Evaluating Viewpoint Control Techniques in Virtual Reality Interface for Teleoperating Construction Welding Robots

Sungboo Yoon[1], Seungmin Shin[1], SangHyun Lee[2], Moonseo Park[1], and Changbum R. Ahn[1]
[1]Seoul National University, Republic of Korea
[2]University of Michigan, USA
cbahn@snu.ac.kr

Abstract. Effective visual feedback is critical for successful teleoperation of construction robots in remote locations. Recently, virtual reality (VR) has been leveraged to enhance teleoperation interfaces, providing enriched visualization and interaction capabilities. However, despite the critical role of viewpoints in 3D exploration and manipulation, the choice between coupled and decoupled viewpoints—where the user's camera is tethered or independent from the end-effector's position—in VR teleoperation interfaces for construction robots remains unclear. In this study, we explore the effect of viewpoint control technique in VR (coupled vs. decoupled viewpoint) on task performance, perceived workload, and perceived usability in the context of teleoperating welding robots in construction. Our comparative study with 10 participants demonstrated that under the coupled condition, participants completed the welding tasks significantly faster and with greater consistency across different locations when compared to the decoupled condition. These findings offer design implications for the integration of viewpoint control techniques in the development of visual interfaces for robotic teleoperation in construction.

1. Introduction

With the recent shift towards the adoption of robotics in the construction industry, one of the most active applications is the remote operation, also known as “teleoperation”. When operating robots situated at remote locations, human workers typically rely on visual feedback sent back from the robots’ workspace. Workers, drawing upon their innate spatial cognition and situational awareness, interpret the visual information to understand the task context. This understanding then lead to subsequent actions to operate robots, ranging from directly issuing low-level robot commands to specifying high-level goals. Thus, designing an effective visual feedback interfaces is critical to the success of teleoperation (Kuitert et al., 2023).

Among various design considerations of visual interfaces for teleoperation, previous work has explored various methods for controlling viewpoints within 2D imagery, such as leveraging a view from a secondary “monitoring” robot (e.g., a robotic arm (Rakita et al., 2018) or a drone (Senft et al., 2022)), combining egocentric and exocentric views (Young et al., 2022), and employing an orbital camera view (Talha & Stolkin, 2019). These studies suggest that viewpoint control techniques have significant effect on task performance, such as task completion time (Young et al., 2022), collision (Senft et al., 2022; Thomason et al., 2019), and success rate (Rakita et al., 2018), as well as user experience, such as interface acceptance, perceived workload, and perceived usability (Valiton et al., 2021).

In recent years, research has investigated decoupled viewpoint control in a virtual reality (VR) interface. VR, typically presented through immersive head-mounted displays (HMDs), has been increasingly integrated into user interfaces for robotic teleoperation owing to its enriched visualization and interaction capabilities. In VR, users’ camera can be either coupled or decoupled from a fixation point, which in case of a robotic arm, is usually the position of an end-effector (Kuitert et al., 2023; Talha & Stolkin, 2019; Valiton et al., 2021). Coupled viewpoint involves the user's viewpoint being directly linked to the position of a robot's end-effector, providing a fixed perspective for detailed observation and control. In contrast, decoupled viewpoint allows free navigation in the virtual environment, independent of any tethering, enabling exploration and potentially offering a broader understanding of the remote workspace. Despite significant effects of viewpoint control techniques on interface's performance, the choice of suitable viewpoint coupling for VR interface for teleoperating construction tasks still remains relatively unclear.

In this work, we present the results of a study in which we compared coupled (Figure 1) and decoupled (Figure 2) viewpoints for a VR interface in assisting construction workers to teleoperate robots at remote locations. We developed visualization techniques, grounded by a review of existing literature on immersive visualization techniques across augmented, mixed, and virtual reality interfaces, for coupling or decoupling users' viewpoints. The scope of this work focuses on construction welding tasks that involve precise and skilled operation, as well as high situational awareness to locate welding seams in complex workspaces.

To investigate the effects of the two viewpoint control techniques on teleoperating welding robots, we conducted an experimental comparison with 10 participants. Specifically, we consider a scenario in which a worker, equipped with an HMD, operates a remote robot in a simulated environment, which is equipped with a metal inert gas (MIG) welding tool and vision sensors and located on a construction site with a steel structure, near beam stiffener welding connections at height. This paper contributes to the research on visual interfaces for teleoperation in construction by exploring the differences between coupled and decoupled viewpoints and examining their effects on workers' teleoperation performance and preferences.

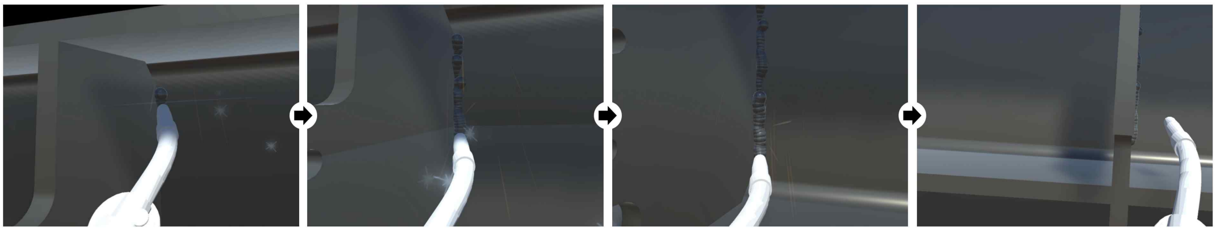

Figure 1: Illustration of the Coupled Viewpoint Control Technique. Note that the camera is linked to the end-effector movement.

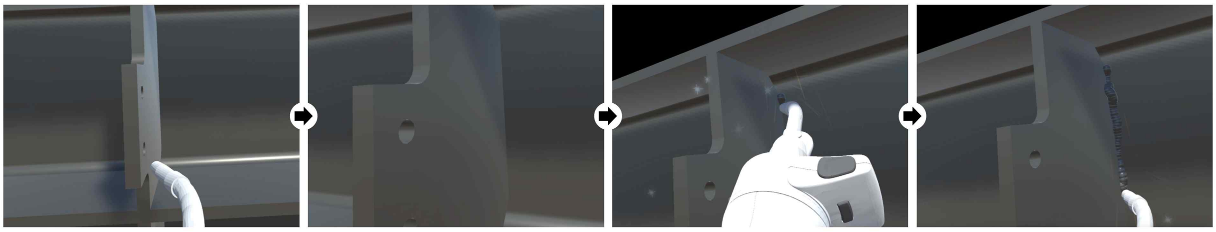

Figure 2: Illustration of the Decoupled Viewpoint Control Technique. Note that the camera operates independently to the robot's end-effector movement.

2. User Study: Coupled vs. Decoupled Viewpoint

We designed and conducted a controlled user study to investigate which of the two viewpoint control techniques better supports teleoperation in construction welding tasks. This section provides a comprehensive overview of the methodology, participants, apparatus, tasks, procedures, and analytical methods employed in our user study.

2.1 Viewpoint Control Techniques

In a simulated environment in VR, participants performed MIG-welding tasks in both coupled and decoupled viewpoint conditions. This section describes these conditions and their implementation in our VR teleoperation interface.

Coupled Viewpoint. In the coupled viewpoint (hereafter, “coupled”) condition, the camera is coupled to the robot’s end-effector at a certain distance (X: +30cm, Y: +10cm, Z: -30cm), pointed towards the tool tip. In this way, the user’s viewpoint is coupled with the positional and orientational (6-DoF) movements of the robot’s end-effector. Users could also alter their viewpoint by rotating their head, with these movements tracked by internal motion tracking sensors of the HMD (see Figure 1).

For teleoperation, a direct mapping technique was applied to align the VR controller’s position and orientation with the robot's end effector configuration, providing direct control over the robot (Rakita, 2017). The orientation of the VR controller and its index trigger were aligned with the orientation of those of a real MIG-welding gun (see Figure 3-A). This design choice aims to enable a natural and appropriate hand posture for welding within the simulated environment. During the welding operation, participants fed the wire by pressing the VR controller’s index trigger, similar to pressing the trigger of a welding gun. Here, we assumed that the MIG-welding parameters, such as wire size, voltage, and wire feed speed, were pre-configured for optimal performance.

Decoupled Viewpoint. In the decoupled viewpoint (hereafter, “decoupled”) condition, the positional and orientational movements of user’s camera, the HMD, are decoupled from robot’s end-effector movements (see Figure 2). While orientational (3-DoF) movements of the HMD are allowed, positional movements are not directly linked to the robot’s movements, as we assume a fixed base position for the robot, similar to the setup in Valiton et al. (2021). To enable positional movements, an additional VR controller with a 2D axis thumbstick (for X and Y axes movements) and a trigger (for switching to the Z-axis) was employed.

As the focus of this study is on comparing viewpoints, all other VR interface features, including teleoperation mapping techniques (see Subsection Coupled Viewpoint), were uniformly applied across both coupled and decoupled conditions.

2.2 Participants and Apparatus

We recruited 10 university students (9 male, 1 female) to participate in virtual tele-welding. Selection criteria included participants with knowledge of construction to better ground our results in real-world construction and to ensure that they understood the context of steel beam welding (Yoon et al., 2024). All 10 participants reported they were right-handed.

The user study utilized a VR system including a Meta Quest 3 VR headset and Meta Quest Touch Plus controllers. Additionally, a virtual robot was integrated into the VR environment, specifically a Franka Emika robot, which was controlled in joint position. The desired joint positions were determined through a nonlinear inverse kinematics optimization aiming to match the desired end-effector pose, while limiting joint velocity and joint limits (Senft et al., 2022). The robot was equipped with a generic MIG-welding gun, modeled based on a design from the RoboDK library.

2.3 Task and Procedure

In our study, we focused on a robotic MIG-welding task involving the attachment of a stiffener to a steel beam at a specific height within a steel structure construction site. The task scenario involved two commercial standard wide-flange beams (W400 X 197) positioned with their flanges facing each other. As the attachment of a stiffener to a steel beam involves welding seams along both sides of the stiffener, a single trial required participants to weld four different seams (see Figure 3-B).

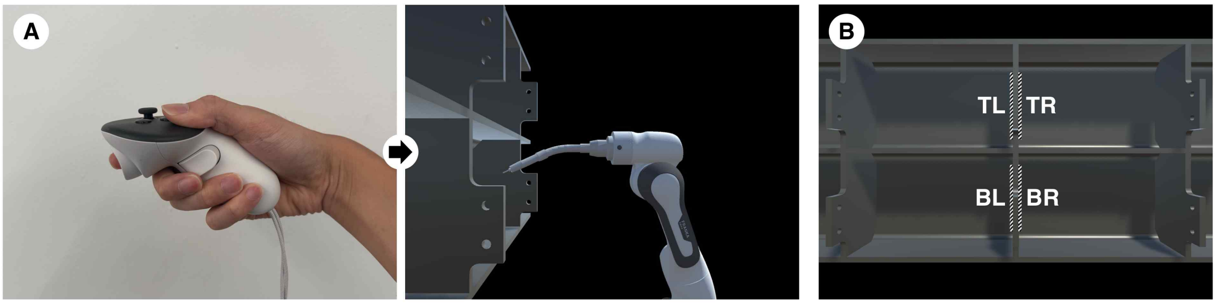

Figure 3: (A) Side view of the VR controller held in a user's hand (Left) and its direct mapping to the robot's end effector in the VR interface (Right). (B) Four welding seam locations in the virtual task scenario. TL = Top left, TR = Top right, BL = Bottom left, and BR = Bottom right.

Participants performed two trials: one using the coupled viewpoint and the other using the decoupled viewpoint. Viewpoint order was counterbalanced such that 5 out of 10 users performed the task in coupled condition first and then in decoupled condition, and the other 5 users performed the task in the opposite sequence. This counterbalancing was used to control possible within-subject effects.

Before each trial, the experimenter demonstrated the interface with the corresponding viewpoint control techniques. Participants were then allowed time to familiarize themselves with the task and the interface. They started the trial when they felt prepared. Throughout the trial, participants remained seated. After the trial ended, participants were asked to fill out two questionnaires: NASA Task Load Index (TLX) and Single Ease Question (SEQ). Following the completion of trials for both viewpoints, the experimenter conducted a semi-structured post-test interview to gather participants' feedback on their preferred viewpoint control technique and their thoughts on the interface design. The entire study duration was approximately 15 minutes.

2.4 Measures and Analysis

The primary measures are welding time, welding error, and path deviation. Welding time is defined as the duration from the start of user interaction to the completion of all four welding seams. Welding error, a measure of accuracy, is calculated as the average distance between each point on the welding path and the nearest point on the ideal path, which is the actual seam location. Path deviation is the standard deviation of these distances, as per its definition by Kim et al. (2023).

Additionally, we collected subjective data through post-task questionnaires. We measured perceived task load with the Raw NASA-TLX (RTLX) and perceived usability with the SEQ.

To analyze the results of both objective task performance and subjective questionnaires, we used parametric paired t-tests. In cases where the normality assumptions were not met (Shapiro-

Wilk test p <.05), the data was analysed using non-parametric Wilcoxon signed-rank test (Luong et al., 2023). For further analysis of welding error and path deviation, we employed one-way repeated measures analysis of variance (RM-ANOVA). When needed, pairwise post-hoc Wilcoxon signed-rank tests with a Bonferroni correction were performed. In cases where the normality assumptions were not met (Shapiro-Wilk test p <.05), the data was analyzed using an aligned rank transform (ART) ANOVA (Elkin et al., 2021). All statistical analyses were performed at a 0.05 significance level, using R for the computations.

3. Results

The results of the analysis of 10 participants are as follows.

3.1 Task Performances

We compared the welding time, welding error, and path deviation of the two viewpoint control techniques. Figure 4 shows the participants' average and distribution of these measures. In terms of welding time, the coupled condition was significantly shorter (Z=-1.99, p<.05) than the decoupled condition: 73.2 s (SD=32.6) and 110.1 s (SD=47.0), respectively.

The average welding errors were 21.7 mm (SD=11.4) and 23.2 mm (SD=12.5) in the coupled and decoupled conditions, respectively. A paired t-test did not find a statistical difference (t(9)=-0.28, p=.78). Similarly, the path deviation averages were 15.1 mm (SD=16.4) for the coupled condition and 12.4 mm (SD=11.0) for the decoupled condition, with no significant difference found (t(9)=0.40, p=.70).

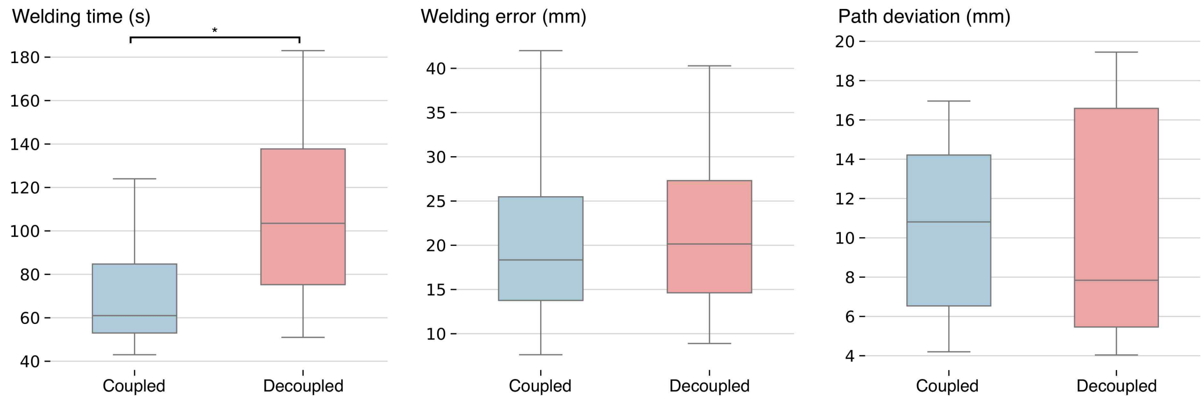

Figure 4: Task Performance Measures by Viewpoint Condition. Welding time (left), welding error (middle), and path deviation (right).

Further analysis compared the welding error and path deviation across different welding seam locations for each condition (see Figure 5). A one-way RM-ANOVA revealed a significant difference in both mean welding error (F(3,27)=3.90, p<.05, η_p^2=0.30) and path deviation (F(3,27)=3.05, p<.05, η_p^2=0.25) of the decoupled condition across seam locations. Post-hoc analysis showed a marginal difference (p=.082) in path deviations between the top right (TR) and bottom left (BL) welding seams. Conversely, the same analysis for the coupled condition did not reveal significant differences in either welding error (F(3,27)=0.35, p=0.786, η_p^2=0.04) or path deviation (F(3,27)=1.86, p=0.160, η_p^2=0.17).

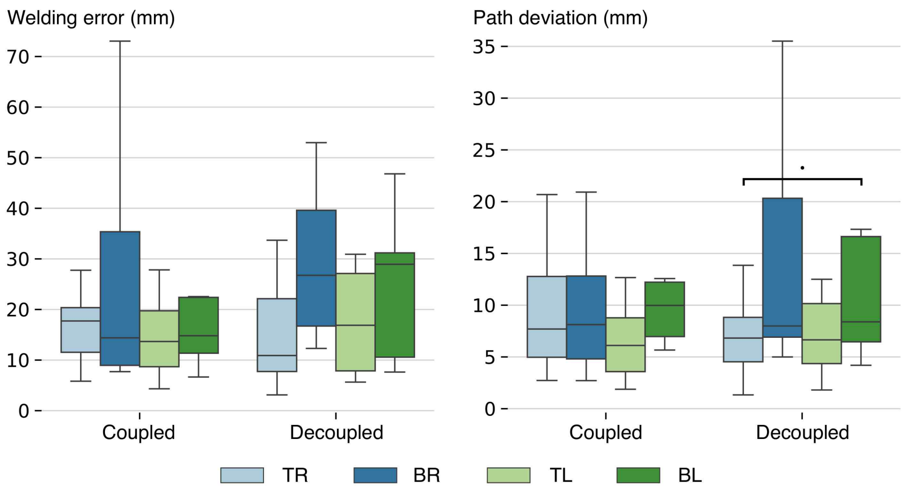

Figure 5: Welding Error and Path Deviation by Viewpoint Condition and Welding Seam Location

3.2 Subjective Results

Figure 6 shows the perceived workload (RTLX) for both conditions. On a scale of 0-100, the average RTLX scores were 51.1 (SD=19.1) for the coupled condition and 48.8 (SD=21.8) for the decoupled condition. A paired t-test found no statistically significant difference (t(9)=0.39, p=.708). Furthermore, paired t-tests found no significant difference across all RTLX dimensions: mental demand (t(9)=1.06, p=.317), physical demand (t(9)=0.62, p=.548), temporal demand (t(9)=0.36, p=.726), performance (t(9)=1.27, p=.236), effort (t(9)=0.28, p=.788), and frustration (t(9)=0.23, p=.822).

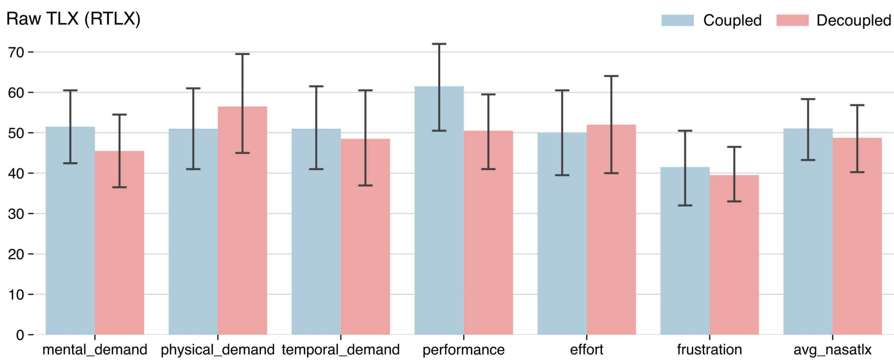

Figure 6: Raw NASA Task Load Index (RTLX) by Viewpoint Condition. Lower score is preferable.

Figure 7 shows the perceived usability (SEQ) scores, which ranges from 1 (Very difficult) to 7 (Very easy). The perceived usability for the coupled and decoupled conditions were 5.20 (SD=1.23) and 5.10 (SD=1.66), respectively. A paired t-test found no statistically significant difference (t(9)=0.16, p=.876). However, there was a slight trend towards better scores for the coupled condition.

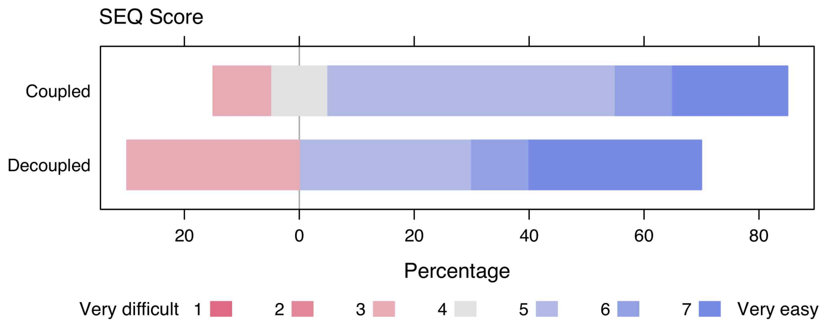

Figure 7: Single Ease Question (SEQ) Scores by Viewpoint Condition. Higher score is preferable.

In terms of overall preference, three participants (P3, P4, P9) expressed their preference for the coupled viewpoint due to ease of use (P3), similarity to actual welding hand postures (P4), and perceived performance (P9). P3 shared her thoughts regarding the impact of viewpoint control on task difficulty:

"I think welding itself is a challenging task, but the addition of [the interface feature for] adjusting the viewpoint made [the task] even more difficult. (P3)"

Conversely, three participants (P1, P8, P10) expressed their preference for the decoupled viewpoint due to the partial occlusion at certain welding seams (P1), lower perceived mental demand (P8), and perceived performance (P10). P8 expressed his preference to have autonomy in controlling the viewpoint:

"I found that having control over adjusting the viewpoint is less mentally demanding for me. (P8)"

The other four participants (P2, P5, P6, P7) remained neutral, expressing no clear preference for either viewpoint.

4. Discussion

In this study, we conducted a comparative user study with 10 participants to investigate how two viewpoint control techniques influence the teleoperation welding robots in construction. Results of the user study demonstrated that the coupled condition led to enhanced task efficiency, with participants completing the welding tasks significantly faster compared to the decoupled condition.

In terms of task accuracy, while no significant differences in welding error and path deviation were found between the viewpoints, we observed performance variations by the location of the welding seams. This observation is particularly relevant in construction welding, where the large size of components and the variability of welding positions can introduce accessibility challenges. Welders might need to work at heights or in awkward positions to complete the welds. In other words, welding robots in construction may not always work in optimal poses, which can significantly restrict the precision of teleoperated welding tasks. Considering the right-handedness of all participants and the spatial relation of welding seams to the robot's end-effector, the top right (TR) position was more "optimal" compared to the bottom left (BL). This perspective was supported by participants' feedback during post-test interviews.

We observed a decrease in weld quality associated with unnatural welding postures, particularly under the decoupled condition. A significant difference in welding error and path deviation was observed depending on the seam locations. In particular, path deviation was increased by 77.4% at the BL position compared to the TR position. Welding error was increased by 58.5%.

Our results did not align with previous studies that suggest exocentric (decoupled) views have a positive effect on the task performance such as task completion time (Kuitert et al., 2023) and task success rate (Young et al., 2022), by improving situational awareness in general robot teleoperation scenarios. However, the unique characteristics of construction welding, including diverse welding postures, dispersed welding locations, and the large size of the components involved, may hinder a user's ability to fully perceive information about all welding target positions in a single viewpoint, and thus making viewpoint adjustment essential. In this context, our study revealed that a coupled viewpoint maintained a consistent, location-invariant task performance in our welding task scenario. This is not surprising given the fact that the coupled condition maintained a stable viewpoint irrespective of the position of the robot's end-effector, whereas the decoupled condition presented participants with irregular viewpoints throughout the tasks. However, it should be noted that these findings are based on a limited study involving only 10 university students and extended training with the VR interface could also potentially lead to different results. With that said, the current results should be viewed as preliminary, highlighting the need for further research to confirm these findings.

Moreover, previous studies has linked the diminished task performance associated with an egocentric view to the "soda straw" or "keyhole" effect (Woods et al., 2004; Young et al., 2022), in which operators struggle to understand and comprehend the remote environment due to a limited viewing angle (Young et al., 2022). However, our observations suggest that with appropriate adjustments, such as maintaining appropriate distances between the user's viewpoint and the robot's end-effector and leveraging the orientational movements of the HMD as seen in our coupled condition, the limited viewing angle of a robot-following viewpoint does not adversely affect task performance.

5. Conclusion

In our comparative study involving 10 participants, we explored the impact of coupled and decoupled viewpoint control techniques on the teleoperation of welding robots. The findings suggest that the coupled viewpoint led to improved task efficiency, with participants completing welding tasks 33.5% faster than when using the decoupled viewpoint. Furthermore, the coupled viewpoint demonstrated greater consistency across different locations, though no significant differences were observed in mean welding errors and path deviations across all welding locations. Perceived usability, workload, and user preferences showed no significant variations between the two viewpoints. Our results suggest that coupled viewpoint are overall more adapted for efficient and consistent task performance to support teleoperation for construction welding.

This paper expands the research landscape of visual interfaces for teleoperation in construction by offering three main contributions. First, we developed a VR interface designed to facilitate in-situ welding operations in construction settings. We evaluated viewpoint control techniques that enable workers to enhance spatial cognition with visual data in remote environments. Second, through an empirical study on the differences between coupled and decoupled viewpoints, we closely observed the interaction between users and VR and confirmed the effects of viewpoint coupling on workers' teleoperation performance and preferences. Finally, informed by the results of our user study, we discussed design implications for employing the two viewpoint control techniques within the context of teleoperation in construction and its visual interfaces.

However, there are several limitations in our current work. First, our evaluation included only 10 participants, and thus the interaction dynamics in larger groups might not be fully represented (Sato et al., 2023). Additionally, the gender distribution of our participants was significantly skewed (9 males and 1 female), which may not accurately reflect the diversity of potential end-users in construction. Future work with expanded participant samples is essential to understand interaction dynamics comprehensively and to mitigate any potential biases from the small sample size or skewed gender distribution. Second, all our participants were university students. Although the students' academic background provided basic understanding of construction welding tasks, it may not fully encapsulate the expertise of skilled welders. For future experiments, we not only need larger groups and a balanced gender distribution but also participants with professional experience in construction welding. Lastly, this study focused exclusively on welding tasks within a simplified setting, presenting only the steel beams and the welding robot in an unlimited workspace. However, due to dynamic and complex nature of construction environments, workers, equipment, or materials from other tasks in parallel in the surrounding environment may lead to potential collisions, which could significantly impact safety and reduce productivity (Yoon et al., 2023). Future work should expand the evaluation of the teleoperation interface by integrating those scenarios into the user study framework.

Acknowledgements

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