Controlling First-Person Character Movement: A Low-Cost Camera-based Tracking Alternative for Virtual Reality

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***Abstract*—Virtual reality (VR) gaming is a billion-dollar industry that aims at providing a more realistic and exciting immersive experience in computer-simulated environment. Besides hardware capabilities and high-quality 3-D graphics, the feeling of immersion is augmented by incorporating realistic player-game interactions, including the control of game characters movements based on real/natural movements of the player and objects. To this intent, modern VR gaming usually leverages virtual reality headsets and additional devices/sensors whose costs are normally expensive for ordinary games users. In this paper, we propose a low-cost VR gaming system in which the smartphone is used as display and processing units, and its rear camera is used as the main sensor for controlling the character movements in a first-person shooter game (FPS) developed in this work. The VR game system can operate, on average, at 31 frames per second. Regarding the usability, 19 of 24 interviewed users evaluated the character movement precision as good or very good, while 95.8% considered the gun movement as good or very good. Also, all the users would recommend the movement control system as a real-virtual interaction alternative for VR gaming.**

***Keywords*-Virtual reality gaming; Character movement controller; Camera-based tracking; First-person shooter game.**

I. Introduction

Virtual reality (VR) technology provides the user an interactive experience in a 3-D computer-generated environment and has been increasingly explored in different field of human activities, ranging from purely entertainment purposes to military ones. Particularly, VR is a trend towards a more realistic and exciting immersive gaming experience given the various possibilities of human-machine interactions: eye movements/gestures [1], head gestures [2], and skin contact between people [3], indirect physiological inputs [4], [5] (e.g,. heartbeat, breath), to name a few. According to the openPR's report in [6], the VR gaming market is estimated to achieve the quantity of US$ 14.6 billion by the end of 2023, which represents 30.5% of Compound Annual Growth Rate (CAGR) for the period of 2017-2023.

Modern VR gaming usually leverages virtual reality headsets (e.g. Oculus Rift and HTC Vive) that basically include a stereoscopic head-mounted display (HMD) and a stereo sound (headphones). Additionally, VR headsets capabilities may also be extended when aided by specific sensors and controller devices, however these additional equipment make the VR setup costly to ordinary games users. For the intended movement control application, the Oculus Rift headset can be empowered with a pair Oculus Touch tracked controllers, as in the VR game "Bullet Train" [7]. Also, the game system (or other VR applications) may allow the combination at software level of interfaces from different manufacturers. This idea can be seen in [8], where the HMD Oculus Rift head tracker is combined with the Leap Motion, which is used to track hand-based gestures for first person movement control. Oculus Rift in [9] is also combined with Microsoft Kinect 2 for walk-through navigation based on body and legs tracking. For additional reference, the reader may refer to [10]–[12].

For cheaper VR equipment, the VR industry has been heavily investing in headsets which allow coupling smartphones as processing and display units (e.g., Samsung Gear VR and Google Cardboard). Nevertheless, the smartphone processing capabilities and sensors are still underused in the context of VR gaming industry. Particularly, we are interested in providing low-cost movement control using the smartphone built-in camera as a capture device following a similar approach to that in [13], [14]. To this intent, we developed a first-person shooter (FPS) game [9], [15] as scenery for this investigation.

Two movement control tasks are included in the scope of this work: the gun movement handling and the first person walk-through navigation. In the context of FPS games, a handheld controller device that resembles a real gun (e.g., pistol joystick) is important for an immersive feeling experience [16] instead of relying on purely in-air gestures. Also, the shooter character navigation in the game can be mapped directly on the player movement across the real space. The player movements are directly translated into the same character movements, i.e., they are not required to be decoded to trigger an associated action, as in the human-flying metaphor [17].

The proposed low-cost VR gaming system is basically composed of four components: a VR BOX headset – one

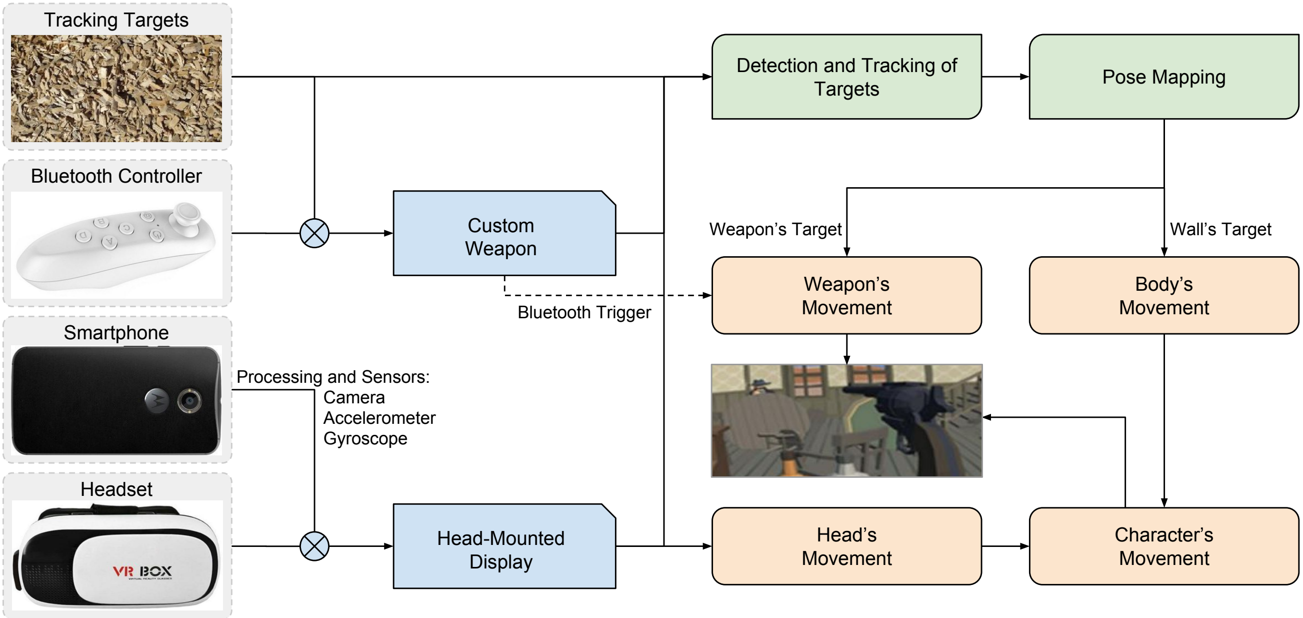


Figure 1. Overview. The proposed system comprises four components: a headset, a smartphone, a Bluetooth controller, and tracking targets. The player can customize its own weapon by combining a Bluetooth controller with a tracking target. The smartphone attached to the headset is used as a head-mounted display. The camera of the smartphone is used to capture image wherein tracking targets are detected and tracked. The poses of the tracking targets are mapped to their virtual counterparts, enabling the control of the movements in the game.

of the cheapest headsets commercially available – , a smartphone, a Bluetooth controller, and tracking targets. All the processing is performed in the smartphone (which is coupled to the VR BOX), including the movement control handling. Throughout the game execution, images are captured by the smartphone rear camera which points forward in relation to the player face. These images are processed by the smartphone CPU/GPU using computer vision techniques to detect and track the targets (i.e., textured pattern markers made of paper) placed onto the objects of interest: the wall, a fixed reference used to estimate the relative movement of the game character (i.e., shooter's walk-through); and the shooter's pistol, so that its position (i.e., location and pose) can be determined for the sake of gun movement control. The Bluetooth controller, whose shape resembles to a pistol handle, has the button trigger function. Actually, the marker-based tracking paradigm can be easily applied to hand-made controllers (e.g., car steering wheel, flight joystick), following the Nintendo Labo's [18] "build your own controller" philosophy.

To evaluate the proposed movement control system, a first-person shooter game was developed. The usability of the system was evaluated by 24 participants using question forms, and it was also analyzed the system time performance for different smartphone models. The obtained results show that 19 of the interviewed users evaluated the character movement precision as good or very good, while 95.8% considered the gun movement as good or very good. Also, all the users would recommend the movement control system as a real-virtual interaction alternative for VR gaming. On average, the system can operate in 31 frames per second (using the Moto X 2).

In summary, the main contributions of this work are:

- A low-cost smartphone-based VR gaming system;
- A low-processing movement control scheme implemented directly into the smartphone and that can be applied to a variety of hand-made controllers;
- A first-person shooter game created as a testing scenery;
- An usability investigation of the proposed implementation.

The rest of this paper is organized as follow. The proposed gaming system, focusing on the movement control, is described in Section II. The experimental methodology is present in Section III, and Section IV discusses the obtained results. Concluding remarks are made in Section V.

II. Proposed System

The proposed low-cost alternative for controlling movements in Virtual Reality (VR) games comprises four components: a headset, a smartphone, a bluetooth control, and tracking targets. The headset is responsible for housing the smartphone, and together they are used as a head-mounted display (HMD). The smartphone, besides being the display, is also responsible for processing both the movement control system and the game itself. The bluetooth control is responsible for triggering actions, such as shooting a gun. The tracking targets (for simplicity, we will call them *targets*), patterns printed in a piece of paper, are responsible for enabling the alternative movement control system. In the proposed system, the sensors of the smartphone are used to help controlling the character in the game environment. For instance, with the help of computer vision techniques, the built-in camera is used to detect and track the targets. Once detected, their poses are used to control both the weapon and the character. Moreover, the accelerometer and gyroscope sensors are also used to control the pose of the character. An overview can be seen in the Figure 1.

Even though the proposed alternative can be used for a variety of controls (e.g., guns, car wheels, airplane sticks, etc.), in this paper a first-person shooter game is used as an example. The game itself is better described in the Section III. In summary, the example used in the rest of this section is based on a first-person shooter game where the player controls a character whose goal is to kill an adversary. To achieve this goal, the character must be able to move in the map to dodge from the bullets of the adversary, played by the computer; and hunt the adversary shooting at him. In this context, the proposed system helps players to control the movements of the character and the weapon, leveraging the detection and tracking of low-cost targets.

A. Detection and Tracking of Targets

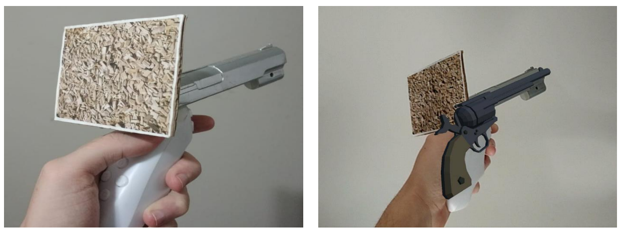
The detection and tracking of targets is an essential step of the proposed system. Targets can be seen as pieces of paper with some pattern printed on it, and they are used to enable the control of the movements (character and weapon) in the game. First, a pattern is chosen and printed in a piece of paper. Depending on the technique used for the detection and tracking, some patterns may work better than others. Therefore, choosing a good pattern to use as a target is also important. After that, images of the world are captured using the built-in camera in the back of the smartphone. Given these images, the targets are detected and tracked using computer vision algorithms. Finally, the pose of the targets in the images are mapped to the virtual world, changing the pose of the weapon or the character in the virtual environment.

B. Controlling the Movements of the Character

The movements of the character can be split into two main ones: head and body. The head movements are those that allow a player to look at both the environment and the adversary. The body movements are those that allow a player to walk through the map to both look for places to hide and hunt the adversary. The former are enabled by the sensors of the smartphone alone. Specifically, accelerometer and gyroscope data are fused to provide an accurate pose of the player's head and its movement. This pose is then replicated by the head of the character in the virtual reality of the game. The latter are enabled by the aforementioned process of detection and tracking of the targets attached to fixed places (e.g., walls). To enable the movement of the body, a pre-defined position in the virtual environment is linked to a given target. Once detected, this target is assumed to be static and treated as a virtual anchor, i.e., when the player moves away from the target in one direction, this movements is replicated by the character in the virtual environment. Using only one target can be troublesome, though. When playing a game, the target can eventually go out of the field of view of the camera and, then, the character will no longer be able to move. The proposed alternative also includes the possibility of using multiple targets to avoid this problem. However, using multiple targets also means increasing the need of processing power and would require a more powerful device.

C. Controlling the Movements of the Weapon

In first-person shooter games, it is essential to be able to point the weapon at a desired location. In this context, weapons can freely move in space with very few restrictions. To enable these movements, the proposed approach leverages a target linked to a Bluetooth controller. The Bluetooth controller is required only to trigger a shoot command. In addition, it may be used as a platform to build your own replica of what the character uses in the game (in our example, as can be seen in Figure 2, a gun). To move the weapon, the target of the weapon needs to be in the field of view of the camera. Once detected, the pose of the virtual weapon is changed according to the current pose of the weapon's target and its previous calibration. As the player is responsible to build his own weapon, they can place them in slightly different positions than those pre-calibrated. For these cases, the game is delivered with an optional calibration step for the weapon, where the players have the chance to adjust the pose of the weapon to what they feel more natural.



(a) (b)

Figure 2. Custom weapon example. The player can build its own weapon by combining a simple Bluetooth controller with a target: (a) shows an example of weapon and (b) displays the virtual weapon overlaid in the camera image.

D. Optimization Strategies

Two main strategies were used to optimize the performance of the game. First, whenever possible, the physics components of an object were simpler than the object. For instance, a bottle may have various fine-grained shapes. Instead, their physics components were simple boxes. Second, a technique called batching was applied. Batching comprises combining multiple objects into one to reduce the number of draw call that are dispatched to the GPU. Batching must be used carefully, otherwise it may lead the loss of performance instead. Both strategies were applied in the game to alleviate the need for processing power increased by the detection and tracking of the targets.

III. Experimental Methodology

To assess the proposed system as an alternative for controlling movements in virtual reality games, experiments concerning both technical aspects and player's experience were performed. In this context, a game was developed to enable a proper evaluation.

A. Game

The game developed to evaluate the proposed system is a first-person shooter set in the American Old West. The game has two modes: single-player (versus PC) and multi-player. The single-player mode comprises a one-versus-one shooting game and wins the match whoever kills the opponent first. The PC player is a simple rule-based player that randomly chooses to shoot, hide, and move. The single-player mode was the one used in all the experiments. The multi-player mode is also a one-versus-one game, but both are humans. In this mode, one player is responsible to release monsters (without the VR headset) and the other to kill them (using a VR headset and the proposed system to control movements). There is a limited number of monster the player can release, and if the shooter is alive after the release of all monster he is the winner, otherwise he is the loser. The multi-player mode was not used in the experiments. Both modes are shown in Figure 3.

The game was developed using Unity[1], a well-known game development platform. For the detection and tracking of the targets, the world's leading AR platform, Vuforia[2] Image Targets, was used. The multi-player mode was implemented in such a way that the first player to enter the match will run both the server and a client (playing as the one that releases the monsters). The other player to enter the match will play as the shooter and is expected to be using a VR system with the proposed system. The communication between them is performed through the local network.

B. Experiments

The experiments can be roughly split into three groups: (i) performance of the targets, (ii) performance on devices, and (iii) player's experience.

[1]https://www.unity3d.com
[2]https://www.vuforia.com

(a) (b)

Figure 3. Game modes. The game has two game modes: single-player (a) and multi-player (b).

Performance of the targets: To evaluate the performance of the targets, five different patterns were used in the experiments: three ArUco-like patterns with different levels of resolution, and images of stones and wood. These patterns (see Figure 4) are roughly sorted according to their "complexities". In this context, complexity can be related to the number of features detected by the algorithm used to detect and track the targets. Each pattern was printed in a piece of paper. The size of the paper also impacts on the detection and tracking performance, therefore different sizes were evaluated: small ($41cm^2$), medium ($52cm^2$), and large ($80cm^2$). Moreover, the luminance of the room also impacts on the performance of the detection and tracking algorithms. For this purpose, the detection and tracking of the targets was evaluated in three different rooms varying from 10-20, 20-40, and 50-70 lux, each. These values can be associated with low to normal light (no sunlight) in an indoor environment (such as a bedroom). In all these experiments, the performance was evaluated in terms of detection rate, i.e., the targets were presented 50 times to the camera and the number of times the system immediately detected them was recorded.

Performance on devices: To evaluate the performance of the proposed system, the game was played 5 times in 4 different devices (see Table I). Two experiments were performed: the impact of the number of targets and the effectiveness of the optimization strategies. In the former, the experiments were performed with 0, 1, and 2 targets. In the latter, they were performed with and without the optimization strategies. These experiments were evaluated in terms of average frames per second during the 5 matches. Every combination was evaluated, i.e., 5 matches were played in each device, for each different number of targets with and without the optimizations (in total, 120 matches).

Player's experience: To validate the proposed system, 24 volunteers (all undergraduate students) were invited to play the game using this alternative to control the movements of the character and weapon. All the volunteers played the game in the same device (Moto X2). Every player began at the menu and listened to an explanation about the mechanics of the game. Still in the menu, the volunteers were advised to evaluate the weapon: there were some items to shoot so

(a) ArUco 1 (b) ArUco 2 (c) ArUco 3 (d) Stones (e) Wood

Figure 4. Features detected in five patterns. These patterns are sorted (from left to right) according to the number of features detected by the algorithm. The features are represented by the red crosses.

Table I
DEVICES USED IN THE EXPERIMENTS

Smartphone	CPU	RAM
Moto G	1.2 GHz Quad Core	1 GB
Samsung Galaxy S4	1.9 GHz Quad Core	2 GB
Moto X2	2.5 GHz Quad Core	2 GB
Xiaomi Mi 6	2.4 GHz Octa Core	6 GB

the player could practice before going into the match. After beginning the match, each volunteer was advised to follow an evaluation protocol. First, they had to evaluate only the movements of the character, dodging from the bullets of the opponent. Then, they could play freely to complete the experiment. After the match, an interview was conducted. During the interview, 7 questions were asked:

1) How accurate were the weapon's movements?
2) How accurate were the character's movements?
3) How accurate were both movements when using two targets?
4) How good was your game experience?
5) How comfortable were you during the game?
6) Would you like to play other games that use this system to control the movements?
7) Would you think this system can be used as an alternative to the currently available ones?

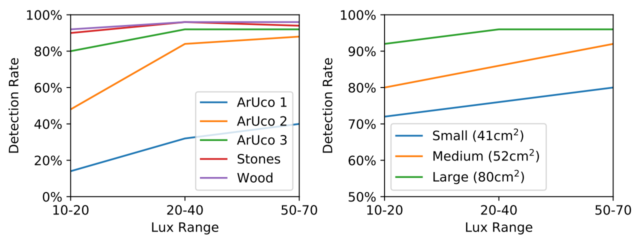
All questions are answered on a 5-point Likert scale ranging from 1 to 5 in which higher scores are better. The results are reported in terms of total answers per alternative for each question.

IV. RESULTS

The results of the aforementioned experiments are presented, and the relevant ones are discussed.

A. *Performance of the targets*

The first step is to visually inspect the features that are being detected. In this case, increasing the number of detected features should also increase the probability of that target to be detected. As can be seen in Figure 4, based on the aforementioned assumption, one would expect that the images of stones and wood should achieve greater detection rates. Results in the Figure 5 show that this expectation is correct. Overall, the greater the number of detected features, the higher the detection rate. Thus, the patterns with the best results were the stones and the woods. In addition to that, results shown in Figure 5a also allows to conclude that illumination is most important when using simpler patterns. For the two best patterns, the difference is negligible (on average, 1.3%). Moreover, the impact of the size of the target was also evaluated. In this experiment, only the wood pattern was used, given that it achieved the best performance (on average, 94.7%) in the previous experiment. As shown in Figure 5b, the best target size was the largest one. It also shows that smaller target sizes lead to larger variations in the performance of detection algorithm in terms of illumination changes. Despite the relatively high detection rate, visual inspection showed that smaller target sizes also presented a less stable tracking (the weapon in the virtual world was shaking, even though the player was not moving it), which could lead to bad experiences for the players.



(a) (b)

Figure 5. Detection rate of different targets with different sizes and environments with different illumination.

B. *Performance on devices*

Four different smartphones were used in this experiment. The average number of frames per second (fps) was measured when 0, 1 and 2 targets were being used. Moreover, the performance was measured with and without applying the optimization strategies. The results are presented in the Figure 6a and Figure 6b. As expected, the optimization strategies helped to increase the performance across a wide range of devices: on average, Moto G (+20.4%), Samsung Galaxy S4 (+21.8%), Moto X 2 (+15.0%), and Xiaomi

Mi6 (+15.8%). Furthermore, the detection of 1 target drops the performance in 26.8% (on average), when compared to no targets at all. However, detecting a second target does not decrease proportionally, dropping the performance in 9.4% (on average). The performance drop is lower in the Xiaomi Mi6, which differs from the other on the availability of 8 cores instead of the 4 cores in the others. Overall, as expected, the worse performance was achieved by the oldest smartphone (Moto G, released in 2013) with an average of 15fps, and the best performance was achieved by the newest smartphone (Xiaomi Mi6, released in 2017) with an average of 54fps. As a preliminary result, an extra experiment was run using the Moto X 2, where up to 5 targets were used. As can be seen in the Figure 6c, there is a consistent drop of ≈13% in the performance after the first target. Unfortunately, using more than 2 targets is still prohibitive in terms of performance (the loss of performance does not compensate the increase in robustness), therefore the subsequent experiments used a maximum of two.

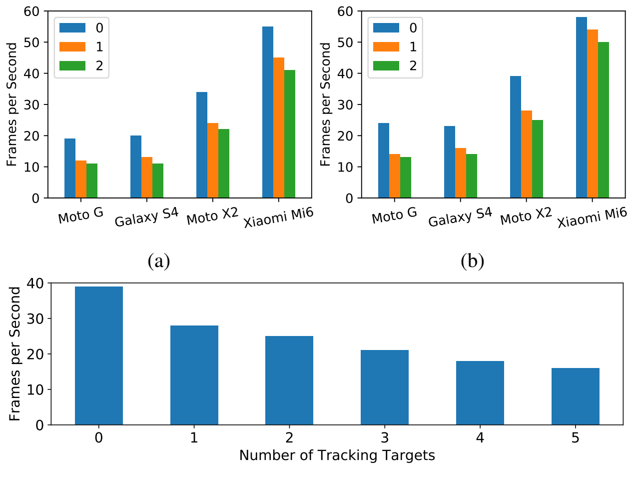


Figure 6. Performance of the system on different devices without (a) and with (b) the optimization strategies. An extra experiment (c), with up to 5 targets, was performed as well.

C. Player's experience

In this experiment, 24 volunteers (undergraduate students) played the game (using the Moto X 2) and, afterwards, answered to 7 questions. Their answers are now presented and discussed. The first two questions are about the movement of the weapon and the character. Overall, the volunteers found the movement control to be accurate enough (average of 4.3 and 4.1 for the movement of the weapon and character, respectively – see Figure 7a and Figure 7b). These two questions were answered when they evaluated the weapon and the movement of the character separately, as advised. When playing freely, they were playing with both targets (on the weapon and on the wall) and, eventually, a volunteer would point the weapon towards the target in the wall, hiding the latter from the camera. Sometimes, while learning to play, the volunteers also used to turn the head in such a way that the target in the wall would go out of the field of view of the camera. In the game, the volunteers could see a blue dot characterizing the target in the wall. Therefore, they could see when the target went out of the field of view, and understand why the body's movement of the character was disabled. In the beginning, when these situations happened the volunteers were oriented on how to proceed: (i) avoiding to occlude the blue dot with the weapon and (ii) turning the head back to the target when blue dot goes out of sight. Later, players create awareness and incorporate this constraint naturally. Multiple targets on the wall could help solving this issue, but as shown in a previous experiment, there is still need for improvements in the performance for these cases. These instabilities were the main reason for the average answer of 3.7 for the third question (also in Figure 7c). It is important to note that the game can be constructed for controlling the gun only, instead of controlling both, the player and the gun.

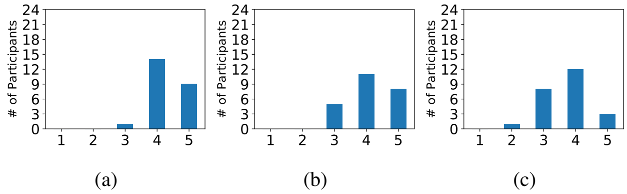


Figure 7. Results about the accuracy of the movements of both the weapon and the character.

When asked about the level of comfort while using the proposed system, most volunteers answered 5 (highest level), with an average of 4.25 (see Figure 8a). Most of the discomfort came from the low-cost headset used in the experiments, sometimes bothering the hair and nose of the volunteers. In general, the volunteers were satisfied with the overall experience, with 62.5% of them answering 5 and the others 4 (average of 4.6 – see Figure 8b).

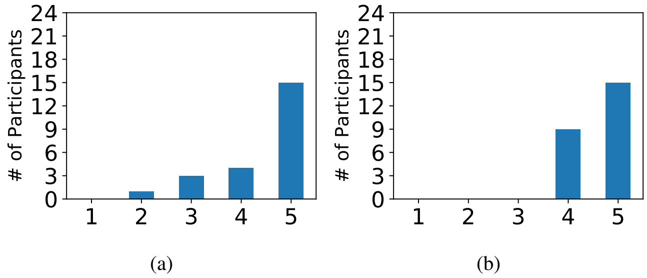


Figure 8. Results about the overall player's experience.

The volunteers were also asked if they would like to play other games that use the same system to control movements, and 83.3% of them answered 5 (with 0 meaning "no" and 5 "absolutely"). The other volunteers answered 4. Moreover, they were asked if this kind of system can be seen as an alternative to the current movement control systems. All volunteers answered either 4 or 5, with an average of 4.6. The results are showed in the Figure 9.

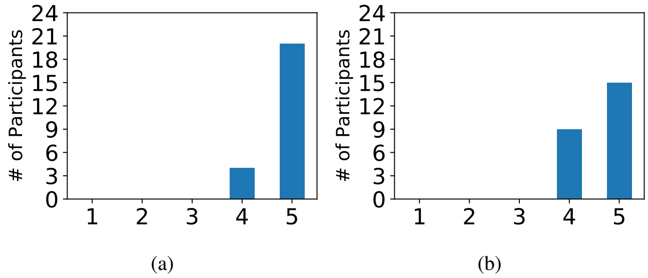


Figure 9. Results about what the volunteers think about the proposed system.

D. Qualitative analysis

In general, the volunteers reported that the feeling of holding a gun-like object (the Bluetooth controller with our adaptations) helped to increase the immersiveness of the experience. In addition, a video of a match was recorded and will be publicly available[3]. Figure 10 shows a player during a single-player match.

Figure 10. On the left, a player holding a custom weapon built out of a target (wood pattern) attached to a Bluetooth controller. A second target (stones pattern) can be seen on the wall. On the right, what the player is seeing on the head-mounted display.

V. Conclusion

Virtual reality has been receiving increasingly attention of the gaming market in the last years. The immersive experience provided by VR is very attractive for game users, in particular the ability of controlling the game characters movement using real/natural movements of the player and objects, i.e., the shooter and the gun in the context of our FPS game. However, traditional VR equipment setup is, in general, costly for ordinary game users.

This paper proposed a low-cost VR smartphone-based gaming system focusing on character movement controlling, i.e., the shooter and his gun in our FPS game. We conducted an usability experiment with 24 participants who were posteriorly interviewed by means of question forms. The main results are briefly listed as follow:

- 19 of 24 users evaluated the character movement precision as good or very good, and
- 95.8% considered the gun movement as good or very good;
- all the participants recommended the movement control system as an alternative for VR gaming.

Despite the general acceptance of the proposed approach, the system still presents some limitations, such as the fact that the user cannot simply download and play; he has to print the targets and calibrate. Future directions of this research includes exploring the movement control based on markers tracking for other types of game (e.g., driving and flight simulators) and VR application domains.

[3] https://youtu.be/a030bzVP9MI

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