Effectiveness of a Novel Untethered Augmented Virtuality System for Immersive Industrial Training

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Abstract

The application spectrum of Immersive technologies, i.e. Virtual Reality (VR) and Mixed Reality (MR), is expanding but their effectiveness is often constrained by critical factors such as the restricted 6DOF movement of the VR user, limited immersion level and restrained interactions within the VR scene. This paper proposes a novel untethered self-embodiment based Augmented Virtuality (AV) system named Immersive Hybrid Reality (iHR), that aims to address these issues. The iHR system allows VR users to roam around the (scalable) VR workspace, untethered with 6DOF thanks to an external state of the art infrared tracking system. Furthermore, immersiveness is increased by blending spatially the 3D structural information of the near ambience of the VR user (real world), particularly the limbs (i.e. hands and legs) with the VR scene. This AV solution also enables the VR user to interact with real and virtual objects simultaneously. The effectiveness of the proposed iHR system is assessed against typical VR technologies in the context of immersive industrial training (i.e. offshore wind turbine nacelle inspection). A set of attributes are first identified to measure user experience and performance level. These then make up a comparative survey, for which the results exhibit the superior impact of iHR over typical VR systems in the industrial training domain.

Keywords: Hybrid Reality, Self-embodiment, Serious game, VR training performance measures.

1. Introduction

Current immersive technologies such as Virtual Reality (VR) and Mixed Reality (MR) have seen unprecedented popularity in recent times due to the increasing availability of powerful consumer VR hardware. Their application has been considered in various domains e.g. Construction Training [1] and Industrial Education [8]. Yet, they possess few fundamental limitations that bound the potential effectiveness of these technologies, such as: restricted **6 Degree-of-Freedom (DOF)** movement of the VR user [2], limited immersion level and restrained interactions within the VR scene [3]. This is more apparent in instances when VR users have to perform **self-affordance -based** tasks [4].

The realism and effectiveness of the immersive experience are maximized when the users completely suspend their sense of disbelief during the virtual experience [5]. At the same time, preserving the sense of reality, for example by correctly perceiving the user's body and other ambient real objects pertinent to the VR scenario, can make the VR experience more realistic and engaging [6]. Additionally, the immersive experience can be elevated to a substantial degree, especially, in the case where the VR experiences are task-oriented (the VR user himself has to perform a task), if the VR users are permitted to roam around a sizable VR working space untethered [7]. Another dimension in the VR applications can be added if the VR users are able to interact in a continuous and simultaneous manner with both virtual and real objects. This is particularly evident in VR based industrial training applications [8], where ideally the interaction of the user with real tools is very important and should ideally be preserved within the VR experience (possibly alongside virtual interactions). For example, it can be important for manual trade training that the trainee be able to perceive his presence immersed within the working environment, safely experiencing potentially hazardous and distressing situations (e.g. working at heights) and at the same time be able to grasp and manipulate real tools and materials (i.e. harnesses, hammer, etc. In simpler terms, the immersive system should not only provide high-level self-embodiment, but also an effective mechanism to accommodate interaction with both real and virtual objects simultaneously.

This paper proposes a novel untethered self-embodiment -based Augmented Virtuality (AV) system named Immersive Hybrid Reality (iHR), which addresses these issues. The iHR allows VR users to roam around the VR workspace (scalable), untethered with 6DOF thanks to an external state of the art infrared tracking system. The immersiveness is further increased by blending spatially consistently the 3D structural information of the near ambience of the VR user (real world), particularly the limbs (i.e. hands and legs), with the VR scene. This AV solution also provides the VR user with the opportunity to interact with real and virtual objects simultaneously.

We have evaluated the effectiveness of our proposed iHR against the state-of-the-art VR technologies for immersive industrial training. This evaluation was conducted using a comparative survey assessing aspects of performance and user experience. The scarcity of already validated measurement metrics to measure the performance, effectiveness and user experience of immersive systems in an industrial training setting has obliged us to conduct research and propose a specific set of parameters.

The contribution of the paper is thus four folds: **(1)** Free 6-DOF motion within scalable volume: Our proposed system is fully wearable and untethered, which permits the free movement of the VR user within a volume of 5m×5m×3m, that is easily scalable. **(2)** The proposed iHR system uses an ego-centric RGBD camera to capture the visual and structural (i.e. 3D) information surrounding the user. That information is processed and filtered, and relevant objects within the vicinity (the extent of the real space can be controlled) of the user are integrated to the VR content in a spatially-consistent manner to form the AV, or HR, view displayed to the user through the HMDs. These real objects particularly include the user's limbs, which enhances the level of self-embodiment and affordance. In particular, this enables the user to interact with their hands (not avatar) with real objects, while immersed, which is of significant value for industrial training, particularly for manual trades. **(3)** We propose a set of parameters (combining key elements and influencing factors from the most contemporary fields of Virtual Reality (i.e. education, entertainment, edutainment) and also from quintessential industrial training modules) which attempt to measure the training effectiveness, as well as the performance and user experience of VR systems. **(4)** We provide a comprehensive comparative analysis between iHR and contemporary VR technologies by means of paired experiments and associate survey conducted with college trainees.

2. Previous Works

2.1 General Approaches for Enhancing Self-Embodiment

Some of the leading works and relevant immersive setups from the literature are described in this section, with focus on enhancing presence/self-embodiment. The set-up presented in [9], called AR-RIFT, provides a video see-through AR HMD by mounting two monocular cameras on an Oculus Rift headset in correspondence to the two eyes' positions, so that the real world can also be 'seen' through the Oculus Rift. The resulting immersiveness are noticeable, due to the large field of view (FOV) achieved. However, this set-up acquires the real scene and performs the rendering of the virtual content independently on the two camera images without any stereo matching, so that not full, stereoscopy is achieved. Accordingly, real depth information is not available and virtual/real object interaction cannot be fully consistent. A similar hardware set-up is used in [10], where an AV system is employed to investigate height perception. In this work, only hands/arms are extracted from the real scene based on a colour model (separately on the two camera images). As mentioned by the authors, the main limitations of this approach are the low frame rate (14 fps) and most importantly the lack of real depth information, which prevents correct occlusion handling. In [11] the authors propose a novel AV approach that partially blends reality and virtuality, and they study the effect of varying the amount of blending of the two. Like us, preserving the sense of touch on real objects while being immersed in a virtual environment is considered important for user presence awareness when performing a task. According to the author themselves, since the system is not able to perform true stereoscopy, real depth cannot be measured, and the user can just roughly orientate himself within the real environment. The system described in [12] employs a set-up very similar to ours. The user's hands are reconstructed from the RGB-D camera data, and coloured thimbles attached to fingers are tracked to simulate simplified grabbing of virtual objects. However, the user is tethered to a dedicated workstation performing hand reconstruction while head movements are tracked by a 6-DOF optical tracking system. No calibration procedure between the depth camera and the HMD is reported, although it is clearly critical to the correct perception of the real environment within the virtual environment, and accordingly the correct execution of reach and grab tasks of real objects. It is worthwhile to note that they report results on the assessment of the user experience in term of (increased) self-embodiment. This assessment, however, focuses on the manipulation of virtual objects only.

2.2 Mixed Reality for Training

A number of works have described the benefits and limitations of mixed reality for training of procedural tasks in manual trades, broadly in manufacturing [13] and construction [14]. Below we discuss recent works that are particularly relevant to the scope of this paper. The work in [15] aim to assess the effectiveness of AR for conducting real basic assembly tasks, like building LEGO structures, providing error detection (e.g. missing model parts) and virtual guidance during the process. The approach proposed in [16] aims at tracking manual workflow in first-person videos and assessing its correctness by comparison with video examples. In [16] a bare hand (gesture recognition) interface that provides different modalities of guidance depending on the user cognitive stage (perception, attention, memory and execution) is presented. Detection of objects and associated tools is marker-based and allows tracking and augmentation with virtual components, as well as their manipulation for on-site assembly simulation. In construction, mobile AR has seen applications mainly in maintenance assistance [17] and collaborative visualization of construction processes. The study in [18] provides preliminary insights regarding the experience of assembly/disassembly sequences using an immersive set-up similar to ours, to assess the effect of ownership of the user's hands while dragging virtual components. We are not aware of works targeting the assessment of procedural tasks conducted with real tools and materials while experiencing challenging simulated/virtual working conditions. The current work represents an extension of the works in [19] and [20]. In those works, a proof-of-concept of a training system based on a tethered static prototype of the iHR was presented. In the current paper, a novel fully wearable untethered version is presented. Furthermore, a first study is reported on the formal assessment of the effectiveness of the system on immersion and affordance.

2.3 User Experience and Performance Evaluation

User Experience (UX) in Immersive Virtual Environment (IVEs) can be measured by both subjective methods (e.g. questionnaires, interviews etc.) and objective methods (e.g. electroencephalogram, electromyogram, task completion time, level reached) [21]. Currently, questionnaires are considered the most popular method for measuring the UX components, thanks to a number of reliable and valid questionnaires already available. In contrast, the state-of-the-art objective methods available today for quantitative UX assessment are still questionable [21], while remaining costly. In this work, a questionnaire is used solely.

A review of the literature showed a lack of existing questionnaire containing all the components of UX relevant to the context of industrial training, while also addressing performance evaluation. For example, the Simulator Sickness Questionnaire (SSQ) [22] is a popular questionnaire to measure the physical constraints of the user while in the VR world. In contrast, the Immersive Tendencies Questionnaire (ITQ) [23] is applied to measure the level of immersion of the user within the virtual environment. A few questionnaires such as [24] endeavor to explore most of the components of UX in IVE, such as presence, flow, usability, technology adoption, immersion etc. But usually these questionnaires are designed to explore the UX in IVE from a video gaming perspective, thus excluding key independent features that are important to safe and effective training and can be good indicators for

VR based training system evaluation, (e.g.: communication capability of a VR user with others outside the VR space, or safety while immersed in the VR space). When reviewing the literature on conventional industrial trade training [25] and VR based simulation training [26], the following independent UX and Performance attributes are identified that are of relevance to the case of industrial/manual training in an IVE setting:

Physical constraints: Physical constraints are one of the important aspects of any training mechanism. With the increased use of HMD and VR ready backpacks, their long-term use can trigger discomfort and unusual posture related issues [27]. Exposure to the HMD displays for longer periods can also lead to eye strain and hygiene related issues [28]. Moreover, Visually-Induced Motion Sickness (VIMS) is a major impediment to the growth of VR.

Visual Quality: The visual quality of VR HMDs (i.e. resolution, Field of View etc.) is critical to enhance the sense of presence [29], and thus the quality of VR-based training.

Tracking quality and space: To support an immersive and realistic VR experience, the tracking system should be accurate, have low latency with a fast refresh rate, and be robust [30]. Moreover, the size of the trackable space is also critical for VR based industrial training as the VR user often requires performing non-static physical activities that include substantial movements [30].

Safety: Safety is a big concern that the users face in a modern HMD based VR [31], a user wearing an HMD, most likely along with headphones, is functionally blind and deaf in real-world terms. This can lead to physical accidents. Furthermore, this leads to users focusing less on the game/training.

Presence, Energy and Immersion: Presence is defined as the user's 'sense of being there' in the virtual environment. Energy is defined as the 'energy in action, the connection between a person and his/her activities consisting of a behavioral, emotional and cognitive form'. And lastly, Immersion is defined as the 'illusion that the virtual environment technology replaces the user's sensory stimuli through the virtual sensory stimuli'. These are the core attributes of any VR system, determining the effectiveness of the system. From the industrial IVE training perspective, these components are also undoubtedly important. For example, when health and safety training is provided for working at height [32], a proper balance between presence and immersion can produce effective training outcomes.

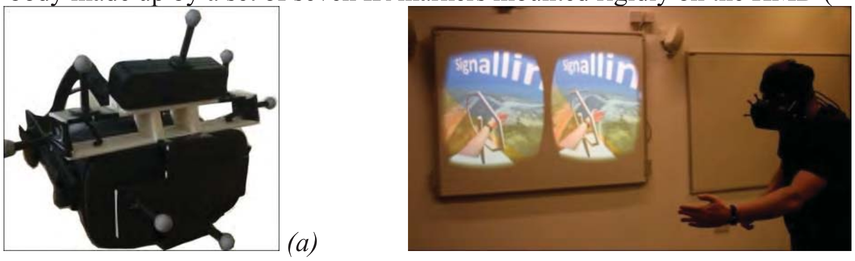
Communication: During VR-based training, users may need to respond to queries of trainers, and more generally may have to communicate with the trainer, for example by pointing at certain parts of the virtual environment while commenting about them.

Tool Usage: The majority of conventional industrial training processes involve different tools/objects [33] (i.e. Harness etc.). For VR-based training of industrial/manual workers, being able to use real tools and materials (as opposed to virtualized ones) within the IVE could be valuable.

3. The iHR System

Figure 1) provides an overview of the system with its main functional components.

Localisation: We use a scalable *OptiTrack Motive* Tracking system (with Flex13 cameras), operated by a Desktop PC (labelled *Tracking Workstation* at Figure 1). The optical tracking system is calibrated to cover a tracking area of approx. 6m x 5m with a position accuracy of 3.4 mm (mean 3D error). We use this system to track with, a frequency of 120 Hz, the 3D position and orientation of a rigid body made up by a set of seven IR markers mounted rigidly on the HMD (



(a) (b)

Figure 2. (a): VR HMD with reflective markers and mounted RGB-D camera. (b): Occlusion between real entities (hand) and virtual (turbine equipment) is correctly represented. (a)). The location information provided by the Optitrack Tracking system is then communicated wirelessly from the server *Tracking Workstation*) to the client (*Wearable Computing Unit*). The client then integrates this

information with the IMU data of the VR HMD (Oculus Rift) to deliver precise and latency-free head pose estimations. Further details about our complete localisation approach can be found in [19-20].

Hybrid Reality (Augmented Virtuality): To capture the structural data of the surrounding environment, an RGB-D camera (Softkinetic DS325) is mounted integrally to the HMD (Oculus Rift, see

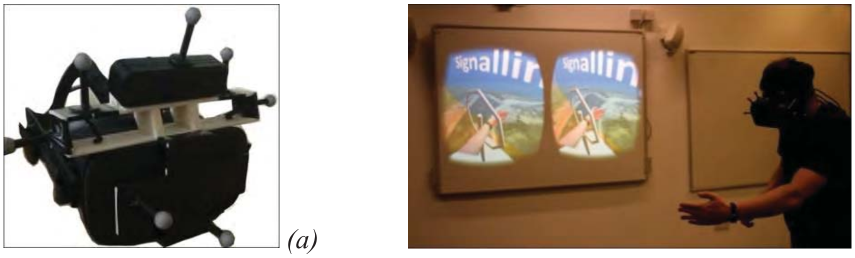

(a) *(b)*

Figure 2. (a): VR HMD with reflective markers and mounted RGB-D camera. (b): Occlusion between real entities (hand) and virtual (turbine equipment) is correctly represented. (a)).

Following noise filtering, the RGB-D data is then processed to segment and reconstruct in real time a smooth representation of the surface (textured 3D mesh) of surrounding real objects (e.g. user hands or tools). Figure 2(b) shows an example of the system capabilities to correctly handle occlusions between real and virtual entities (in both directions) in a wind-turbine maintenance scenario. The generated textured mesh is expressed in the RGBD camera's reference frame and must be transformed into the HMD's reference frame to be correctly perceived by the user within the scene. Accordingly, we developed a calibration process [20] which estimates the rigid transformation between the two reference frames. This calibration ensures that reaching and grasping of real objects is possible without removing the HMD. In our context, this means that tools (e.g. hammer) and real mock-ups of parts of working environments manipulated during training (e.g. hooks for harness anchoring) are correctly aligned within both the field of view and with the 'extending' virtual environment. The data processing framework described above is implemented as a C++ plugin for Unity 5 game engine.

Wearability and motion freedom: The wearable system (*Wearable Computing Unit* in Figure 1, is basically a VR-ready backpack, to which the HMD and the depth camera are connected. The backpack performs all the RGBD data processing and game rendering tasks along wirelessly receiving the 6DOF location data packets from the *Tracking Workstation*. As stated earlier, the location information provided by the Optitrack Tracking system is then communicated wirelessly to the wearable system. This is done using an ad-hoc wireless network. Being the size of the packets of few bytes, this stage does not impact at all on the overall performance (e.g. by introducing latency). This means that the user just carries a 3.6Kg backpack (and headset) that is completely untethered. As a result, the users are able to navigate freely and fully untethered, which is rare in typical VR systems.

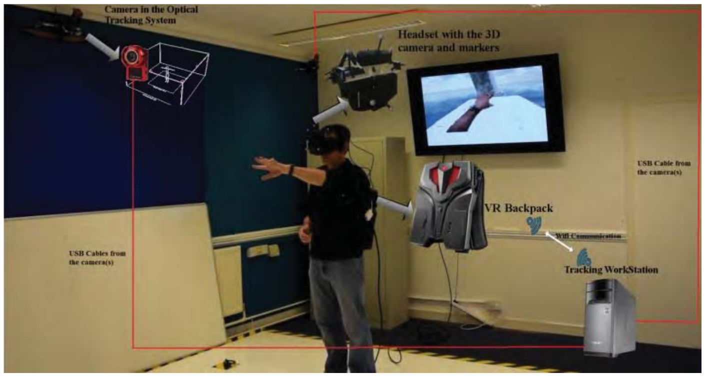
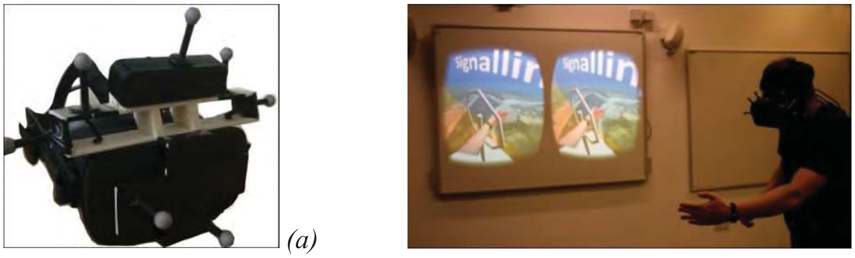


Figure 1: Schematic overview of the iHR system.



(a) (b)

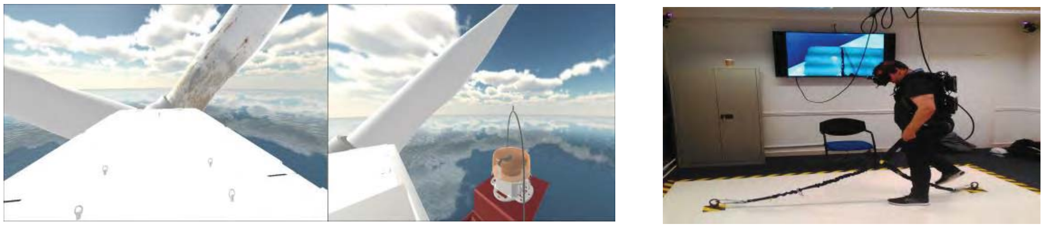
Figure 2. (a): VR HMD with reflective markers and mounted RGB-D camera. (b): Occlusion between real entities (hand) and virtual (turbine equipment) is correctly represented.

4. User Experience and Performance Evaluation

The proposed system is piloted to evaluate its UX and other performance related features in comparison with contemporary immersive VR technology, in the context of an industrial training scenario. The comparison is assessed through a post experience survey.

4.1 Experimental Setup

In order to conduct the survey, an IVE based ‘Wind turbine nacelle inspection’ game and training session were set. The game consists of a 3D model of an actual offshore wind turbine. The trainees are virtually placed on top of the turbine nacelle, the game automatically generates a random set of typical defects for each training session that the trainees must detect. The defects include: rust on a blade, crack on a blade etc. Figure 3(a) shows examples of the user’s view of some of those defects.



(a) (b)

Figure 3. (a): Examples of random defects generated in the turbine nacelle (i.e. Rust on the blade, broken navigation light). (b): The iHR wind turbine maintenance training system

The training session was conducted in a 5m×4m room which was augmented with a 4m×2.5m mock-up model of the top surface of the nacelle equipped with four typical safety anchors (Figure 3(b)). The Optitrack tracking system setup for that room uses 6 “Flex13” cameras mounted on the room walls. A group of 10 participants took part in the experiment. The participants were wind turbine maintenance trainees, who did not have any prior experience of being at the top of a turbine. Each participant was asked to complete the following two tasks involving two distinct activities (1) Being hooked, explore the virtual game environment to find defects, while in iHR mode. (2) Being hooked, explore the virtual game environment to find defects, while in VR mode. The sample size for this study is arguably small, but this was due to the fact that the 10 participants constituted the entire year cohort on that programme.

4.2 Questionnaire

Following the completion of the tasks, the trainees were given a questionnaire to fill in. The questionnaire contains 25 questions that capture the user’s opinions regarding their experience of the virtual environment and game in both VR and iHR modes. The questions are inspired by existing questionnaires from the literature, related to VR based training and non-VR training: Simulator sickness questionnaire [22], Presence questionnaire [34], User experience questionnaire [24], Nasa TLX questionnaire [33], and Immersive tendencies questionnaire [23]. All the 25 questions comprising the questionnaire use a 5-point Likert scale. For analysing the statistical significance within the responses, we use two statistical significance tests:

Pearson's Chi-Squared test. For the responses that were categorical/nominal in nature and did not involve any comparison aspects, we have applied the Pearson's Chi-Squared test [34]. In this statistical test, the test statistic is a Chi-Square random variable $\chi^2(p)$, and the Null Hypothesis is rejected if the $\chi^2(p)$ value does not exceed the critical value (α) that depends on the Degree of Freedom (DF) and the probability value of (P $(X \leq x)$) or if the Test Statistic value exceeds the Critical value (obtained from the χ^2 single tailed table).

Wilcoxon signed-rank test. For the responses which are ordinal in nature (i.e. 5- point Likert scale) and are used to compare the iHR system against the VR system, we use the Wilcoxon signed-rank test [35]. The Wilcoxon procedure computes a test statistic W_{STAT} that is compared to an expected value and the null hypothesis is rejected if the value remains lower than $W_{CRITICAL}$ value. There is been a longstanding dispute about the most valid way to analyse Likert data, which are discrete, ordinal, and have a limited range. The basic choice is between a parametric test (i.e. student's t-test) and a nonparametric test (i.e. Wilcoxon signed-rank test). Since Likert scale data typically do not follow the "normal distribution", we use the Wilcoxon signed-rank test (which can be considered as an alternative to the paired student-t test) [35].

4.3 Results - Comparison of iHR and VR

Physical Constraints: Three questions are asked to the participants in relation to physical constraints: One about eye strain; one about motion sickness; and one about the weight of the backpack. The questions regarding the eye strain and motion sickness are comparative in nature (between VR and iHR). The backpack configuration is common in both systems and thus does not yield any comparative response. Table 1 reports the results regarding eye strain and motion sickness. It shows that the participants did not feel any substantial physical constraints related to eye strain in both the VR and iHR as the mean (μ) value is similarly very low in both cases (Note: multiple instances of identical scores for both VR and iHR means that the W_{STAT} cannot be calculated). Similarly, the results show, this time with statistical significance, that the participants did not experience significant motion sickness (though the iHR performed slightly better than VR). Regarding the weight of the backpack, all participants unanimously qualified it as 'not heavy'. The weight is clearly not a concern.

Table 1: Results and analysis of statistical significance for the Physical Constraints questions.

Question	System	μ	σ	W_{STAT}	$W_{CRITICAL}$	Significance
Motion Sickness 1-Nil 5-Extreme	VR iHR	2.3 2	.823 1.24	11	5	NS
Eye Strain 1-Nil 5-Extreme	VR iHR	1.1 1.1	0.31 0.31	N/A	5	N/A

$*\rho = 0.05; * df = 4$ $* df = Degree\ of\ Freedom; * \rho = Deee\ of\ Signifinance; * \mu = mean; * \sigma = Std.Daviation$

$* S = Statistically\ Significant$; $* NS = Not\ Statistaccaly\ Significant$; $* N/A = Not\ Applicable$

Visual Quality: Four questions were asked to the participants in relation to 'Visual Quality'. Three questions evaluate the graphical quality of the iHR system and do not involve any comparison. The remaining question compares the overall graphical quality of the VR and iHR systems. The iHR-related questions are about the quality of rendering of real-world objects captured by the HMD-mounted RGBD camera (i.e. participants' own hand and the harness) inside the VR game and the standard (i.e. size) of the *Field of View (FOV)* of the real-world window inside the virtual world *FOV*. Table 2 shows that the visual quality of the iHR rendering is moderately impressive (μ= 3.77 for the hand, and μ=3.22 for the harness), with statistical significance. This said, shiny objects are challenging to capture and render consistently. Furthermore, due to a threshold range of the depth camera, inconsistencies in rendering real objects can be experienced (e.g. walls of the room could sometimes be seen, although beyond the depth camera range threshold). But, as shown in Table 2, the main challenge remains the FOV of the range camera (μ=2.11). While this is a result that we expected, it must nonetheless be noted that this result is not statistically significant.

Table 2: Results and analysis of statistical significance for the iHR Visual Quality questions

Question	μ	$\chi^2(p)$	Critical Value	Test Statistic	Significance
Rendering of Hand 1-Not Realistic 5-Very Realistic	3.77	0.028	9.48	10.88	**S**
Rendering of Harness 1-Not Realistic 5-Very Realistic	3.22	0.026	9.48	11.05	**S**
Size of FOV 1-Too small 5-Large Enough	2.11	0.287	9.48	5.10	**NS**

$*\alpha = 0.05; * df = 4$ $* df = Degree\ of\ Freedom; * \alpha = Alpha\ Value; * \mu = mean; * \chi 2(p) = ProbabilityValue$ $* S = Statistically\ Significant$; $* NS = Not\ Statistaccaly\ Significant$; $* N/A = Not\ Applicable$

Table 3 summarizes the results regarding the comparison of the overall graphical quality between VR and iHR modes. It shows that the users found the graphical quality of the VR (μ=1.8) system better than that of the iHR (μ=3), a result that is statistically significant. This was expected, because of some of the limitations of the iHR system in acquiring and rendering the real world in a fully consistent way, as discussed earlier.

Table 3: Results and analysis of statistical significance for the comparative Visual Quality question

Question	System	μ	σ	W_{STAT}	$W_{CRITICAL}$	Significance
Overall Graphics 1-Excelent 5-Worse	VR iHR	1.8 3	1.032 0.666	2	5	**S**

Tracking Quality and Space: Five questions investigate the performance in terms of 'tracking quality and space'. Three comparative questions relate to the motion tracking quality in both VR and iHR conditions. The remaining two questions focus on the untethered tracking space. Since both the VR and iHR systems use the same tracking space and both of them are untethered, these questions are not comparative.

Table 4 summarises the results obtained for the motion tracking quality. The responses first unveil that in both VR and iHR modes, the users did not feel any significant latency (μ=1.8 & μ= 2.0 respectively). Then, the participants reported some instances of judder, slightly higher in the case of iHR. One reason might be the higher computational demand that the iHR has compared to the VR. The W_{STAT} value suggests (minor) significance in the results. Finally, the results show that the participants reported good overall tracking quality for both the VR and iHR modes, and these results are statistically significant.

Table 4: Results and analysis of statistical significance for the comparative Tracking Quality questions

Question	System	μ	σ	W_{STAT}	$W_{CRITICAL}$	Significance
Felt Latency 1-Nil 5-Extreme	VR iHR	1.8 2.0	0.63 0.87	N/A	5	**NA**
Felt Judders 1-Nil 5-Extreme	VR iHR	2.3 2.7	0.48 0.67	5	5	**S**
Overall Tracking 1-Worst 5-Great	VR iHR	4.0 3.6	0.61 0.73	3	5	**S**

Regarding the tracking space, the participants were asked if they had felt complete freedom while roaming around the room. Table 5 summaries the responses and shows that a majority of participants felt that there was enough freedom (μ=3.556), which also shows that the participants felt very little constraint in moving. We argue that this could add to the overall impact on presence and immersion in the VR game.

Table 5: Results and analysis of statistical significance for the Space question

Question	μ	$\chi^2(p)$	Critical Value	Test Statistic	Significance
Level of Freedom 1-Restricted 5-Complete Freedom	3.55	0.013	9.48	12.67	**S**

Safety: Three questions assess the level of safety the participants felt in both the VR and iHR systems. Two questions are concerned with 'tripping' and 'hitting nearby objects' while immersed in the VR and iHR systems. The last question asks the participants to rate the overall level of safety they felt when using both systems. Table 6 summarises the results. Since the iHR system lets the users see their surroundings (within a defined range), it is expected that they can control their motion to some extent and thus feel more confident. The statistics confirm this. The participants undoubtedly had greater concerns of tripping and hitting nearby objects in the VR system (μ=2.3) in comparison with the iHR system (μ=3.4). Similar results are obtained for the risk of hitting nearby objects. Regarding the overall safety, the results show μ=2.3 for the VR system and μ =3.2 for the iHR system, which clearly suggests that the users felt safer in the iHR system.

Table 6: Results and analysis of statistical significance for the comparative Safety questions

Question	System	μ	σ	W_{STAT}	$W_{CRITICAL}$	Significance
Fear of Tripping 1-Extreme 5-Nil	VR iHR	2.3 3.4	1.33 0.84	2	5	**S**
Fear of Hitting 1-Extreme 5-Nil	VR iHR	2.8 3.6	1.23 0.96	2	5	**S**
Overall Safety 1-Nil 5-Extreme	VR iHR	2.3 3.2	0.98 1.15	3	5	**S**

Presence, Energy and Immersion: Eight questions were designed to measure and compare the Presence (two questions), Energy (one question) and Immersion (four questions) level of the VR and iHR systems. Among these, seven questions were comparative. In Table 7, the first two rows show the results for the questions related to **Presence**. Firstly, they were asked to what level they felt the urge to secure themselves with the harness while in the game, and secondly, they were asked to rate the overall presence for both VR and iHR systems. The results reveal that the participants felt an enhanced sense of presence when using the iHR system, although the result is not statistically significant. In the **Immersion** section, the questions asked the level of feeling at height and anxiety while looking down from the edge of the turbine nacelle in the game. The answers of the first question show that they felt the height substantially more in iHR than in VR, although opposite results are revealed for the level of anxiety. This may be explained by the fact that, since the participants could see their body in particular legs while walking and looking down the edge, they were more confident in controlling their body movement (and thus surer about their own safety) which subsequently helped to reduce the level of anxiety. Moreover, due to the erroneous/inconsistent reading from the depth camera, the users sometimes could see portions of the ground within the iHR, which may also have contributed in reducing the level of anxiety. In the third question, the participants were asked how fast they felt they lost awareness of the real world and felt immersed in the VR world. According to their answers, we can see the iHR was better at immersing the players in the virtual environment. In the last question, the participants were asked to rate the overall Immersion level of the two systems. As expected from the results above, the iHR proved substantially more immersive than the VR. We note that of all the results in the Immersion section, only the result to the second question (anxiety level) was not statistically significant. For measuring the **Energy** within the game, the participants were asked if they felt any urge to touch/ interact with the virtual objects (which linearly correlates with the level of energy). The result shows that thanks to being able to see their own hands the participants had greater urge to interact (subsequently energy) with the virtual objects in the iHR system (μ=3.7) than in the VR system (μ=2.4).

For the Presence, Energy and Immersion attribute, one last question solely related to the iHR asked the participants if the self-embodiment feature of the iHR improved/ increased the level of presence. As Table 8 shows, the participants agreed that self-embodiment helped increase the presence.

Table 7: Results and analysis of statistical significance for the comparative Presence, Energy and Immersion questions

Question	System	μ	σ	WSTAT	WCRITICAL	Significance
Presence						
Urge of Securing 1-Nil 5-Extreme	VR iHR	3.1 3.5	0.99 0.52	3	5	**S**
Overall Presence 1-Nil 5-Extreme	VR iHR	3.4 3.9	0.84 0.56	N/A	5	**N/A**
Immersion						
Felt Height 1-Nil 5-Extreme	VR iHR	3.0 3.7	0.47 1.05	4	5	**S**
Anxious of Height 1-Nil 5-Extreme	VR iHR	3.7 3.0	1.42 0.82	11	5	**NS**
Loose Awareness 1-Slow 5-Fast	VR iHR	2.9 3.5	0.87 0.70	5	5	**S**
Overall Immersion 1-Nil 5-Extreme	VR iHR	2.7 3.7	0.67 0.82	3	5	**S**
Energy						
Urge to Touch 1-Nil 5-Extreme	VR iHR	2.4 3.7	0.52 1.16	2	5	**S**

Table 8: Results and analysis of statistical significance for the iHR Presence question

Question	μ	$\chi^2(p)$	Critical Value	Test Statistic	Significance
Level of Presence (1-Increased Hugely 5-Didn't Increase)	1.66	0.026	9.48	11.05	**S**

Communication: Two questions assess the iHR and VR systems as a communication medium. The first question asks to rate (compare) the overall ease of communication by the VR game user with an external person in both VR and iHR conditions. Table 9 summarises the results and shows that the participants strongly endorse that the iHR system provides a better communication medium.

A second question asks to give an opinion on the specific hypothesis that 'being able to point with their own hands made the communication easier in the iHR condition'. Table 10 summarises the results and shows, with statistical significance, that the participants strongly believe that self-embodiment enhances communication.

Table 9: Results and analysis of statistical significance for the comparative Communication question

Question	System	μ	σ	WSTAT	WCRITICAL	Significance
Communication 1-Easy 5-Difficult	VR iHR	3.2 2.0	0.91 0.94	3	5	**S**

Table 10: Results and analysis of statistical significance for the iHR Communication question

Question	μ	$\chi^2(p)$	Critical Value	Test Statistic	Significance
Self-embodiment and Communication 1-Easy 5-Difficult	.0	0.013	9.48	12.67	**S**

Tool Usage: To measure the value of the iHR system to support the manipulation of actual objects/tools while immersed, the participants were asked whether being able to manipulate real tools/objects while training, like the harness, was helpful for effective training. The results summarised in Table 11 show that the participants agreed (μ=1.9), with statistical significance.

Table 11: Results and analysis of statistical significance for the iHR Tool Usage question

Question	μ	$\chi^2(p)$	Critical Value	Test Statistic	Significance
Level of Presence (1-Increased Hugely 5-Didn't Increase)	1.9	0.023	9.48	11.34	**S**

5. Conclusion and Future Direction

The paper has presented a fully untethered AV system that seamlessly integrates, both visually and structurally, the local real world surrounding the user within the virtual environment. We refer to such new form of MR as Hybrid Reality (HR). The set-up of the system was fully described, and its benefits were compared experimentally with typical VR through a piloting involving college trainees. Experimental results suggest, with some statistical significance, the benefits of the proposed system for IVE -based industrial training, in comparison with typical VR. The self-embodiment and spatially consistent rendering features of the iHR substantially increase the presence and immersion level of the users. Furthermore, the HR functionality enables users to use real objects/tools, which can often be critical for industrial training. The untethered nature of the system enables users to enjoy 6-DOF motion freedom within a scalable space. While this enables more active training, the HR functionality effectively balances the enhanced safety concerns deriving from such freedom. Finally, the iHR showed its value in allowing VR users to communicate effectively with people in the outside world (e.g. trainers).

The piloting also highlighted some limitations of the proposed iHR system. In particular, hardware limitations of the depth camera (i.e. erroneous depth readings, and limited FOV) negatively impacted the visual quality delivered by the iHR. As a result, future studies should focus on increasing hardware capability (i.e. FOV of the depth camera), by at least using new generations of TOF cameras. Furthermore, the HR functionality should be leveraged to design a robust controller-free, hand-based user interface.

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