Virtual Reality Controller with Directed Haptic Feedback to Increase Immersion

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Abstract: In the context of this paper we propose the Directed Feedback Controller (DFC). This is a prototype controller, which is able to generate haptic feedback from all directions. Its purpose is to increase the immersion in Virtual Reality (VR) games. A user study has shown that the current prototype is perceived as very innovative. The participants enjoyed the experience and would tell their friends about it. In addition, most of the respondents see great potential in the idea behind the DFC. However, the DFC still has some minor issues. For example, due to the high weight of the DFC, the participants could not always determine the exact direction of the impact. Therefore, several ideas for weight reduction are proposed at the end of this paper.

1 INTRODUCTION

In recent years, the demand for Virtual Reality (VR) technologies has increased continuously. Wearing a Head Mounted Display (HMD) takes the user to another world but discrepancies between the experienced and the real world can quickly break this immersion.

As Hunter G. Hoffman shows in his paper, it tears the user out of the immersion of the Virtual Environments (VE) when he reaches through virtual objects with his cyber hand and receives no feedback (Hoffman, 1998). We assume that the same applies to touching objects with a tool in a VE even if the motion control gives some feedback through vibration.

Sensory modalities such as vision and audition are already basic requirements of VEs (Bowman and McMahan, 2007). However, haptics such as force feedback are relatively underrepresented and unexplored in the gaming industry, even though there is a lot of research on it within papers. Although it has already been shown that force feedback increases the user experience of the application as well as realism and immersion (Srinivasan and Basdogan, 1997; MacLean, 2000).

Even a comparatively weak feedback already adds a lot to the immersion for the user (Orozco et al., 2012). Our goal was to generate a strong feedback that really feels like hitting an object, blocking an attack, or perceiving the recoil of firing a weapon. That formed the motivation to create this prototype of our haptic feedback controller called ”Directed Feedback Controller” (DFC). The DFC is able to generate feedback from any direction, depending on the colliding object in the virtual world.

The DFC is primarily designed to simulate heavy melee and ranged weapons immersively in the VE of action-packed video games. Another possible application for DFC is the simulation of tools inside and outside games.

We have chosen directional feedback because in reality you can also feel from which direction a collision with another object or a recoil is generated. In theory, this should increase the sense of immersion. Also on a gameplay level, this mechanism offers possibilities for new game concepts as an additional source of information, such as a magic tool that guides the way based on the direction of the feedback.

In this paper, we first describe how the DFC works and how it is constructed. Then we present the results of the user test we conducted with a tech demo to investigate the effects of the DFC on the VR experience.

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2 RELATED WORK

The DFC is inspired by technology, which utilizes haptic feedback for VR applications.

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2.1 Feedback Controllers for Static or Slowly Moving Objects

The VRHapticDrones are quadcopters, which act as levitating haptic feedback proxies and are seen as movable objects in the VR space (Hoppe et al., 2018).

A very unique concept and usage of haptic feedback are the Haptic Links (Strasnick et al., 2018). They are used as connection between two handheld controllers, which are able to change their stiffness to simulate different objects like for example a rifle or two onehanded weapons.

Wolverine (Choi and Follmer, 2016) is a wearable mobile haptic device, which simulates the grasping of rigid objects in VR. The force feedback is created by constant stiffness executed with an exoskeleton structure.

Another approach of using haptic feedback is for social interactions like touching another person inside the VE (Boucaud et al., 2019). This work describes an experiment, which utilizes an interface consisting of two devices, a sleeve and a glove equipped with several vibrators, such as those integrated in smartphones. The idea is to transmit emotions. By touching the virtual avatar of another user, a signal is sent to that user, which generates haptic feedback on both ends. During the experiment, the second actor is controlled by a simple artificial intelligence (AI). The emotions that should be recognized by touch patterns of duration and intensity are: sympathy, anger and sadness.

NormalTouch and TextureTouch are hand-held controllers, which generate feedback via physical displacement (Benko et al., 2016).

The concept of Thor's Hammer is comparable to that of the DFC because it is able to generate haptic feedback from multiple directions and has a similar shape since the part with the feedback mechanisms is on top of a handle (Heo et al., 2018). The difference however is that Thor's Hammer uses six propellers, each driven by a motor and designed for continuous contact instead of short strong impulses like the DFC. The reason why Thor's Hammer is less suitable for fast applications is the latency problems that users had noticed in the user test for a specific use case.

Altogether it can be said, that the main focus of these inventions is to feel haptic feedback of static or slowly moving objects. These are barley suitable for fast paced action driven games. While these types of games are the unique selling point of the DFC.

2.2 Feedback Controllers Suitable for Action Driven Games

Nevertheless, there are a few other feedback devices that are also suitable for action games.

The Haptic Vest is a haptic feedback device integrated into a vest. With this vest, the user wears several vibrotactile and thermal actuators at different parts of the body (García-Valle et al., 2017). In their use case, a train station was simulated where the participants can interact with different objects through which the user perceives tactile interactions. After a certain time, a fire breaks out in the simulation. If the participant approaches the fire in the virtual world the vest increases the temperature via the thermal actuators. Because the vest affects only the torso instead of being a handheld controller, it has a different focus compared to the DFC. To further increase the immersion, the Haptic Vest would be a perfect addition to the DFC.

Aero-plane is a handheld haptic feedback device as well (Je et al., 2019). It utilizes two mineature jet-propellers to simulate weighted objects moving on a 2D plane. In reality, the plane is just an illusion based on the modulation of speed of the two propellers and the usage of the users wrist as pivot point. Despite its main focus, it is also capable for the use in action games like for example burst fire.

The PaCaPa (Sun et al., 2019) simulates a tool in the hand such as a stick. When the tool collides with an object in virtual reality, PaCaPa generates haptic feedback by changing its shape by opening or closing two movable wing parts. How far these wings open or close depends on the angle of the collision. Although it feels realistic and users could even distinguish the strength of an object, this prototype only works for one direction as opposed to the DFC.

In this sense, the HaptiVec (Chen et al., 2019) is probably currently the most similar invention to the DFC. Just like the DFC, it can be used in action games and is able to generate feedback from eight different directions. The HaptiVec is presented as two custom VR controllers, each containing a 3x5 tactile pin array in their handles. The pins of this array can go in and out to give users local pressure sensations depending on the directional signal given from the application. Although the HaptiVec contributes to immersion and helps the user to understand the environment better, it is clear to the user that it is still a controller, while the purpose of the DFC is to really feel like a weighty item, such as a weapon in the user's immersion. The feedback from the HaptiVec is meant to represent the whole body, e.g. it indicates the direction the user was hit by or raindrops that rattle down on the user. In contrast the DFC only gives feedback when the item in the hand of the user hits something or when recoil occurs. Noteworthy, the impact of the DFC's feedback is also stronger.

Due to its high weight and strong feedback, the DFC, unlike the other devices listed, feels less like a controller and more like a weighty object or a close combat or ranged weapon, which results in increased immersion.

3 DESIGN AND IMPLEMENTATION

3.1 Requirements and Constraints

The motivation behind the DFC is to develop a controller that enhances the gameplay feel and immersion of using a weapon in VR through a clearly perceptible feedback. The goal of the DFC is to allow users to feel from which direction the feedback is generated, both as a source of information and to simulate recoil or collision with other objects. The main focus of the DFC is the generation of strong short feedback pulses, therefore continuous feedback cannot be simulated with it. In contrast to ordinary VR controllers, the DFC has only one button, which simulates for example the trigger of a pistol. The reason for the lack of many buttons is that when the user uses the DFC, he should not have the feeling of holding a controller in his hand, rather a real weapon or tool, which should enhance the sense of immersion. While ordinary VR controllers mostly rely on haptic feedback in the form of vibrotactile actuators, the DFC contains its own mechanism for generating feedback, which will be explained in the following sections.

Both the ordinary VR controller and the DFC are not able to track the arm position of the user, so they cannot be displayed correctly in the VE, which counteracts the sense of immersion.

The weight of the controller is about 1500 g, which consists of: 110 g per coil, 20 g per plug and 25 g per iron bolt. The sum of these individual parts is multiplied by 6, since there are two of these parts per tube and there are three tubes. This adds up to 930 g. In addition there is a 90 g tracking device and the rest is the casing with 470 g.

The total costs for the proposed DFC prototype amounted to be about 250 euros.

3.2 Controller Basics

The DFC contains three tubes wrapped with copper wire at the two opposite ends of the tube, each resulting in a copper wire coil. Each tube contains two iron bolts and one steel spring. Due to the insertion of electricity, one of the two copper wire coils of one or more of these tubes becomes magnetic and pulls the nearest iron bolt with its magneticity through it. That jolt generates the haptic feedback. The steel spring slows down the iron bolt and then pushes it back to its start position like shown in Figure 1.

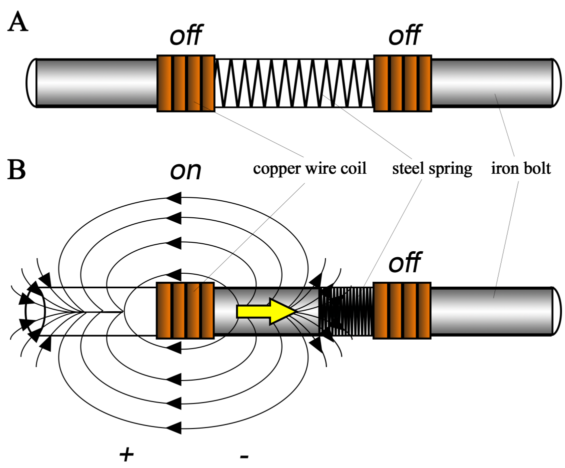

Figure 1: Feedback generation inside a single tube. (A) No electricity given, the initial situation of the tube. (B) When electricity is applied, the copper wire of one of the two coils becomes a magnet for a short duration (which copper wire coil is addressed depends on the incoming signal) and pulls the nearest iron bolt through it. The steel spring slows the bolt down and pushes it back to its starting position. The initial situation (A) is restituted again.

We attached a tracking device to the controller to track its position and rotation data. The DFC includes a micro controller which communicates via the Universal Asynchronous Receiver Transmitter (UART) with the computer (Osborne, 1980; Nanda and Pattnaik, 2016).

3.3 Previous Iterations and Alternative Design Approaches

The first prototype of the DFC was pistol-shaped and had only one feedback direction. Since we already had the idea of generating feedback from different directions, this iteration was only there to test the mechanism with the acceleration of the iron bolt by a magnetic copper wire coil. We were satisfied with the generated recoil. The second iteration already contained the directed feedback and had the form of a box, to which two tubes per axis for two opposite directions were attached. These contained the iron bolts and the copper wire coils. The prototype was placed on the arm joint and it was held by a handle, but the high weight was uncomfortable for the arm joint and the prototype itself was not really stable. Our second prototype was overall even heavier than the current iteration of the prototype because it used six tubes instead of only three. Each tube contained only one iron bolt and one copper wire coil instead of two as in the current prototype, so one tube could only provide feedback in one direction and not both directions as in our current version. Furthermore, the tubes were not orthogonally arranged, but directed to the axis system, two on each axis for the back and forth direction. This led us to the final design of our current prototype, as described in the following section.

3.4 Design

The casing and handle of the controller were printed with a 3D printer. The design of the handle is based on conventional VR controllers and is equipped with a button that can be used to send a signal to the computer. Inside the casing are three orthogonal tubes, each of them is equipped with two coils, an iron bolt and two springs, as depicted in Figure 2. The shape of the casing results from the orthogonality and symmetrical distribution of the axes and the goal of bringing the center of gravity of the controller as close as possible to the user's hand in order to minimize leverage and imbalance while moving the controller. Based on these requirements, the first design looked like a sphere. In order to reduce the weight of the casing, we then left out material that was not necessary for stability. The orthogonal alignment of the three axes makes it possible to generate feedback from any direction by combining the pulses.

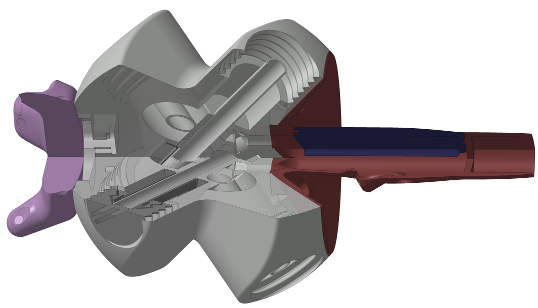

Figure 2: Directed Feedback Controller. This Computer Aided Design (CAD) model of DFC casing shows the inside of the DFC. The violet part represents the tracking device attached to the controller. The grey part represents the casing with the three orthogonal tubes, which contain the iron bolts and springs. The red part is the handle, which contains the cables and a button. The casing and the handle are 3d printed.

4 EXPERIMENT

4.1 Tech Demo

To showcase the functionality of the DFC and to make it testable for the user study, we created a game as tech demo. The game is a basic First Person Shooter (FPS) where the user has to fight waves of enemies with different weapons. The weapons in the game have been designed to optimally showcase the capabilities of the controller:

- The melee weapon is a sword, which utilizes the directional features of the DFC the most. Depending on which side of the weapon hits the enemy, feedback is generated from the opposite side.
- The grenade launcher utilizes only the front direction of the DFC to simulate the weapon recoil.
- The disc thrower releases the mounts at the left and the right side of a spinning disk, which results in feedback from both sides and then the disc is shot afterwards, which results in a feedback from the front side.
- The shield can block projectiles and melee attacks. The feedback is generated from the angle of the attack.
- The grappling hook is the weapon, which enables the user to move around the map. If shot, the user feels a feedback from the backside at first because of the releasing bowstring and frontal afterwards when she is pulled to the target.

4.2 User Study Setup

We conducted tests with 22 participants over the course of two days. 82% of these participants have played VR games already. 57% played a lot of videogames, 24% sometimes and 19% rarely or never. The age distribution was as follows: 77% were 15-29 years old and 23% were 30-44 years old. Every participant played for about 10-15 minutes including four waves of enemies and a tutorial for the game. After the play session, they had to fill in two surveys about the controller and the game. One survey containing ratings on a Likert scale (Likert, 1932), closed-ended and open-ended questions and an AttrakDiff survey (Hassenzahl et al., 2003). The time how long every participant used every weapon was tracked in the background by the game itself.

5 EVALUATION

After analyzing all the data we collected from our user study we obtained the following results.

5.1 Weight of the Controller

95% of the participants answered the question considering the weight of the controller on a scale from *too light (1)* to *unbearably heavy (4)* with the controller is *too heavy (3)*. The result indicates that the weight of the DFC should be reduced in future iterations.

5.2 Determination of the Feedback Direction

As the survey shows, only 23% of the participants were able to determine the feedback direction. The reason for this is that the proportion of the weight of the iron bolt in the total weight of the controller is only about 1.8%. Even with three times as heavy iron bolts, we would only achieve a share of 4.4% of the total weight of the controller and thereby increase the total weight from 1400 g to 1700 g. In conclusion either the total weight of the controller has to be reduced or the weight distribution has to be optimized.

5.3 Immersion

The question whether the feedback feels realistic was answered with yes only by 45% of the participants. On the other hand 77% of the participants answered yes to the question whether the feedback added to the immersion. The conclusion is that even when the feedback does not feel realistic, the mere existence of stronger and directed feedback adds a lot to the immersion of the game.

In the open-ended questions section of the first questionnaire, one of the participants said: *"I think the combination is really great, it felt real while playing"* and another: *"The controller contributed to better immersion due to its heavy weight. Even though it is exhausting to hold such a heavy controller in the long run, it reflected the weight of the weapon well"*. One participant also said *"Very good / realistic feedback - fits very well in combination with the game"*. According to the comments of these participants, the controller helped them to feel more immersed in the game world.

5.4 Potential and Entertainment Value

On a scale from *not entertained (1)* to *very entertained (4)* 91% of the participants felt *very entertained (4)* and only 9% *somewhat entertained (3)*. We had previously told participants that the questions in this first questionnaire were all related to the controller and not to the game, unless otherwise specified. If you add the results of the AttrakDiff survey (Hassenzahl et al., 2003) into the equation, one could argue that the controller is the main reason for the positive entertainment rating. On a scale from *no potential (1)* to *big potential (4)*, 73% of the participants answered that there is a *big potential (4)* and 27% that there is *some potential (3)* behind the controller if it would be developed further. That tells us that the prototype itself is not perfect but the idea of a feedback controller is worth further developing. 64% of the participants answered the question, whether they would tell their friends about our project on a scale from *never (1)* to *in any case (4)*, with in *any case (4)*. 36% would *probably tell their friends (3)*.

5.5 Design Evaluation

The question considering the design of the controller from a scale of the controller *seems unprofessional (1)* to the controller seems *professional (4)*, 18% of the participants answered that the controller *seems professional (4)*, 68% that it *seems solid (3)* and 14% that the controllers *seems a little improvised (2)*. According to the survey, only 27% of the participants were bothered by the cables, but during the user tests we made sure the cables did not disturb the participants by holding them up ourselves, thus keeping them out of the way. Although we think it would still make sense to find a wireless solution.

5.6 Weapons

The participants were asked in the survey, how much they liked every single weapon from a scale between

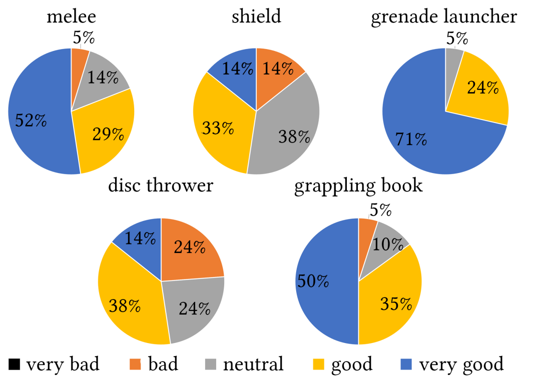

Figure 3: Weapon usage diagram. The y-axis represents the percentage how long the participants used each weapon (x-axis) in correlation to the other weapons.

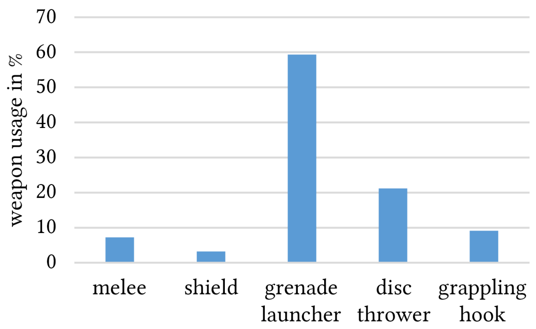

Figure 4: Weapon rating pie charts. Every pie chart represents one of the five weapons and the percentages of how much the participants liked the individual weapons on a scale from *very bad (1)* to *very good (5)*.

very bad (1) and *very good (5)* like depicted in Figure 3. At this point, we want to compare it with the tracked time how long they used the different weapons. The tracking of the weapons usage started after the tutorial and is showcased as percent usage compared to the other weapons, see Figure 4.

This is interesting for us because how much a weapon utilizes the feedback varies between each weapon. A disconnect between the usage time and the weapon rating is noticeable at the melee weapon because the rating is good but the usage is poor. The melee weapon is the weapon, which makes the most use of the directional feedback. We conclude from these results that the melee weapon is fun because of the feedback you can feel when hitting enemies but not effective in the context of our game.

The melee weapon is inefficient because all enemy types except one are ranged and sometimes you can't reach them because of the limited range of movement in the VR area.

5.7 AttrakDiff Survey

In Addition to the other survey questions, we made use of the AttrakDiff method (Hassenzahl et al., 2003).

AttrakDiff is an evaluation technique that focuses on the usability of a product, but at the same time offers a wide range of questions that leave much room for interpretation. Especially since users have to evaluate what they perceive in different areas, it can also be used to draw conclusions about the feeling of immersion. Through the experience of testing our earlier iteration of the prototype, we have found that AttrakDiff is a suitable method to evaluate the quality and novelty of a product.

The participants had to answer the same questions for our tech demo and the controller separately:

- Game as a Tech Demo - The game was perceived as attractive and practical. Furthermore the hedonic qualities were also rated positively as depicted in Figure 5. Due to the game being in VR, it was evaluated as insulating and compared to the controller rather conventional and conservative.
- Directed Feedback Controller - The controller achieved very high scores in the areas of novelty, innovation and all other areas except the *"technical/human"* category as shown in Figure 5. Whereas according to our opinion the technical aspect of the controller is not negative because it is supposed to be a technical device. The fact that almost all areas of the pragmatic quality of the controller has reached such positive values is important because interaction with virtual reality, which feels awkward, could drastically reduce the feeling of immersion (Witmer and Singer, 1998). Since isolation of the physical environment is also one of the prerequisites for immersion, it is positive to note that the categories *"isolating - connecting"* and *"separating me from people - bringing me closer"* are low compared to most of the other values. However, we would have expected these to be even in the negative range. The high values in the area of *"hedonic quality - stimulation"* lead to the fact that due to the novelty of the controller the player is fully focused on the novel tasks, which also supports the feeling of immersion by not paying so much attention to his environment at least as long as the feeling of novelty lasts.

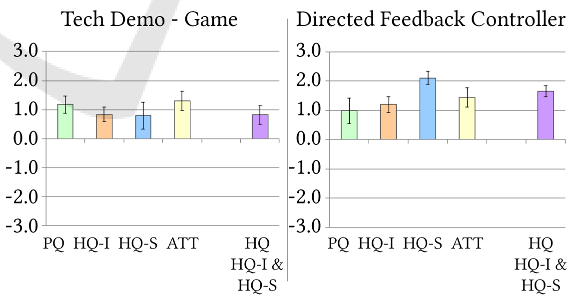

Figure 5: AttrakDiff diagram for the tech demo on the left and for the Directed Feedback Controller on the right. The values of the y-axis represent averages (mean with standard deviation) for the item groups of the x-axis considering the categories: pragmatic quality (PQ), HQ-I: hedonic quality (identification), HQ-S: hedonic quality (stimulation). The higher the value the better.

6 DISCUSSION

Expertise, gender, age and VR and gaming experience did not seem to have had any discernible influence on the users' results.

6.1 Weight Reduction

Although the heavy weight makes the DFC feel more immersive when simulating heavy weapons or tools, the weight is too high for longer game sessions, which can be tiring for the arm.

With 660 g, the coils make up almost half of the weight of the controller. However, lighter coils would only be possible with fewer windings or thinner wire. If you look at the formula for the magnetic field strength, which is decisive for the strength of the generated impulse, you can see that both measures to reduce the weight of the coil would lead to a weaker magnetic field.

$$H = \frac{I * n}{\sqrt{l^2 + D^2}} \quad (1)$$

In our case l is the length of the coil and D its diameter. The lower number of windings n has a direct effect on the magnetic field strength. A thinner wire on the other hand, would not be strong enough and would thus have an indirect effect on the magnetic field strength, since the amperage I would have to be reduced.

At about 470 g, the casing accounts for a third of the total weight. Especially for the screw caps and the transition from handle to main-body, as shown in Figure 2, a certain stability has to be guaranteed to withstand the impacts of the bolts and the movements of the user. Therefore, not much weight can be saved on the casing anymore. However, a different shape of the controller could optimize the weight distribution so that it feels lighter despite having the same weight.

Another 10% of the weight is contributed by the iron bolts, which are to be accelerated by the coils. Lighter bolts are accelerated faster in the magnetic field than heavier ones. The kinetic energy is therefore the same as with the heavier but slower bolts. Nevertheless, a lighter bolt will lead to a weaker result, because the proportion of the weight of the bolt to the total weight of the controller is decisive for the perceived impact.

The most effective way to save weight is to reduce the number of axes. One way to reduce the number of axes and to be still able to cover all directions would be the construction of two interlocking bearings with one axis in its center. The bearings could be moved separately by two small stepper motors and the axis could thus be brought into the correct position. The question remains open whether the rotation would be fast enough to avoid too much delay between the triggering event and the generation of the impact. But with good game design you can create enough time for these rotations. Using our tech demo as an example, you could do this rotation during the time of changing weapons.

6.2 Future Work and Limitations

As a next step, we would create another prototype where the weight is reduced and the tubes are repositioned so that the direction of the feedback can be recognized better. Because at the current state of the prototype, it could be argued that directed feedback does not have enough advantages over normal feedback, as so far only 23% of the participants could identify the direction of the feedback. However, we are convinced that this value could be drastically increased with some improvements, as the user test also showed that 73% of the participants see great potential and 27% some potential in the controller concept. Afterwards, we would also conduct another user test testing the same application with a plain controller that only has the standard vibration or no feedback integrated, one of the other experimental feedback controllers listed in Related Work and the DFC. This could prove that directed feedback contributes even more to immersion than normal feedback.

7 CONCLUSION

The results of our project and user tests are that there are still some issues with the DFC. The main issues are that the controller is too heavy even for a short play duration like 10-15 minutes and that the direction of the feedback is barley determinable.

On the other hand, the feedback from the user tests about the idea itself and the innovation behind it and the experience was very positive. With a few more tweaks, it has potential to become something worth buying and a promising tool to increase the immersion in VR games.

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