson et al., 2004; Anderson & Lebiere, 1998) to model the robot's reasoning, including its modeling of the human. ACT family of theories ("ACT-R Research Group") has a long history of integrating and organizing psychological data. It has also been broadly tested in psychological and computational terms.

This project builds on our embodied robotic systems (Kennedy et al., in press; Trafton, Schultz, Bugajska, & Mintz, 2005; Trafton et al., 2006). To make the project tractable, we modeled both the human and robot as having the same movement capabilities such that both would take the same number of steps to cover the same distance. This assumption will clearly need to be revisited when we add the models to physical robots. The necessary spatial representations and reasoning capabilities were already included in the system: the cognitive model had the use of a 10-by-10, 2-D cognitive map from which the security stations closest to each agent could be determined. However, to simulate human's general weakness in accurately estimating distances outside the grasping range (Previc, 1998), the system could not always determine which station was closer and the model had to deal with that ambiguity. Finally, the robot's cognitive model of the human presumed the human would reason and behave the same as the robot would.

For this project, we have initially modeled two simple cases. The first case represents neither agent having any model of the other agent and simply doing what is best for each agent independently, i.e., going to their nearest station. If both agents arrive at the same station, one must go to the other station and this is inefficient in both time and safety. The second case represents a leader-follower shared mental model where the leader, typically the human, goes to her closest station, and the follower, typically the robot, must go to the other station. This avoids the conflict of both going to the same station.

Simulating others in ACT-R

The robot could "see" the environment and used rule-based behavior to patrol the perimeter of the warehouse prior to an alarm and, with no shared mental model, what to do after the alarm. To decide what to do when the alarm sounded when using a shared mental model, the robot needed to model the behavior of the human. The robot modeled the human by explicitly taking information about how the robot would deal with the alarm and spawning that knowledge off as a simulation of the human teammate's decision making. The simulation decided what action the human would take in the current situation. Hence, the robot simulated what the human would do by explicitly modeling what it would do itself in a similar situation.

To run a spawned ACT-R model, a new model needs to be initialized with its own declarative memory, productions, and initial goal. This capability is part of the current version of ACT-R (R1.2-370]). To model how the human would react to the current situation, the robot's cognitive model spawned a cognitive model of the human using declarative memory of the current situation appropriately modified to place the robot in the human's situation, and provided the productions the robot itself used to decide what to do for the first, i.e., self-centered case. The simulation's initial goal was to determine which station the robot would go to if it was in the human's situation.

With the results of the simulation of what the human would do, the robot then decided to go to the other station, in accordance with the shared mental model that the human will lead and the robot follow. Figure 1 shows traces of a run in which both agents arrive at the same station and one then goes to the other station and a run in which, through having a shared mental model, they avoid the collision. The human began in the top line at position "a" and the robot began at "a" in the bottom. The sequential letters mark their steps counterclockwise prior to the alarm. The alarm sounded at "p" and the run ends when both guard stations "1" and "2" are filled.

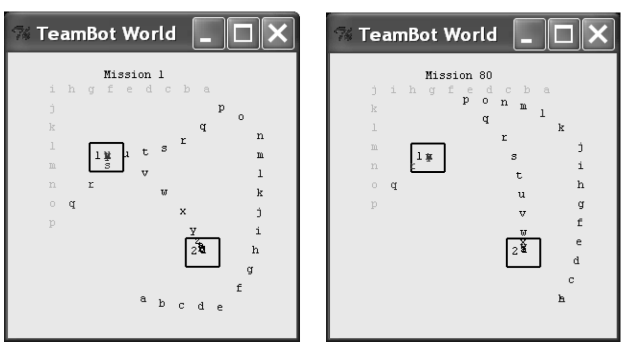

Figure 1. Traces of agents colliding (left) and avoiding collision (right) based on a shared mental model.

Results and Discussion

We found that for even this simple scenario, the useful, shared mental model significantly improved the team's performance: with 25 simulated runs each, the system that used a shared mental model and cognitive modeling of its teammate took 3.28 fewer steps than the system that did not, $t(27.7) = 8.1492$, $p < .001$ with the Welch correction for unequal variances.

By basing the robot's cognitive model of the human on what it would do in the human's place, the task required creating only the declarative memory to simulate the robot taking the human's place and one additional production to terminate the simulation.

This work demonstrates that the impact of one agent's cognitive modeling of another agent can be effective even in a simple scenario. We expect that there are many aspects of teamwork and cognitive modeling of shared mental models that can be explored using similar techniques. As an example, the flexibility of specifying the declarative memory and productions that will be used by the spawned cognitive model, allows cognitive models to consider the effects of hypothetical declarative knowledge and productions.

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