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Eetu Laukka

eetu.laukka@oulu.fi

University of Oulu

Evan G. Center

University of Oulu

Steven M. LaValle

University of Oulu

Timo Ojala

University of Oulu

Matti Pouke

University of Oulu

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Reconstructed Reality: Enabling Teleportation-Based Locomotion in Immersive Telepresence

Eetu Laukka[1*], Evan G. Center[1], Steven M. LaValle[1], Timo Ojala[1], Matti Pouke[1]

[1*]Faculty of Information Technology and Electrical Engineering, University of Oulu, Pentti Kaiteran katu 1, Oulu, 90570, Finland.

*Corresponding author(s). E-mail(s): eetu.laukka@oulu.fi;
Contributing authors: evan.center@oulu.fi; steven.lavalle@oulu.fi; timo.ojala@oulu.fi; matti.pouke@oulu.fi;

Abstract

High latency and virtual reality (VR) sickness hinders the mass adoption of telepresence or teleoperated systems utilizing head-mounted displays (HMDs). In immersive telepresence scenarios that use 360 degree cameras to present the remote environment, latencies of up to seconds are expected. Such delays make traditional continuous manual control of these systems difficult. In addition, due to the use of HMDs, users of these systems are prone to VR sickness. We present a novel method to enable an improved telepresence locomotion experience under these constraints. The paper first recounts a previously published article of a prototype design, and then integrates new findings of a realistic use-case, replicating and extending these findings. We conclude that it is highly beneficial to use teleportation through a real-time 3D reconstructed virtual environment as an interface to a physical environment (VEIPE) in embodied immersive telepresence, relative to a standard joystick-based continuous control method.

Keywords: Telepresence, teleoperation, 3D reconstruction, locomotion, virtual reality, VR interface, digital twin

1 Introduction

For better or worse, daily life is increasingly shifting to remote options, whether that means working (Barrero et al. 2023), studying (Mehta et al. 2024), or even accessing healthcare (Shaver 2022). The COVID-19 pandemic did not itself produce these technologies; they existed before, however, the pandemic accelerated and normalized their widespread use (Ng et al. 2022; Srisathan and Naruetharadhol 2022). The pandemic also accelerated research in related areas, one of which is *telepresence* (Minsky 1980), or the "sense of being there" in a remote location through technology. This feeling of presence, which can make you feel close to your loved ones, can be achieved by using technologies available to most of us. Video calls can make you feel as if the person is there with you through social presence illusion (Skarbez et al. 2017). The technique itself has existed for thousands of years, as story tellers used emotions and convincing storytelling to exhibit this same feeling of maybe even being in a fictional environment. However, the grand idea of using technology to transfer yourself to a remote location was coined in the 1980s by Minsky (1980). The pandemic brought demand to study and develop more

telepresence systems. As such, telepresence was incubated as one of the IEEE Future Directions Initiatives (van Erp et al. 2023).

To become immersed in VR, the system must create vivid illusions that fool one's senses by simulating sensory cues as closely as possible to those in actual reality. The more sensory modalities that are simulated, the more immersive the experience is considered to be (Slater et al. 1997). In VR, much like in telepresence, the construct of presence is central when it comes to creating a perceptual illusion of being in a virtual environment (Steuer and others 1992). In virtual environments, *Presence* is considered to be formed by place illusion, plausibility illusion and social presence illusion (Skarbez et al. 2017). Within this view, immersion is a primary driver of place illusion (Slater 2009). Because the use of more immersive systems can enhance the feeling of presence, HMDs are increasingly used in telepresence to provide a more immersive view of the remote environment. Such systems can be referred to as immersive telepresence systems or VR telepresence systems (Widagdo et al. 2022; Huang et al. 2023).

Telepresence can be achieved in many ways. When it comes to telepresence with mobile robots, most commonly researchers have studied mobile robots that have a regular camera attached to them (Kristoffersson et al. 2013), which is streamed to the remote user controlling the mobile robot through a computer screen. However, the full remote environment is not visible unless the camera is rotated, and even in that scenario, the user cannot use their head to look around unless multiple screens are used, or a clever rotating devices that rotate the screen with you (Aguilar et al. 2025), or a CAVE system is used (Cruz-Neira et al. 1992). As HMDs have become more accessible, they are an easy way to increase immersion in telepresence. Even a do-it-yourself cardboard VR HMD has shown evidence of significantly higher immersion over a regular desktop display (Amin et al. 2016). This way, users' head rotations can be tracked, and those motions can then be mimicked by the camera to enable the user to look around the remote location (Aykut et al. 2018). An even easier option is to use a panoramic or a 360° camera, to stream the entire surrounding to an HMD (Zhang et al. 2018a). Unlike when using rotating cameras, the use of 360° cameras for this purpose does not require additional actuators on the robot and the only thing needed is to attach the 360° camera to a moving platform.

Along with a stronger place illusion, higher immersion can yield other benefits, such as better task performance (García et al. 2015) and situational awareness (Martins and Ventura 2009). However, even though using an HMD is an easy way to improve immersion, they have many drawbacks. VR headsets inherently bring along a common problem: VR sickness. A prior systematic review and a meta-analysis of VR sickness in HMDs revealed that the average sickness score is still very high among studies that use HMDs (Saredakis et al. 2020). This sickness develops from many components. One major component is believed to be the sensory mismatch between visual and vestibular systems (Reason and Brand 1975). This mismatch is strong during locomotion in virtual environments, as your visual system is perceiving that you are moving. However, in this scenario the vestibular organs within your inner ear are not sensing any movement, leading to visually induced motion sickness. Another popular explanation of the cause of VR sickness has been the theory of postural instability, developed by Riccio and Stoffregen (1991). They hypothesize that due to a prolonged instability in maintaining one's posture, the body will respond by producing motion sickness symptoms. This instability in posture arises from a rapidly changing environment that can occur in VR when moving, for example. VR sickness has been one of the main focuses that researchers in the field have tried to overcome, as the symptoms can be so severe that in some cases it can cause vomiting (LaValle 2023). Unsurprisingly, these experiences can lead to some users avoiding any further use of these technologies (Sagnier et al. 2020), creating a major barrier to the mass adoption of these systems.

Another key problem in telepresence is system latency (Farajiparvar et al. 2020). When sending data back and forth long distances, the laws of physics limit how quickly the control actions of the remote robot can become visible on the end user's screen. This problem is significantly worse when using 360° cameras which require more processing and extra bandwith. Currently, when streaming a 360° video stream over the Internet, the latencies reach up to seconds (Yan and Yi 2022; Liu

et al. 2022). Even in an optimal setting, the current commercially available solutions struggle to reach the delay requirement for interactive real time applications of around 250 ms (Neumeier et al. 2019; Lane et al. 2002), due to poorly optimized servers and the additional processing that is required (Yan and Yi 2022). Longer delays can significantly affect users' quality of experience when teleoperating a remote robot (Jahromi et al. 2020), leading to reduced performance and increased perceived workload (Chen et al. 2025; Kim et al. 2021).

In this article, we extend a previous study to address these issues in immersive telepresence. Our previous study showed that teleportation-based locomotion through VEIPE improves immersive telepresence navigation by reducing VR sickness and increasing task performance compared with traditional continuous joystick control (Laukka et al. 2024). The main limitations of the prototype study were that it used a rather simple navigation task, and that the virtual environment that was used to interface with the remote physical environment was pre-modeled, which limited the robot navigation to only that known environment, thus reducing the ecological validity of the experiment. In this paper we present a follow-up study addressing these limitations, along with the previous findings. We present a system capable of navigating any unknown static environment traversable by the remote robot, using a real-time reconstructed VEIPE, and yielding superior results compared to the standard alternative. The follow-up study replicates all of the findings of the previous study with the exception of user preference, and offers new insights and future directions.

2 Related work

2.1 Locomotion in telepresence

The locomotion of telepresence systems can be enacted in multiple ways, most often with either full manual control by using a keyboard or a joystick, or with semi-autonomous capabilities that require localization and mapping in the environment. Enabling point to goal, or waypoint navigation, has been helpful for less trained operators (Kristoffersson et al. 2013).

Safe navigation is one major requirement for telepresence robots in settings such as elder home care (Laniel et al. 2021). The communication delay that introduces the mismatch between the display that the operator sees and the controls that the operator sends to the remote robot often degrades performance and can make the safe navigation of such a telepresence system difficult (Das and Dobie 2025). This latency was also mentioned as one of the biggest bottlenecks in immersive telepresence locomotion using real walking (Spada et al. 2019). Predictive displays have been offered as a framework to provide a promising solution to this problem (Das and Dobie 2025). These systems provide a predicted state of the robot's position based on the control inputs and try to show the actual movement of the robot regardless of the system latency. The illusion of self-motion (vection) can be exploited to support locomotion (Riecke 2011). During control latency, vection could provide immediate feedback to operators, improving the perceived response. However, this approach carries a potential risk of increased VR sickness, which must be carefully addressed (Laukka et al. 2025).

2.2 Sickness

Whenever immersive technologies such as HMDs are used, users may experience VR sickness, which remains a major barrier to widespread adoption. The motion characteristics of the user traveling in the virtual environment while wearing an HMD have been identified as one of the main contributors to this effect (Chang et al. 2020; LaViola Jr 2000). Although these factors might stem from various different sources, VR sickness generally increases when there is a mismatch between the physical movements of the user's head and the visually simulated motion presented in the HMD. Examples of such mismatches include system latency, display flicker, and locomotion techniques that induce vection (Chang et al. 2020). Similar effects have also been reported in the context of telepresence (Suomalainen et al. 2021).

There is ongoing research in immersive telepresence to find ways to mitigate this sickness. Unwinding or decoupling the rotations of the robot from the camera view is one way to reduce the mismatch experienced and thus reducing VR sickness and improving comfort (Cash and

Prescott 2019; Kulisiewicz et al. 2025). Another interesting research direction is including human comfort considerations in robot path planning. Instead of selecting narrow hallways, the robot could prefer open areas to reduce close-by objects to reduce optical flow, or minimize the amount of turns (Suomalainen et al. 2021). Similarly to VR applications, the reduction of the field of view (FOV) and blurring the peripheral areas have also shown to help reduce sickness in 360° videos, which can share similarities with riding onboard a mobile immersive telepresence robot (Groth et al. 2021). Finally, our previous work shows that redesigning the locomotion interface to hide all the sickness inducing motions of the camera is a very powerful way of mitigating the VR sickness in immersive telepresence (Laukka et al. 2024).

2.3 Latency

Some research has investigated the sources of latency when streaming equirectangular 360° video from a camera to a client. A major contributor to this latency appears to be poorly optimized server-side processing for 360° streaming (Yan and Yi 2022). Yan et al. dissected the event-to-eye latency by estimating the delay between all the components in the whole streaming pipeline. While the metadata construction and one-time processing during stream initiation causes most of the delay (about 2.4 s), the rest of the frames do not undergo this delay but are nevertheless affected by the propagation of the previous delay. Even if optimized away, their optimal event-to-eye delay, where the server was in the same room as the client, was around 240 ms in 1440p video resolution. Additionally, the delay is positively correlated with the resolution. Article by Nadir et al. (2021) reported approximately 1.5 s of glass-to-glass latency when streaming 360° video from a Vuze XR camera to an Oculus Quest headset at 30 fps. Another study reported approximately 700 ms of glass-to-glass latency when streaming 360° video from an Insta360 ONE X camera using a more optimized pipeline (Taleb et al. 2022). These latencies vary considerably across 360° streaming systems and can remain substantial, depending on system configuration, optimization, and network conditions.

Advances in wireless communications show some promise for these latency problems, as 5G has been shown to significantly outperform WIFI and Ethernet in streaming 360° video (Liu et al. 2022). However, Liu et al. (2022) emphasize that while 5G helps with respect to the communication side of the delay, the major bottleneck seems to manifest on the computational side. A similar observation was mentioned by Yan and Yi (2022).

2.4 3D reconstruction in telepresence

Reconstructing physical spaces into virtual replicas is a wide area of research focusing on computer vision and computer graphics. The implementation of these techniques has increased with the emergence of affordable, consumer-grade depth cameras. Existing systems can be broadly categorized as either image-based solutions or depth camera-sensor-based solutions (Fadzli et al. 2023). Within each category, the systems can be further divided into single- or multi-camera configurations depending on how many cameras are used to capture the remote environment. Research into multi-camera capturing scenes for reconstructing the view or person into a virtual scene or virtual character dates back to the 1990s (Kanade et al. 1997; Fuchs et al. 1994). The key to selecting an appropriate 3D reconstruction method is dependent on the task at hand (Fadzli et al. 2023). For example, choosing a high fidelity reconstruction may be essential for recognizing facial expressions (Lawrence et al. 2021). However, increased reconstruction fidelity often comes at a cost of greater computational power requirement, which can cause higher processing times and longer network latency. This trade-off can make it more difficult to interact or communicate through 3D reconstructed immersive environments (Mulligan and Daniilidis 2000). Higher fidelity and real-time throughput promotes a higher sense of presence (Cummings and Bailenson 2016; Slater 2009) and the feeling of being there can be achieved even in plain 3D reconstructed environments (Towles et al. 2003).

In teleoperation, 3D reconstructions have been used to control remote robots and improve situational awareness. Instead of only showing the robot's POV camera view to the operator, these systems also present a 3D reconstructed environment from the remote location, which can be viewed from an exocentric perspective either

through an HMD (Stotko et al. 2019; Stedman et al. 2022) or from a regular computer screen (Ferland et al. 2009). Stotko et al. (2019) used a similar approach to our solution to manually control a teleoperated robot through a 3D reconstruction enabled by virtual reality. However, their system provides an exocentric perspective of the robot, whereas our solution uses an egocentric perspective. They found improvements to situational awareness and navigation precision compared to a purely video based control. However, the use of the VR interface hindered the users' time to complete the navigation task. Baker et al. (2020) tested a fully virtual simulation of a mobile robot capable of waypoint navigation, where participants pointed to locations that the robot could reach while maintaining an onboard viewpoint during movement. Their interface showed benefits over direct control. However, VR sickness remained an issue for the participants.

To the best of our knowledge, research on using a fully embodied telepresence robot and 3D reconstruction to explore an environment, especially with a 360° camera enabled setup, is very limited. A closely related study by Li et al. (2024) overlaid a stereo projection over a 3D reconstructed photorealistic environment, improving the operator's situational awareness, performance and user preference, while driving the robot. However, similar to many 360° camera-based telepresence robots (Zhang et al. 2018b), their approach was still affected by VR sickness resulting from continuous control. In our previous work, we introduced a novel prototype which showed that immersive telepresence can greatly benefit from using 3D reconstruction as a locomotion interface, enabling teleportation as a locomotion method (Laukka et al. 2024). This paper aims to replicate and extend these findings by deploying a complete system capable of creating this VR interface using real-time 3D reconstruction.

3 Apparatus

3.1 Mobile robot

As the mobile robotic platfrom, Husarion ROSBot XL was used in both studies, equipped with a 360° LIDAR capable of mapping the surroundings in a 2D plane. An Insta 360 Pro 2 camera was attached on the robot streaming the 360° equirectangular video in 4k resolution to the computer running the virtual environment using Unity Game Engine[1]. It should be noted that in the previous study we used a lower, 1080p resolution, in order to achieve slightly lower latency, however, in hopes to lower the VR sickness for the follow-up study, we increased the video resolution to 4k. The robot is shown in Fig. 1.

The latency of the 360° video stream was estimated by filming a two-minute clip that captured both a physical timer and the same timer rendered in Unity while the robot was driven around. The recording was then processed with Tesseract[2] (an optical character recognition engine), which extracted the timer values from each frame and computed each frame's time difference between the two displays. The measured video streaming latency in 4k resolution for the setup was ($Mdn = 1.8s, sd = 0.2s$). The latency was slightly higher in study 2 compared to study 1, where the latency was measured around 1.6 s. due to the lower video resolution. For the reconstruction in the second study, we attached an Intel Realsense d455 RGB-D camera onboard the robot. This camera was wirelessly connected to an edge computer that handled the reconstruction of the remote environment via USB/IP protocol.

3.2 VR system

A Valve Index was used as the HMD in both studies to display the 360° camera stream and the virtual environment. In both studies, Valve Index controllers were used for teleportation-based locomotion. The Valve Index controllers are two separate controllers in each hand. The controllers are accurately tracked with external lighthouses of the VR system. Tracking enables the ability to point locations with your hands for teleportation, a typical locomotion method for VR applications (Cherni et al. 2020). For the continuous control method, a Logitech F710 controller was used. This controller is a typical game controller with two joysticks (one for each thumb). This was chosen for the baseline control method to separate the locomotion method completely from the teleportation method and to provide a potentially

[1] https://unity.com/
[2] https://github.com/tesseract-ocr/tessdoc

familiar controller for a driving-like task (Rupp et al. 2015).



Fig. 1 Telepresence robot used in the studies, 360° camera on top, RGB-D camera attached in the middle.

4 Research questions

The aim of this project was to advance immersive telepresence by developing techniques that address two major barriers to real world use: VR sickness and degraded performance in high-latency conditions. Improving user comfort and overall usability is essential for broad adoption of telepresence systems (Kristoffersson et al. 2013; Aguilar et al. 2025).

The research questions were as follows:

RQ1: Does implementing locomotion through a 3D reconstructed interface fundamentally improve the usability and experience of immersive telepresence systems?

RQ2: To what extent can a real-time reconstructed virtual environment replicate the benefits of a pre-modeled VEIPE in supporting teleportation-based locomotion in immersive telepresence?

5 Study 1 (RQ1)

The purpose of study 1 (S1) was to answer RQ1. Direct control has been the traditional way to control telepresence robots (Björnfot 2021). This was chosen as our control condition in S1. This was then compared to the condition where the operator would use the 3D reconstructed interface to teleport themselves to other locations around the virtual room, meanwhile the robot autonomously navigates to the selected location. Once the robot reached the chosen destination, the 360° video stream was again shown to the operator. This condition was called VEIPE. In S1 our primary hypothesis (H1) was that participants' VR sickness would be significantly lower in the VEIPE condition compared to the control condition, as measured by the total weighted simulator sickness questionnaire (SSQ) score (Kennedy et al. 1993). Additionally, we hypothesized (H2) that participants' navigation performance would increase in the VEIPE condition, compared to the control condition, measured by the number of navigation goals reached in the given time. A navigation goal was reached when an operator navigated within a 20 cm radius of a colored ribbon. Finally, we hypothesized (H3) that users would prefer to use the VEIPE condition navigation method over the control condition navigation method, by the forced choice question "Which method would you choose for this task if you had to pick one?" As an exploratory result, we also measured the subjective workload perceived by the participants using the NASA-TLX questionnaire (Hart 2006). These directional predictions along with the sample size and analysis methods were preregistered in the Open Science Framework (OSF) at https://osf.io/qg2sc.

5.1 Methods

5.1.1 Conditions

In S1 control condition, the participants were provided with only the 360° video stream, that had around 1.6 s event-to-eye latency. The participants controlled the telepresence robot using a Logitech F710 controller with a joystick to directly send translational and rotational commands to the robot. In S1 VEIPE condition, on top of the 360° video stream, the participants could switch their view between the video stream and the 3D reconstructed version of the room, which was pre-modeled beforehand. For navigation in the VEIPE condition, they were required to switch to the virtual environment and use a VR controller to teleport around the room. The robot then

autonomously navigated to the selection location as the coordinates of the virtual environment matched roughly the real world coordinates for the robot. The coordinates of the virtual environment and the real physical environment were aligned using a marker. Once the robot reached the participant selected location, the view would switch back to the 360° video stream. Compared to the control condition, the VEIPE condition control method does not produce a perceivable control-delay latency to the operator. Both of these control methods are depicted in Fig. 2.

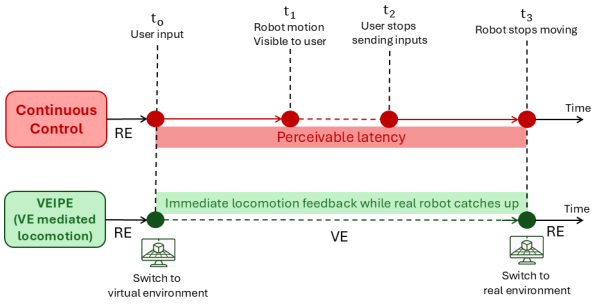


Fig. 2 Control conditions depicted in the study. In the continuous control condition, users continuously perceive the real environment (RE). In VEIPE, users are temporarily switched to the virtual environment (VE) during locomotion, where immediate feedback is provided while the real robot state catches up.

5.1.2 Procedure

The study protocols were approved by the ethics committee of the University of Oulu. The participants gave written informed consent before starting the experiment. The study was conducted in two sessions scheduled one to seven days apart to reduce possible carryover effects, as VR sickness can linger beyond a single session (Dużmańska et al. 2018). The participants completed one condition each session, and the order of the conditions was counterbalanced between participants. In both conditions, the navigation task was identical. Participants had to navigate through the environment by passing under colored ribbons in a pre-defined order. When the participant reached the correct ribbon within a 20 cm accuracy, the navigation goal was logged as a success. They had four minutes to get as many navigation goals as possible. Additional details are provided in the prior work (Laukka et al. 2024). After each condition, the participants filled out questionnaires including the SSQ and NASA-TLX. Following the second session, they also answered the preference question related to H3.

5.1.3 Measures & Analyses

We tested H1 using the SSQ Total Score, indicating the overall level of sickness of a participant after exposure to each condition. Although newer measures of VR sickness have been proposed, such as the VR sickness questionnaire (VRSQ) (Kim et al. 2018), and the Fast Motion Sickness Scale (FMS) (Keshavarz and Hecht 2011), the SSQ is still the most used and standard way to measure VR sickness (Chang et al. 2020). In S1, we conducted an a priori power analysis to determine the required sample size of 32 participants, based on previous literature comparing teleportation and continuous locomotion methods using the SSQ total score as an outcome measure. Therefore, to remain consistent with the power analysis and facilitate comparisons with a broader range of studies, we chose to use the SSQ total score as our outcome measure. A Wilcoxon-signed-rank test (one-sided, alpha = .05) was used to compare the SSQ total scores between the two conditions. This test was appropriate, as we did not expect the total SSQ score to be normally distributed.

The 95% confidence intervals for the medians were estimated using the percentile bootstrap method with 10,000 resamples drawn with replacement. The same method was used for all median confidence intervals reported throughout this paper.

H2 was tested based on the number of navigation tasks that participants could complete in the given time window in each condition. The navigation task was marked as success after the participant reached beneath the correct ribbon within a 20 cm accuracy. The total scores between the conditions were then compared with a Wilcoxon-signed-rank (one-sided, alpha = .05) test for matched pairs. Similarly to SSQ, we did not expect the navigation performance to be normally distributed.

Finally, we tested H3 with a forced choice question which asked participants which method would they prefer to use in this type of teleoperated robot. The proportions of answers choosing the

VEIPE method were then analyzed with an exact binomial test.

Because we only had three related confirmatory analyzes in the first study, and four in the second study which were preregistered prior to data collection and tested using one-sided tests, we did not apply additional Type I error control methods. However, we note that even when applying a conservative Bonferroni-corrected significance level (alpha = .0125), none of our conclusions regarding the confirmatory outcomes would change.

5.2 Results

5.2.1 VR sickness (H1)

The SSQ questionnaire was used to measure the amount of VR sickness after each condition. The VEIPE condition ($Mdn = 0, CI = [0, 7.48], IQR = 14.96$) was found to induce significantly less VR sickness compared to the joystick condition ($Mdn = 20.57, CI = [11.22, 50.49], IQR = 53.30$), $Z = 4.02, p < 0.001, r = 0.71$. The SSQ results are plotted in Fig. 3

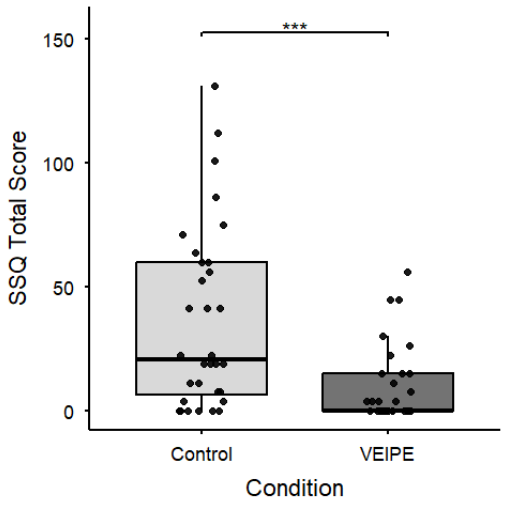


Fig. 3 SSQ Total Score between conditions

5.2.2 Navigation performance (H2)

Navigation performance was measured by counting the total number of navigation goals successfully reached within the given time. Navigation goals reached in the VEIPE condition ($Mdn = 10, CI = [9, 11], IQR = 3$) indicated a significant improvement over the control condition ($Mdn = 7, CI = [6, 8.5], IQR = 4$), $Z = 3.82, p < 0.001, r = 0.68$. The navigation performance between conditions is depicted in Fig. 4.

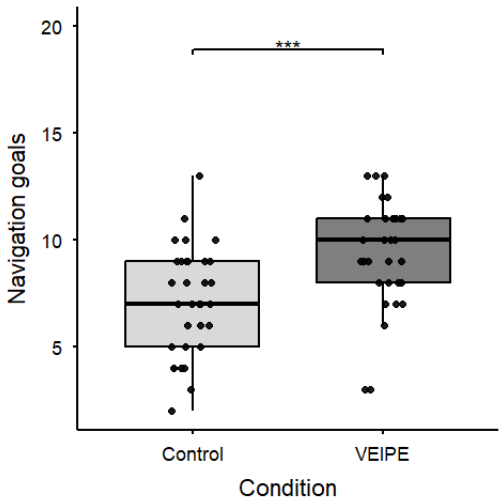


Fig. 4 Navigation goals reached between conditions

5.2.3 Preference (H3)

The participants were given a forced choice question: "If you would need to control a telepresence robot, which method would you choose: Teleporting or continuous control?" with the response options: "Continuous control/Joystick" or "Teleporting". 25 out of 32 chose the answer: "Teleportation." indicating that the participants preferred the VEIPE condition over the control condition. This result was statistically confirmed with an exact binomial test (one-sided, alpha = .05), $p < 0.001$.

5.2.4 Exploratory results

In addition to our preregistered hypotheses, we measured the perceived subjective workload and presence during both conditions for exploratory analysis. The subjective workload was measured with a common variation of the NASA-TLX measure called RAW-TLX (Hart 2006). This version is simplified and easier to administer than the traditional NASA-TLX questionnaire. However, the

effectiveness of the RAW-TLX has been shown to vary compared to the NASA-TLX (Liu and Wickens 1994; Hendy et al. 1993). For convenience, the RAW-TLX was selected for the study.

The subjective workload in the VEIPE condition ($Mdn = 4.5, CI = [3, 5.17], IQR = 3.71$) indicated a significant improvement over the control condition ($Mdn = 7.75, CI = [7.08, 9.67], IQR = 4$), $Z = 4.07, p < 0.001, r = 0.72$. The subjective workload measured with RAW-TLX between conditions is depicted in Fig. 5

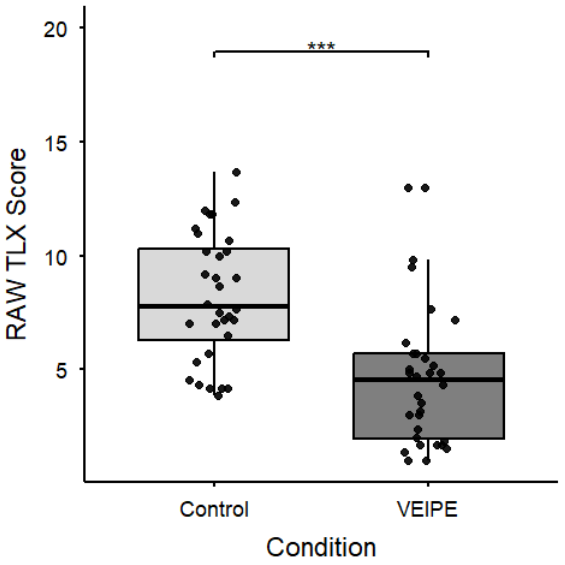


Fig. 5 Perceived subjective workload between each condition, lower is better.

Finally, presence was measured using the Slater-Usoh-Steed presence questionnaire (Usoh et al. 2000). Participants assessed their own subjective feeling of presence in the remote environment in both conditions. These scores were then compared using a Wilcoxon-signed-rank test (two-sided, alpha = .05). However, we found no significant difference between the conditions. Median presence was the same in both conditions, ($Mdn = 1, IQR = 2$), Z = 0.89, p = 0.19, r = 0.16.

5.3 Discussion

The results from S1 supported all three hypotheses, H1, H2 and H3, providing an answer to RQ1. In short, teleportation locomotion through a 3D reconstructed interface improves the usability and user experience of immersive telepresence systems by reducing VR sickness and increasing navigation performance compared to a standard alternative. Moreover, the participants preferred the locomotion using VEIPE over the traditional manual control. In addition, the exploratory findings suggest that the 3D reconstruction interface may also reduce the subjective workload under high-latency conditions. The results as a whole indicate that in immersive telepresence systems using 360° video streaming, a framework similar to VEIPE is a superior locomotion method compared with a more traditional approach, particularly when the goal is to reduce VR sickness or to enable effective navigation when using telepresence robots under substantial latencies.

Our results were limited by the use of a pre-modeled 3D reconstruction and the relatively simple navigation task. Because the reconstruction was created in advance, the robot's movement was limited to a previously known environment, which does not reflect a realistic real-world scenario with dynamic or unknown environments. Furthermore, as the reconstruction was pre-modeled, it is unclear whether a lower fidelity or a constantly updating/partial reconstruction would cause VR sickness. Finally, the environment itself was fairly small, which made the task in the previous study highly simplistic, since the distances between the navigation goals were very short.

To address these limitations of the prototype study, we developed a robot capable of being placed in any traversable unknown static environment and reconstructing the remote physical space in near real time, enabling its use as a virtual environment interface. Moreover, we implemented a more realistic task to generalize the results of S1.

6 Study 2 (RQ2)

As S1 showed promising results, the goal of S2 was then to investigate whether we can replicate the results with an actual real-time reconstructed virtual environment instead of a pre-modeled one. In addition, the aim was to address the limitations of S1, such as using a more complex task that requires navigation and making the results more generalizable by implementing a robot capable of navigating any unknown static environment.

The hypotheses, sample size, measures and analysis methods (including any directional predictions using one-sided tests) were preregistered to OSF at https://osf.io/46eyf. Our primary hypothesis (H1) was that in an immersive telepresence scenario, navigation using teleportation through the VEIPE real time (VEIPE RT) condition will result in significantly lower VR sickness compared to navigation using the control condition, as measured by the SSQ. In addition, we hypothesized (H2) that task efficiency will be higher in the VEIPE RT condition compared to the control condition as measured by the number of tasks successfully completed in a simulated elderly-assisting robot task requiring navigation. Since S1 showed evidence that the method also reduced subjective perceived workload, we also hypothesized (H3) that using the VEIPE RT condition will result in a lower subjective perceived workload compared to the control condition, as measured by the overall RAW-TLX score. Finally, we hypothesized (H4) that the VEIPE RT condition will be the preferred method of navigation over the control condition, as measured by a binomial forced-choice question: "If you needed to control a telepresence robot for navigating around, which method would you choose: teleportation using the virtual interface, or continuous control using the joystick?".

6.1 Methods

6.1.1 Participants

Analysis of the S1 results revealed large effect sizes for differences between conditions in SSQ total scores, subjective workload, and task efficiency (dz >= 0.89). An a priori power analysis for a one-sided Wilcoxon-signed-rank test using a minimum asymptotic relative efficiency (ARE) parent distribution setting showed that a sample size of 18 participants would be sufficient to achieve a power of 0.95 at alpha = .05. However, for greater robustness, the target sample size was increased to 20. This rounding of the sample size allows us to detect slightly lower effect sizes (dz >= 0.83).

The University of Oulu Sona System was used to obtain a sample from the broader university community. Studies are advertised through this system, from which participants can voluntarily sign up to participate in available studies. The participants were compensated with a gift card worth 10 euros for their participation in the study. Participants who had participated in S1 were excluded from participating S2, based on our exclusion criteria.

Of the 20 participants, 15 were male, four were female, and one preferred not to disclose their gender. The participants ranged in age from 19 to 53 years ($M = 27.4, sd = 8.32$). All participants reported normal or corrected-to-normal vision. The participants were also asked how often they used VR systems and played video games. Regarding VR use, nine of the 20 participants had used VR once or twice, six had used VR once or twice a year, five had used VR once or twice a month, indicating that all had some prior experience in VR systems, but none could be considered frequent users who would be using VR more than once per week. For video game experience, six answered that they had played video games once or twice, six answered to play video games once or twice a year, five answered to play video games once or twice a month, one answered to play video games once or twice a week, and two answered to play video games several times a week. Similarly to VR systems usage, we had no daily video game players in the sample.

6.1.2 Conditions

For S2, we used a study design similar to that used in S1. The study consisted of two conditions that differed in the control method used to operate the telepresence robot. The control condition was the same as in S1: Participants navigated the robot continuously while viewing only the 360° video stream. The experimental condition is referred to as VEIPE RT, which differs from S1 by employing the real-time 3D reconstruction of the remote environment that was then used as the navigation interface with teleportation as the locomotion method.

In the VEIPE RT condition, participants needed to switch the view to the virtual reconstruction and point locations with a VR controller to move around the room. An example of a view of a participant from one position is shown in Fig. 6. Once the participant selected a location with the controller, they would instantly teleport to that location in the reconstruction. They would then have to wait until the robot reached that same position in the real physical environment.



Fig. 6 The two different views for the user. 360° video stream on the left and the 3D reconstructed virtual environment on the right. The user was able to change between these views with a press of a button.

The robot's location was visible in the virtual environment constantly. After the robot reached the participant's selected location, the view would change back to the 360° video stream. This comparison of the control conditions is shown in Fig. 2.

6.1.3 Procedure

The study protocols were approved by the ethics committee of the University of Oulu. Consistent with S1, S2 was conducted in two separate sessions to reduce the potential carryover effects related to VR sickness. At the beginning of each session, participants signed an informed consent form and received brief information about the study. They then completed a short background questionnaire using an online survey tool. The experimenter then explained that they would use a teleoperated elder-care robot to complete a list of observational tasks in a remote location, and demonstrated a couple of examples not related to the actual tasks. Before starting the actual experiment in each session, participants completed a separate practice task to practice each method of navigation. After finishing the practice task, they proceeded to the main tasks.

For a more realistic scenario, S2 was conducted in a larger environment. This environment consisted of two separate spacious rooms: one functioned as the "remote" room, shown in Fig. 7, allowing the robot to navigate over longer distances, while the other served as a separate local environment, shown in Fig. 8, from which the participants controlled the remote robot. In the remote room, the participants had to go to different locations doing various observational tasks such as: checking whether there were pills in a container, checking whether a mannequin was sitting or standing, checking whether there was anything plugged in an electrical outlet, checking the temperature of the room from a wall, checking notes from a piece of paper, and whether a trash can was full or empty. Some of the tasks would repeat. These tasks were designed to represent a real use-case, such as checking up on an elderly person. Telepresence robots have been studied in a similar scenario, and a previous study has identified navigation as a challenge due to limited FOV (Niemelä et al. 2021), which can potentially be solved with 360° cameras. The participant was shown the next task in the HMD with a location target. The task instructions appeared as a text box positioned towards the side of the user within the panoramic sphere. For example: "Check the laptop battery on the table, center of the room." The participant was required to respond orally to the question. A task was logged as complete once the participant correctly answered it, and the participant could then move on to the next task.

After the time limit of 6 minutes ran out, the screen went blank and they were instructed to remove the HMD and fill out another questionnaire with the online survey tool. This questionnaire included the SSQ, NASA-TLX, and system usability questionnaire (Brooke 1996). After the second session, they were also asked to pick which of the two navigation methods they preferred for this task.

6.2 Reconstruction

In our previous study (Laukka et al. 2024), a pre-modeled virtual environment was used as



Fig. 7 Remote environment for the robot seen far in the background.



Fig. 8 Participant controlling the robot from the local environment.

the reconstruction. Extending this work, the present study implements a real-time reconstruction method in an actual environment. For the real-time reconstruction, NVIDIA nvblox (Millane et al. 2024) was chosen because it provides a fully GPU-accelerated reconstruction pipeline. Its approach is based on the truncated signed distance function (TSDF) and the marching cubes algorithm (Lorensen and Cline 1998). Moreover, NVIDIA nvblox supports dynamic environments through dynamic occupancy mapping and people segmentation. However, these capabilities were not evaluated in this study. Although other reconstruction frameworks exist, nvblox appears to be unique in avoiding CPU-based processing entirely. This, along with direct library support for ROS, makes nvblox particularly well suited for mobile robotics and was thus chosen for this study. The 3D reconstruction was handled by an edge computer running on a Nvidia RTX 3090 TI graphics card, an AMD Threadripper PRO 3955WX CPU, and 64 GB of RAM.

The edge computer transmitted the reconstructed mesh to the laptop running the Unity application over ROS2 TCP connection as triangle indices, vertex positions and colors, and block indices. Although this pipeline is relatively fast, in our setup we intentionally used a lower mesh update rate and buffering to preserve a high frame rate in Unity. The processing time of the reconstruction in our setup varies, but was estimated to be around 300 ms. This was measured by recording a 240 FPS video showing the robot turning alongside the Unity display, then counting the number of frames between the physical motion and the corresponding newly visible mesh chunk in Unity. This setup was severely limited by the wireless connection of our depth camera. Although NVIDIA nvblox can easily reconstruct a mesh with a resolution of 1 cm, the resolution of the reconstruction was set to 5 cm in our setup, as the system was not able to remain stable when using a more accurate resolution with the added latency of the wireless connection. However, this limitation can be circumvented by using a better computer equipped with a CUDA enabled graphics card carried by the robot, thereby eliminating the need for a wireless connection. For locomotion, the lower fidelity was considered sufficient.

6.2.1 Measures & Analyses

As S2 was designed to replicate the findings of S1 in a real-time reconstructed environment, we used the same measures and statistical procedures to test the previously established hypotheses. Specifically, H1 was tested using the SSQ Total Score, while H2 was tested based on the number of successfully completed navigation tasks. As in S1, the outcomes were compared between conditions using one-sided Wilcoxon signed-rank tests (alpha = .05).

In addition, we introduced a new hypothesis H3 concerning perceived workload, which was tested using the NASA-TLX questionnaire. The RAW-TLX score was calculated as the average of the six components of the NASA-TLX questionnaire, providing an estimate of the overall perceived workload experienced during navigation in each condition. As we had already collected this measure for exploratory purposes in S1, we

included it as an additional confirmatory outcome in S2 to further assess the usability of the experimental navigation method. The RAW-TLX scores between the two conditions were compared using a one-sided Wilcoxon signed-rank test (alpha = .05).

Finally, H4, concerning user preference, was tested using a similar forced-choice question and exact binomial test as in S1.

6.3 Results

6.3.1 VR sickness (H1)

Participants filled in the SSQ after exposure and their responses were used to calculate the SSQ total score. The analysis revealed that the VEIPE RT condition ($Mdn = 13.09, CI = [1.87, 22.44], IQR = 22.44$) induced significantly less VR sickness relative to the control condition ($Mdn = 44.88, CI = [20.57, 87.89], IQR = 80.41$), $Z = 3.09, p = 0.002, r = 0.69$. The VR sickness result obtained in S2 mimics the result of S1. Fig. 9 shows the VR sickness result in S2. This pattern suggests that teleportation remains superior to traditional navigation even in a partial reconstruction with a lower fidelity than that used in S1, despite higher sickness scores in both conditions compared to S1. The higher VR sickness is possibly due to the longer duration of the experiment.

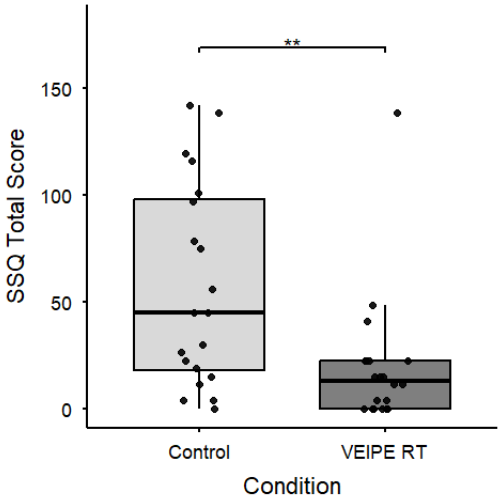


Fig. 9 SSQ Total Score between conditions

6.3.2 Performance (H2)

Performance was measured by the number of navigation tasks the participants were able to complete successfully within the given 6 minute time limit. Participants in the VEIPE RT condition ($Mdn = 7, CI = [6, 8], IQR = 2$) managed to complete significantly more navigation tasks compared to how many they reached in the control condition ($Mdn = 5, CI = [4.5, 5.5], IQR = 2$), $Z = 3.61, p < 0.001, r = 0.81$. The results are shown in Fig. 10. The results indicate that in high-latency conditions the task performance in fully manual control degrades significantly. However, by using teleportation with a 3D reconstruction interface such as VEIPE, the effects of the high latency on performance can be mitigated.

Compared to S1, the participants reached fewer navigation goals in both conditions, though this discrepancy is likely due to the fact that the distances were longer and the task required observation in addition to navigation, which took more time than simply reaching the navigation goal in S1.

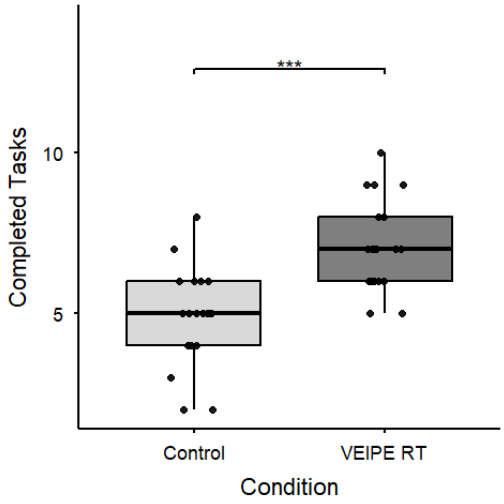


Fig. 10 Completed navigation tasks between conditions.

6.3.3 Subjective workload (H3)

The subjective perceived workload of the participants was measured after each condition. The participants filled in the standard NASA-TLX questionnaire, from which we derived the RAW-TLX score. This score is an average of the

NASA-TLX components: mental demand, physical demand, temporal demand, performance, effort, and frustration level, giving a rough estimate on the participants' perceived workload. In the VEIPE RT condition ($Mdn = 3.92, CI = [2.50, 5.25], IQR = 3.33$), the subjective workload was significantly lower than in the control condition ($Mdn = 5.92, CI = [5.25, 9.42], IQR = 4.79$), $Z = 2.55, p = 0.005, r = 0.57$. The results are shown in Fig. 11.

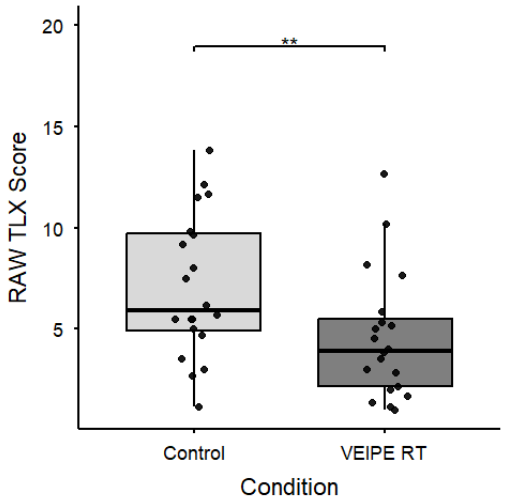


Fig. 11 RAW-TLX score between conditions, lower is better.

6.3.4 Preference

The preference of the navigation method was measured by using a binomial forced-choice question: "If you needed to control a telepresence robot for navigating around, which method would you choose: teleportation using the virtual interface or continuous control using the joystick?" 13 out of 20 answers chose the VEIPE RT condition and 7 chose the control condition, revealing no significant preference towards the VEIPE RT condition (one-sided, alpha = .05), $p = 0.13$.

6.3.5 Exploratory

As an exploratory analysis, we measured system usability with the system usability scale questionnaire. The questionnaire includes 10 questions that the participants answer on a 5-point Likert scale. The overall usability score is then calculated from the responses and can be used as a rough estimate of the usability of the system. The VEIPE RT condition ($Mdn = 70, CI = [62.5, 78.75], IQR = 18.13$) had a significantly higher score than the control ($Mdn = 66.25, CI = [51.25, 72.5], IQR = 30.63$), $Z = 2.25, p = 0.024, r = 0.50$. The results are shown in Fig. 12.

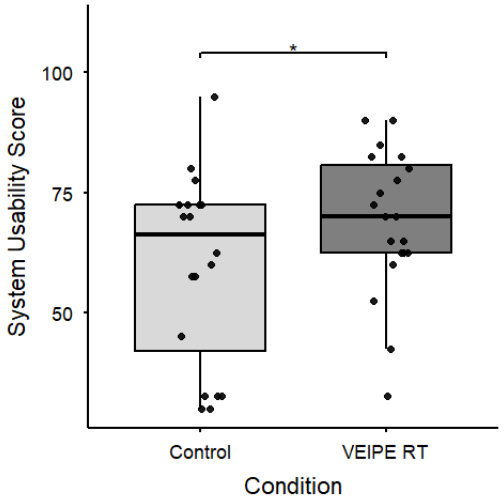


Fig. 12 System Usability Score between conditions.

6.4 Discussion

The results support our preregistered hypotheses H1, H2, and H3 in S2. However, surprisingly, we did not find support for H4. Participants in the VEIPE RT condition experienced significantly less VR sickness, reported significantly lower perceived workload, and performed better overall. Despite these improvements, many participants still preferred the control condition. Review of open-ended responses suggested that participants who preferred the control condition tended to like being in full control of the robot if they were confident in their use of the manual joystick. In addition, one participant reported that they felt more disembodied in the VEIPE RT condition and thus preferred the control condition. Individual differences regarding sense of control and level of embodiment represent interesting research directions for future work.

A minor improvement in usability was observed for the VEIPE RT condition relative to

the control, as measured by the system usability scale. However, the median score of 70 remains only slightly above the overall median reported in studies using the system usability scale (Bangor et al. 2009), roughly corresponding to a rating of "Good" usability. This outcome suggests that there is still room for improvement in the usability of our system. Anecdotally, one participant mentioned after the experiment that if the navigation method in the VEIPE RT condition was a bit more user friendly, they would have chosen that as the preferred method. In particular, the participant found it frustrating that the robot struggled to reach the target position when they teleported too close to an object, requiring the participant to move slightly farther from the object to adjust. It is possible that low usability partly explains the variability in the preference results. However, it should be kept in mind that the control condition achieved similar rating with the system usability scale. In addition, the sample size of 20 is quite small, which means that individual differences may have led to only a modest effect size for preference which we could have lacked statistical power to detect. Sensitivity analysis reveals that the study had 80% power to detect preference imbalances of only 80/20 or stronger.

7 General Discussion

The prototype study S1 revealed strongly positive results when using VEIPE-enabled teleportation to improve simple navigation of an immersive telepresence robot. In order to ensure that these findings were not limited to a pre-modeled virtual reconstruction, the findings were replicated in a second study using an immersive telepresence robot with real-time 3D reconstruction. Significantly lower VR sickness was measured in both studies when using the VEIPE framework. In S2, overall sickness was slightly higher in both conditions, possibly due to a longer exposure within the immersive setup. This phenomenon is consistent from prior research on VR sickness (Davis et al. 2014; Risi and Palmisano 2019). However, it remains unclear whether a partial or continuously updating virtual environment influences VR sickness, as a slight increase in VR sickness was observed from S1 to S2. The results of S1 are not directly comparable to those of S2 in relation to VR sickness, as the exposure time is significantly different. This question should be examined in future studies. Moreover, the imbalanced gender distribution may limit the generalizability of the findings to the general population. Nonetheless, the generalizability of VEIPE in reducing VR sickness relative to the standard control method across different samples, tasks, implementation methods, and environments is a strength. Our findings support the benefits of point-and-click locomotion. However, unlike Baker et al. (2020), our method also reduced VR sickness by eliminating camera movement from user view by making teleportation locomotion method possible for telepresence.

A similar increase in navigation task performance was observed in both S1 and S2, providing evidence of a clear benefit for navigating through a 3D reconstructed interface with embodied immersive telepresence robots. In contrast, other implementations, such as the system proposed by Stotko et al. (2019), where the user controls the robot from an exocentric perspective, can reduce the speed of navigation when the control method is fully manual. A more optimized approach should benefit both the speed and precision of teleoperating robots, such as our solution, which uses a semi-autonomous control. This observation also aligns with the findings by Li et al. (2024) that 3D reconstruction as an aid improves task performance. Moreover, like Li et al. (2024) we also show an improvement in perceived workload when using 3D reconstructions to navigate a remote environment.

Based on the results of prototype S1 and the replicated results in S2 with a generalized application, there is strong evidence supporting the notion that using teleportation through a 3D reconstructed virtual environment to navigate an embodied immersive telepresence robot is superior to latency-inducing standard methods in minimizing VR sickness for users. In addition, the technique can improve navigation performance by up to 30% to 40% when control latencies are around 1.6 s to 1.8 s. Finally, the subjective perceived workload can be significantly lower when using a virtual environment as an interface to a physical environment compared to traditional control methods. In relation to our research questions RQ1 and RQ2, these findings provide clear support to our hypotheses.

For future work, it is important that more complex navigation methods, such as VEIPE, remain user-friendly and intuitive. For example, a navigation mesh should be integrated with the visual reconstruction to restrict navigation to positions that are physically reachable by the robot. In addition, comparing the two locomotion methods in a simulated virtual environment without latency would help to measure what is the baseline effect on the performance. This would also provide a clearer indication of whether latency significantly affects immersive telepresence and whether it contributes to VR sickness.

Although the reconstruction used in S2 had limited visual fidelity at a voxel resolution of 5 cm, all participants were able to navigate the environment and complete observational tasks. Some comments made by participants indicated that the scene should be "Better looking". Studying the level of reconstruction fidelity needed for different use-cases remains a very interesting research question. These reconstructions can range from a very low-fidelity point cloud representing the room dimensions to a photorealistic reconstructions utilizing deep neural networks such as Gaussian Splatting techniques (Kerbl et al. 2023).

8 Conclusion

With the exception of user preference, the findings of study S2 replicated those of the prototype study S1, providing further evidence that reconstructed virtual environments can effectively support embodied locomotion in immersive telepresence scenarios. The results indicate that using a framework like VEIPE can mitigate locomotion challenges arising from latency while minimizing VR sickness, thus improving overall locomotion experience compared to traditional navigation methods.

In general, this work contributes to the understanding of immersive telepresence locomotion by demonstrating the practical benefits of reconstructed virtual environments as an interface in realistic use cases, especially by enabling the use of conventional VR locomotion techniques such as teleportation. The results support both RQ1 and RQ2, suggesting that VEIPE can be used as a better alternative locomotion method to conventional solutions.

However, some limitations remain. The discrepancy in user preference needs further investigation. Designing the VEIPE interface from purely user-centered design can be a valuable future direction to improve usability, and this would help to make the system intuitive and easy to learn. In addition, the experiment was conducted in a controlled environment, which may affect the generalizability of the findings.

Future work should focus on different levels of fidelity of the reconstruction. Investigating trade-offs between minimal required reconstruction fidelity for different tasks and achieving higher presence and embodiment in higher fidelity reconstructions is a valuable and very interesting future direction. Bare point clouds can be enough for certain tasks, however, collaboration and communicating with other humans through VEIPE might require a very high fidelity. Finally, research on interactions and different locomotion methods in a more dynamic environment using this framework remains a subject of future work.

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Declarations

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Competing interests

Not applicable

Ethics approval and consent to participate

The protocols for both studies were approved by the ethics committee of the University of Oulu. Written informed consent was obtained from all participants before participation.

Consent for publication

Not applicable

Data availability

The data supporting the findings of this study are available from the corresponding author upon request, subject to participant privacy.

Materials availability

Not applicable.

Code availability

Available upon request.

Author contribution

All authors contributed to the conception and design of the research. The corresponding author performed the implementation, data collection and analysis, and drafted the manuscript. All authors revised the manuscript and approved the final version.

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