An Evaluation Framework of Human-Robot Teaming for Navigation Among Movable Obstacles via Virtual Reality-Based Interactions

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***Abstract*—Robots are essential for tasks that are hazardous or beyond human capabilities. However, the results of the Defense Advanced Research Projects Agency (DARPA) Subterranean (SubT) Challenge revealed that despite various techniques for robot autonomy, human input is still required in some complex situations. Moreover, heterogeneous multirobot teams are often necessary. To manage these teams, effective user interfaces to support humans are required. Accordingly, we present a framework that enables intuitive oversight of a robot team through immersive virtual reality (VR) visualizations. The framework simplifies the management of complex navigation among movable obstacles (NAMO) tasks, such as search-and-rescue tasks. Specifically, the framework integrates a simulation of the environment with robot sensor data in VR to facilitate operator navigation, enhance robot positioning, and greatly improve operator situational awareness. The framework can also boost mission efficiency by seamlessly incorporating autonomous navigation algorithms, including NAMO algorithms, to reduce detours and operator workload. The framework is effective for operating in both simulated and real scenarios and is thus ideal for training or evaluating autonomous navigation algorithms. To validate the framework, we conducted user studies ($N = 53$) on the basis of the DARPA SubT Challenge's search-and-rescue missions.**

***Index Terms*—Human in the loop, telerobotics, virtual reality.**

Manuscript received 14 September 2023; accepted 13 January 2024. Date of publication 5 February 2024; date of current version 28 February 2024. This letter was recommended for publication by Associate Editor F. Finitial and Editor A. Peer upon evaluation of the reviewers' comments. This work was supported in part by Taiwan's National Science and Technology Council under Grant 111-NU-E-A49-001-NU, Grant 112-2221-E-A49-109, and Grant 111R10093Y-2; in part by Qualcomm through the Taiwan University Research Collaboration Project; in part by the Commonwealth Cyber Initiative's Cyber Acceleration Fund 2023; and in part by the National Science Foundation under Grant 1942531. Lap-Fai Yu holds GMU's IDIA P3 Faculty Fellowship. *(Corresponding author: Hsueh-Cheng Wang.)*

This work involved human subjects or animals in its research. Approval of all ethical and experimental procedures and protocols was granted by NYCU Institutional Review Boards under Application No. NYCU-REC-111-048E.

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This letter has supplementary downloadable material available at https://doi.org/10.1109/LRA.2024.3362138, provided by the authors.

Digital Object Identifier 10.1109/LRA.2024.3362138

I. Introduction

ROBOTS have become indispensable tools for performing hazardous or challenging tasks, such as search-and-rescue (SAR) missions. The Defense Advanced Research Projects Agency (DARPA) Subterranean (SubT) Challenge, was established to advance the field of robotics for performing scientific and rescue missions. The competition has attracted researchers and innovators worldwide as participants in both real and simulated contests in which robots search for, detect, and visit the locations of objects of interest with minimal human intervention. The SubT Challenge has resulted in numerous operational insights and revealed not only the effectiveness of heterogeneous robot platforms in terms of both their mobility and functionality but also the integral role of the human supervisors of the deployment teams [1], [2], [3].

Researchers have typically interacted with individual robotic systems through engineering interfaces that often have multiple distinct windows or tabs that present different robot data; examples include applications developed using the RViz or QT frameworks. However, many of these interfaces require time-consuming manual data entry; for example, an user may need to copy and paste reports between windows. An enhanced interface could be developed by leveraging virtual reality (VR) technology, which can deliver immersive user experiences with intuitive controls. The flexibility of VR views could more directly provide users with data on robot actions than could previous systems. With real-time three-dimensional (3D) scene reconstruction and efficient data transmission, VR could greatly improve scene comprehension and visual navigation [4], [5], [6].

Human supervisors are often the critical factor limiting the performance of robots in complex environments [1]. As environmental complexity increases, the number and complexity of the deployed systems must also increase, and detecting multimodal target objects also becomes more difficult [7], [8]. Human supervisors are adaptable and can adjust robot deployment and employment strategies, such as by assigning manual goal points for further exploration or inspection. Correcting erroneous detection of a target object's location or type requires human involvement; high false-positive rates can considerably compromise target identification [8], [9]. The results of the SubT Challenge Final Event revealed that human supervisors, despite being mission enablers, can also be a weak link in human–robot teams. The

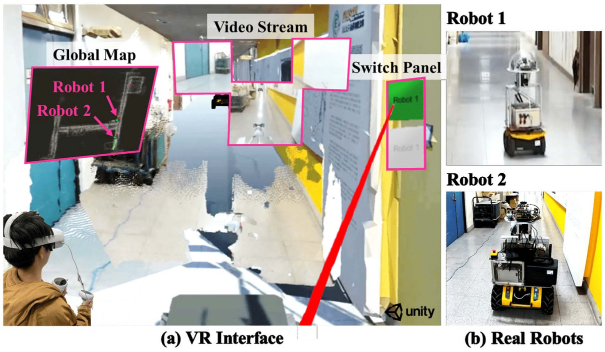

Fig. 1. Real-time immersive VR interface for human–robot teams that enables users to swiftly take control of any robot on the team.

TABLE I
COMPARISONS OF HUMAN-ROBOT TEAMING METHODS

	SubT Teams	Kuo [5]	Stotko [4]	Lungh [6]	Ours
Heterogeneous fleet	✓	✗	✗	✓	✓
Autonomous navigation	✓	✗	✗	✓	✓
VR interface	✗	✓	✓	✓	✓
3D reconstructed environment	✗	✓	✓	✓	✓
Dynamic scenes for NAMO	△	✗	✗	✗	✓
Simulation and physical contexts	✗	✗	✗	✗	✓

✓: *feasibility*, ✗:*inability*, △ :Realized by Image streaming

limiting factors affecting team performance are user interface design and the cognitive load of the human supervisor. In addition, a lack of situational awareness is a key factor contributing to inefficiencies and errors. Studies [10], [11] suggested that closely supervising more than two robots can impair strategic thinking and cause the operator to rely heavily on checklists.

During navigation among movable obstacles (NAMO), jointly controlling a vehicle and manipulator is challenging because of the complex action space. To alleviate the operator workload, advanced autonomous algorithms have been explored. Researchers have investigated the use of subgoals and sample-based motion planning to track the states of target objects [12]. In our previous study [13], we successfully applied curriculum learning to achieve NAMO tasks in which the agent pushes movable obstacles away to reach a goal without explicit tracking. To expand the applicability of this algorithm, the present study presents an adaptable user interface that can accommodate various autonomous navigation algorithms, enabling developers to evaluate their effects on robot team strategies. Our proposed framework is designed for intuitive supervision of a robot team using a VR interface, especially for NAMO tasks in SAR missions.

In this framework, VR technology, specifically a head-mounted display, is selected as the user interface to provide users with complete viewing freedom. Data are integrated into immersive scenes, facilitating the provision of spatial information and enhancing situational awareness. By producing large-scale 3D environment reconstructions, our framework enables seamless navigation in both physical and simulated contexts. The source code and tutorial can be found on our webpage. Our contributions encompass the following:

- **Developing an immersive VR interface usable in both virtual and physical environments for human–robot collaboration.** A VR interface facilitates operations in both virtual and real settings and is suitable for pretest evaluations. The realistic real-time panorama, combined with real sensor data and textured mesh models, provides an intuitive user experience.
- **Facilitating multiuser collaboration with robots to enhance efficiency.** Our framework supports multiuser robot operation and oversight, enabling collaboration between operators. This is essential if a robot can no longer work autonomously or the human supervisor is overwhelmed.
- **Integrating an autonomous NAMO algorithm to reduce user workload.** We conducted evaluation experiments to validate that autonomous algorithms, particularly NAMO algorithms, can reduce cognitive workload for the operator. This decrease in cognitive workload can enhance the overall performance and productivity of the team.

II. RELATED WORK

A. VR Robot Teleoperation and Scene Reconstruction

VR experiences can be enhanced through advanced immersive visualization techniques such as point-cloud rendering for nearby scenes [5], [6], [14]. However, achieving high-quality reconstructions remains a challenge because of sensor noise and temporal inconsistency in the reconstructed data. This limitation confines VR applications to room-scale environments. Although voxel block hashing techniques offer real-time dense volumetric mapping, their high bandwidth requirements (175 Mbps in [15]) constrain scene exploration to a single client. Notable advancements include the use of real-time dense volumetric simultaneous localization and mapping based on voxel block hashing [4], which enables the current 3D model to be handled by a server. The model is streamed to the remote user as a low-bandwidth representation. However, inconsistent scenes caused by dynamic changes, such as movable obstacles, remain a challenge for SLAM-based visualization, often leading to failures. These simulations aid in refining and improving software solutions prior to field testing, facilitating the evaluation and optimization of teams of heterogeneous robots with various levels of autonomy. Accordingly, we propose a robot evaluation framework with a VR interface to facilitate the assessment of robot team performance in both simulated and real-world contexts. Our study is compared to state-of-the-art works, as summarized in Table I.

B. Heterogeneous Robot Team

Real-world operations are complex and require multifaceted solutions that can effectively address all relevant challenges [1], [11]. The majority of SubT teams deployed multiple types of robots. On average, each Systems Competition team deployed 3.4 unique robot types. Heterogeneous robots can each leverage their unique strengths and compensate for others' weaknesses. For example, wheeled robots excel at traversing long distances and overcoming large obstacles but struggle with slopes and steps. Flying robots can navigate any terrain but have a limited flight duration and difficulty navigating narrow spaces. Walking robots struggle on slippery surfaces but are optimal for navigating steps and tight spaces [9]. In addition to mobility considerations, single robots have many resource constraints, including size, weight, power, and other factors. Hence, multirobot solutions are often necessary [11]. In large-scale environments, autonomy is key for enabling the simultaneous deployment of multiple robots with minimal human intervention, which can ensure continuous robot operation, even in areas beyond the range of their communication network. Hence, many teams have attempted SAR missions by employing efficient exploration strategies with heterogeneous robot teams [2], [7], [9], [11].

C. Level of Autonomy

The exploration strategies of SubT teams typically included were based on a bifurcated approach incorporating both local and global planning modes [7], [8], [9], [11]. Local exploration prioritizes admissible, collision-free paths, whereas global planning guides the overarching trajectory. For example, Team MARBLE [8] used frontier-relative goal poses for both air and ground vehicles, Team CERBERUS [9] applied a graph-based exploration path planner (GBPlanner) [16], and Team CoSTAR [7] integrated GBPlanner [16] with a kinodynamic model predictive control planner [17] for local planning and employed a partially observable Markov decision process for global planning in unknown environments. Techniques such as finite state machines, behavior trees, and copilot assistive task scheduling further facilitate mission autonomy.

Teams also struggled in NAMO scenarios, including those involving target objects concealed behind movable obstacles or inside rooms with closed doors, exposing the constraints of prevailing strategies. Conventionally, autonomous navigation strategies have relied on passive obstacle avoidance, but this often yields suboptimal outcomes. Devising an autonomous navigation algorithm that can enable a robot to interact with the environment to enhance its navigational efficiency remains a considerable challenge. Existing algorithms for solving the NAMO problem typically use graph-based path planning or simple open-loop path plans that are generated in standard simulators. However, these algorithms have mostly been validated through simulations [18] or in room-scale testing environments [19]. Our previously proposed Curriculum RL algorithm [13] is an exception; it was tested and confirmed to be effective in both simulations and larger-scale real-world environments. Considering its effectiveness, Curriculum RL could be suitable for enhancing autonomy levels in SAR missions.

III. System Description

Our framework supports multiple heterogeneous robots in both simulated and physical environments. It includes an immersive VR interface for realistic environment reconstruction and the flexible application of autonomous navigation algorithms. The VR interface is based on the Unity platform; moreover, the robot-side software is based on the Robotic Operating System (ROS). To realize bidirectional transmission between the VR interface and robot side, the ROSbridge framework, a JSON application programming interface (API) in the communication layer used in the proposed framework. Notably, the proposed framework was not designed for a specific commercial VR device nor a specific robot type; instead, it was designed to be scaled or adapted to various applications. Unity is a widely used engine that supports numerous VR devices. For testing, we selected the commercially available Oculus Quest2 VR device, which is both cost-effective and popular. ROS was selected because it is the most widely adopted middleware for robotics and has broad compatibility, ensuring support for the majority of robotic systems. Our framework is presented in Fig. 2.

A. VR Interface

1) Pre-Recorded 3D Model Reconstruction: Unity was used for 3D environment reconstruction. Scene data were captured by a Matterport camera and used to reconstruct a building-scale environment with globally consistent depth data, providing 360° color panoramas at each location [20]. The user could act as an agent in the reconstruction and thus freely explore the environment beyond the constraints of the robot's camera field of view. More details regarding the reconstructed environment are provided in the supplementary webpage in Appendix A.

2) Real-Time Scene Capture: The current state of the environment may differ from the recorded state preserved in the reconstruction; hence, the robot sensors were used to capture the scene and send it to the operator through point-cloud streaming (PCS) at 15 fps. By meticulous calibration, PCS covers the corresponding position of the reconstruction, thereby enabling for example, a teleoperator to notice and avoid new debris in a SAR scenario. In addition to the dynamic scene, the interface includes a robot selection panel (switch panel) for team management, a global map, and a pointer for interactions. Operators can use the switch panel to swiftly transition to the first-person view of any robot. The global map not only facilitates navigation but also tracks all team robots and enables operators to easily assign them goal points by simply pointing with a controller. Moreover, the controllers can be used for direct teleoperation of both mobility and manipulation to increase robot efficiency and adaptability in complex scenarios.

B. Robot Side

Simulations were conducted on GAZEBO platform– which can effectively simulate physical parameters such as weight, friction, and collisions–and data from cameras, LiDAR, and other sensors. The virtual environments were imported into GAZEBO, and the simulator was used for expedited trials by increasing robot movement speed. The iterative closest point (ICP) registration algorithm [21] was used for positioning. The algorithm aligns robot LiDAR scans with the mesh reconstructions to accurately position the robot within both the real environment and the 3D reconstruction (and hence the VR interface). This

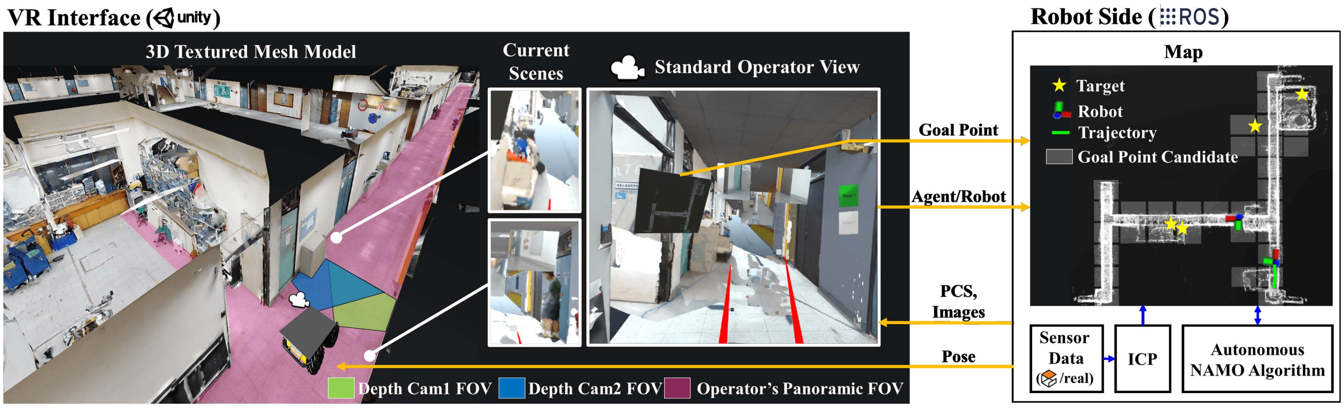

Fig. 2. Our framework supports VR-based human-robot collaboration with an immersive, real-time first-person view to achieve intuitive operation. The panoramic view, combines a 3D mesh with sensor data to display the current scene, including pedestrians and temporary items. It seamlessly integrates simulated and real-world environments by drawing from either sensor data source.

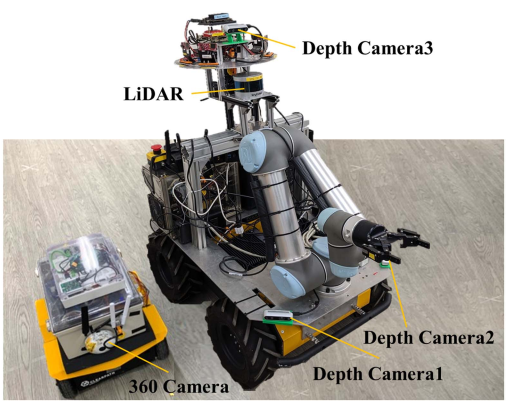

Fig. 3. Two robots were used for testing. Jackal (left) with a 360° camera and Husky (right) with an arm and three depth cameras. Two of these cameras covered a 3 m × 2 m forward area, and the third spanned the arm's full 0.7-m stroke. Husky also had a LiDAR for ICP positioning.

precise method achieves superior positioning to wheel odometry alone.

Standard ROS networking protocols were used to integrate commands from multiple users within a shared local network to facilitate cooperation. Our heterogeneous robot team (Fig. 3) comprised two unmanned ground vehicles: Husky (Clearpath) and Jackal (Clearpath). Husky had a high-payload robot arm (UR5, Universal Robots), and Jackal was approximately 50% times faster than Husky as a scout robot. Husky had three depth cameras to provide colored point-cloud representations of the proximate environment. We conducted a series of user studies to evaluate the effectiveness of the proposed system and each component of the framework.

IV. Experiments and Results

We conducted a three-phase user study to assess whether our framework can overcome the challenges noted after the competition. A total of 53 participants aged 20–35 years were recruited, as detailed in Table II. None of them had prior experience using our platform. The details of T-test are reported in our supplementary webpage.

TABLE II
Participant Count for Each Experiment Phase

Phases	Methods	N
A	Visualization Presentation: MP3D vs. MP3D+PCS, PCS vs. MP3D+PCS	29
B	Multi-Users and Workload: 1P_RC vs. MP_RC	12
C	Autonomous Algorithms: TARE vs. CuRL	12
Sum		53

A. Evaluation in Simulated and Real-World Contexts

We evaluated the system in both simulated and real-world settings, utilizing our campus building as the environment and placing two target objects in rooms at corners and behind doors, respectively.

1) Methods: The Matterport 3D mesh model (hereafter denoted as MP3D) was used in the simulations for visualization representation. Owing to depth information constraints, targets were only revealed if the robot was within a 2-m range. Robot positions were synchronized using a GAZEBO agent that emulated their properties but had a speed 2.5 times that of its real-world counterpart. Moreover, the weight of doors was reduced, and their opening mechanisms were simplified to expedite testing. For the real-world tests, MP3D was integrated with PCS (MP3D+PCS) for positioning by precisely aligning the robot's real-time point clouds with the model. For comparison, we also tested the approach with MP3D or PCS alone; a comparison of the representations is presented in Fig. 4. During the real-world tests, robust network connectivity between the robots and participants was maintained using three strategically placed Wi-Fi 6 access points spanning a 108 m × 20 m zone [purple triangles in Fig. 4(a)]. Within 60 m and in line of sight, the latency was low [average latency: 25.6 ms; standard deviation (SD): 10.7 ms], ensuring near-real-time data transfer. Even in enclosed spaces without a direct line of sight, the latency was less than 405 ms (average: 404.5 ms; SD: 290.7 ms).

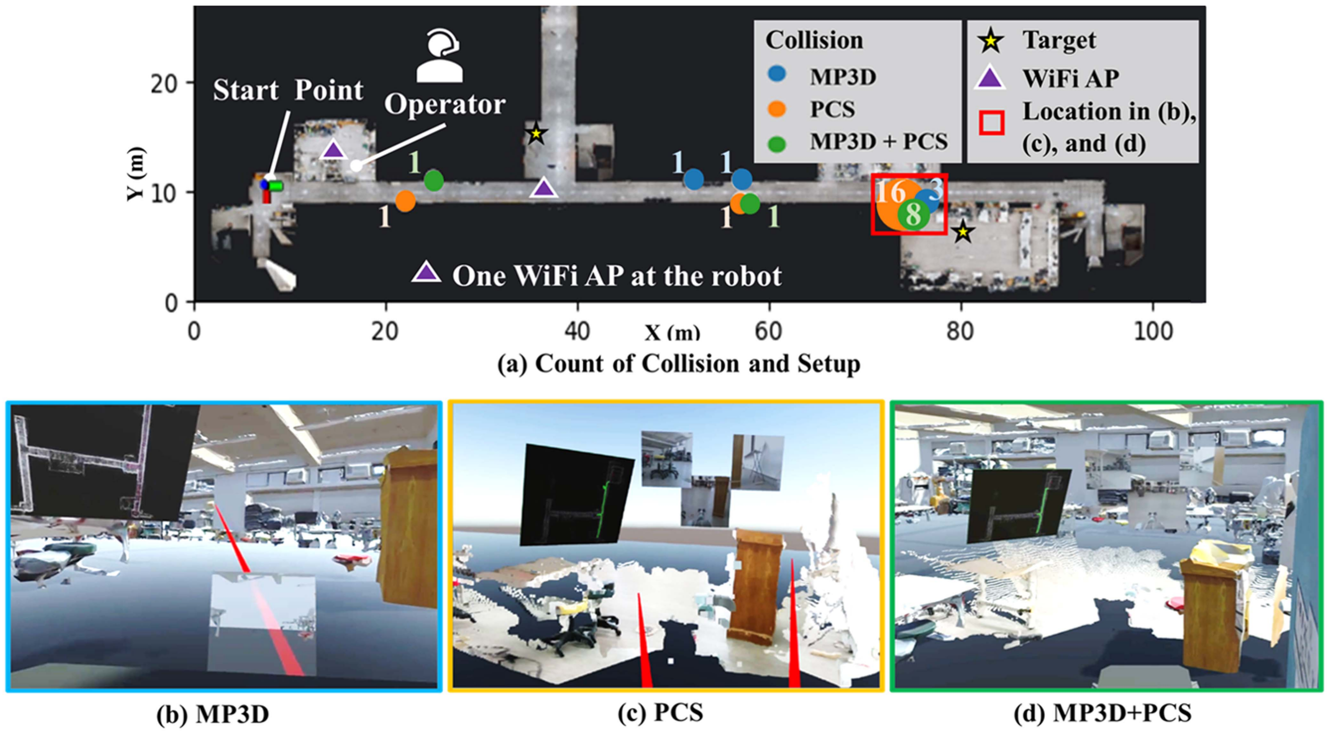

Fig. 4. Configuration of the simulated and physical tests scenarios. (a) Building map including the number of collisions for each test method (b-d) Screenshots of the VR interfaces for the three methods. For clarity, the real-time sensor data are brightened for MP3D+PCS to differentiate them from the environment model; similar sensor data are clearly visible in (c).

TABLE III
EVALUATION RESULTS IN SIMULATED AND REAL-WORLD CONTEXTS

MP3D (Sim)	Average	Standard Deviation
Completion time (s)	103.7	11.3
Pushing time (s)	3.3	2.3
Navigation time (s)	100.4	11.2
Counts of collision	0.3	0.5
PCS (Real)	Average	Standard Deviation
Completion time (s)	287.5	99.6
Pushing time (s)	31.9	34.0
Navigation time (s)	255.6	89.7
Counts of collision	1.3	0.7
MP3D+PCS (Real)	Average	Standard Deviation
Completion time (s)	308.4	91.4
Pushing time (s)	67.2	46.7
Navigation time (s)	241.2	64.8
Counts of collision	0.7	0.8

2) Participants: We recruited 30 participants (1 absence) and randomly assigned them to simulation (N = 15) and physical groups (N = 14). To mitigate bias, participants in the physical group were randomly assigned to first test with either PCS or MP3D+PCS; they subsequently tested the other method.

3) Results and Discussion: As the results shown in Table III, MP3D+PCS users in the physical group and MP3D users in the simulation group exhibited similar operating times. Except for the time spent pushing doors, the average operating time recorded for the MP3D+PCS users (average: 241 s; SD: 65 s) was approximately 2.4 times that recorded for the MP3D users (average: 100 s, SD: 11 s); this finding was noted to be consistent with the speed increase in the simulations. Collisions also occurred in similar locations in the simulation and physical groups, despite the simplifications of the door and robot arm mechanisms in the simulator. These results indicate that simulations are effective strategies for preliminary assessments before actual tests.

The PCS users required 16 s (average: 256 s; SD: 90 s) more to complete the movement task (without door pushing) when compared with the MP3D+PCS users. This was attributed to their uncertainty regarding the environment beyond the point clouds, resulting in greater caution during operation. Moreover, they had far more collisions (1.8 times, total counts: 18), particularly at room entrances with doors (2 times, total counts: 16). This also demonstrates the challenges of the limited field of view. The pushing duration observed for the MP3D+PCS users (average: 67 s; SD: 47 s) was twice that observed for the PCS users (average: 32 s; SD: 34 s). This increase could be attributed to the participants' efforts to avoid collisions; they spent more time verifying before pushing. The participants understandably preferred MP3D+PCS to PCS (10 to 1, with 3 neutrals). These results suggest that MP3D is most effective for unrestricted virtual tours; however, PCS is still effective for first-time site visits before the establishment of a model.

B. Multiuser Collaboration for Workload Reduction

We evaluated the effectiveness of multiuser teams through comparisons with single-user operation for the two robots in simulated context (MP3D).

1) Methods: Single-user remote control (1P_RC) and multiuser remote control (MP_RC) tests were performed. In the

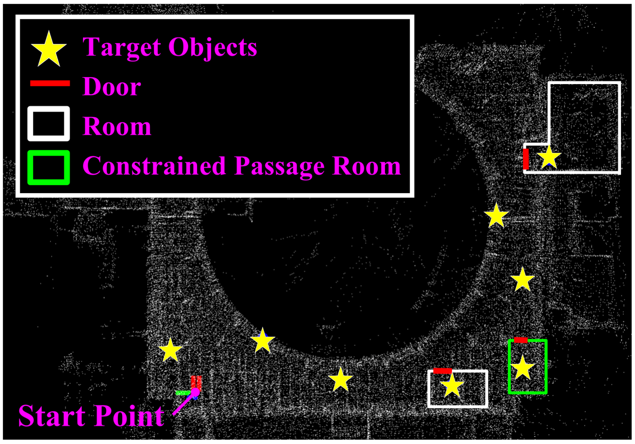

Fig. 5. Trojan Nuclear Power Plant test environment (105 m × 105 m; from DARPA) for the single-user and multiuser human–robot teamwork evaluations.

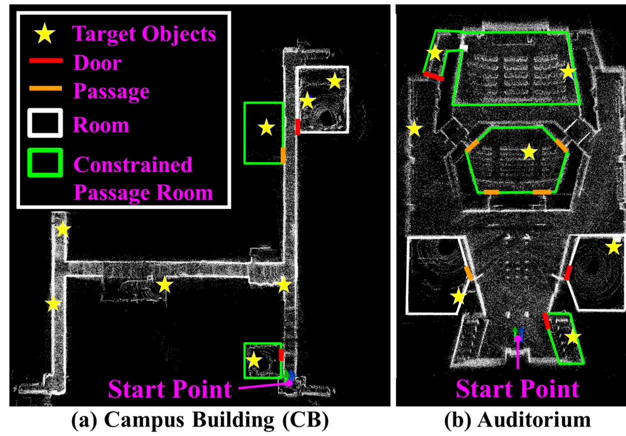

Fig. 7. Maps of the simulated (a) campus building and (b) auditorium environments for the autonomous navigation algorithm testing.

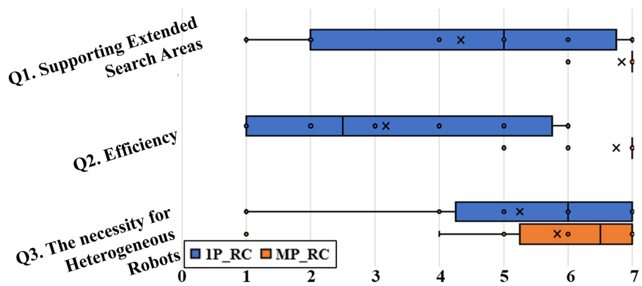

Fig. 6. Participant questionnaire responses by 7-point Likert scale, ranging from 1 (strongly disagree) to 7 (strongly agree).

1P_RC test, one user controlled both robots through the switch panel; in the MP_RC test, two users independently controlled their respective robots. The complex scenario of the Trojan Nuclear Power Plant setting was simulated for the tests by using a mesh model obtained from DARPA after our participation in the 2020 DARPA SubT Challenge. Eight target objects were distributed within the environment (Fig. 5). Three target objects were located behind doors in rooms, and one object was through a narrow passage and could only be accessed by the smaller robot, necessitating collaboration between the robots to locate all objects.

2) Participants: We enrolled 12 participants to evaluate both 1P_RC and MP_RC. In the MP_RC test, the participant operating Husky was the supervisor and directed the Jackal operator. The participation order and robot assignment in MP RC were randomized to avoid bias.

3) Results and Discussion: The mean completion time for the 1P_RC test was 384 s (SD: 64 s), which was significantly longer (1.7 times, $t(11) = 6.99$, $p\_value < 0.01$) than that observed for the MP_RC test (228 s; SD: 38 s). A questionnaire was administered to the participants for further assessment; the questionnaire contained items rated on a 7-point Likert scale ranging from 1 (strongly disagree) to 7 (strongly agree). The assessment results (Fig. 6) indicated that the participants felt that 1P_RC was less efficient ($t(11) = 6.28$, $p\_value < 0.01$) and less effective for broad searching ($t(11) = 3.62$, $p\_value < 0.01$) than MP_RC. They stated that employing heterogeneous robots was critical for both methods, echoing the conclusions made after the DARPA SubT Challenge [1]. Increasing robot autonomy is critical to enhance the performance of heterogeneous robot teams.

C. Efficiency of Autonomous NAMO Algorithms

We investigated the performance and efficiency of autonomous goal-point navigation algorithms with collision avoidance and NAMO functions for the heterogeneous robot team in simulated context (MP3D).

1) Algorithms: Two algorithms were evaluated:

- **TARE [22] (local-path part)**: This algorithm was developed by CMU-OSU team for the DARPA SubT Challenge. The algorithm iteratively selects path nodes from a candidate set and autonomously generates an optimal exploration path by minimizing a cost function.
- **Curriculum RL [13]**: This algorithm is a multistage deep reinforcement learning approach that effectively explores a continuous action space. It can navigate the robot toward a goal and can decide to interact with movable obstacles in a NAMO task.

Both algorithms can navigate around static obstacles, but Curriculum RL enables autonomous NAMO to handle obstacles such as doors with the robot arm. This increased autonomy could enhance efficiency in human–robot collaborative tasks, such as SAR missions. To ensure the generalizability of the results, the algorithms were tested in two simulated environments: a campus building and an auditorium.

Fig. 7 presents maps of the environments; the campus building and auditorium had 7 and 8 target objects, respectively. As in Experiment B, some objects were placed behind doors or in narrow passageways that could only be accessed by the smaller robot. Each participant supervised both robots by assigning them goal points and helping them locate the target objects in the environment.

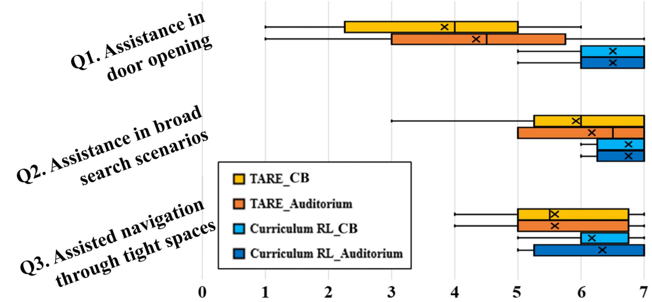

Fig. 8. Participant questionnaire responses by 7-point Likert scale, ranging from 1 (strongly disagree) to 7 (strongly agree).

2) Participants: A total of 12 participants were recruited, and each participant completed four trials, one in each environment and with each of the TARE and Curriculum RL algorithms. The order of the trials was randomized for each participant.

3) Results and Discussion: The average completion time for the TARE algorithm was 417 s (SD: 74 s) for the campus building and 428 s (SD: 51 s) for the auditorium; by contrast, the average completion time for the Curriculum RL algorithm was 311 s (SD: 43 s) for the campus building and 362 s (SD: 26 s) for the auditorium. A T-test revealed that participants who used the TARE algorithm required significantly longer to complete the task in both Campus Building ($t(11) = 7.86$, $p\_value < 0.01$) and Auditorium ($t(11) = 5.13, p\_value < 0.01$), indicating that the Curriculum RL algorithm is more efficient for this task. This could be attributed to its easy operation; doors could be opened by simply assigning a goal point within a room. The aforementioned questionnaire was also administered to the participants for further assessment. In the assessment, the participants reported that Curriculum RL facilitated the opening of doors in both Campus Building ($t(11) = 4.58$, $p\_value < 0.01$) and Auditorium ($t(11) = 3.28$, $p\_value < 0.01$), execution of wide-field searches in Campus Building ($t(11) = 3.08$, $p\_value < 0.05$) and Auditorium ($t(11) = 2.24$, $p\_value < 0.05$) respectively, and also passage through narrow spaces in Campus Building ($t(11) = 2.55, p\_value < 0.05$) and Auditorium ($t(11) = 2.69$, $p\_value < 0.05$). The National Air and Space Administration Task Load Index (NASA-TLX) was used to evaluate the participants' cognitive load. The NASA-TLX indicated that autonomous door opening through the Curriculum RL algorithm significantly reduced temporal demand in both Campus Building ($t(11) = 2.73$, $p\_value < 0.05$) and Auditorium ($t(11) = 2.35$, $p\_value < 0.05$) and effort in both Campus Building ($t(11) = 2.84, p\_value < 0.05$) and Auditorium ($t(11) = 3.25$, $p\_value < 0.05$). These findings collectively demonstrate the effectiveness of the Curriculum RL algorithm and indicate that the proposed system can be successfully used with various algorithms. Accordingly, the proposed system is a robust platform for estimating algorithm performance.

V. Conclusion

Our proposed framework facilitates human–robot collaboration through seamless integrations with both simulated and real-world setups. Simulated and real-world tests for the same location demonstrated that challenges, such as likely collision locations, can be initially assessed in the simulation. Moreover, compared with the conventional PCS-only approach, our immersive MP3D+PCS approach not only reduces operator uncertainty but also considerably increases situational awareness during operation from the robot's perspective. However, either MP3D or PCS alone can be used in the system if necessary for practical applications, such as simulations and unfamiliar environments, respectively. The results reveal that without autonomous navigation, multiuser control increased mission efficiency and was superior to single-user control. Furthermore, the autonomous NAMO algorithm Curriculum RL streamlined robot operations by enabling the participants to easily set goal points without considering movable obstructions (i.e., doors). The participants were satisfied with the ease of exploration when transitioning between robots and reported that Curriculum RL achieved greater efficiency than the obstacle-avoidance algorithm TARE, which required manual door opening. Hence, our VR-based evaluation framework delivers a streamlined experience for human–robot collaboration, even for heterogeneous robot teams during NAMO tasks in SAR missions. Future work may investigate the persistence of pre-recorded items in the reconstruction, even if no longer present, may pose a challenge. In our user study, participants tended to avoid non-existent chairs in the corridor despite understanding their absence through image streaming or observation. While the results indicate minimal impact on performance, we recommend clearing the environment before recordings to minimize additional cognitive load. Further investigation into the confusion caused by non-existent obstacles is warranted.

References

[1] T. H. Chung, V. Orekhov, and A. Maio, "Into the robotic depths: Analysis and insights from the DARPA subterranean challenge," *Annu. Rev. Control Robot., Auton. Syst.*, vol. 6, pp. 477–502, 2022.

[2] N. Hudson et al., "Heterogeneous ground and air platforms, homogeneous sensing: Team CSIRO data61's approach to the DARPA subterranean challenge," *Field Robot.*, vol. 2, pp. 595–636, 2022.

[3] I. D. Miller et al., "Mine tunnel exploration using multiple quadrupedal robots," *IEEE Robot. Automat. Lett.*, vol. 5, no. 2, pp. 2840–2847, Apr. 2020.

[4] P. Stotko et al., "A VR system for immersive teleoperation and live exploration with a mobile robot," in *Proc. IEEE/RSJ Int. Conf. Intell. Robots Syst.*, 2019, pp. 3630–3637.

[5] C.-Y. Kuo, C.-C. Huang, C.-H. Tsai, Y.-S. Shi, and S. Smith, "Development of an immersive SLAM-based VR system for teleoperation of a mobile manipulator in an unknown environment," *Comput. Ind.*, vol. 132, 2021, Art. no. 103502.

[6] G. Lunghi, R. Marin, M. Di Castro, A. Masi, and P. J. Sanz, "Multimodal human-robot interface for accessible remote robotic interventions in hazardous environments," *IEEE Access*, vol. 7, pp. 127290–127319, 2019.

[7] A. Agha et al., "NeBula: TEAM CoSTAR's robotic autonomy solution that won phase II of DARPA subterranean challenge," *Field Robot.*, vol. 2, pp. 1432–1506, 2022.

[8] M. T. Ohradzansky et al., "Multi-agent autonomy: Advancements and challenges in subterranean exploration," *Field Robot.*, vol. 2, pp. 1068–1104, 2022.

[9] M. Tranzatto et al., "CERBERUS: Autonomous legged and aerial robotic exploration in the tunnel and urban circuits of the DARPA subterranean challenge," *Field Robot.*, vol. 2, pp. 274–324, 2022.

[10] J. Delmerico et al., "The current state and future outlook of rescue robotics," *J. Field Robot.*, vol. 36, no. 7, pp. 1171–1191, 2019.

[11] S. Scherer et al., "Resilient and modular subterranean exploration with a team of roving and flying robots," *Field Robot.*, vol. 2, pp. 678–734, 2022.

[12] F. Xia, C. Li, R. Martín-Martín, O. Litany, A. Toshev, and S. Savarese, "ReLMoGen: Integrating motion generation in reinforcement learning for mobile manipulation," in *Proc. IEEE Int. Conf. Robot. Automat.*, 2021, pp. 4583–4590.

[13] H.-C. Wang et al., "Curriculum reinforcement learning from avoiding collisions to navigating among movable obstacles in diverse environments," *IEEE Robot. Automat. Lett.*, vol. 8, no. 5, pp. 2740–2747, May 2023.

[14] G. Bruder, F. Steinicke, and A. Nüchter, "Poster: Immersive point cloud virtual environments," in *Proc. IEEE Symp. 3D User Interfaces*, 2014, pp. 161–162.

[15] O. Kähler, V. A. Prisacariu, C. Y. Ren, X. Sun, P. Torr, and D. Murray, "Very high frame rate volumetric integration of depth images on mobile devices," *IEEE Trans. Visual. Comput. Graph.*, vol. 21, no. 11, pp. 1241–1250, Nov. 2015.

[16] J. G. Mangelson, D. Dominic, R. M. Eustice, and R. Vasudevan, "Pairwise consistent measurement set maximization for robust multi-robot map merging," in *Proc. IEEE Int. Conf. Robot. Automat.*, 2018, pp. 2916–2923.

[17] A. Dixit, D. D. Fan, K. Otsu, S. Dey, A.-A. Agha-Mohammadi, and J. W. Burdick, "STEP: Stochastic traversability evaluation and planning for risk-aware off-road navigation; results from the DARPA subterranean challenge," 2023, *arXiv:2303.01614*.

[18] M. Wang, R. Luo, A. Ö. Önol, and T. Padir, "Affordance-based mobile robot navigation among movable obstacles," in *Proc. IEEE/RSJ Int. Conf. Intell. Robots Syst.*, 2020, pp. 2734–2740.

[19] K. Ellis, H. Zhang, D. Stoyanov, and D. Kanoulas, "Navigation among movable obstacles with object localization using photorealistic simulation," in *Proc. IEEE/RSJ Int. Conf. Intell. Robots Syst.*, 2022, pp. 1711–1716.

[20] A. Chang et al., "Matterport3D: Learning from RGB-D data in indoor environments," 2017, *arXiv:1709.06158*.

[21] A. Segal, D. Haehnel, and S. Thrun, "Generalized-ICP," *Robot.: Sci. Syst.*, vol. 2, no. 4, 2009, Art. no. 435.

[22] C. Cao, H. Zhu, H. Choset, and J. Zhang, "TARE: A hierarchical framework for efficiently exploring complex 3D environments," in *Proc. Robot.: Sci. Syst. Conf.*, 2021.