

Enhancing Immersion in Virtual Reality

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Abstract

Despite the technological advances in Virtual Reality, there is an inadequate feeling of presence within the Virtual Environment. This can be improved by including technology which makes it possible for the VR users to interact with the physical world while being in VR. Currently, systems that combine Virtual Reality and Augmented Reality within one cohesive user experience are largely uninvestigated, especially within game settings. Thus, in our first project, we propose Clash Tanks, which is a game that is developed to investigate how VR and AR can coexist within one game environment. We present the technical architecture of this approach to embody both VR and AR, related interaction methods and game mechanics. Our developed prototype is an immersive VR cockpit, containing various AR components and game elements, which are used to operate two-real robots in various game modes. We carried a preliminary user study to investigate the immersion and enjoyment aspects of our combined gaming experience. Overall, participants favoured our approach in terms of enjoyment, specifically citing that they felt immersed within the VR cockpit while controlling the robot. Participants also mentioned some shortcomings such as motion sickness and vision blurriness because of the head mounted display. Lastly, we present our future direction for our project. In our second project, we present FeelVR, which is a waist-worn robotic arm capable of providing various kinds of haptic feedback on the torso, neck, face, arms and hands. We present the design structure of our robot and its implementation specifications, followed by an evaluation to measure the users experience of receiving haptic feedback in a simple VR software experience. We also measure components like flow and immersion. Overall, our robotic arm was perceived very positively by the users. Finally, we discuss various research opportunities and fundamental design challenges and present our future direction.

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1 Introduction

Virtual Reality (VR) involves simulating a real environment for a user in the digital space. Unlike traditional user interfaces, in VR, users can interact with the 3D visual world resulting in a higher level of user involvement and interaction with the 3D visual world which gives the users a better digital experience. Due to the realistic effect it creates, in recent years, there has been a surge of interest in VR and our understanding of the subject has grown multifold. VR technology has been gaining attention because of the widening of the area of application. Additionally, reduced costs and improved hardware further propagate this technology along with advancements in its hardware and software capability [1].

1.1 Inadequate Feeling of Presence

‘Presence’ is the feeling or experience of ‘being’ in the VR environment. Having an inadequate feeling of presence is one of the limitations of VR. Witmer and Singer (1998) define presence as "the subjective experience of being in one place or environment, even when one is physically situated in another"[29]. There are multiple factors contributing to the feeling of presence in the Virtual Environment (VE) which have been investigated [29,30,32,33]. Many research articles have investigated the factors that contribute to the presence in Virtual Environments. There are various categorizations of these factors. Slater and Usoh (1993) [32, 30] have classified the factors responsible for level of presence in VE to be high quality/resolution of information, interaction with the VE and having a virtual body which imitates the physical body in the VE. Witmer and Singer [29,30] have mentioned control (user control within VR), sensory (quality of displayed information), distraction (if the user can be distracted when present in the Virtual Environment) as the factors. Sheridan [33] states the ability to modify or interact with the physical environment as a factor. VR technology is thus not being used to its maximum potential due to technical limitations which fail to generate a feeling of complete ‘presence’ for the user. Our focus in this research is to enhance the experience of VR by improving this ‘feeling of being’ in the VE.

- Interaction with Virtual Reality

Interaction with VR is one of the leading factors leading to an elevated feeling of presence. With current technology, in virtual reality environments, the user is restricted to interact by using the sense of sight and hearing. Devices which enable the user to interact with the physical world by being mobile are still at their initial stages. VR experience can be made more interactive if all 5 senses of the user are utilized within the experience. Such inclusion of all senses in a VR experience is a significant loophole because our understanding of VR Visuals and Haptics is still limited. Efforts are being made to engage all the senses of the user, to improve achieving reality in virtual environments.

1.2 Our Approach

In our research, we have implemented two different approaches to enable interaction with the physical world while being present in VR.

1. ClashTanks: An Investigation of a mobile Virtual and Augmented Reality Gaming Experience

In our first approach, we have investigated a gaming approach combining Augmented Reality and Virtual Reality in a single experience and evaluated if such an approach tends to a more immersive gaming experience. The characteristics of our approach are:

- **Physical world mobility within VR**

The user is able to move physically in the physical world while still being present within Virtual Reality and able to interact with it.

- **Combining AR and VR in a singular experience**

In our project, augmented objects can be viewed and interacted with in a Virtual Environment.

2. FeelVR: Wearable Robotic Arm for Interaction Within Virtual Reality Environment.

Haptic feedback is the most primary way to increase immersion with VR because of the tactile feedback it offers. Hoffman et al. (1996) [31] studied the level of presence in VR with tactile augmentation by conducting experiments under 2 conditions: In the first, the subjects could only visually see the ball while in the second condition, they could interact and touch the ball because a real ball was physically placed in the same position as the virtual experience. Within VR, research literature and products are mainly limited to vibrotactile feedback for the torso. We believe that additional types of haptic feedback around other areas of the body could potentially yield interesting VR experiences.

Thus, in our second project, we have investigated FeelVR, which is a waist-worn robot capable of providing various kinds of feedback to the user on torso, neck, face, arms and hands. The robotic arm can provide a variety of tactile feedback types, such as providing normal or shear forces, as well as gestural output such as poking or stretching the skin. It can also be used to rub the user's body with a brush as an end effector or provide air flow to the face via a fan. Along with the variety of feedback types, the robotic arm can provide feedback in multiple locations on the body. The main characteristics of our approach are:

- **Varied Feedback Locations**

FeelVR can deliver feedback to areas beyond just the torso. For example, the neck area, face, forearms and upper arms.

- **Extended Feedback**

With changeable end effector, FeelVR can deliver variations of haptic feedback. FeelVR can accommodate distinct user preferences or ergonomic differences. For instance, taller users may use bigger or longer end effectors so that the robot arm may reach the whole torso.

- **Multifunctional**

FeelVR can be utilized for a variety of experiences beyond tactile feedback. It can be used for effects like feeding the user in VR, or delivering wind-effects to the user's face or any such variation which is required for the VR experience.

- **Varied Applications**

FeelVR can be used for purposes beyond VR experiences. It can be used for drawing the user's attention to hazards and emergencies, like earthquakes, or for smartphone notifications. It can be used for breaking VR immersion and making the user aware of the things going on in the physical environment.

1.3 Thesis Structure

In the thesis, we first present ClashTanks. We show how the game architecture provides different advantages in extended interaction and visualization capabilities, enabled by both AR and VR, which enrich the game experience. We further discuss prototype implementation and evaluation results.

Subsequently, we present FeelVR, which is a waist-mounted robot arm. Unlike the previous literature and existing commercial products, FeelVR can provide all types of haptic touch responses and a variety of other physical feedback types like blow wind, grabbing or pulling the user's clothing or stroking with a brush. We present our prototype specifications followed by our evaluation and the future direction. We then discuss the advantages of our design direction within the context of VR feedback, highlighting various challenges and opportunities for future work.

2 Clash Tanks: An Investigation of a Mobile Virtual and Augmented Reality Gaming Experience

2.1 Introduction

Almost all VR/AR systems, whether in the industry or research literatures, utilize a singular user experience by solely using VR or AR. Such experiences are also hindered with effective visualization and interaction methods which are yet under research. Thus, we take the first steps to investigate a research which enables the user to be mobile and roam in the physical world while still being present in VR. To investigate the possibility of such an approach in VR, we developed Clash Tanks, which is a multiplayer game that comprise a VR cockpit and AR Head-Up Display (HUD) to control a real robot. Accordingly, the contributions of our work are the following:

- 1. Cohesive game experience:** An approach that leverages both VR and AR to deliver a cohesive game experience where the user can be mobile in the physical world.
- 2. User immersion evaluation:** Preliminary user study results that examined the effect of VR immersion on the game experience and enjoyment aspects.

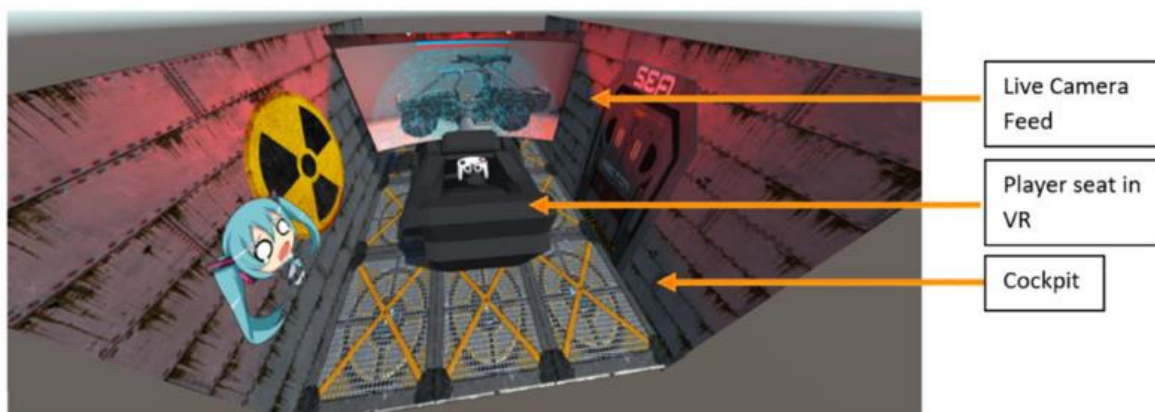


Figure 1: Player's view in cockpit, with live camera feed and AR contents

2.2 Related Work

Previous work and projects have investigated the use of AR or VR only to enhance the gaming experience. "AR Drone" [2] and "AR Quake" [3, 4], have introduced AR based gaming elements to piloting drones. Players can engage in a drone fight using the drone's equipped cameras and sensors. The drone's camera feed, viewed from a smartphone, is used to visualize missiles and opponents as well as other match related contents. Moreover, our approach is closely related to telepresence [5, 6], where users could convey their presence through robots in remote locations. Such approaches utilize a wide variety of interaction techniques, such as VR to immerse users [7] while controlling robots [8] or hand gestures to initiate various robot actions [5]. Albeit their similarity, such previous literatures lack evaluations from a gaming perspective; on which competitiveness, ease of use and enjoyment factors play larger role than telepresence related elements, such as precise robot controls.

2.3 Our Approach

Like previous works, Clash Tanks emphasizes the engagement of both VR and AR within a mobile gaming experience for controlling robots. We extend each medium in the following method: VR is utilized to immerse the player within the robot's cockpit (see Figure 1 and Figure 2). Besides being able to naturally look around the cockpit, we can introduce other interaction methods to enhance the player's immersion and enjoyment. Accordingly, our approach enables flexible implementation of various interaction techniques and play mechanics that would suit various game types. AR is used to extend the robot's live camera feed of the real world by adding various 3D contents, effects, and other game elements. AR additionally used to enhance the opponent's robot, by augmenting its physical appearance with a 3D model and energy shield (see Figure 2 and Figure 3). Elements such as player's Heads-Up display (HUD), and damage and weapon effects are also shown in VR enabling players to view weapon trajectories, executions, and outcomes. The user can move the robot via VR controls. The aspect of the robot being mobile gives the presence of physically existing at that location to the user. We believe that VR can be utilized with mobile robots to enhance impressiveness and introduce interesting interaction mechanisms to enhance the gaming experience.



Figure 2: Left and Right views of the cockpit as seen on the HMD

2.4 Implementation

Like previous works [5, 8] The game is implemented in a client-server design structure, each host maintaining its own connection to a single dedicated robot with all communications happening over wireless network (see Figure 3). Game components, such as hit points and shield status, are all registered locally in each client and synchronized through the server.

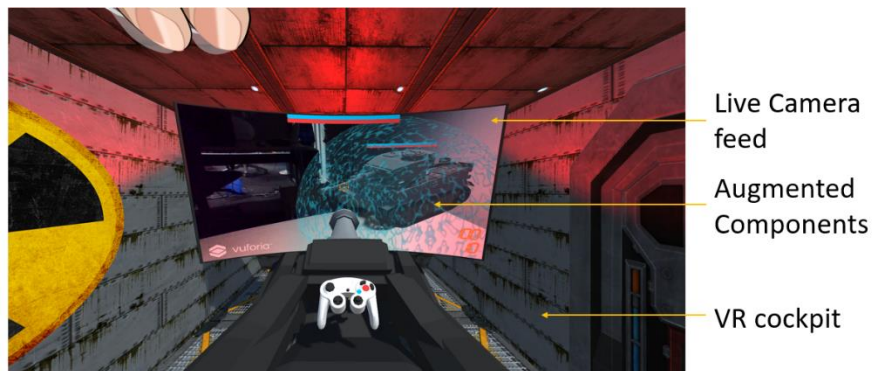


Figure 3: Overlaying of AR content on the camera feed in VR cockpit

Hardware

The game instance runs on a VR capable personal computer. Oculus DK2 [9] is used as an HMD and the player controls the robot with the help of a keyboard. The battle vehicles comprised two EZ-Robot Adventure Bots [10], strapped with a Logitech HD webcam. Each of the robots was also fitted with an AR-marker shell (Figure 4).

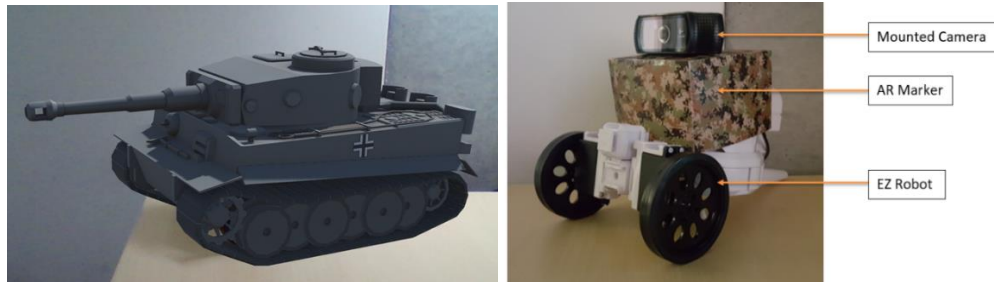


Figure 4: Robot fitted with AR – marker shell and webcam (Left) and the overlaying AR model (Right)

Software

The entire project was developed based on Unity3D game engine [11]. Vuforia [12] was utilized for all AR contents (see Figure 4). The robots were controlled wirelessly from Unity3D via a client-server software architecture between the robot and Unity3D.

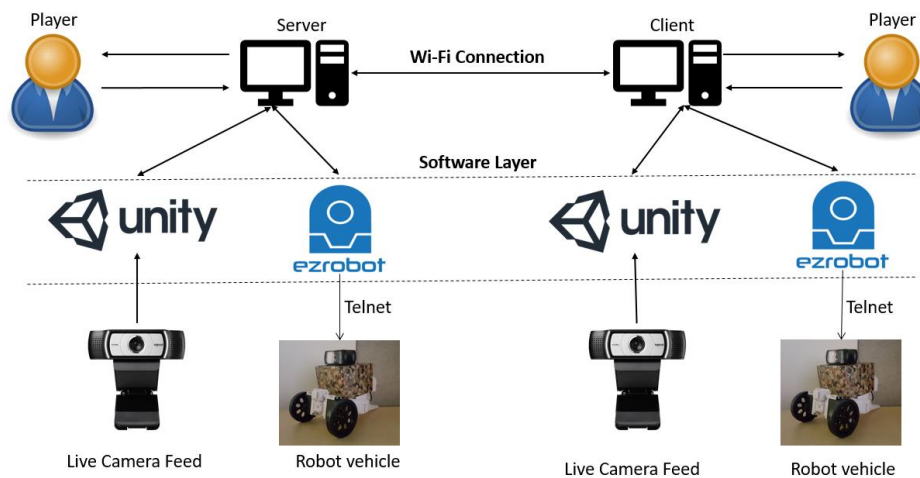


Figure 5: System architecture

2.5 User Study

Objective:

Our evaluation mainly aimed to investigate how our approach impacted game enjoyment and impressiveness within our developed game. Thus, we designed two tasks that gauged such aspect which had to be performed under two conditions; with the VR set up and without it.

The tasks were as follows:

- **Task (T1)** was an object finding task, where players had to control the robot, under both mentioned conditions, and navigate through a limited physical space to locate such object.
- **Task 2 (T2)** was a multiplayer fighting mode, where players could fight against other robots by shooting lasers and avoiding being damaged. As in traditional battle games, the player inflicting most damage would destroy the other robot and win the battle.

The prototype was set up in a room where the scenario of the game was set up. Participants controlled the robot using a keyboard while watching a screen with a video feed from the robot-mounted camera (Figure 6). We hired 6 participants (5 Males) between ages 21 and 23 ($m=21.83$), who were all college students. Two participants had knowledge and experience of using AR/VR while the other four participants did not have any prior experience with VR and AR.

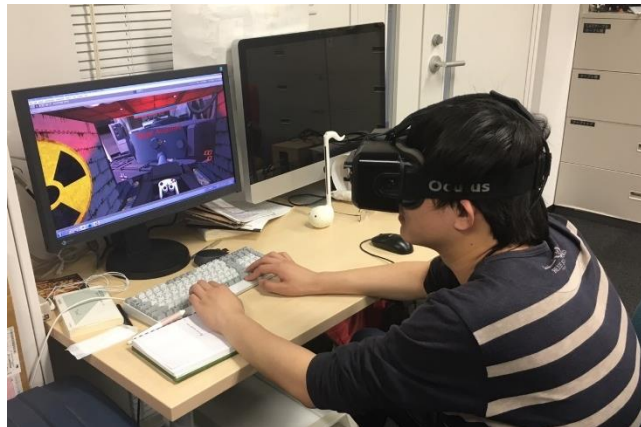


Figure 6: A participant playing our game

We carried the study with a pair of participants at each trial. Every participant performed the experiment with a separate researcher. We started by briefing the participants about our study and collecting basic information. Then, each participant had 10 minutes to familiarize and try the system, where they could try the HMD and robot controls. Next, the participants proceeded to accomplish T1 (5 minutes). Later, participants executed T2 (6 minutes). As we carried the user study in pairs, the participants played against each other. One participant starting in the VR environment while the other on the PC, and vice versa. Accordingly, we counterbalanced the procedures and participants to cancel the learning effect from the VR environment and tasks. At the end of each condition, the participants were asked to answer a questionnaire about their interface preference. The overall experiment procedure took about 35 minutes per participant including the time to practice and answer the questionnaire.

Measures

T1 was time measured from the moment the robot starts moving until the participant touches the target object to be located. Two measures were used to evaluate immersion, experience, and fun. After each condition, the participants were asked to rate how much they liked the experience on a Likert scale [14] 0 (No) and 5 (Yes) to receive qualitative

feedback. They were also asked to finish a modified version of the Game Engagement questionnaire (GEQ) [15]. GEQ is designed as a measure of engagement in games. Since the participants were made to answer the questionnaire after their interaction with each condition, we can compare the values for two different interaction systems used.

2.6 Results and Analysis

Tasks and Immersion Evaluation

On examining the task completion times for T1 under both the conditions, it was found that the participants who had experience in using VR HMDs completed the task at a faster rate ($m=153$ seconds and $SD= 32.46$, vs $m=110$ seconds and $SD= 28.02$). We believe that participants probably required more time to be accustomed to the HMD, which probably had an impact on their performance to a degree. A further analysis of results also indicated that, particularly, participants 3 and 5, who had prior experience in VR HMDs, performed better while using the HMD. Likewise, additional game interaction capabilities, such as controlling the robot were noticeably better with participants who had prior VR experience.

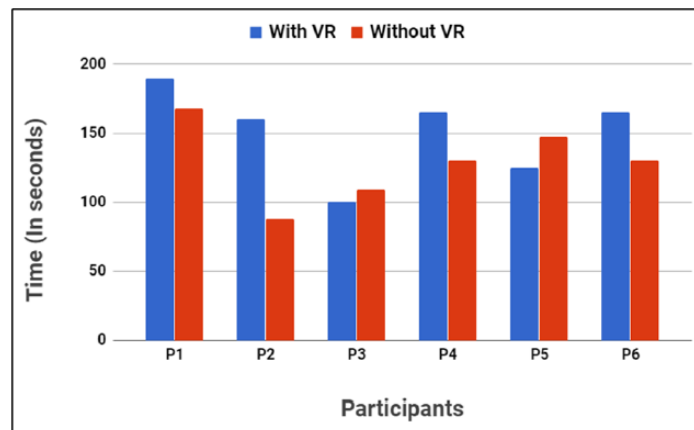


Figure 7: Time taken by each participant to perform T1

The GEQ results are presented in Figure 8. Results indicate that immersion was higher using the HMD, which is expected. Moreover, absorption, flow and presence were higher within our approach. Accordingly, we believe that such results are encouraging to investigate further VR immersion techniques.

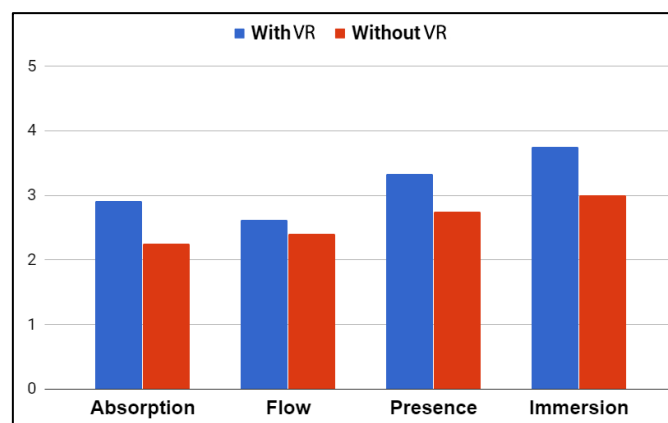


Figure 8: GEQ Results

Qualitative Analysis

Overall, the participants mentioned to have a much more immersive and fun experience when using the VR to control the robots. The participants mentioned that *the experiment gave the players the feeling of being a pilot and that it also felt more realistic than the PC experience*. Additionally, the experience and the fun factor questionnaire (Figure 9) indicated that participants significantly favoured our approach over a standard PC experience. A sole participant disliked the VR experience citing his personal discomfort and dizziness with the HMD. Such negative effects such as dizziness, motion sickness or discomfort are widely cited as common side effects of HMD usage, especially for first timers.

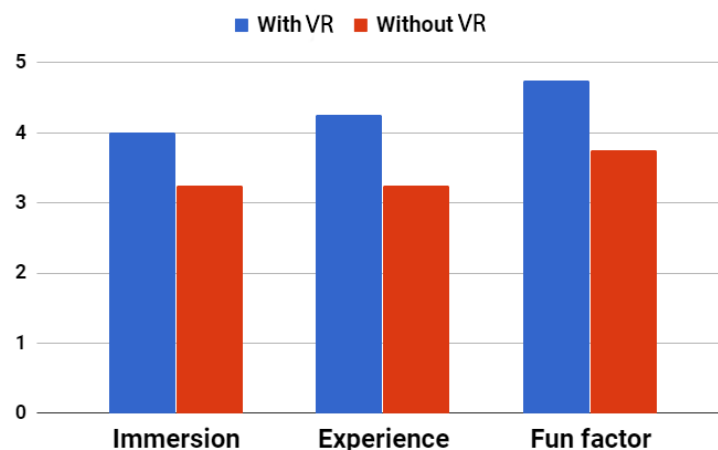


Figure 9: Rating of the level of immersion, experience, and the fun factors. The level of immersion denotes how engaged the participants felt during the experiment. Higher number indicates deeper level of immersion.

Furthermore, participants' comments indicated two positive characteristics of our approach:

- According to the participants, the most interesting experience was the ability to drive in a physical space. The game gave the players a feeling of driving a small toy car, which they saw as tank within VR, within any physical space.
- As the project being portable, it can be physically carried and played in any area that the player desires.

Likewise, participants specified a few shortcomings:

- First, controlling the robot using the keyboard whilst wearing the HMD made it difficult for participants to use the keyboard due to the lack of eye contact, especially when altering their hand placement during the game.
- Moreover, various participants reported discomfort issues and vision-blurriness, which are essentially related to the limitations of current HMD. Thus, we believe that developing better and suitable interaction methods does not just yield better and more engaging experiences but is a critical aspect of our approach.
- The overall experience of playing the game was reported to be of short duration by the participants.

2.7 Conclusion

Clash Tanks is a multiplayer game that combines elements of AR and VR in one user experience. The game creates a sense of tele-presence for the user by having the player control a surrogate robot. The ability to interact with the robot in a cyber-physical environment, allows for a deeply immersive and highly enjoyable experience for all.

3 FeelVR: Wearable Robotic Arm for Interaction Within Virtual Reality Environment

3.1 Introduction

Various kinds of feedback types have long been investigated for VR as methods to increase immersion or enhance the interaction within the virtual environment. Many platforms like HTC Vive[16] and Oculus Rift[9] allow players to move physically in a tracked space while being engaged in VR. Similarly, numerous consumer products and research literature investigated wearable haptic feedback methods for interacting with Virtual Reality. Yet, a variety of possible feedback types have been left unexplored for the context of VR. While there exists a lot of works around vests for vibrotactile feedback around the torso, such works remain limited in terms of the types of feedback that can be given to the user. Our contributions from this research include:

1. **Wearable feedback robotic arm:** The design and implementation of a wearable variable feedback robot that can provide a variety of feedback methods in multiple locations on the body.
2. **Evaluation results** that suggest acceptance of such a design approach and high immersion levels within VR.

3.2 Related Work

Previous works have investigated a variety of feedback methods that can enhance VR experiences. Several works explored vibrotactile feedback at various locations on the body, especially the chest [17,18]. Other works attempted to simulate impacts and pressure using solenoids a vest [19]. Yet, such feedback remains confined to predetermined points and is limited to a single type.

Whereas, Maimani et al [20] have developed a suit that can provide physical feedback by restricting user's movements and described the possible applications of the suit for haptic games. Strasnick et al [21] have investigated an alternate way of providing tactile feedback with the use of brushes via wearable wristbands by which they are able to transmit real world information to the user by actuation of specific servo motors. CLAW [22] is a multifunctional handheld device which can be used for grasping, touching and triggering in Virtual Reality. It provides traditional controller operations along with force feedback and Delazio et al [23] developed vests with pneumatically-actuated airbags and force sensors that provide precisely directed force to the upper body. Although, most of the mentioned novel approaches to providing feedback to the user are limited to specific locations and they do not provide a collective solution to transmit different kinds of feedback experiences in a single device.

Likewise, various commercial grade products like Hardlight VR [24] and Eyeronman [25] are vests that embed vibrotactile motors for VR feedback like previously mentioned literature. Lastly, ARAIG [26] utilizes inflatable bladders to emulate pressure or impact applied to the torso. Thus, we conclude that the surveyed literatures and products were mainly focused on delivering feedback to pre-defined stimulation points (as in [17]) and were mostly capable of vibrotactile feedback.

3.3 Implementation and Functional Prototype

The main design objective of our approach is rich feedback of various types in a wearable form. To extend previous works by diversifying and combining the into a singular device, we designed a serpentine-shaped robot with multiple end effectors.

We have chosen the serpentine design for the robot as its high degrees of freedom allow the attached end effector to deliver a variety of feedback types to the user. Moreover, such flexibility also allows the robot to reach the user's face, neck, shoulders and arms. The robotic arm is attached with a rotatable end effector

3.3.1 Prototype

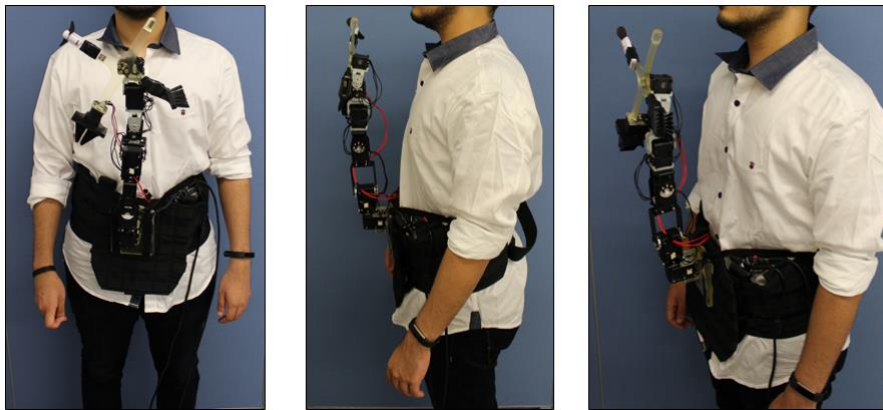


Figure 10: Robot Design, Front view(left), Side view (centre) and Diagonal view(right)

Robot Design

Our implementation uses six servomotors connected serially in a serpentine formation (Figure 10). The three servomotors of the base are of type Robotis X64AT [27], which were selected due to their high torque and PID control capabilities. The upper three servomotors are of type Robots AX12[28], which are essentially used to position the end-effectors and apply haptic feedback at desired points. The lower brackets connecting the stronger servos are made from aluminium, while the upper ones are made from plastic. We selected these servo motors as they provide good trade-off between power and weight for our intended applications.

Dimensions and Attachment

The total length of the robot is 42 cm and weighs 1.5kg. The robot is mounted on a base which is attached to a vest using a modelled and 3D printed servomotor bracket with straps.

Vest

The base of the robot is strapped to a vest, weighing 300 g. The vest makes the robot comfortable and easy to wear or take off.

End effectors

The rotatable module has four end-effectors (Figure 11) which are a finger, brush, fan and a gripper. The rotatable module can rotate 360 degrees making it possible to use the required end effector in any direction.

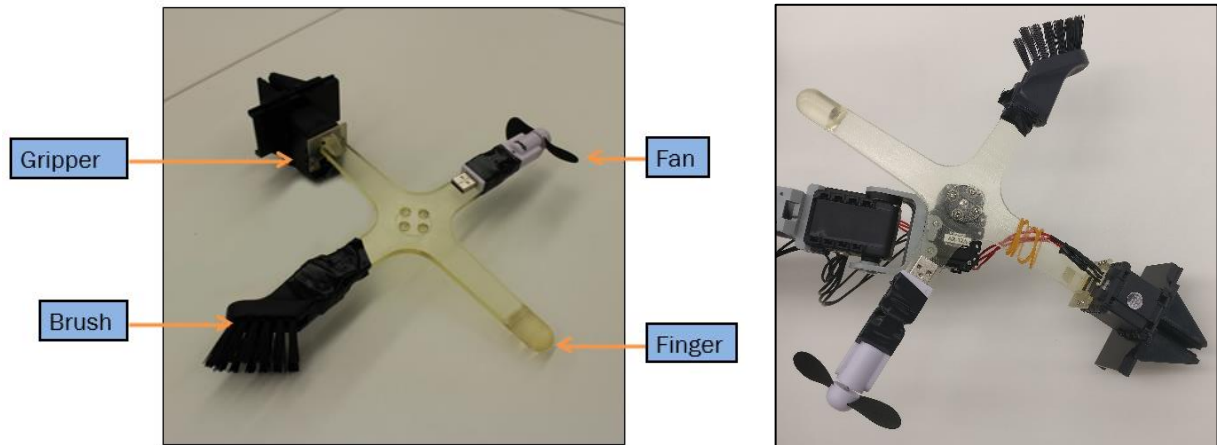


Figure 11: Rotatable end-effector

Control and Power

We extended Robotis control software to develop our own API system to control the robot. Our control software allows us to create, playback movements and motions as needed.

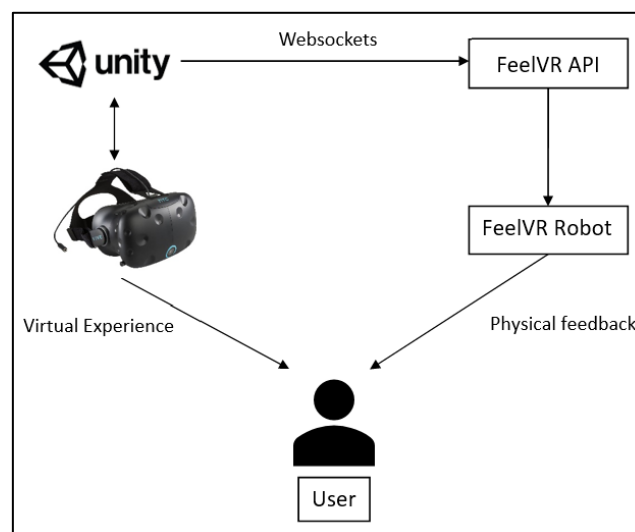


Figure 12: System Design

3.3.2 Possible Outcomes

Using the robot's variable end effector, FeelVR can apply various types of feedback with differentiating forces and time durations. Furthermore, by varying and combining forces and end effectors of different types, FeelVR can provide a variety of feedback types such as

pulling, pushing, hitting, scratching, and pinching (Figure 13). Gestural feedback can also be created by applying directional and tangential forces on the user's body.


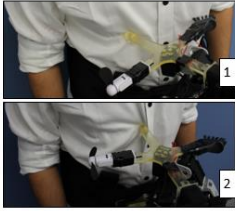




Feedback Type	Taps	Swipes and Gestures	Press	Blow wind	Gripper based experience	Brush based experiences
		 1  2				
Intensity, Strength	Degree of pressing against the users body			Fan Speed	Soft or hard pinch	Light stroke or rigid movement
Speed, Duration	Prolonged tap against the users' skin.			Duration of wind blowing	Speed of pulling clothes	Speed of stroke
Direction	Angular/ Perpendicular tap			Wind direction	Direction of pull	Direction of brush stroke
Scenario	Any physical visualization			Player movement visualization	Notification alert/ pulling experiences	Involving texture, terrain visualizations

Figure 13: Design space

3.4 User Study

Our user study is designed to find out users' usability and desirability of various feedback types within various immersive VR experiences. We investigate how haptic feedback enabled by FeelVR is perceived, when paired with matching visual and auditory stimuli within VR. In this user study, we have focused on the following types of feedbacks: taps, swipes, pressing against the body, and blowing wind.

Participants: We hired 10 college students, aged between 18 and 31 ($m=24$, all males), who came from different backgrounds and eight nationalities. Six of the participants have experienced VR before, and none had experienced haptic feedback in VR before.

Software and Hardware: Our experience was fully developed on Unity [11]. We used HTC Vive [16] head mounted display to run our developed VR experience on. Our Unity software communicates with the FeelVR robotic arm using websockets[34]. Robot control commands are sent from our software to trigger every individual haptic stimulus in synchronization with the auditory and visual ones running on our experience.

To minimize the delays between haptic and visual stimuli, we calculated the approximate time needed to deliver every individual haptic feedback type. Then, we triggered each haptic feedback action prior to the visual stimuli, thus compensating robot movements delays and initialization within each experience.

VR Experience: We developed an immersive VR experience with a simplistic story, visual and auditory effects to match each stimulus within the experience.

The torso of the user has been divided into various zones where the robot arm hits and interacts with during the VR experience. The zones are divided into 7 sections where each zone is interacted with a different end effector or a different gesture.

The structure of the experiences was that the user would go through a bad dream, with various events and experiences that he or she would be able to feel. The flow in this experience is predetermined and it is not interactive.

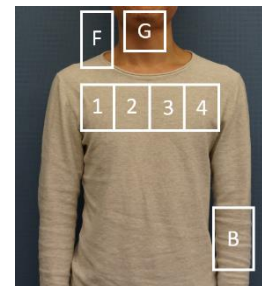


Figure 14: VR experience feedback points

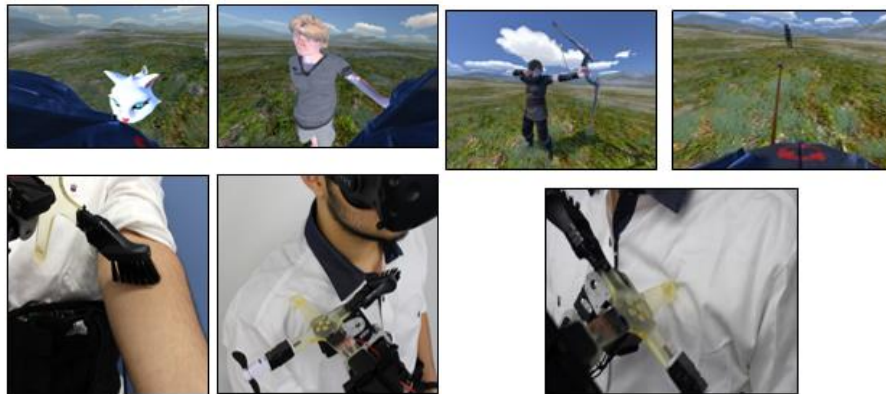


Figure 15: Brush visual and haptic feedback(left), tapping visual and haptic feedback(centre), arrow hit visual and haptic feedback(right)

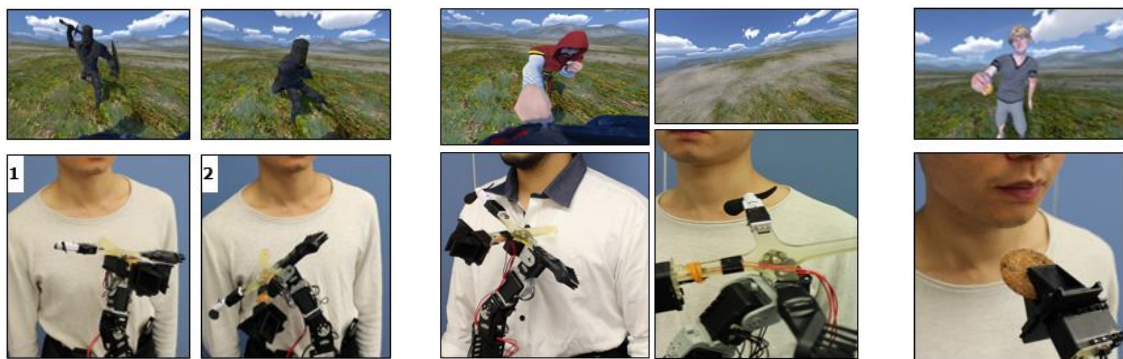


Figure 16: Sword attack visual and haptic feedback(left), punch hit and flying away visual and haptic feedback(centre), feeding visual and physical feedback(right)

First, the experience starts by a narration to welcome the user to the experience by a protagonist character. Next, experience 1 starts with a cat walking to the user and jumping on their left forearm causing the robotic arm to scratch the users arm with the brush end effector at location B (Figure 14 and Figure 15). After that, the character would approach the user, patting their right shoulder twice and telling them “you are tired, you should get some sleep” which causes the robot to tap at location 1 (Figure 14 and Figure 15) after which the screen fades out.

The next scene in the experience begins with the user being placed in stormy and dark surroundings. An Archer appears in front of the user, and she shoots arrow at the users’

chest causing the robot to hit the participant at location 4 and keep the end effector applied at that location for 4 seconds (Figure 14 and Figure 15). Next, a knight appears, and he proceeds to slash the user with his sword causing the robot to scratch the participant's torso from block 3 to block 2 imitating a sword slash (Figure 14 and Figure 16). Lastly, a brawler walks towards the user and punches the user's chest triggering a robot hit at block 2 (Figure 14 and Figure 16), making the user fly away from the impact of the punch. While flying away, the fan blows air on the user's face at block F (Figure 14 and Figure 16). Next, the screen fades out and the fan is stopped.

The third scene in the experience begins with the user fading in to the initial scene, where it is day time and fine weather. The protagonist tells the user "wake up, you had a terrible nightmare". The character feeds the participant a cookie which causes the robotic arm to take a cookie near the user's mouth.

Each experience lasts for around 30 seconds, including the appearance and disappearance of characters. Environmental graphics and sound effects were also added and were varied through the experience. These factors contribute to immersion and enable a smooth flow among the experiences.

Calibration: We calibrated and tested all feedback stimuli for every participant prior to the user study. First, we instructed users to stand casually, and each of the following movements were calibrated based on that pose. Brushing was calibrated on the user's left forearm, where we applied 2 swipes on the user's skin at a speed of 10 rpm. Pats were carried by moving the finger end effector towards the user's shoulder at a speed of 10 rpm from 5cm. This movement was carried twice, where the robot briefly rested against the user's shoulder in between taps to resemble a pat.

Pressing was carried using the finger end-effector on left side of the user's chest. Upon calibrating the position, the robot inclination angles against the body were slightly increased so the robot would produce a shear force against the chest for a period of 4 seconds. The punch was also carried using the finger end effector, yet it resembled high impact force. This was done by moving the robot at the speed of 25 rpms and 8cm from the user's mid-section of the chest. Blowing wind was carried by positioning the fan 10cm in front of the user's face, we controlled the fan manually by supplying or cutting its power source. Feeding the user was calibrated to move the gripper in front of the user's mouth. The calibration process took 25 minutes.



Figure 17: User Study conditions and hardware.

Flow: Users are first briefed about the purpose of the user study and the system. Then, all participants were familiarized with VR through a 5-minute basic VR experience that showcases HTC Vive. After that, we carried our calibration process for intended feedback. The user study started by wearing the HTC Vive, and the experiences would proceed as explained previously and shown in Figure 15 and Figure 16. After finishing, users took a post-study questionnaire. The first section gauged users' impression and effectiveness of each of the experiences and robot. In the second section, we adapted Game Experience Questionnaire (GEQ) [35] to gauge immersion and positive/negative effect of our experiences. The third section in the user study was designed to get feedback regarding the robotic arm's design and hardware. The study took one hour to complete.

3.5 Results and Analysis

3.5.1 Analysis of Haptic Feedback

Participants were asked to rate each experience individually. Participants rated *flying* (5, SD=4.2), *cat rubbing* (4.2, SD=0.91), *knight slashing* (4, SD=0.94), *feeding* (4.4, SD=0.70), *patting* (4.2, SD=1.14), and *arrow* (3.9, SD=1.20).

To gain further insights, participants were asked to rank these experiences from most to least liked. This enabled us to extract information about the quality and enjoyment by comparing each experience to another. We used a Likert scale (7 is best) where each experience can be allocated a unique rank and average rank values of each experience was calculated as follows: 1) *flying* (5.9, SD=1.3). 2).; *knight slashing* (4.3, SD=1.64).; 3) *feeding* (4.2, SD=1.98) and *arrow* (4.2, SD=1.75) were almost equally rated.; 4) *Punch* (3.6, SD=1.71).; 5) *cat rubbing* against the arm (3.3, SD=2.50), and lastly 6) *patting* (3.3, SD=2.50).

Through the interviews, multiple factors appear to affect the users' preferences, namely: overall enjoyment, predictability of feedback and consistency of stimuli.

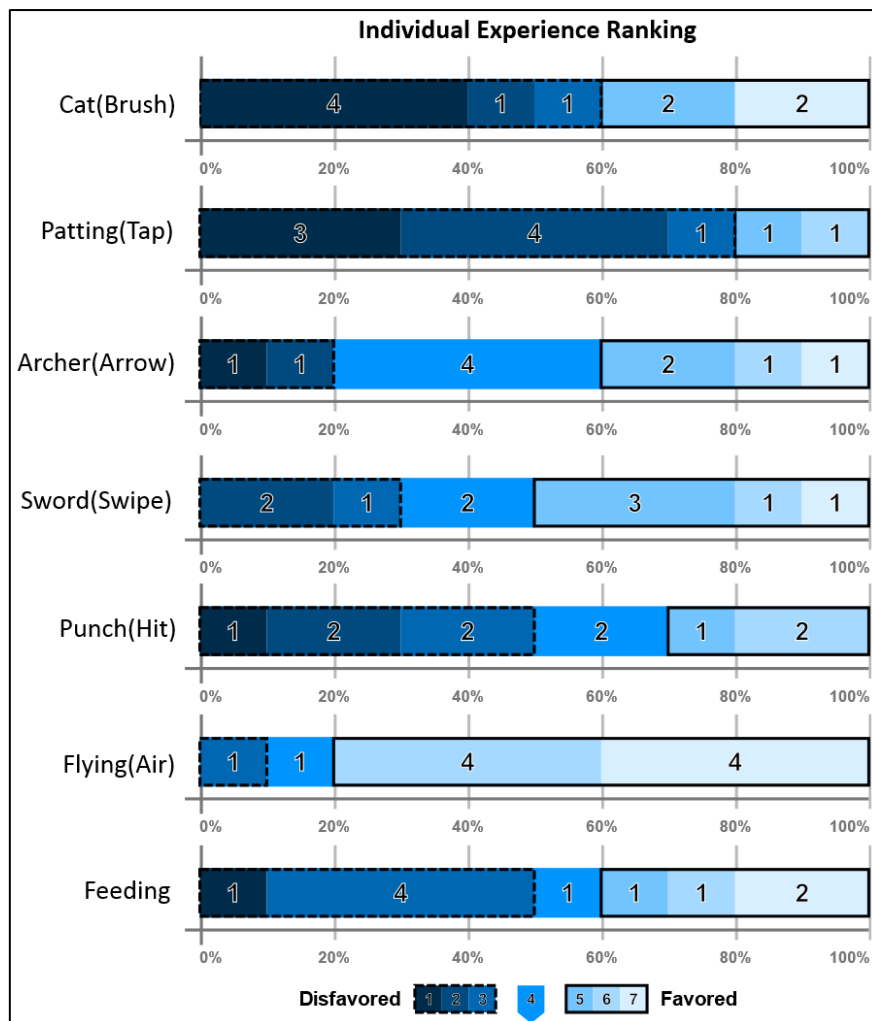


Figure 18: Individual Experience Ranking

We examine each experience as follows:

Rank 1: Flying: This was the most favoured experience, with eight participants ranking it in top 3. One participant mentioned *“The effect of air blowing was very appropriate; it wasn’t too much or too little”*, another added *“...it was very realistic, it felt like I was really flying away”*. These comments indicate that the experience was very enjoyable. Additionally, it was indicated that auditory, visual and haptic stimuli were consistent, and hence realistic.

Rank 2: Sword slash: Participants generally liked this experience, and five participants ranked it as one of their top 3 experiences. Similar to feeding, this experience received mixed views. Some participants mentioned *“...it was most realistic because the whole slash was carried out”* and *“it was intuitive, and the timing was good and motion on chest was intense.”*. These indicate that the visual stimuli and slashing gesture on the body were well received. However, on the other hand, some participants also mentioned that the slash gesture should have been stronger to be consistent.

Rank 3: Feeding: This experience was favoured by various participants, with four participants ranking it in their top 3 experiences, however, mixed views were received about being fed in VR. Some participants thought it was very novel and enjoyable. A participant

mentioned *"feeding is the most realistic experience, because get to taste the food in VR"* while another added *"It was good, eating the cookie was easy"*.

In contrary, other participants mentioned some challenges: *"I had to bend a little for eating the cookie"*, *"The cookie hit my chin when I tried eat it"*. These comments highlight the issue of correctly aligning the cookie both in VR and, so it would be easier to eat. A number of issues effected this experience, especially robot shaking in accordance to user's movements and the harness loosening upon extended use. Finally, one participant raised an important safety concern *"...Machines close to the face are dangerous"*. We further discuss safety within limitations and future works.

Rank 4: Arrow hit: The participants generally received this experience well, and four thought it belongs to their top 3 experiences. It received almost similar ranking to the feeding experience. They mentioned: *"I felt the arrow hit and stick to my body"*, *"the whole arrow effect felt realistic, the animation, timing and hit was believable"*. This indicates that the experience was both enjoyable and consistent. Some participants discussed some shortcomings, they thought arrow's animation should be faster, and proposed that feedback should have more impact and pressing strength.

Rank 5: Cat Rubbing: Participants had different opinions about this experience, and four participants rated this experience among their top 4 experiences. One participant said, *"Cat rubbing is my favourite, I felt the cat on my skin when it jumped at me"*, *"the cat was unexpected, it was scary but awesome"*. These comments indicate that the visuo-haptic stimuli were well synchronized. Yet, three participants complain about some discrepancy in stimuli: *"The brush is rough so I didn't like how it feels"*, another added *"..it should have been softer a bit, like a cushion"*. Such discrepancy made them dislike this experience.

Rank 6: Punch: In general, participants thought that this experience was enjoyable, however, only three participants only rated it among their top 3 experiences. Four participants criticized the impact force, which they thought should be much stronger to resemble a punch, while six participants thought the end-effector was too small for a fist and should have a wider contact surface.

Rank 7: Patting: This experience was least favoured by the participants, and only two participants ranked it as their top 3 favourites. They mentioned: *"...it is the most basic action compared to all others"*, *"it is not memorable"*. These comments indicate the experience was not as enjoyable as the others. Moreover, since we used the end-effector to apply the taps, participants mentioned the difference in sensed feedback in comparison to the character's hands by saying *"The feel of the hand is very different"* and *"a pat should be all over my shoulder"*. We thus conclude that the experience was not intriguing to users, and the end-effector should be improved to match visual stimuli.

Participants rated their ability to distinguish among patting, sword slashing and arrow with 4.2 (SD=0.95), so we conclude that they were distinguishable. We specifically asked about such feedbacks as they utilize the same end-effector albeit different locations, intensities and frequencies.

A few issues were reported by the participants. Feeding in VR had issues, the user leans forward but the robot also leans. The robot should compensate the user's movement in VR for feeding to work. Additionally, the location and orientation of the food items should match those in VR to enable users to perfectly grasp and eat these cookies in VR. If users lean their bodies forward, the robot also leans. This is a shortcoming of our current implementation as it does not compensate user's body movements. Our system functions if the users maintain their posture throughout the experiment.

3.5.2 GEQ Results

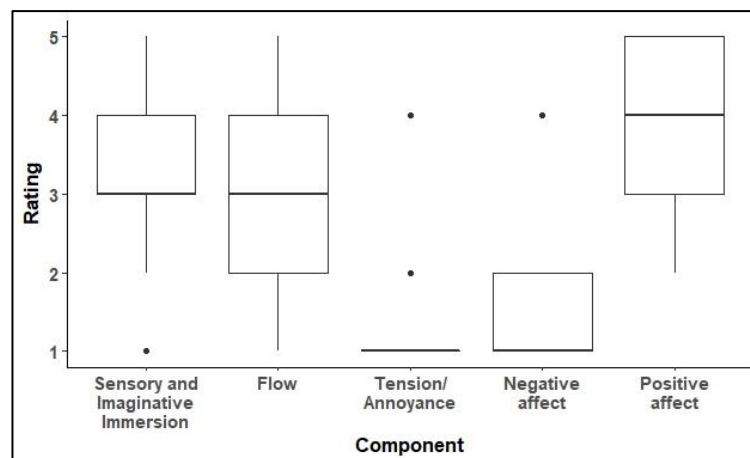


Figure 19: GEQ Results

The components which are evaluated from this user study are Sensory and Imaginative Immersion (SII), Flow, Positive affect, Negative affect and Tension/Annoyance. Flow can be defined as loss of self-consciousness within the experience. It is a state in which the user is completely absorbed within the system and experiences a sense of total concentration and control while sensory and imaginative immersion evokes a feeling of being present in the location which involves being “present” in the environment.

It appeared from our user study that although a few users felt sick during the experience, most of the users enjoyed the virtual experience and the experience did not evoke any upsetting emotion within the users. Most users also did not experience any annoying effect or tension during the study.

Mixed opinions were received for flow and SII. However, responses tend more towards positive for SII. This can be attributed to the fact that the experience is quite short which does not give enough time for the users to enter the flow state within the experience. Also, there was no method to interact with the Virtual Environment which resulted in low flow ratings as compared to immersion. We believe that immersion had higher ratings because of the haptic feedback given to the users which enhanced the feeling of being in the VE.

Similarly, though mixed responses were received for 'positive affect' from users, the study had an extremely high positive effect on most users. Overall, the experience had a positive effect on the users and gave them an immersive experience within VR.

3.5.3 FeelVR Wearability, Comfort and Weight

FeelVR was rated with 3.6 (SD=1.07) for comfort and 3.1 (SD=.99) for weight. Aggregating the results from the previous evaluation. Several participants reported back pain and pressure against their back and abdomen

we conclude FeelVR ergonomics and weight should further be improved, especially for longer periods of use. Also, the comfort should be improved through other strapping mechanisms.

3.6 Challenges and Opportunities

Users Cloth and Vest Fit: The type of user's cloth, such as their thickness, distance from the users' body and whether they are wrinkled or not. At the beginning of the study, we instructed participants to remove jackets and sweaters that could absorb feedback and straightened their clothes to remove wrinkles. Yet, it is natural for clothes to become loose upon a person's movement. Likewise, the vest is continuously checked to make sure it is securely fastened in accordance to the calibration, yet continuous robot movements affect the alignment of the robot after some time.

Visuo haptic/tactile synchronization: Despite its versatility, the serpentine morphology imposes several limitations. Since the robot arm must move to different points to apply feedback, there is an unavoidable delay in orienting and moving the arm. This is especially prevalent if the visual feedback in VR is much faster or very frequent, such that it outpaces the capability of the robot arm synchronously to deliver haptic feedback in accordance with visual stimuli.

Unintended Feedback: As most users utilize VR joysticks, the robot arm could collide with the users' hands, resulting in unintended haptic feedback. Moreover, quick user movements, such as leaning forward, could result in overshooting intended feedback force magnitude or location. Such issues require further optimization in the wearability and mechanical design.

Calibration: An easy and precise calibration method ensures a replicable and high-quality user experience. A quick calibration method is important for instantly adapting to differences between users. Lastly, delicate areas, like the neck present calibration and safety challenges for haptic feedback.

4 Discussion

We are further motivated to develop longer and richer experiences by which the user can indulge deeper within the VE while using our technology.

In ClashTanks, we would like to integrate further interaction methods, such as motion and gesture control. Additionally, we wish to investigate physical robot customizations and their effect on our approach's play experience. Lastly, we intend to integrate spatial augmented reality which utilizes projectors and depth cameras such

Microsoft Kinect [13]. Such research directions would provide a wide variety of application domains that are beyond gaming, such as in immersive tele-presence robots and drone-control environments, where our approach would have potential advantages in efficient control and feedback of such systems.

FeelVR should be mechanically improved in terms of actuation and design. We would like to shorten the required calibration time for adjusting the robot according to the user body and also diminish the safety issues involving the movement of the robotic arm near the user's face. We also plan to improve the reach of FeelVR and attempt other end effectors. Also, creating a lengthy software experience which makes capable for the users to also interact with the VE would prove fruitful. FeelVR can also be used as an input device for VE which is the direction we finally wish to proceed.

5 Conclusion

In both the projects, the ability to interact with the physical environment was reported to be a very interesting and unique concept which makes research in this domain even more interesting to pursue. Thus, we conclude that our research projects make it possible for the user to interact better with the physical world with different ways and give a higher level of immersion within Virtual Reality.

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