Collaborative Planning and Negotiation in Human-Robot Teams

Christine T. Chang
christine.chang@colorado.edu
University of Colorado Boulder
Boulder, Colorado, USA

Mitchell Hebert
mhebert@draper.com
Charles Stark Draper Laboratory, Inc.
Cambridge, Massachusetts, USA

Bradley Hayes
bradley.hayes@colorado.edu
University of Colorado Boulder
Boulder, Colorado, USA

ABSTRACT

Our work aims to apply iterative communication techniques to improve functionality of human-robot teams working in space and other high-risk environments. Forms of iterative communication include progressive incorporation of human preference and otherwise latent task specifications. Our prior work found that humans would choose not to comply with robot-provided instructions and then proceed to self-justify their choices despite the risks of physical harm and blatant disregard for rules. Results clearly showed that humans working near robots are willing to sacrifice safety for efficiency. Current work aims to improve communication by iteratively incorporating human preference into optimized path planning for human-robot teams operating over large areas. Future work will explore the extent to which negotiation can be used as a mechanism for improving task planning and joint task execution for humans and robots.

CCS CONCEPTS

• **Human-centered computing → Mixed / augmented reality**; • **Computer systems organization → Robotics**.

KEYWORDS

human-robot teaming, augmented reality, airborne robots

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1 INTRODUCTION AND MOTIVATION

As research in autonomy progresses and safety is improved, humans and robots increasingly occupy shared space environments. Augmented reality (AR) holds substantial promise for facilitating safe and efficient collaboration of humans and robots working in close proximity. A significant body of research exists that shows the usefulness of augmented reality for human-robot interaction (HRI), such as in [12, 14, 17, 20, 25, 26] and many others. However, the use of AR does not guarantee safety or human compliance [6]. **Our work is aimed at providing iterative communication modes for human-robot teams with a particular focus on applications to extraterrestrial environments (1) to expose insights about human behavior and (2) to elicit robot behavior incorporating human-provided insights.**

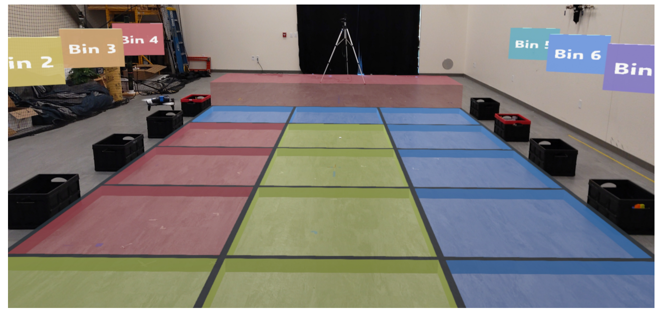

Figure 1: Recent work used augmented reality to facilitate communication between a quadcopter robot and a human participant in a shared workspace. The virtual overlay on the experimental environment is shown here, with the blue squares providing the user a route to Bin 4.

Prior work demonstrates that AR can facilitate human-robot communication in terrestrial environments [13, 15, 20, 25]. Substantial research also shows the utility of robotics for space applications [4, 9, 10]. NASA has also been investigating the implementation of augmented reality into its next generation spacesuits [1, 18, 22]. The Artemis missions returning humans to the lunar surface (and human Mars missions of the future) will include robotic rovers and other autonomous systems; human-robot teams aided by AR in these high-risk space environments will almost certainly have extensive, novel, and far-reaching applications.

As we imagine what kinds of technologies these future use cases might require, it is clear that there are many open questions about the ways in which humans and autonomous systems can communicate using augmented reality. Thus motivates our research question: **How can iterative planning be leveraged to improve human-robot team function in extraterrestrial environments?** When in an environment such as a lunar base or Mars outpost, ahuman-robot team must be agile and functional, able to promote understanding, compliance, and safety for all agents. We hypothesize that iterative planning that leverages collaborative optimization is a foundational component for producing such teams.

2 HUMANS ARE NON-COMPLIANT

At present, even state-of-the-art autonomous systems require physical barriers and additional safeguards like emergency shutdown buttons when humans are working in close proximity. In a recent analysis, quadrotors were found to cause 4,250 injuries between the years 2015-2020 in the United States [11]. Our recent work [6] serves as a step in exploring human-robot communication using augmented reality in a collocated high-risk environment without

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physical barriers. We designed our experimental system and environment to investigate the question, **How do humans violate instructions communicated by a robot in a noisy and dangerous environment? If they decide not to comply, how do they rationalize their decisions?**

The participant's main activity was to follow printed instructions in a strict order to collect blocks from 8 parts bins and to assemble them in sequence at their home base. Meanwhile, a noisy airborne quadcopter robot conducted inventory at various bins. This quadrotor was slightly louder than a vacuum cleaner and has a maximum speed of 37 mph [2]. The participant wore an AR head-mounted display (ARHMD) displaying a virtual 3x5 grid and selectable bin labels (see Fig. 1). The grid contained up to 3 colors: red for robot-owned spaces; blue for human-owned spaces; and yellow for no one's space. Participants were explicitly told multiple times only to walk on the blue grid areas. After bin access was requested via the ARHMD and granted by the robot, blue grid squares appeared to provide a route to the bin (e.g. Bin 4 in Fig. 1).

Partway through the experiment, when the participant was at a remote bin, their blue route back to home disappeared, those grid squares turning red and yellow. At this point, a surprising 25% of participants chose to disregard the explicit instructions they had received as well as the implicit instructions from the robot and instead walked directly through the red and yellow regions to return to Home. Over half of participants deviated from protocol and produced their own process to establish a route back to Home. Seven participants admitted to considering other processes, including going entirely outside the grid and experimental area. Furthermore, **all participants felt safe**, despite being as close as 1.5 meters to the loud and dangerous flying robot.

This work clearly shows that humans working in proximity to robots both overestimate their safety and appear **willing to sacrifice some amount of safety** to increase efficiency. Furthermore, they **establish their own justifications for non-compliance, regardless of whether their choices put them in harm's way**. In post-task interviews, we confirmed that users desire insight into an autonomous system to help them understand its reasoning, decrease frustration, and help them make their own decisions during uncertainty. Results also suggest that increasing a user's perception of the robot's intelligence could subsequently increase their feelings of safety, significantly decreasing cognitive load.

3 HUMANS PREFER PREDICTABILITY

Significant work has investigated robot predictability [5, 7, 8, 19, 24]. Other work has even explored combining optimized path planning with teleoperation using augmented reality [21]. However, our current work includes the ability to iteratively incorporate human preferences in a path planning optimization, particularly for robots operating over large spatial scales, improving communication of plans and desires between agents. In the application area of space exploration, our collaborative autonomous airborne robot can be used to search an area for Mars outpost construction, perform geological exploration, or advance path-planning for rover traversal.

To begin our iterative optimization, we start with a search path composed of a set number of waypoints. Our objective function is first designed such that the we (*a*) minimize the number of waypoints required to accomplish our search path, while (*b*) maintaining

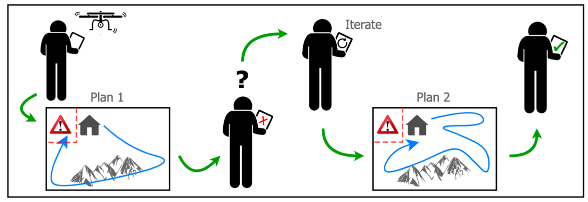

Figure 2: In our current work, we use path planning optimization to maximize an airborne robot's area coverage adhering to preference and predictability. A user first sees the original optimization. If unpredictable, unclear, or undesirable, they can iteratively provide additional inputs to the plan.

a maximum distance between waypoints and (*c*) maximizing *coverage*. In a search area that is divided into a discrete gridspace, we define coverage as the number of unique grid cells that have been visited by the robot, either with a distinct waypoint that lies within the grid cell or by traversing across a cell when traveling between two waypoints. Next, the human may input details about obstacles and no-go zones, with appropriate radii for avoidance, and then iterate on the optimized path. In the third step, the human teammate is given the opportunity to directly augment the optimized path further in support of discovering latent objective criteria known only to the human. In this way, we incorporate human-provided guidance and preferences into an optimization to improve the robot behavior's performance and predictability.

4 HUMAN-ROBOT NEGOTIATION

Our future work will continue to build on the throughlines of safety, compliance, preference, and understanding by allowing humans and robots to directly negotiate during instances of conflict. In a recent survey of human negotiation literature [3], authors noted the dearth of research on how relationships impact the negotiation outcome. This gap is mirrored in the human-robot interaction research, wherein we find a lack of work examining human-robot relationships, particularly for negotiation. Research in human cooperation [16] showed that people playing the Prisoner's Dilemma game [23] are twice as likely to cooperate when the game is called the Community Game as when it is called the Wall Street Game, demonstrating how simple construal manipulation affects outcomes. In our future work, we plan to examine how construal of the human-robot relationship affects the outcomes of the required negotiation.

5 IMPACT AND RELEVANCE

We anticipate that the results of our work will have significant impacts on human-robot communication, particularly collaborative planning and negotiation. High-risk environments are prime for the incorporation of autonomous systems as well as augmented reality. The aim of our work is to ensure that a human-robot team can iteratively collaborate and develop plans, thus resulting in increased efficiency, throughput, safety, and compliance.

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REFERENCES

[1] 2021. *NASA SUITS Microgravity University*. Retrieved 2021-11-02 from https://microgravityuniversity.jsc.nasa.gov/nasasuits.cfm

[2] 2022. Parrot. https://www.parrot.com/assets/s3fs-public/media-public/EN_Pressrelease2015/parrotbebop2theall-in-onedrone.pdf

[3] Erica J. Boothby, Gus Cooney, and Maurice E. Schweitzer. 2023. Embracing Complexity: A Review of Negotiation Research. *Annual Review of Psychology* 74, 1 (2023), null. https://doi.org/10.1146/annurev-psych-033020-014116 _eprint: https://doi.org/10.1146/annurev-psych-033020-014116.

[4] Maria Bualat, Jonathan Barlow, Terrence Fong, Chris Provencher, and Trey Smith. 2015. Astrobee: Developing a Free-flying Robot for the International Space Station. In *AIAA SPACE 2015 Conference and Exposition*. American Institute of Aeronautics and Astronautics. https://doi.org/10.2514/6.2015-4643 _eprint: https://arc.aiaa.org/doi/pdf/10.2514/6.2015-4643.

[5] Tathagata Chakraborti, Anagha Kulkarni, Sarath Sreedharan, David E. Smith, and Subbarao Kambhampati. 2019. Explicability? Legibility? Predictability? Transparency? Privacy? Security? The Emerging Landscape of Interpretable Agent Behavior. *Proceedings of the International Conference on Automated Planning and Scheduling* 29 (2019), 86–96. https://doi.org/10.1609/icaps.v29i1.3463

[6] Christine T. Chang, Matthew B. Luebbers, Mitchell Hebert, and Bradley Hayes. To appear. Human Non-Compliance with Robot Spatial Ownership Communicated via Augmented Reality: Implications for Human-Robot Teaming Safety. In *2023 IEEE International Conference on Robotics and Automation (ICRA)*.

[7] Akansel Cosgun, Emrah Akin Sisbot, and Henrik Iskov Christensen. 2016. Anticipatory robot path planning in human environments. In *2016 25th IEEE International Symposium on Robot and Human Interactive Communication (RO-MAN)*. 562–569. https://doi.org/10.1109/ROMAN.2016.7745174 ISSN: 1944-9437.

[8] Anca D. Dragan, Kenton C.T. Lee, and Siddhartha S. Srinivasa. 2013. Legibility and predictability of robot motion. In *2013 8th ACM/IEEE International Conference on Human-Robot Interaction (HRI)*. 301–308. https://doi.org/10.1109/HRI.2013.6483603 ISSN: 2167-2148.

[9] Terrence Fong and Illah Nourbakhsh. 2005. Interaction Challenges in Human-robot Space Exploration. *Interactions* 12, 2 (March 2005), 42–45. https://doi.org/10.1145/1052438.1052462

[10] Terrence Fong, Jennifer Rochlis Zumbado, Nancy Currie, Andrew Mishkin, and David L. Akin. 2013. Space Telerobotics: Unique Challenges to Human–Robot Collaboration in Space. *Reviews of Human Factors and Ergonomics* 9, 1 (Nov. 2013), 6–56. https://doi.org/10.1177/1557234X13510679 Publisher: SAGE Publications.

[11] Serap Gorucu and Yiannis Ampatzidis. 2021. Drone Injuries and Safety Recommendations. https://edis.ifas.ufl.edu/publication/AE560

[12] Jared Hamilton, Thao Phung, Nhan Tran, and Tom Williams. 2021. What's The Point? Tradeoffs Between Effectiveness and Social Perception When Using Mixed Reality to Enhance Gesturally Limited Robots. In *Proceedings of the 2021 ACM/IEEE International Conference on Human-Robot Interaction (HRI '21)*. Association for Computing Machinery, New York, NY, USA, 177–186. https://doi.org/10.1145/3434073.3444676

[13] Hooman Hedayati, Michael Walker, and Daniel Szafir. 2018. Improving Collocated Robot Teleoperation with Augmented Reality. In *Proceedings of the 2018 ACM/IEEE International Conference on Human-Robot Interaction (HRI '18)*. Association for Computing Machinery, New York, NY, USA, 78–86. https://doi.org/10.1145/3171221.3171251

[14] Bryce Ikeda and Daniel Szafir. 2022. Advancing the Design of Visual Debugging Tools for Roboticists. In *Proceedings of the 2022 ACM/IEEE International Conference on Human-Robot Interaction (HRI '22)*. IEEE Press, Sapporo, Hokkaido, Japan, 195–204.

[15] Linh Kästner and Jens Lambrecht. 2019. Augmented-Reality-Based Visualization of Navigation Data of Mobile Robots on the Microsoft Hololens - Possibilities and Limitations. In *2019 IEEE International Conference on Cybernetics and Intelligent Systems (CIS) and IEEE Conference on Robotics, Automation and Mechatronics (RAM)*. 344–349. https://doi.org/10.1109/CIS-RAM47153.2019.9095836 ISSN: 2326-8239.

[16] Varda Liberman, Steven M. Samuels, and Lee Ross. 2004. The Name of the Game: Predictive Power of Reputations versus Situational Labels in Determining Prisoner's Dilemma Game Moves. *Personality and Social Psychology Bulletin* 30, 9 (Sept. 2004), 1175–1185. https://doi.org/10.1177/0146167204264004 Publisher: SAGE Publications Inc.

[17] Matthew B Luebbers, Christine T Chang, Aaquib Tabrez, Jordan Dixon, and Bradley Hayes. 2021. Emerging Autonomy Solutions for Human and Robotic Deep Space Exploration. In *Proceedings of Workshop on SpaceCHI : Human-Computer Interaction for Space Exploration (SpaceCHI '21)*. ACM, Virtual, 5.

[18] Paromita Mitra. 2018. *Human Systems Integration of an Extravehicular Activity Space Suit Augmented Reality Display System - ProQuest*. Dissertation. Mississippi State University.

[19] Lorenzo Nardi and Cyrill Stachniss. 2016. Experience-based path planning for mobile robots exploiting user preferences. In *2016 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS)*. 1170–1176. https://doi.org/10.1109/IROS.2016.7759197 ISSN: 2153-0866.

[20] M. Ostanin, S. Mikhel, A. Evlampiev, V. Skvortsova, and A. Klimchik. 2020. Human-robot interaction for robotic manipulator programming in Mixed Reality. In *2020 IEEE International Conference on Robotics and Automation (ICRA)*. 2805–2811. https://doi.org/10.1109/ICRA40945.2020.9196965 ISSN: 2577-087X.

[21] Christos Papachristos and Kostas Alexis. 2016. Augmented reality-enhanced structural inspection using aerial robots. In *2016 IEEE International Symposium on Intelligent Control (ISIC)*. 1–6. https://doi.org/10.1109/ISIC.2016.7579983

[22] Carlos Pinedo, Jordan Dixon, Christine Chang, Donna Auguste, Mckenna Brewer, Cassidy Jensen, Chris Hill, Devin Desilva, Amanda Jones, Allison Anderson, and James Voss. 2019. Development of an Augmented Reality System for Human Space Operations. In *Proceedings of International Conference on Environmental Systems 2019*.

[23] Anatol Rapoport. 1960. *Fights, Games, and Debates*. University of Michigan Press.

[24] Christopher Reardon, Kevin Lee, and Jonathan Fink. 2018. Come See This! Augmented Reality to Enable Human-Robot Cooperative Search. In *2018 IEEE International Symposium on Safety, Security, and Rescue Robotics (SSRR)*. 1–7. https://doi.org/10.1109/SSRR.2018.8468622 ISSN: 2475-8426.

[25] Christopher Reardon, Kevin Lee, John G. Rogers, and Jonathan Fink. 2019. Communicating via Augmented Reality for Human-Robot Teaming in Field Environments. In *2019 IEEE International Symposium on Safety, Security, and Rescue Robotics (SSRR)*. 94–101. https://doi.org/10.1109/SSRR.2019.8848971 ISSN: 2475-8426.

[26] Mark Zolotas and Yiannis Demiris. 2019. Towards Explainable Shared Control using Augmented Reality. In *2019 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS)*. 3020–3026. https://doi.org/10.1109/IROS40897.2019.8968117 ISSN: 2153-0866.