Comparing VR Exploration Support for Ground-Based Rescue Robots

Julius von Willich
Technical University of Darmstadt
Darmstadt, Germany
willich@tk.tu-darmstadt.de

Andrii Matviienko
Technical University of Darmstadt
Darmstadt, Germany
matviienko@tk.tu-darmstadt.de

Sebastian Günther
Technical University of Darmstadt
Darmstadt, Germany
guenther@tk.tu-darmstadt.de

Max Mühlhäuser
Technical University of Darmstadt
Darmstadt, Germany
max@tk.tu-darmstadt.de

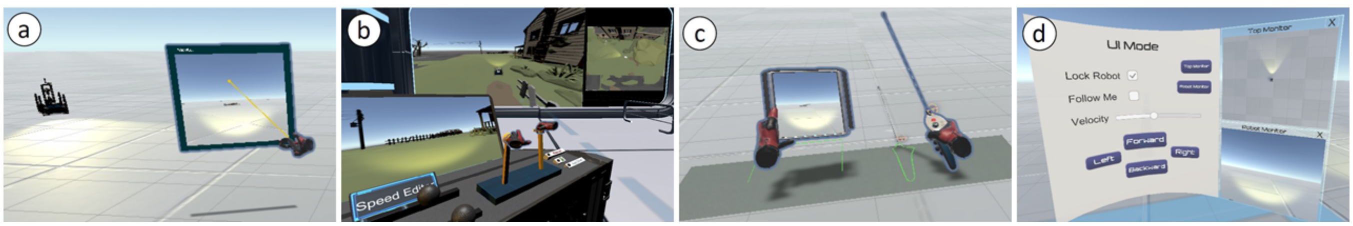

Figure 1: Overview of four operation modes: (a) *Handle Mode* is similar to a traditional remote control, but using touchpad and trigger, (b) *Lab Mode* uses interactive levers and a virtual screen, (c) *Remote Mode* is similar to *Handle Mode* but with added autonomous navigation to a way-point, (d) *UI Mode* a menu with buttons controlling the robot and the an autonomous "follow me" mode

ABSTRACT

Rescue robots have been extensively used in crisis situations for exploring dangerous areas. This exploration is usually facilitated via a remote operation by the rescue team. Although Virtual Reality (VR) was proposed to facilitate remote control due to its high level of immersion and situation awareness, we still lack intuitive and easy-to-use operation modes for search and rescue teams in VR environments. In this work, we propose four operation modes for ground-based rescue robots to utilize an efficient search and rescue: (a) Handle Mode, (b) Lab Mode, (c) Remote Mode, and (d) UI Mode. We evaluated these operation modes in a controlled lab experiment (N = 8) in terms of robot collisions, number of rescued victims, and mental load. Our results indicate that control modes with robot automation (UI and Remote mode) outperform modes with full control given to participants. In particular, we discovered that UI and Remote Mode lead to the lowest number of collisions, driving time, visible victims remaining, rescued victims, and mental load.

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CCS CONCEPTS

• **Human-centered computing** → **Laboratory experiments**; **Virtual reality**; **Empirical studies in interaction design**.

KEYWORDS

rescue robots, virtual reality, operation concepts, interaction techniques

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1 INTRODUCTION

Natural disasters, such as earthquakes or tsunamis, have remain a serious threat to human life and property. Moreover, given the changes caused by global warming, the number of disasters, their severity, and complexity have gradually increased over the last years [3]. Thereby, if such a disaster occurs, the first 51 hours are crucial for rescue teams [1], however, the unstructured environment of disaster sites makes it often difficult to work quickly, efficiently, and – in particular – safely.

To reduce the risks for first-responders, modern rescue teams typically employ rescue robots. Such robots have high mobility, can search continuously for victims or hazards, and map the terrain in the area of their operation using a high number of integrated sensors. While static approaches exist [24] robots offer great versatility, and can even replace human rescuers [15] in order to reduce life risks and injuries caused by secondary collapses or other accidents following the initial disaster. However, this requires the operators to control the robots remotely from a safe distance. Current setups for a remote robot control employ traditional 2D displays, a mouse and a keyboard or joysticks which often leads to mentally demanding switching between the 2D space of the display and the 3D location of the robot [7]. This additional mental load increases the operators' exhaustion, which leads to more errors or shorter operating sessions.

To improve the existing interaction setup for rescue teams previous research has proposed novel solutions, which include mobile devices [6, 33], gesture recognition [8, 27, 36], facial voice recognition [32], adopting eye movements [20], Augmented Reality (AR) [35] and Virtual Reality (VR) [23]. With such approaches, the robots take an assistant role rather than a tool, allowing the operator to act independently. In particular, VR has gained much attention due to its high immersion, which facilitates easy adaptation of established control methods. For example, first steps towards VR in combination with Light Detection and Ranging (LiDaR) have been taken [41], however, there is still a lack of understanding of efficient interaction techniques in VR setups without introducing additional mental load for operators [9].

In this paper, we evaluated four operation modes for ground-based robots in VR environment. These modes include (a) *Handle Mode*, (b) *Lab Mode*, (c) *Remote Mode*, and (d) *UI Mode* (cf. Fig. 1). Hereby, *Lab Mode* is based on existing approaches, using direct control and robot's camera for orientation. The other three modes feature an external view, allowing users to explore the area independently from the robot, thus removing the need to navigate the robot to an interesting area in order to get a better look. Additionally, *Handle Mode*, *Remote Mode* and *UI Mode* increasingly shift the responsibility for navigation towards the robot. With *Handle Mode* still using direct control, *Remote Mode* using way-points and autonomous navigation, and *UI Mode* having the robot automatically follow the user. To investigate the proposed four operation modes, we conducted a user study (N = 8) in a controlled lab setting, simulating a potential disaster environment supported by a rescue robot in VR. As part of our results, we found that modes with robot automation (*UI* and *Remote*) outperformed modes where participants had to take full control of the robot. In particular, we discovered that *UI* and *Remote* modes lead to the lowest number of collisions, time spent driving, visible victims remaining, rescued victims, and the mental load.

2 RELATED WORK

Rescue robots have been widely used in disaster scenarios. Prominent examples include supporting search and rescue during the World Trade Center collapse in 2001 [4] and the disaster at Fukushima Daiichi in 2011 [14], but also generally scouting disaster sites [26] and accessing hazardous environments, such as searching for bodies drowned at sea [12]. However, considering the training time and space constraints for rescuers [25], the efficiency of collaboration [11] and appropriate Human-Robot Interaction (HRI) approaches require further investigation. Although there are approaches to visualize and control the robots utilizing VR [13, 19, 28] and AR [16], there is still a lack of efficient interaction methods for operating rescue robots [2].

Multiple, existing VR systems focus on manipulation tasks once the robot is in place [5, 21, 34, 40]. The system proposed by Ostanin et al. [30] relies on Mixed Reality (MR), enabling the user to plan and execute robot arm trajectories. Another aspect addressed by previous work has focused on VR-based systems to train rescue teams. For example, Elias Matsas et al. [22] provided a VR-based training system for factory workers, and Luis Pérez et al. [31] proposed a framework to train operators in a realistic 3D environment. An advantage of VR environments is the increased situational awareness [39]. This can provide a high level of immersion and situational awareness not possible with video-only systems [37] and increase the user's efficiency and performance, as shown previously [17]. Thus, we employed a VR setup in our experiment, given that there is no significant difference in tasks performance users can achieve in real environments compared to VR, as shown by Villani et. al. [38].

Although previous work explored multiple approaches to control rescue robots remotely and employed VR environments to train operators, we still lack an understanding of interaction concepts [23]. In the following, we present four operation modes, which facilitate the control of ground-based rescue robots using VR, leveraging the intuitive presentation to ease the users' understanding of the environment they explore.

3 OPERATION MODES

We designed and implemented four VR-based operation modes for a ground-based rescue robot that focus on assisting users' in examining dangerous areas. The modes are (a) *Handle Mode*, (b) *Lab Mode*(c) *Remote Mode*, and (d) *UI Mode*. We decided to evaluate all methods in VR to keep evaluation consistent and reduce visual distraction in the real world.

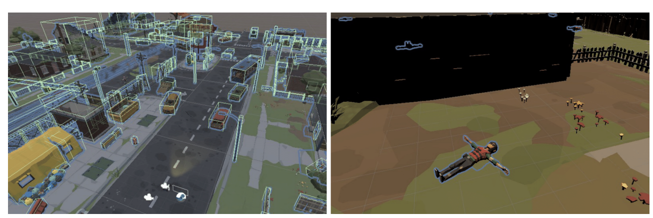

Figure 2: An example of a virtual scene with visible colliders (left) and a depiction of the victims the participants had to find (right).

3.1 *Handle Mode*

In this mode, the user controls the robot's movement directly via buttons on the motion controllers, similar to a real-world remote control and approaches like [29]. The touchpad of the motion controller determines the robot's rotation, and the controller's trigger controls the speed. A handheld monitor window shows camera views installed on the robot, which can be toggled using the menu button and adjusted to a suitable position by grabbing the motion controllers.

	Handle Mode	*Lab Mode*	*Remote Mode*	*UI Mode*
Number of Collisions	21.5, 12.2 $^{**a},^{*c}$	26.8, 19.3 $^{**b},^{*d}$	2.25, 1.91 $^{**a},^{**b}$	3.88, 2.1 $^{*c},^{*d}$
Time Spent Driving (s)	131, 29.1 $^{***a},^{***b}$	243, 25.8 $^{***a},^{***c},^{*e}$	134, 32.7 $^{***c},^{**d}$	192, 37.4 $^{***b},^{**d},^{*e}$
Visible Victims Remaining	2.63, 1.69 ^{*c}	4.5, 0.92 $^{***a},^{***b}$	0.875, 0.835 ^{***a}	0.75, 1.04 $^{***b},^{*c}$
Rescued Victims	6.63, 2.07 ^{*c}	5, 1.07 $^{***a},^{***b}$	8.63, 1.3 ^{***a}	9.13, 1.25 $^{***b},^{*c}$
NASA TLX Score	57.3, 12.0 ^{**c}	61.7, 22.1 $^{***a},^{***b}$	28.9, 13.3 ^{***a}	28.2, 15.4 $^{***b},^{**c}$

Table 1: *** $p < 0.001$, ** $p < 0.01$, * $p < 0.05$, matching letters denote between which IVs. Values are Mean and Standard Deviation.

	Handle Mode	*Lab Mode*	*Remote Mode*	*UI Mode*
I found it easy to move the robot to a desired position.	4, 0.25 $^{***a},^{*d}$	3.25, 2.25 $^{***b},^{**c}$	5, 0 $^{***a},^{***b}$	5, 0.25 $^{**c},^{*d}$
I found it easy to concentrate on controlling the robot.	4, 2.0 $^{**a},^{**b}$	3, 1.5 $^{**c},^{*d}$	5, 0.25 $^{**a},^{**c}$	5, 0.25 $^{**b},^{*d}$
I found it easy to perceive the details of the environment.	4, 1.0 ^{*c}	2, 2.25 $^{***a},^{***b},^{*c}$	5, 1.0 ^{***a}	5, 1.25 ^{***b}

Table 2: *** $p < 0.001$, ** $p < 0.01$, * $p < 0.05$, letters denote between which IV. Values are M, IQR, 1 strongly disagree, 5 strongly agree.

3.2 *Lab Mode*

This mode is designed with reference to the system proposed by Matsas et al. and Pérez et al. [22, 31]. Their frameworks train operators to work with the robot, avoiding risks and saving learning costs. In addition, they also mention that being in a simulated factory or laboratory can improve immersion. Therefore, we constructed a virtual lab environment with a simulated control interface and monitoring equipment. A large display is placed in VR in front of the robot control console, allowing the user to monitor the robot's cameras. In the middle of the console are two operating joysticks that determine the robot's forward motion and rotation, respectively, the speed of which can be adjusted with a slider.

3.3 *Remote Mode*

In this mode, the user can set the driving target point directly, taking advantage of the autonomous navigation capabilities of future, real-world robots. The target point is set using the right motion controller and is represented as a cube in the virtual scene. Alternatively, users can also control the robot by picking up the remote control placed on the toolbar. This toolbar with remote control and a monitoring device can be opened by clicking the menu button.

3.4 *UI Mode*

In this mode, users are given a virtual menu which they can interact with by using the motion controllers as pointing input devices. They can set the robot's speed, toggle a view from the robot's cameras, toggle a "follow me" mode and directly control the robot should the need arise. This lets users focus on observing the depicted VR scene, with additional information on a separate menu. This mode is a simplified version of [18].

4 EVALUATION

To investigate the performance of the purposed operation modes we conducted a controlled lab experiment.

4.1 Participants

We recruited 8 participants (3 female, 5 male), all university students, aged between 22 and 32 years (M = 25.75, SD = 3.37). Four participants had no previous experience with VR, and the other four had only limited experience.

4.2 Study Design and Task

The study was designed to be within-subject with the *operation mode* as independent variable and four levels: (1) *Handle Mode*, (2) *Lab Mode*, (3) *Remote Mode*, and (4) *UI Mode*, described in the previous section. The participants' task was to explore the city using the robot in VR, find ten victims per scene laying on the ground, and touch them to confirm they were found. In total, we designed four different arrangements of a city scene of similar complexity for the study to ensure consistent difficulty and minimized learning effects between the conditions. The order of the operation modes was counterbalanced.

4.3 Apparatus

The experimental setup consisted of a HTC Vive headset with two motion controllers. To simulate the use of rescue robots in disaster scenarios, the test scenes were designed to mimic the post-disaster urban environments [1] (Figure 2) to create less distraction with a unified look and ensure participants' mental well-being. The virtual robot was equipped with a simple, emulated LiDaR, revealing the world in a limited area around it, and with three cameras. One of the cameras is a simulation of a surveillance camera mounted on the robot, which can see all the items in the scene, and other two cameras can only see the area detected by LiDaR, simulating synthesised views. All autonomous driving was controlled by Unity3D's built-in NavMesh, allowing for automatic obstacle avoidance and simulating a near perfect autonomous navigation algorithm.

4.4 Measures

For comparison, we measured the following dependent variables:

- *Robot collisions*: number of robot collisions with an obstacle.
- *Remained Visible Targets*: number of victims revealed by the LiDaR, but not marked by participants.
- *Time spend driving, in s*: time the robot was in motion.
- *Rescued Targets*: number of victims found by participants.

[1] Using the POLYGON Apocalypse assets https://assetstore.unity.com/packages/3d/environments/urban/154193

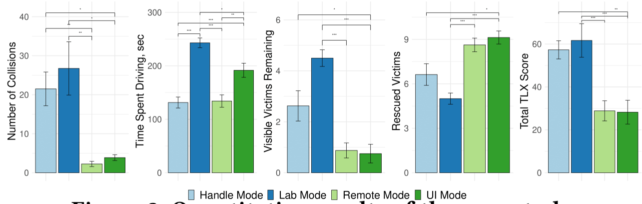

Figure 3: Quantitative results of the user study.

- *Mental load*:per mode, using NASA TLX questionnaire [10].
- *Custom questionnaire*: for each condition, we asked participants to specify how easy it was to control the robot, concentrate on controlling and perceive the environment using a 5-point scale.

4.5 Procedure

Before starting the experiment, we welcomed the participants and gave a brief overview of the work, their task, and the data that would be collected. After obtaining informed consent, we collected participants' demographic data and they could familiarize themselves with each operation mode before each task. Once the participants felt comfortable, we started the experiment. Participants' task was to find and rescue all ten victims in the simulated post-disaster city within 5 minutes. The test would automatically end when time ran out or when all the victims on the scene were rescued. After every condition, we presented the participants with our custom questionnaire and NASA TLX questionnaire. At the end of the study, we asked the participants about their preferences for the operation modes. The entire study lasted approximately 45 minutes per participant. Further, we adhered to our universities health department's guidelines for user studies during the COVID-19 pandemic, and all testing equipment was disinfected for each participant.

5 RESULTS

Overall, we found that control modes with robot automation outperform modes where participants had to take full control of the robot. In particular, we discovered that *UI Mode* and *Remote Mode* lead to the lowest number of collisions, time spent driving, visible victims remaining, rescued victims, and the mental load. Additionally, we observed participants getting lost and repeatedly passing by previously visited areas in all modes. For the assumption of normality, we used Shapiro-Wilk's test and for the homogeneity of variances, we used Levene test. If the assumption of normality was violated, we used Friedman's test, otherwise, we used Fisher's test if the homogeneity of variances was not given, and Welch's test otherwise. The results are shown below in Table 1 and Table 2

6 DISCUSSION AND CONCLUSION

Our results could show significant insights into different visualization and remote control modes for rescue robots. In the following, we conclude by discussing the advantages and disadvantages revealed by our studies.

6.1 Searching

Using *Remote Mode* and *UI Mode*, participants managed to find more and overlook fewer victims compared to *Lab Mode* and lower TLX scores. The same is also found comparing *Handle Mode* to *UI Mode*. From this, we can draw two conclusions: First, navigating the world independently from the robot while not directly controlling it allows users to search the area it explored more efficiently. Furthermore, since these modes are less mentally demanding, they would also allow for longer exploration sessions than a viewpoint anchored to the robot. Secondly, shifting only the task of path-finding away from the user is not sufficient to significantly improve performance. However, this can be achieved by the robot simply following the user, so they do not need to occupy themselves with sending the robot to where it is needed. Overall we found less mental resources spent on controlling the robot meant increased search performance.

6.2 Resource management

Mental capacity is not the only resource influenced by the methods used to control the robot, but battery charge, damage, and time are also important factors in operating (rescue) robots.

6.2.1 Potential Damage. Considering damage, we found both automated control modes reduced the number of collisions compared to manual control. This effect is less pronounced for *UI Mode*, which can be attributed to participants not considering the robot when moving around, thus forcing it to follow them into rugged terrain.

6.2.2 Time spent for robot control. We observed a similar effect on time spent driving, relatable to battery usage. All modes were outperforming *Lab Mode* as this mode required participants to move the robot around to take closer looks at their surroundings. We also found that, given the ability to navigate the environment independently, explicit control (*Handle* and *Remote Mode*) outperformed implicit control (*UI Mode*). This can be attributed to the participants leaving the robot in place while searching the discovered area. Additionally, once participants started backtracking, in *UI Mode* they forgot about the robot, having it follow them needlessly through previously discovered areas. This could mean an additional, undesired drain on the robot's battery. However, this would have the positive side-effect of a real-time update of the world map.

6.2.3 Time spent for search tasks. For search time, we found *Handle Mode* and *Remote Mode* significantly differing concerning search success but not for time spent driving. This can be attributed to the direct control method of *Handle Mode* requiring the participants to concentrate on moving the robot. Thus not searching the environment while driving, resulting in lower efficiency. Using *UI Mode*, participants often had to wait for the robot to catch up to them since they could not send it ahead while inspecting their environment.

6.2.4 Ease of use. Finally, participants found it significantly more difficult to control the robot directly (*Handle Mode*, *Lab Mode*), compared to both automated modes (*Remote Mode* and *UI Mode*), as indicated by their scores for "I found it easy to move the robot to the desired position.". This is supported further by the fact that participants did not fall back to direct control when the robot was stuck in *Remote Mode*, but instead changed the way-point to get the robot out of tight spots. This indicates that direct control is undesirable compared to automated navigation.

REFERENCES

[1] Annette L Adams, Terri A Schmidt, Craig D Newgard, Carol S Federiuk, Michael Christie, Sean Scorvo, and Melissa DeFreest. 2007. Search is a time-critical event: when search and rescue missions may become futile. *Wilderness & Environmental Medicine* 18, 2 (2007), 95–101. https://doi.org/10.1580/06-weme-or-035r1.1

[2] Greg Baker, Tom Bridgwater, Paul Bremner, and Manuel Giuliani. 2020. Towards an immersive user interface for waypoint navigation of a mobile robot. (mar 2020). arXiv:2003.12772v1

[3] Michael Berlemann and Max Friedrich Steinhardt. 2017. Climate change, natural disasters, and migration—a survey of the empirical evidence. *CESifo Economic Studies* 63, 4 (2017), 353–385. https://doi.org/10.1093/cesifo/ifx019

[4] J. Casper and R. R. Murphy. 2003. Human-robot interactions during the robot-assisted urban search and rescue response at the World Trade Center. *IEEE Transactions on Systems, Man, and Cybernetics, Part B (Cybernetics)* 33, 3 (2003), 367–385. https://doi.org/10.1109/TSMCB.2003.811794

[5] Francesco de Pace, Gal Gorjup, Huidong Bai, Andrea Sanna, Minas Liarokapis, and Mark Billinghurst. 2021. Leveraging Enhanced Virtual Reality Methods and Environments for Efficient, Intuitive, and Immersive Teleoperation of Robots. *Proceedings - IEEE International Conference on Robotics and Automation* 2021-May (2021), 12967–12973. https://doi.org/10.1109/ICRA48506.2021.9560757

[6] F. Faisal and S. A. Hossain. 2019. DOORMOR: A Functional Prototype of a Manual Search and Rescue Robot, In 2019 1st International Conference on Advances in Science, Engineering and Robotics Technology (ICASERT). *2019 1st International Conference on Advances in Science, Engineering and Robotics Technology (ICASERT)*, 1–6. https://doi.org/10.1109/ICASERT.2019.8934515

[7] Jung-Leng Foo, Marisol Martinez-Escobar, Bethany Juhnke, Keely Cassidy, Kenneth Hisley, Thom Lobe, and Eliot Winer. 2013. Evaluating mental workload of two-dimensional and three-dimensional visualization for anatomical structure localization. *Journal of Laparoendoscopic & Advanced Surgical Techniques* 23, 1 (2013), 65–70. https://doi.org/10.1089/lap.2012.0150

[8] Alessandro Giusti, Jawad Nagi, Luca M. Gambardella, Stéphane Bonardi, and Gianni A. Di Caro. 2012. Human-Swarm Interaction through Distributed Cooperative Gesture Recognition. In *Proceedings of the Seventh Annual ACM/IEEE International Conference on Human-Robot Interaction* (Boston, Massachusetts, USA) *(HRI '12)*. Association for Computing Machinery, New York, NY, USA, 401–402. https://doi.org/10.1145/2157689.2157818

[9] Michael A Goodrich and Alan C Schultz. 2008. *Human-robot interaction: a survey.* Now Publishers Inc.

[10] Sandra G Hart. 2006. NASA-task load index (NASA-TLX); 20 years later. In *Proceedings of the human factors and ergonomics society annual meeting*, Vol. 50. Sage publications Sage CA: Los Angeles, CA, 904–908. https://doi.org/10.1037/e577632012-009

[11] Guy Hoffman and Cynthia Breazeal. 2007. Effects of Anticipatory Action on Human-Robot Teamwork Efficiency, Fluency, and Perception of Team. In *Proceedings of the ACM/IEEE International Conference on Human-Robot Interaction* (Arlington, Virginia, USA) *(HRI '07)*. Association for Computing Machinery, New York, NY, USA, 1–8. https://doi.org/10.1145/1228716.1228718

[12] Ya-Wen Huang, Y. Sasaki, Y. Harakawa, E. F. Fukushima, and S. Hirose. 2011. Operation of underwater rescue robot anchor diver III during the 2011 Tohoku Earthquake and Tsunami. *OCEANS'11 MTS/IEEE KONA*, 1–6. https://doi.org/10.23919/OCEANS.2011.6107198

[13] Boris Illing, Bastian Gaspers, and Dirk Schulz. 2021. Combining Virtual Reality with Camera Data and a Wearable Sensor Jacket to Facilitate Robot Teleoperation. In *2021 IEEE Conference on Virtual Reality and 3D User Interfaces Abstracts and Workshops (VRW)*. IEEE, 649–650. https://doi.org/10.1109/vrw52623.2021.00207

[14] Shinji Kawatsuma, Kuniaki Kawabata, Yoshihiro Tsuchida, and Yuta Tanifuji. 2021. Analysis of emergency response robots deployed for Fukushima Daiichi Nuclear Power Plants' accidents. *Nuclear Science and Engineering* (2021).

[15] Stefan Kohlbrecher, Johannes Meyer, Thorsten Graber, Karen Petersen, Uwe Klingauf, and Oskar von Stryk. 2013. Hector open source modules for autonomous mapping and navigation with rescue robots. In *Robot Soccer World Cup*. Springer, 624–631. https://doi.org/10.1007/978-3-662-44468-9_58

[16] Chuhao Liu and Shaojie Shen. 2020. An Augmented Reality Interaction Interface for Autonomous Drone. In *2020 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS)*. IEEE, 11419–11424. https://doi.org/10.1109/iros45743.2020.9341037

[17] O. Liu, D. Rakita, B. Mutlu, and M. Gleicher. 2017. Understanding human-robot interaction in virtual reality, In 2017 26th IEEE International Symposium on Robot and Human Interactive Communication (RO-MAN). *2017 26th IEEE International Symposium on Robot and Human Interactive Communication (RO-MAN)*, 751–757. https://doi.org/10.1109/ROMAN.2017.8172387

[18] S ; Livatino, D C Guastella, G ; Muscato, V ; Rinaldi, L ; Cantelli, C D Melita, A Caniglia, R Mazza, and G Padula. 2021. Intuitive Robot Teleoperation through Multi-Sensor Informed Mixed Reality Visual Aids. *IEEE Access* 9 (2021), 25795. https://doi.org/10.1109/ACCESS.2021.3057808

[19] Salvatore Livatino, Dario C Guastella, Giovanni Muscato, Vincenzo Rinaldi, Luciano Cantelli, Carmelo D Melita, Alessandro Caniglia, Riccardo Mazza, and Gianluca Padula. 2021. Intuitive robot teleoperation through multi-sensor informed mixed reality visual aids. *IEEE Access* 9 (2021). https://doi.org/10.1109/access.2021.3057808

[20] J. Ma, Y. Zhang, A. Cichocki, and F. Matsuno. 2015. A Novel EOG/EEG Hybrid Human–Machine Interface Adopting Eye Movements and ERPs: Application to Robot Control. *IEEE Transactions on Biomedical Engineering* 62, 3 (2015), 876–889. https://doi.org/10.1109/TBME.2014.2369483

[21] Andrés Martín-Barrio, Juan Jesús Roldán-Gómez, Iván Rodríguez, Jaime del Cerro, and Antonio Barrientos. 2020. Design of a Hyper-Redundant Robot and Teleoperation Using Mixed Reality for Inspection Tasks. *Sensors 2020, Vol. 20, Page 2181* 20, 8 (apr 2020). https://doi.org/10.3390/S20082181

[22] Elias Matsas and George-Christopher Vosniakos. 2017. Design of a virtual reality training system for human–robot collaboration in manufacturing tasks. *International Journal on Interactive Design and Manufacturing (IJIDeM)* 11, 2 (2017), 139–153. https://doi.org/10.1007/s12008-015-0259-2

[23] Annette Mossel and Christian Koessler. 2016. Large scale cut plane: An occlusion management technique for immersive dense 3D reconstructions. In *Proceedings of the ACM Symposium on Virtual Reality Software and Technology, VRST*, Vol. 02-04-Nove. Association for Computing Machinery, 201–210. https://doi.org/10.1145/2993369.2993384

[24] Max Mühlhäuser, Christian Meurisch, Michael Stein, Jörg Daubert, Julius Von Willich, Jan Riemann, and Lin Wang. 2020. Street lamps as a platform. *Commun. ACM* 63, 6 (2020), 75–83.

[25] R. R. Murphy. 2004. Human-robot interaction in rescue robotics. *IEEE Transactions on Systems, Man, and Cybernetics, Part C (Applications and Reviews)* 34, 2 (2004), 138–153. https://doi.org/10.1109/TSMCC.2004.826267

[26] R. R. Murphy. 2012. A decade of rescue robots, In 2012 IEEE/RSJ International Conference on Intelligent Robots and Systems. *2012 IEEE/RSJ International Conference on Intelligent Robots and Systems*, 5448–5449. https://doi.org/10.1109/IROS.2012.6386301

[27] J. Nagi, A. Giusti, L. M. Gambardella, and G. A. Di Caro. 2014. Human-swarm interaction using spatial gestures, In 2014 IEEE/RSJ International Conference on Intelligent Robots and Systems. *2014 IEEE/RSJ International Conference on Intelligent Robots and Systems*, 3834–3841. https://doi.org/10.1109/IROS.2014.6943101

[28] Valentina Nejkovic, Nenad Petrovic, Milorad Tosic, and Nenad Milosevic. 2020. Semantic approach to RIoT autonomous robots mission coordination. *Robotics and Autonomous Systems* 126 (apr 2020), 103438. https://doi.org/10.1016/j.robot.2020.103438

[29] Fumio Okura, Yuko Ueda, Tomokazu Sato, and Naokazu Yokoya. 2013. Teleoperation of mobile robots by generating augmented free-viewpoint images. *IEEE International Conference on Intelligent Robots and Systems* (2013), 665–671. https://doi.org/10.1109/IROS.2013.6696422

[30] 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). *2020 IEEE International Conference on Robotics and Automation (ICRA)*, 2805–2811. https://doi.org/10.1109/ICRA40945.2020.9196965

[31] Luis Pérez, Eduardo Diez, Rubén Usamentiaga, and Daniel F. García. 2019. Industrial robot control and operator training using virtual reality interfaces. *Computers in Industry* 109 (2019), 114–120. https://doi.org/10.1016/j.compind.2019.05.001

[32] S. Pourmehr, V. M. Monajjemi, R. Vaughan, and G. Mori. 2013. "You two! Take off!": Creating, modifying and commanding groups of robots using face engagement and indirect speech in voice commands, In 2013 IEEE/RSJ International Conference on Intelligent Robots and Systems. *2013 IEEE/RSJ International Conference on Intelligent Robots and Systems*, 137–142. https://doi.org/10.1109/IROS.2013.6696344

[33] S. Sarkar, A. Patil, A. Hartalkar, and A. Wasekar. 2017. Earthquake rescue robot: A purview to life, In 2017 Second International Conference on Electrical, Computer and Communication Technologies (ICECCT). *2017 Second International Conference on Electrical, Computer and Communication Technologies (ICECCT)*, 1–7. https://doi.org/10.1109/ICECCT.2017.8118044

[34] Max Schwarz, Christian Lenz, Andre Rochow, Michael Schreiber, and Sven Behnke. 2021. NimbRo Avatar: Interactive Immersive Telepresence with Force-Feedback Telemanipulation. https://doi.org/10.1109/iros51168.2021.9636191 arXiv:2109.13772 [cs.RO]

[35] João Soares, Alberto Vale, and Rodrigo Ventura. 2015. A Multi-purpose Rescue Vehicle and a human–robot interface architecture for remote assistance in ITER. *Fusion Engineering and Design* 98-99 (2015), 1656–1659. https://doi.org/10.1016/j.fusengdes.2015.06.148 Proceedings of the 28th Symposium On Fusion Technology (SOFT-28).

[36] Patrick Sousa, Tiago Esteves, Daniel Campos, Fábio Duarte, Joana Santos, Joao Leao, José Xavier, Luís Matos, Manuel Camarneiro, Marcelo Penas, Maria Miranda, Ricardo Silva, António Neves, and Teixeira Luís. 2017. *Human-Robot Interaction Based on Gestures for Service Robots*. Vol. 27. 700–709 pages. https://doi.org/10.1007/978-3-319-68195-5{_}76

[37] Patrick Stotko, Stefan Krumpen, Max Schwarz, Christian Lenz, Sven Behnke, Reinhard Klein, and Michael Weinmann. 2019. *A VR System for Immersive Teleoperation and Live Exploration with a Mobile Robot.* https://doi.org/10.1109/IROS40897.2019.8968598 arXiv:1908.02949

[38] V. Villani, B. Capelli, and L. Sabattini. 2018. Use of Virtual Reality for the Evaluation of Human-Robot Interaction Systems in Complex Scenarios, In 2018 27th IEEE International Symposium on Robot and Human Interactive Communication (RO-MAN). *2018 27th IEEE International Symposium on Robot and Human Interactive Communication (RO-MAN)*, 422–427. https://doi.org/10.1109/ROMAN.2018.8525738

[39] Veiko Vunder, Robert Valuer, Conor McMahon, Karl Kruusamae, and Mitch Pryor. 2018. Improved situational awareness in ROS using panospheric vision and virtual reality. *Proceedings - 2018 11th International Conference on Human System Interaction, HSI 2018* (aug 2018), 471–477. https://doi.org/10.1109/HSI.2018.8431062

[40] Peng Wang, Xiaoliang Bai, Mark Billinghurst, Shusheng Zhang, Xiangyu Zhang, Shuxia Wang, Weiping He, Yuxiang Yan, and Hongyu Ji. 2021. AR/MR Remote Collaboration on Physical Tasks: A Review. *Robotics and Computer-Integrated Manufacturing* 72 (dec 2021), 102071. https://doi.org/10.1016/J.RCIM.2020.102071

[41] P. Wang, J. Xiao, H. Lu, H. Zhang, R. Yan, and S. Hong. 2017. A novel human-robot interaction system based on 3D mapping and virtual reality, In 2017 Chinese Automation Congress (CAC). *2017 Chinese Automation Congress (CAC)*, 5888–5894. https://doi.org/10.1109/CAC.2017.8243836