Improving Human-Robot Team Performance with Proactivity and Shared Mental Models

Extended Abstract

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ABSTRACT

Recent work in human-robot teaming has demonstrated that when robots build and maintain “shared mental models”, the effectiveness of the whole human-robot team is overall better compared to a baseline with no shared mental models. In this work, we expand on this insight by introducing proactive behaviors to investigate potential further improvements of team performance and task efficiency. We hypothesize that, combined with shared mental models, robots with these more proactive behaviors become even more effective teammates. To this end, we developed a set of robot behaviors aligned with reactive, active and proactive team behaviors in human-human teams. We ran a human behavioral study to evaluate our system. The results show that proactive robot behavior improves task efficiency and performance over mere reactive behavior in high cognitive load environments.

KEYWORDS

Robots; Teamwork; Proactivity; Shared Mental Models; Human Robot Interaction

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1 INTRODUCTION

Teams consisting of humans and robots have incredible potential to improve our lives in numerous areas like search-and-rescue missions, manufacturing and education. An open question in this area is how to enable *effective* task-based communication between humans and robots. There is increasing evidence showing that humans prefer to work with proactive robots (e.g. Fong et al. [5], Baraglia et al. [1], Cakmak et al. [2]), however as Bhattacharjee et al. [4] show “more autonomy is not always better”. Additionally, Shared Mental Models (SMMs) have shown great promise in increasing effectiveness of human-robot teams (e.g. Gervits et al. [6]). In this work, we design a system that integrates three different autonomous teaming behaviors (*reactive*, *active* and *proactive*) and SMMs in the cognitive robotic architecture *DIARC*. We evaluate our system with a human behavioral study and show that proactive human-robot teams perform better than reactive ones on team performance metrics.

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2 TECHNICAL APPROACH

We build on DIARC [8] by implementing event memory, three autonomous actions with different behavior types, initiation of dialogue, initiation of shared goals, further goal management behaviour, autonomous reactivation, and shared mental models. The robots use a “supervisory control” policy [3] where actions are carried out independently, but the human can intervene.

Setting. We utilize a spaceship environment in virtual reality with **one** human and **two** PR2 robots that have SMMs. The simulation was developed to simulate a use case for human-robot teams in space via a collaborative intravehicular activity (IVA) with a mission and a maintenance task. The spaceship has three wings and a central area that contains the mapping console. The human “astronaut” is given a “primary task” to record geological information given verbally and written by an off-ship rover onto a map in the ship’s central area. This is a **distractor** task meant to increase the cognitive load of the participant throughout the experiment. Their **real** task is to keep the spaceship running, by repairing tubes, when they start breaking, as they are vital for the spaceship’s health. The human-robot team has to collaboratively repair the tubes before they become unfixable. In order to repair a tube, the robot is either commanded to do so by the human or receives confirmation after asking whether the human wants to repair the tube. The process follows: the human turns the tube off, the robot repairs it and finally the human turns it back on.

Teaming Behaviors. In this study, we designed three robotics behaviors: *reactive*, *active*, and *proactive*. All agent teaming behaviors behave in the exact same way, but for their communication with the human. Thus, all agent teaming behaviors use SMMs with the same base autonomy script. Following [7, 9], the best teammates try to independently identify the team’s goal and take steps to achieve it. To this end, all teaming behaviors are aware of the overall goal (keep the space-station working) and independently choose which area to patrol next. Two of the teaming behaviors (active, proactive) share unsolicited information with the human.

(1) **Reactive:** The reactive agent silently patrols, only giving information when prompted.
(2) **Active:** In addition to patrolling, the active agent readily offers information related to breaking tubes to the human teammates, being mindful of becoming a distraction.
(3) **Proactive:** The proactive agent will offer information to the human teammates, attempt to initiate shared tasks (repairing a tube) when the situation calls for it, and reminding the human to perform necessary actions that have already been committed to, but unfinished.

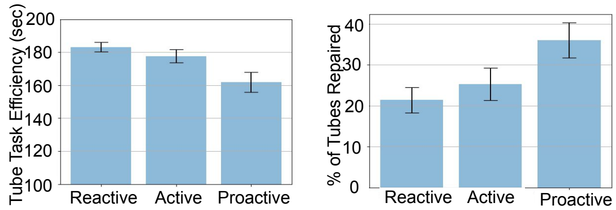

Figure 1: (Left) We show the mean tube task efficiency per agent behavior. (Right) We show the mean % of tubes repaired per agent behavior. The error bars represent standard error. We show that the more proactive an agent is (vs reactive), the more efficient the human-agent team is and the better it performs.

3 HUMAN SUBJECT EVALUATION

We evaluate the effect of the different behaviors on mixed-initiative human-robots teams with a within-subjects evaluation study with 23 participants (with approval by our University's Internal Review Board), where each human participant was paired with two robots (with the same behavior) in the simulated environment and three trials one of each with reactive, active, and proactive robots. The trial order was always randomized to account for learning curve and fatigue. Participants were told that the robot behaviors *may* change between trials. Participants had two tasks: to log all rover events announced by the space station and to collaborate with the robots on board to keep the station running.

We hypothesize that robot proactivity would improve the performance and efficiency of human-robot teams and that the most significant differences would be between the reactive and proactive cases. For our *performance* measure we use the *% of tubes repaired*. We measure the *task efficiency* of the teams by computing the *average time to repair a tube* (in case a tube was never repaired, we defaulted to 200 seconds which is the maximum logged repair time).

We performed several one-way ANOVAs together with Tukey HSD tests on the above performance measures to determine whether the data supported our hypotheses. We plot the results in Fig. 1.

Hypothesis H_1. We predict that the % of tubes repaired would improve as the agents become more proactive.

Results. We found that the percent of tubes repaired was higher as the agents' proactivity increased ($F = 3.87, p = .0257, \eta^2 = .10$). Using Tukey's HSD test, we found that there was no statistically significant difference between the reactive and active behaviors ($p = .73$) or the active and proactive behaviors ($p = .12$). However, the difference between reactive and proactive behaviors was significant ($p = .024$). Our results support H_1, i.e., teams with proactive agents achieve better task performance than ones with reactive agents.

Hypothesis H_2. We predict that participants would have an increased task efficiency in teams with more proactive agents.

Results. The task efficiency significantly improved when the agents were proactive ($F = 6.02, p = .0039, \eta^2 = .15$). Tukey's HSD test showed no significant difference between the reactive and active behaviors ($p = .65$), but there was a statistical significance between the active and proactive behaviors ($p = .04$). The statistical significance was even higher between the reactive and proactive behaviors ($p = .0039$). Our results thus support the hypothesis.

4 DISCUSSION

There was a significant difference in task performance and efficiency under the proactive vs. the reactive condition, supporting our hypothesis that proactive behavior can further increase team performance building upon the benefits of SMMs. The active behavior was not able to cause as large of a change in team performance since it did not relieve the participant of enough responsibilities.

H_1 Supported: Proactivity of Robots Under SMM Conditions Increase Task Performance. We found improvement in our main task performance metric, percent of tubes repaired. Based on our data, only the proactive case actually made a statistically significant difference to our task performance metric. Our results show that volunteering information to the human does not suffice to improve teamwork. Agents need to actively take responsibility in shared tasks to be better teammates. The combination of the human not needing to determine which tubes need to be repaired and being relieved from some decision-making, allows the proactive agent-human team to repair more tubes and thus perform better than the reactive or active agent-human. Interestingly, we found that there is no significant difference in performance of the reactive versus active agents, or the active versus proactive agents. This leads us to believe that the active behavior is a right step towards better teams since the team performance was not significantly different from either the reactive or proactive behavior.

H_2 Supported: Proactivity of Robots Under SMM Conditions Improves Task Efficiency. Agents with proactive behaviors improve the task efficiency over reactive agents. Additionally, teams with proactive agents perform significantly better than teams with active agents. The proactive agents both inform the human of the breaking tubes, but also initiate the task of fixing a tube. The salient difference between the active and proactive agent is the task initiation. Our results show that the simple act of initiating a task, without changing any of the steps, had a positive impact on the team efficiency.

Participant Feedback. During our experiments, we gathered written and oral feedback from the participants. The participants preference for proactive behavior was sometimes exhibited verbally during their proactive trial with one participant mentioning *"These robots are helping me out this time and I really appreciate that."*. In the post survey, one participant wrote *"There's definitely room for humans and robots to work together to advance human goals."*.

5 CONCLUSION

We developed methods for proactive robot behavior in teaming contexts and integrated them into cognitive architecture DIARC. A human subject evaluation to validate our system showed that in a high cognitive load scenario, human-robot teams where robots exhibit more proactive behaviors tend to perform better in terms of task efficiency and task performance. This is a promising result suggesting that extending the current methods to a broader more general range of proactive behaviors in autonomous robots could significantly improve the performance of mixed-initiative human-robot teams.

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REFERENCES

[1] Jimmy Baraglia, Maya Cakmak, Yukie Nagai, Rajesh Rao, and Minoru Asada. 2016. Initiative in robot assistance during collaborative task execution. In *2016 11th ACM/IEEE International Conference on Human-Robot Interaction (HRI)*. 67–74. https://doi.org/10.1109/HRI.2016.7451735

[2] Jimmy Baraglia, Maya Cakmak, Yukie Nagai, Rajesh PN Rao, and Minoru Asada. 2017. Efficient human-robot collaboration: When should a robot take initiative? *The International Journal of Robotics Research* 36, 5-7 (2017), 563–579. https://doi.org/10.1177/0278364916688253 arXiv:https://doi.org/10.1177/0278364916688253

[3] Jenay M Beer, Arthur D Fisk, and Wendy A Rogers. 2014. Toward a framework for levels of robot autonomy in human-robot interaction. *Journal of human-robot interaction* 3, 2 (2014), 74.

[4] Tapomayukh Bhattacharjee, Ethan K. Gordon, Rosario Scalise, Maria E. Cabrera, Anat Caspi, Maya Cakmak, and Siddhartha S. Srinivasa. 2020. Is More Autonomy Always Better? Exploring Preferences of Users with Mobility Impairments in Robot-Assisted Feeding. In *Proceedings of the 2020 ACM/IEEE International Conference on Human-Robot Interaction* (Cambridge, United Kingdom) *(HRI '20)*. Association for Computing Machinery, New York, NY, USA, 181–190. https://doi.org/10.1145/3319502.3374818

[5] T. Fong, C. Thorpe, and C. Baur. 2003. Multi-robot remote driving with collaborative control. *IEEE Transactions on Industrial Electronics* 50, 4 (2003), 699–704. https://doi.org/10.1109/TIE.2003.814768

[6] Felix Gervits, Dean Thurston, Ravenna Thielstrom, Terry Fong, Quinn Pham, and Matthias Scheutz. 2020. Toward Genuine Robot Teammates: Improving Human-Robot Team Performance Using Robot Shared Mental Models. In *Proceedings of the 19th International Conference on Autonomous Agents and MultiAgent Systems* (Auckland, New Zealand) *(AAMAS '20)*. International Foundation for Autonomous Agents and Multiagent Systems, Richland, SC, 429–437.

[7] Jasmin Grosinger, Federico Pecora, and Alessandro Saffiotti. 2016. Making Robots Proactive through Equilibrium Maintenance.. In *IJCAI*, Vol. 16. 3375–3381.

[8] Matthias Scheutz, Thomas Williams, Evan Krause, Bradley Oosterveld, Vasanth Sarathy, and Tyler Frasca. 2019. An overview of the distributed integrated cognition affect and reflection DIARC architecture. *Cognitive architectures* (2019), 165–193.

[9] Yu Zhang, Vignesh Narayanan, Tathagata Chakraborti, and Subbarao Kambhampati. 2015. A human factors analysis of proactive support in human-robot teaming. In *2015 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS)*. 3586–3593. https://doi.org/10.1109/IROS.2015.7353878