A Study of Preference and Comfort for Users Immersed in a Telepresence Robot

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Abstract—In this paper, we show that unwinding the rotations of a user immersed in a telepresence robot is preferred and may increase the feeling of presence or “being there”. By immersive telepresence, we mean a scenario where a user wearing a head-mounted display embodies a mobile robot equipped with a 360° camera in another location, such that the user can move the robot and communicate with people around it. By unwinding the rotations, the user never perceives rotational motion through the head-mounted display while staying stationary, avoiding sensory mismatch which causes a major part of VR sickness. We performed a user study (N=32) on a Dolly mobile robot platform, mimicking an earlier similar study done in simulation. Unlike the simulated study, in this study there is no significant difference in the VR sickness suffered by the participants, or the condition they find more comfortable (unwinding or automatic rotations). However, participants still prefer the unwinding condition, and they judge it to render a stronger feeling of presence, a major piece in natural communication. We show that participants aboard a real telepresence robot perceive distances similarly suitable as in simulation, presenting further evidence on the applicability of VR as a research platform for robotics and human-robot interaction.

I. INTRODUCTION

Telepresence robots are a rising trend in robotics, with commercial companies such as GoBe and Double marketing their robots as tools for hybrid meetings. However, these commercial robots do not make users feel like they really were at the robot’s location, due to, for example, the inability to look around: the robot should do a rotation to just explore the view. Additionally, this lack of immersiveness leads to a lack of presence, the feeling of “being there” [1], which is essential for a user to communicate naturally with the people around the robot.

Virtual reality has emerged in the robotics field to complement the trend of hybrid meetings, which have recently increased significantly. The advantage offered by integrated robotics-VR, such as shown in Fig. [1] is the increased immersion of the Head-Mounted Display (HMD), which can make the user really feel present. With the use of a 360° camera capable of capturing omnidirectional videos, instead of a standard camera used in the current commercial telepresence robots, the experience will be more immersive.

Fig. 1: Robotic telepresence: a user wearing an HMD can embody a mobile robot equipped with a 360° camera. Left: Dolly mobile robot platform and a 360° camera on a boom, used in this study. Right: the physical setup of our user study.

However, using an HMD can create side effects, namely VR sickness, with symptoms such as dizziness, headache, eye strain, blurred vision, vomiting, and nausea [2]. This is caused by a sensory mismatch between vision and the vestibular organ; when the user’s eye informs the brain about acceleration of the body, but the acceleration sensor in the form of the utricle and saccule in the otolith organ does not, and the result is a conflict with the information received by the brain [3]. In addition, feeling the immersiveness can also cause discomfort if objects are too close, or if rotations of the robot are surprising, issues that are not present in a conventional telepresence scenario [4], [5].

In this paper, we present a user study on immersive telepresence where participants embodied a real mobile robot that was equipped with a 360° camera and traversed a predefined path at a university campus. We explore unwinding the rotations of the user’s viewpoint, which has been shown to reduce VR sickness in a study based on a simulation [6]. This method negates the rotation of the user’s view relative to the robot, so that the direction of the view is determined solely by the user. We test the same three hypotheses that were confirmed about unwinding rotations in the simulation study. However, this time only the user preference of unwinding the rotations is confirmed; there is no statistically significant difference in user comfort or Simulator Sickness Questionnaire (SSQ) measures, a commonly used questionnaire for VR sickness. We hypothesize, based on answers to open-ended questions, that these different results are more likely due to simply a different sample than other issues such as video quality or the vibrations of the real mobile robot missing from the simulation study, even though the latter cannot be ruled out. These findings call for further studies with more participants with both simulated and real mobile robots. Additionally, we observe participants feeling present enough for these findings to be meaningful.
that 11 out of 32 respond (with either words or gestures) to people in the video waving or talking to the robot, even though the participants are told it is a recording; there is also a perceived difference in how present participants feel between the unwinding and coupled rotations conditions. Finally, we confirm that users perceive the distances to passing objects and the speed of the real robot similarly as in the simulation study, giving further justification to study telepresence and HRI with simulations in the future.

II. RELATED WORK

Most of the previous research investigating teleoperation and telepresence, the idea of embodying a robot equipped with a camera, used standard screen-based technologies, before consumer grade VR headsets and 5G networks [7]. There is an unprecedented opportunity to leverage these technologies to bring telepresence to a new level [8] [9]. The key improvement that an HMD can bring to telepresence is increased immersion, which in turn can lead to greater feelings of presence [10]. Standard telepresence robots equipped with 2D screens provide similar improvement over conventional videoconferencing by enhancing interaction and navigation tasks for remote users [11]; however, the feeling is still closer to video conferencing than really being there. Use cases for telepresence robots are, for example, distance education [12], telemedical consultation [13] and all kinds of remote collaborative work [14], [15].

While a lack of presence can reduce task performance [16], wider field of view improves awareness and immersion for the user of telepresence robots as well as tasks efficiency [17]. Using an HMD in telepresence for increased immersion has been reported to yield better results in many application domains including education [12], collaboration through conversation [18], scenarios for earthquakes [19], and advanced navigation for robots [20]. However, for immersive HMD-based telepresence to reach a wider audience, the comfort of the HMD user and reducing VR sickness needs to be studied further.

VR sickness typically occurs due to a mismatch between the real-world and perceived accelerations in an HMD [21]. Also, issues with hardware and content such as repeated motions often lead to nausea [22]. Several approaches have been introduced for reducing motion sickness, such as minimizing the optical flow to slow down motions [2], adding a rest frame to the user’s view [23], or using a narrow field of view [24]. However, an important aspect is to consider criteria based on human perception [25]. In multimedia, quality of experience (QoE) measures have been developed as system performance criteria [22]. Therefore, it is worthwhile to explore the design of robot motions that would reduce accelerations mismatches, and how such motions could be realized for robots used in immersive telepresence.

Besides telepresence, VR is becoming a popular technology in robotics research in general, especially in human-robot interaction, as VR enables cost-effective simulations of complex real world use cases. However, the applicability of VR simulations is an open question; how much can the results received in VR be generalized to the real world? There are a growing number of studies on the topic, such as the comparison of proxemics between robots and humans in VR and in the real world [26], robot navigation among people in VR [27], and designing robots for human-robot interaction in VR [28]. In this paper, we continue this trend by exploring whether participants aboard a real telepresence robot perceive objects or people similarly or differently (too close or too far) to a previous simulation study.

III. UNWINDING ROTATIONS

In [6], we introduced an approach for decoupling the user’s viewpoint from the rotations of the robot, which we called unwinding rotations. We present our approach applicable for mobile robots here for completeness; details on applying the method to robots with more complex motions than on a plane can be found from [6].

We consider a mobile robot moving in a two-dimensional plane. The discrete-time kinematic model of the robot is given as

\[
\begin{align*}
\dot{x}_k &= x_k + v_k \cos(\theta_k) dt \\
\dot{y}_k &= y_k + v_k \sin(\theta_k) dt \\
\theta_k &= \theta_k + w_k dt,
\end{align*}
\]

in which \((x_k, y_k)\) is the position and \(\theta_k\) is the orientation of the robot at time instance \(k dt\) with respect to an absolute reference frame and \(v_k, w_k\) are the control inputs corresponding to the linear and angular velocity with respect to a robot-fixed reference frame. We assume that the control input is kept constant for time window \(t \in [k dt, (k+1) dt]\).

Suppose that the robot orientation \(\hat{\theta}_k\) can be estimated and denote its estimate by \(\hat{\theta}_k\). Let \(R(\hat{\theta}_k) \in SO(2)\) be the rotation matrix corresponding to the robot orientation. Then, we can define unwinding rotations as rotating the camera frame such that any point \(p_c \in \mathbb{R}^3\) represented in the camera frame is related to the point \(p_c'\), whose coordinates are expressed in the rotated camera frame, through

\[
\begin{align*}
p_c' &= \begin{bmatrix}
R(\hat{\theta}_k)^T & 0_{2 \times 1} \\
0_{1 \times 2} & 1
\end{bmatrix} p_c.
\end{align*}
\]

This operation negates the rotation of the viewpoint caused by the robot rotation. Thus, the users need to rotate themselves in order to face the direction that the robot is facing or face the same direction in the virtual environment for the whole motion.

IV. CONDITIONS AND HYPOTHESES

In the unwound rotations (UR) condition, the user’s viewpoint does not change when the robot changes direction. In the coupled rotations (CR) condition, the user’s viewpoint rotates when the robot rotates.

We pre-registered the following three hypotheses in the Open Science Foundation (OSF, https://osf.io/cw7ef). They are identical to the confirmed hypotheses of a previous study with a simulated robot in a virtual environment [6] (https://osf.io/eks6t), as the goal of this study is to test the hypotheses with a real robot.
H1: Less VR sickness in UR condition as indicated by lower total weighted SSQ score.

H2: The UR condition is more comfortable as indicated by asking directly which was more comfortable (forced choice).

H3: The UR condition is preferred as indicated by asking directly which the user preferred (forced choice).

According to VR sickness theory, that a mismatch between vestibular system and vision induces sickness, we predicted in H1 that there will be less sensory conflict if the user performs their own physical rotations. H2 and H3 were under the general assumption that people avoid sickness, hence UR is most likely to be preferred and comfortable.

V. METHODOLOGY

A. Mobile Robot

We used a wheeled mobile robot Probot Dolly (Fig. 1 left) equipped with a 360° camera mounted on a vertical boom. The dimensions of the robot are 60 (L) x 40 (W) x 20 (H) cm. The robot uses 2 active wheels and 4 omni wheels so that the robot’s movement is based on a differential drive mobile robot (DDMR). The robot is equipped with a laser scanner and an odometer to move according to the direction of the navigation, which is controlled by a motion planning algorithm. The robot uses a client-server software architecture where a laptop hosts Robot Operating System (ROS2) galactic as the main operating system and as the server. The main control board of the robot is a Raspberry Pi 4 and it acts as a client. The client and the server communicate over a WiFi connection using the TCP/IP protocol. A laser connected to Ethernet port of the main control board is used for mapping (SLAM) and obstacle avoidance. The actuator integrated with the HAL sensor is driven by the VESC controller which is connected to the CAN-bus so that it can function as an odometer.

In ROS2, we used waypoint based navigation and dynamic window (DWB) approach as controllers to follow the path. The robot moved inside the building of the University of Oulu campus with a maximum speed of 0.7 m/s, a maximum rotating speed of 0.7 rad/s and a maximum rotational acceleration of 2.5 rad/s². The length of the path traversed by the robot is 61 meters, the route is shown in Fig. 2. Screenshots from the video are presented in Fig. 3. The minimum distance to the obstacles is 0.95 m and the minimum distance to the people is 1.2 m.

B. 360° Video

We used a commercial Kandao QooCam 8K camera to record 360° video as the robot moves in the environment. The camera was mounted on a vertical boom so that the center of the camera lenses was 155 cm above floor level. The camera captured a video of 7680x3840 pixels in resolution at 30fps with H.265 encoding. The duration of the video was 2 minutes 6 seconds, during which the robot rotated a total of 648.7°. This camera has a built-in IMU sensor, making it easy to estimate \( \dot{\theta}_k \) for (2). However, for earlier tests we also implemented unwinding rotations on a camera which did not have a built-in IMU; for such cameras the key point is the synchronization of the IMU and camera data. We also note that in these studies the unwinding rotations was performed as post-processing; adapting the method for online processing is part of future work once we establish that unwinding rotations is favored by the users.

The original video had equirectangular projection for the mapping between 2D textures and 3D direction vectors for tilling the surface of a sphere [29]. However, such a sphere suffers from seam-like artifacts commonly occurring around the poles [30]. We argue that seeing such seam-like artifacts would decrease immersiveness. To remove the seams, we constructed a uniform spherical grid that is originally transformed from a cube (cube-sphere) [31]. First, video textures from the equirectangular mapping are reconstructed into the cube mapping by shaders at the GPU level. Then, the video’s UV coordinates are uniformized with the cube-sphere’s UV mapping, using coordinates generated by the cube-sphere mesh generator, so that the image will be fully projected on the geometry. We render the video under the Unity engine on a desktop PC furnished with an Intel Xeon 3.80 GHz CPU, 32 GB RAM and NVidia Quadro RTX6000 GPU, and transmit the video to an Oculus Quest 2 HMD via a link cable.

C. Procedure

We counterbalanced both the order of the videos (which video is played first) and gender by presenting the two videos of the UR and CR conditions equally for both men and women as the first video. Each participant was asked to read the privacy notice and study information, and to sign the consent form. Before starting the experiment, the researcher did pre-screening such as asking whether the participant has a headache or feels nauseous (rescheduling was an option for a participant if they felt unwell). After that, they were asked to sit and adjust the chair’s height on the swivel chair so that they could rotate around easily (see Fig. 1 right). Next, the researcher gave the instructions and told the participant about the brief experiment information, including
how to put on the HMD. Afterwards, the researcher started
the video, calibrated the participant position, and asked them
to rotate around while wearing the HMD to make sure they
understand they can easily rotate with it; they were however
not prompted to rotate themselves during the video. After
the participant confirmed that they are ready to start, then the
video of the robot moving started playing. During the video,
the participant’s head orientation was recorded. After the
video finished, participants were asked to take off the headset
and fill out the questionnaire regarding their experience.
The same procedure was applied for the second video. The
participants were compensated with a 20€ Amazon gift card.
We used recommended precautions for COVID-19 during the
experiment such as wearing a mask, keeping a safe distance
from the subject and sanitizing the devices (including the
environment).

D. Measures

In terms of questionnaires, we measured sickness with the
SSQ [32] which presented 16 possible sickness symptoms,
rated on a scale of none (0) to severe (3). The SSQ total
score and subscales are calculated by weighting the answers
for a maximum score of 236. We used the SUS questionnaire
[33], [34] to attempt measuring their feeling of presence. The
experience questionnaires also included Likert-scale (ranging
1-7) questions and open-ended questions for reasoning in
some choices. After the second video, there were more
questions in the shape of forced-choice questions to compare
the two videos in regards to choosing the more comfortable,
prefers, and more intuitive condition for the participant.
Furthermore, we also asked questions (in Likert-scale) about
the feeling towards distance to walls, distance to humans,
and linear speed of the robot. In the end, the VR and
gaming experience, and demographics were also queried in
the questionnaire.

E. Participants

We collected the data from 32 participants similarly to the
prior study [6] consisting of equal numbers of both males and
females. Their age ranged from 20 to 33 years old and they
reported having normal or corrected-to-normal vision. There
were no reports of color blindness. The responses of how
often they use VR systems were as such: 18.8% said never,
53.1% once or just a couple of times ever, 9.4% once or
twice a year, 15.6% once or twice a month, and 3.1% once
or twice a week. Meanwhile, they also responded of how
often they play computer games: 15.6% never, 25% once or
just a couple of times ever, 25% once or twice a year, 9.4%
one or twice a month, 12.5% once or twice a week, 9.4%
several times a week, and 3.1% everyday.

VI. RESULTS

We ran data analysis in SPSS with the Wilcoxon signed-rank
test to find whether there was a difference in the total
weighted SSQ score under two different video conditions
(UR and CR). An exact binomial test with exact Clopper-
Pearson 95% CI was used to determine if a greater proportion
of participants were more comfortable and preferred one of
the videos when shown UR compared to the CR conditions.

The SUS score was calculated as the number of SUS
questionnaire items given a 6 or 7 rating by a participant,
resulting in a score that could range from 0 to 6 for each
participant [33], [34]. We performed a Wilcoxon signed-rank
test (one-sided) to test for greater SUS scores

A. Confirmatory Results

A Wilcoxon signed-ranks test showed that UR did not
elicit a statistically significant median decrease in the total
weighted SSQ score ($Z = -0.044, p = .866$) with median
4.96 and 16.83 for the CR.

While 21 out of 32 participants felt more comfortable
in UR (65.6%) than the CR, 23 participants preferred UR
(71.9%) when they responded to the forced-choice questions:
“Which of the two videos is more comfortable?” and “Which
of the two videos do you prefer?” (see Fig 4). A binomial test
with exact Clopper-Pearson found that the condition UR was
not significantly more comfortable, had 95% CI of 46.8% to
81.4%, $p = .112$ and the preference in UR was statistically
significant, had 95% CI of 53.3% to 86.3%, $p = .022$.

B. Exploratory Results

1) Quantitative Data: A Wilcoxon signed-rank test indicated
no statistically significant difference in the Likert-scale
comfort ratings $Z = -1.082, p = .279$ with Mean = 5.03 for
UR and (Mean = 4.78) for CR.

In the SUS scores, UR (Mean = 4.96) and CR (Mean =
4.84) did not have a statistically significant difference in the
In addition to the pre-registered hypotheses, we asked two further forced-choice questions: “Which of the two experiences feels more intuitive for you?” and “Thinking back to both of the experiences, which one gave a better sense of being in the robot’s location?”. A binomial test with exact Clopper-Pearson showed that the UR was significantly more intuitive, 95% CI of 53.3% to 86.3%, \( p = .022 \) and elicited significantly better presence, 95% CI of 56.6% to 88.5%, \( p = .008 \) (see Fig. 4).

We asked Likert-scale questions about how the participants perceived the distance to walls, distance to people and the speed during moving with the robot. The results shown in Table I indicated that the speed and distance to people and objects were considered appropriate on a 7-point Likert scale.

2) Qualitative Data: We analyzed the open-ended data using the inductive approach on thematic analysis [35]. The accumulated responses for the open-ended question about why participants found either video more comfortable can be seen in Fig. 5 in which the most frequent keywords towards open-ended questions of UR as chosen comfortable video were as follows: smooth (3) (for example, “The movement was smoother, both the straight-going parts, and the turning parts”), less sickening (3) (“I did not feel nauseous at all after the first video, after the second one I felt a little nauseous”), and natural (2) (“Moving with the robot felt more natural”).

On the contrary, the participants who chose the CR commented: less sickening (3) (“more static, so less motion sickness. Second video changing position/ changing gaze direction caused discomfort even though it was more engaging”); less self-rotation (2) (“The comfortable is quite the same, but I choose the first one since I dont need to turn the chair. Also, the second one can provide a reversed walk that is not natural for the speed”); and view follows (2) (“I did not require to turn to see where the robot was going”).

The open-ended question on the video preference was commented, shown in Fig. 6. In UR there was smooth (4), “It was much smoother, especially the turning. I did not fully appreciate the first video, until after I watched the second one”; control over viewpoint (5), “maybe more engagement with what I was seeing because I had to move to change view”; comfortable (3), “It didn’t feel uncomfortable at all and I could relax”, natural (3), “it is quite real and comfortable”; less blurry (3), “The video seemed clearer, and the view was less blurry even while robot was making turns”; less sickening (2), “It didn’t feel uncomfortable at all and I could relax” and sense of presence (2), “I think the first video gave me a better sense of actually being in that place, but I don’t know if that’s specifically because of a difference between the videos themselves or it is due to that being my first contact with the video”.

In contrast, the CR had comments such as sense of presence (1), “I feel [sic] like the two videos were honestly the same, but I chose the first one here, because it made me believe I was actually there more (as in I didn’t think how I was sitting in the chair and so on)” and view follows(2), “The first video was less disorienting and rather easier to maneuver in the space. The second video felt as if I was being pushed and not in line with my natural progression (of movement)”.

During the experiments, we observed the participants’ reactions. We created the events (interaction to the robot) in the video, shown in Fig. 2. The first event was when a
lady walked past the robot, secondly a man waved his hand to the robot, thirdly the talking people standing in the middle of the path and a man crossed in front of the robot, and lastly a man greeted, waved hand and asked towards the robot. Surprisingly, there were some participants who responded back, especially towards the second and fourth events; in total 11 of the 32 participants responded to either of both people in the video communicating with them, either with gesture or even by speaking. There were also participants who answered the greeting at the last events.

VII. DISCUSSION

From the pre-registered hypotheses confirmed in a simulation study [6], only H3, namely that users would prefer the unwinding, held: there was no statistically significant difference in either the SSQ scores or the forced-choice question of comfort. This is surprising, since there is not supposed to be a lot of difference between real 360° video and a simulated one when it comes to VR sickness. It is possible that the use of the real robot brings in other causes of VR sickness, such as vibrations; however, this was not found in the open-ended answers, since the word ”smooth” seemed most often to refer to the turns. Moreover, the mean SSQ value (16.83) for CR was exactly the same as in the simulation study, but the UR SSQ value was higher than in the simulation study (14.96 and 9.35). As VR sickness is typically caused by multiple sources [2], it is likely that increased vibrations would also have increased the SSQ scores of the CR conditions. We also note that there was a difference in the total rotation made by the robot: whereas in the simulation the robot rotated a total of 438°, in this study the total amount of rotation was 648.7°. This was mainly due to the small corrections a robot needs to constantly make while moving; however, it is unclear how this could have made the observed difference in SSQ scores between the simulated study and this study.

The answers to open-ended questions reveal interesting differences between the participants of this study and the simulated study, which could partly explain the differences in SSQ scores. Whereas in the simulated study only one person commented annoyance towards having to rotate the chair, here 4 people gave that comment (the participants saying ”view follows” (“I did not need to turn when the robot turned. It was easy for me.”) and “less self-rotations” were different participants). Moreover, it is surprising to observe three people consider CR less sickening, but these answers did not reveal any details of why. Thus, for comfort, it seems that simply the participants had different preferences when it comes to self-rotation than in the simulated study. This does not explain the non-significant difference in SSQ scores; however, as there is partial evidence from these studies together pointing towards unwinding reducing VR sickness, and the confirmed preference from both studies, we can conclude that unwinding does have clear advantages over coupled rotations also in a real-world telepresence scenario. Although in a real-world deployment, it may be beneficial to allow users to choose which condition to use, since it seems personal preferences play a role in this choice.

The large difference in forced-choice answers to presence (“thinking back to both of the experiences, which one gave a better sense of being in the robot’s location?” 24 for UR, 8 for CR, p=.008) was a surprise: the simulated study [6] showed promise towards this direction, which prompted us to explicitly measure it. Again, this was hinted directly in a few open-ended answers, such as “felt like I was more in charge of the situation/ what I was seeing and not just a passive observer”. This result is in agreement with the theory of presence, since sensorimotor contingencies, meaning that the user’s physical actions are matched visually in the user’s HMD view, are shown to increase the feeling of presence [1]. Whereas the nonsignificant difference in the SUS scores limits overemphasizing this result, remembering that the increase in presence was the main reason for using an HMD in the first place, even a small increase with other positive effects is welcome.

When not comparing the conditions, the fact that 11 out of 32 participants responded to greetings in the video is a positive sign of presence; the responses were despite the fact that we told the participants they are watching a recording, which also prompted a few participants to mention afterwards that they felt silly having responded. As this kind of behavior is exactly the reason to use an HMD for this task, we can say that the results are still very promising. The next step is making live telepresence comparison between HMD-based telepresence and conventional telepresence.

Finally, after this study, we can confirm that the suggestions made for the robot’s speed, and distances to people and objects in the simulation study, can be confirmed. The minimal distance to inanimate objects in this study was almost equal when compared against the simulation study (0.95m and 0.9m), and the result was the same, median score 4 in a 7-point Likert scale. The distance to people was slightly more in this study (1.2m and 1m), and this was reflected in the results; whereas in the simulation study the person was considered to be slightly too close at 1m (Median=3), in this study with 1.2m was considered suitable. Whereas this is not an exact comparison, we can conclude that doing telepresence research in VR is a good substitute, at least considering how the person aboard the robot sees the world and its distances.

VIII. CONCLUSIONS

In this study, we evaluated whether the results shown for a simulated telepresence robot in [6] also hold true for a telepresence robot with a 360° camera; namely, that unwinding the rotations of the user, such that the user never sees rotational motion but must rotate themselves along with the robot, are preferred, more comfortable, and induce less VR sickness. However, this study found the same results only for preference as there was no statistically significant difference between the conditions in sickness or comfort. We believe the most likely reason for this difference was simply a different participant population, since there were
several such hints in the open-ended questions. A slightly less likely explanation is that vibrations in the video feed caused by the robot motion increased the sickness scores, but this should have affected sickness in both conditions. We do believe, however, that this evidence shows the promise of unwinding, and also promise of virtual environments as a research platform for immersive telepresence. Future work will include a live immersive telepresence scenario, as well as testing unwinding on different, semi-autonomous steering methods. In the long-term, future research to enable two-way communication is merited as HMD-based telepresence robots should be able to present the remote user’s face to the people around the robot, similarly as current conventional telepresence robots [36] do. There is already research towards showing a person’s face who is wearing an HMD [37]; thus, one should bring this technology to HMD-based telepresence robots to fully unlock the power of immersive telepresence.

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