A Collaborative Building Task in VR vs. Reality

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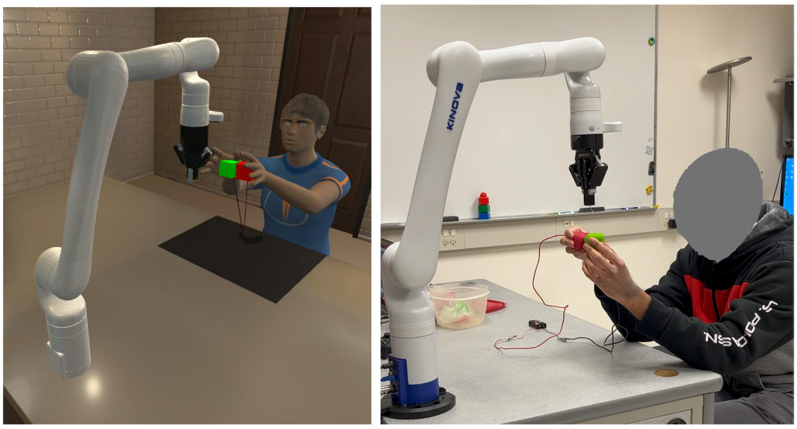
1 Introduction



(a) VR (b) Physical

Fig. 1: Participants interacting with the physical and virtual robot to build a simple electric circuit.

Human-robot interaction is a critical area of research, providing support for collaborative tasks where a human instructs a robot to interact with and manipulate objects in an environment. However, an under-explored element of these collaborative manipulation tasks are small-scale building exercises, in which the human and robot are working together in close proximity with the same set of objects. Under these conditions, it is essential to ensure the human's safety and mitigate comfort risks during the interaction. As there is danger in exposing humans to untested robots, a safe and controlled environment is required. Simulation and virtual reality (VR) for HRI have shown themselves to be suitable tools for creating space for human-robot experimentation that can be beneficial in these scenarios [11, 35].

However, the use of simulation and VR comes with the possibility of failures resulting from the sim-to-real gap, where the behavior of the simulated robot may not accurately reflect the experience of a human collaborator in a real-world setting. This gap can limit the generalizability of research findings and raise questions about the validity of using simulation and VR for HRI research. Our goal in this work is to demonstrate the effectiveness of sim-to-real approaches for contact-based human-robot interaction. To this end, we designed a collaborative joining task of building a simple electric circuit, which can be completed both in the real world and in simulation (Figure 1). By comparing task performance and participant perception in both settings, we gain insight into the potential of VR-based human-robot interaction simulation in HRI research.

The primary contributions of this work are as follows. First, we demonstrate a successful small-scale HRI co-manipulation task in the form of allowing a robot and person to jointly build a simple circuit in both simulation and on a physical robot, and examine the success and failure modes of the task in both settings. Second, we compare the user experience and results of task performance in both reality and VR in order to understand how simulated environments can be used for HRI studies of this sort. We conclude that sim-to-real studies that incorporate virtual reality are a feasible mechanism for studying human-robot interactions.

2 Related Work

Collaborative assembly. There has been significant work done on collaborative assembly in industrial settings, with an emphasis on safety and optimizing workflows. Previous work [22] developed a full body model of a human to optimize for the position of the co-manipulation task in the workspace, and was validated with two co-manipulation tasks: a human using a power tool to polish an object that is held by the robot, and a human-robot object handover. This approach was shown to improve task performance. Other work [8] proposed a method to handle vibrations while working with a human in a shared welding task, which improved the ability of the human to weld successfully.

For large-scale assembly, Tsarouchi et al. [29] studied humans and robots that share an assembly space for sequential assembly of a hydraulic pump, where the humans use gestures to communicate commands for the robot to alter their execution of the sequential assembly task. Timmermann et al. [28] explored smaller-scale joining tasks but focused on the overall workflow rather than the joining itself. Michalos et al. [20] explored a wide range of scenarios in automotive human-robot collaborative assembly, including the use of many technologies such as AR and wearables, while maintaining proper safety practices.

In addition to sequential assembly, some previous works focus on the learning methods and techniques of the robot. Zhang et al. [36] used reinforcement learning to determine how to order and allocate tasks in a human-robot assembly of an alternator. Of eighteen sub-tasks, seven had to be done by a human, seven by either robot or human, and the remaining four sub-tasks required the robot and human to work jointly. Lv et al. [17] explored transfer learning for human-robot collaborative assembly of vehicle power sources (lithium batteries) and examined the efficiencies achieved by learning as compared to pre-programmed assembly. Bilberg and Malik used digital twins [4] for training an assembly task, which were simulations of human-robot collaboration tasks.

Other studies have been directed towards improved robot manipulation, most especially in gripping objects. Raessa et al. [25] explored using human-robot teamwork in a task where the robot retrieved pieces of shelf units to hand to a person for assembly. This work focused on grasping and avoiding slip while minimizing human effort. Realyvásquez-Vargas et al. [26] improved the safety of an assembly line through a two-finger gripper collaborative robot that improved the overall production. Our work differs from these in that, first, we examine a smaller-scale collaboration where the human and robot are in closer proximity; and second, we use sim-to-real approaches to prototype the human-robot interaction in a safe, replicable scenario.

Human-Robot Interaction in Virtual Reality. Simulation has been a useful tool in conducting work in robotics research, reducing the time and expense of acquiring, maintaining, and conducting studies using physical robots. While many of the existing simulation tools utilize 2D displays [6, 7, 15], the increasing capabilities of commodity virtual reality platforms makes VR an attractive alternative. It can provide greater immersion to users while capturing more aspects of human interaction than a controller, mouse, or keyboard. The use of 3D tracked hand controllers allows for users to perform manipulation tasks more intuitively compared to traditional controllers [14]. This makes virtual reality a better tool to gather demonstrations for learning grasping polices [27, 33], as well as gathering the training data to learn to perform a sequence of actions [32]. Following prior authors [2, 18, 13, 23], we leverage the Unity game engine's powerful animation and interaction tools to facilitate the development of HRI studies, using the RIVR interaction platform developed specifically for HRI in VR studies [21].

There has been significant work investigating the differences in how humans behave in real world environments and simulated environments using virtual reality. These have primarily focused on the differences in how humans move about the virtual and real environments [1, 5] or differences in personal space [9]. Previous work comparing human-robot interaction in the real world to virtual reality have investigated the social perception of the real robot versus a virtual one [34]; the differences in proxemics between the real and virtual robot [16]; and the differences in movement as a robot and human follow each other [10]. In this work, we seek to investigate the differences between a collaborative interaction in virtual reality vs. the real world.

Sim-to-real. There also exist differences between simulation and the real world, the so-called "sim-to-real gap." While training in simulated environments simplifies and speeds up the process of gathering data, such environments are not able to fully replicate the nearly infinite variability of the real world. Much of the sim-to-real work in human-robot interaction has focused on training people to use robot systems [19, 24] or studying how humans react to robots in different scenarios [18, 31]. In these cases, the sim-to-real gap is minimized because humans can conceptualize and generalize from the specific cases present in simulation.

3 Technical Approach

We situate our study in a task where a human and a robot work together to build a small-scale circuit. The person attaches power to a circuit and then holds blocks of conductive putty while the robot inserts an LED. Existing work on shared manipulation tends to focus on the handoff of tasks between agents, rather than shared tasks in which the robot is working in the same workspace and serving as a “third hand” for complicated manipulations. The human-robot team performs the circuit-completion operation both in simulation (using the sim-to-real platform RIVR [12], designed specifically for human-robot interaction) and then in the physical world. The goal of our study was to, first, demonstrate a successful shared small-scale manipulation, and second, verify that the simulated tests provide insight into conducting the same actions in the physical world.

The robots used in the task were Kinova Gen3 robotic arms, which have a built-in RGB-D camera and were controlled by ROS. The robot performs all actions autonomously, with steps triggered by a human controller. The robot determines where the human participant is holding the circuit and determines where to insert an LED into an anode and a cathode made of conductive putty. The manipulator visually servos the end effector to insert the LED. During these actions, the robot continually tracks whether the putty is reachable and held in an appropriate pose. If it is not, the robot verbally asks the user to reposition the putty. As soon as the LED leads contact the anode and cathode putty blocks, it lights up, signaling the successful completion of the experiment. Identical human subject experiments were conducted in virtual reality and on a physical robot, and the results were compared to see if VR was an informative sim-to-real setting.

The RIVR simulator was used to conduct experiments in virtual reality [12]. RIVR uses Unity and SteamVR to provide participants with a visually and physically realistic environment. Users are represented through a human avatar animated using the poses of the VR headset and controllers. ROS# links the Unity environment into the Robot Operating System (ROS). ROS captures the robot’s state for Unity while Unity generates the visual percepts. This allows for the same code base to be used in both the VR and real-world modalities, with the only difference being whether a physical robot or a Gazebo simulation is being controlled. The simulated scene was adapted from an AI2Thor [15] environment designed to closely match the physical setting, and all the necessary components were built in Unity.

Two between-user studies (n=20) were conducted with a population unaffiliated with this research. Participants were asked to interact with the robot and help build the circuit either in simulation or reality. In the pilot study, we established the need for the robot to check the location of the circuit components and verbally instruct the user to change the reachable locations of the putty blocks in order to make completing the circuit feasible; this is likely a result of the fact that the participants in the study were not familiar with the robot and its reach or capabilities.

4 Experiment

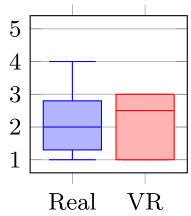
To begin, the robot instructs the participant to hand the LED bulb to the robot with the leads facing the participant. The robot then verbally guides the participant through connecting the battery pack to the conductive putty, placing the positive (red) terminal of the battery pack into the red putty and the negative terminal into the green putty. Once the battery is connected to the conductive putty, the robot prompts the participant to hold the putty blocks where the robot can reach them. The robot then attempts to move its hand into a position where it each of the leads of the LED are inserted into the putty, completing the circuit. Once the robot moves its hand to a position that it thinks will connect the LED to both pieces of putty, it asks the participant if the LED has lit up. If so, the robot releases the LED; if not, the robot moves back to its initial position and repeats the attempt.

This task was performed both with a simulated robot where the participant is in a virtual reality setting, and with a physical robot in the real world. Once the task is either completed or the user decides that success will not be forthcoming, the interaction is ended, and a short survey is given. Because the use of VR equipment is not ubiquitous, participants using VR were allowed to familiarize themselves with the controls prior to starting the experiment.

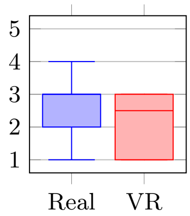
5 Experimental Results

To compare the virtual and physical interactions, both were evaluated using task performance and participant perception. For task performance, the total time to complete the task, the number of attempts, and the time per attempt were recorded. For participant task perception, a post-interaction survey was filled out. In almost all cases, the robot-human dyad was able to complete the joint manipulation task; exceptions are described below in Section 6. These results—in which the task performance was generally successful and performance was comparable between the settings—suggest that a carefully designed VR setting is a practical tool for designing and prototyping HRI experiments.

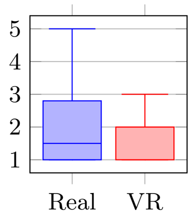
In the main experiment, twenty participants were recruited from a common area of a university campus, ten female and ten male. Eighteen were aged between 18 and 34, and two between 35 and 49. Six identified as white, two as Hispanic or Latino, five as Black or African American, eight as Asian, and one preferred not to say. Ten of the participants interacted only with the virtual robot and the other ten only interacted with the physical robot. Prior to starting the study, all participants signed an IRB-approved consent form. The VR device used was an HTC Vive and participants using VR were allowed to familiarize themselves with the controls prior to starting the experiment.



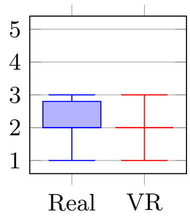
(a) Did you understand the task/instructions? (1: Very clear, 5: Very poorly defined)



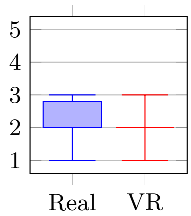
(b) How useful is the task you were trying to accomplish? (1: Very useful, 5: Pointless)



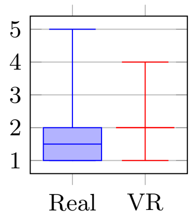
(c) How comfortable were you with the interaction? (1: Very comfortable, 5: Very uncomfortable)



(d) Did you find the interactions with the robot frustrating? (1: Very easy to use, 5: Very frustrating)



(e) How natural/intuitive did you find your interaction with the robot? (1: Very natural, 5: Very unnatural)

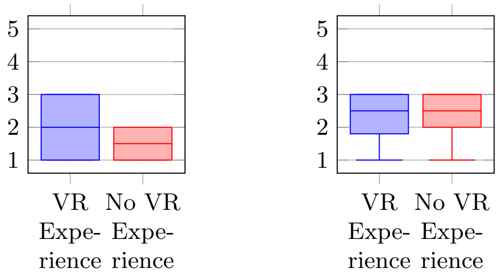


(f) Overall, did you find interacting with the robot pleasant? (1: Pleasant, 5: Very unpleasant)

Fig. 2: Post-interaction survey responses for self-reported user experiences. Responses for interaction with the physical robot vs. the VR setting are comparable for all questions.

Participant Experience Between Settings Experimentally, we seek to determine the differences and similarities of the participant experience between the VR setting and the physical world. After the participants finished the study they were asked to evaluate how well they understood the instructions given by the robot, how useful they thought the task was, how comfortable they were in interacting with the robot, how frustrating the interaction was, how intuitive they found the interaction, and overall how pleasant they found the interaction to be. All measures used a five-point Likert scale. The results are shown in Figure 2.

All metrics were consistent between the physical and VR cases. A one-factor analysis of variance was performed, and there were not statistically significant differences in comprehensibility of instructions (p=0.27), how useful the participants found the task (p=0.24), how comfortable participants were (p=0.57), how frustrating the interaction was (p=0.45), how intuitive they found the interaction (p=0.71), or how pleasant the interaction was (p=0.83). Participants in the VR condition were also asked to evaluate the immersiveness and realism of the simulated environment. They reported that the experience was fairly immersive

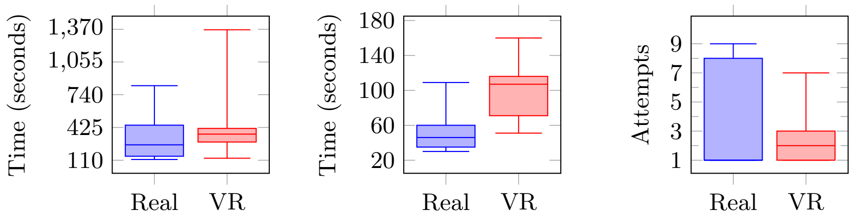


(a) How immersive was the VR experience? (1: I felt like I was there, 5: Not immersive at all)

(b) How realistic was the simulation? (1: Very realistic, 5: Very unrealistic)

Fig. 3: User perception of realism and immersion of the simulated environment. In general, users found the simulation very immersive and moderately realistic.

(mean 1.7 ± 0.8, where 1='I felt like I was there' and 5='Not immersive at all'), and realistic (mean 2.3 ± 0.8, where 1='Very realistic' and 5='Very unrealistic').



(a) Total time required to complete the task.

(b) Average time taken for each attempt for robot to complete the circuit.

(c) Number of attempts for robot to insert the LED into the putty.

Fig. 4: Task performance. The total time to complete the task between settings was roughly comparable, with higher variance in virtual reality. In general, in VR, each attempt took longer, but fewer attempts were required overall.

Participant Performance Between Settings Of the ten participants who worked with the physical robot, only one failed to complete the task. Of the ten who worked with the simulated robot, one was not able to fully complete the task. As can be seen in Figure 4, in the VR setting, it took an average of 436 ± 362 seconds to complete the task and 2.6 ± 1.9 attempts with each attempt taking 100 ± 39 seconds. In the real world, it took an average of 327 ± 239 seconds to complete the task and 3.7 ± 3.8 attempts with each attempt taking

54 ± 11 seconds. A one-factor analysis of variance shows that while the number of attempts (p=0.44) and total times were comparable (p=0.46), there was a significant difference in the time each attempt took (p=0.01). We discuss possible reasons in Section 6.

We further investigated whether a participant's prior experience with VR had any effect on their interaction. Of ten participants who interacted with the virtual robot, six had no previous experience with virtual reality, while four had some prior experience with VR. A one-factor analysis of variance found no significant differences in participants' perceptions of the experience and performance as a result of prior VR experience (Figure 3).

6 Main Experimental Insights

It is promising that there were no significant differences in the participants' perception of the interaction or in their overall performance of the task between VR and the real world. The fact that there was a significant difference between the amount of time each attempt took between conditions merits further investigation. This difference could be due to problems with depth perception in VR, as one participant did express uncertainty about where to hold the putty in order for it to be reachable by the robot. While depth perception issues are common in VR, the scene used in this study contained relatively few objects; providing a richer environment may help improve depth perception [30]. There may also be differences in the Gazebo simulation of the robot compared to the real arm, as one VR participant commented that they thought that the virtual arm's movement was slow, while there were no comments about the real robot moving slowly. It is also promising that previous experience with VR did not correspond to any significant difference in task performance or in perception.

The simulated robot's sensors perceive a virtual human avatar whose pose is determined by the locations of the VR headset and VR controllers. While the avatar's hands are positioned to match the virtual hands seen by the participant, there can still be a disconnect. In one instance, a participant swapped the left and right controllers; because the avatar's pose is extrapolated from the location of the VR headset and controllers, this changed the orientation of the avatar's hands relative to the putty, resulting in a view where the hands completely occluded the circuit from the robot's sensors. In trying to correct this, the participant moved the putty into contact with the robot's manipulator and displaced the LED, leading to task failure. Bringing the putty into contact with the manipulator and knocking the LED out of position occurred in two other cases. In one case, the participant was able to put the LED back in place and complete the task.

While there was noticeably more sensor noise in the perceived position of the putty in the real world, only once did this result in a consistent error, in which the robot perceived the putty blocks as too far apart, leading to a refusal to insert the LED. There was also an instance where the robot made an unexpected move, causing the participant to be concerned about the robot contacting them. This led the participant to provide much lower scores in comfort with the interaction and in how pleasant the interaction was. One possible mechanism for bringing the VR and real-world task into closer alignment is to increase the noise present in the simulated percepts [3].

7 Conclusion

The main future direction is to compare VR and physical performance in more complex human/robot teaming tasks, both in terms of single-step complexity and in tasks with more steps, such as the assembly of more complex circuits. In future work, we will gather a greater number of participants to strengthen our conclusions. We plan to expand our VR familiarization task, which in this study was aimed at getting participants used to the VR controls, to invite participants to interact with the environment by picking up objects and placing them in a particular location. These tasks could be used to determine a participant's experience in interacting with VR.

As our longer-term goal is to determine whether virtual reality can be used to prototype experimental HRI research, the next stage of research will use a within-participant design, in which we establish whether a robot can learn from virtual interactions and bring that knowledge to bear on the physical experiment. We will measure whether learning in this direction reduces the overall time the experiment takes, increases the success rate, and/or changes the human participants' experience. In order to measure the last, we will increase the set of questions on the post-study survey, with the inclusion of open-ended questions about the experience that will be coded for common insights.

We are also interested in exploring additional autonomy where the robot can choose its own actions, including when and how to provide instruction to the human collaborator. We furthermore will examine the potential of the data collected from this experiment for use in training a robot to perform the steps of this task, such as inserting the wires into the putty and presenting the putty to a partner during shared tasks.

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