Simulating Skydiving Experience in Virtual Reality

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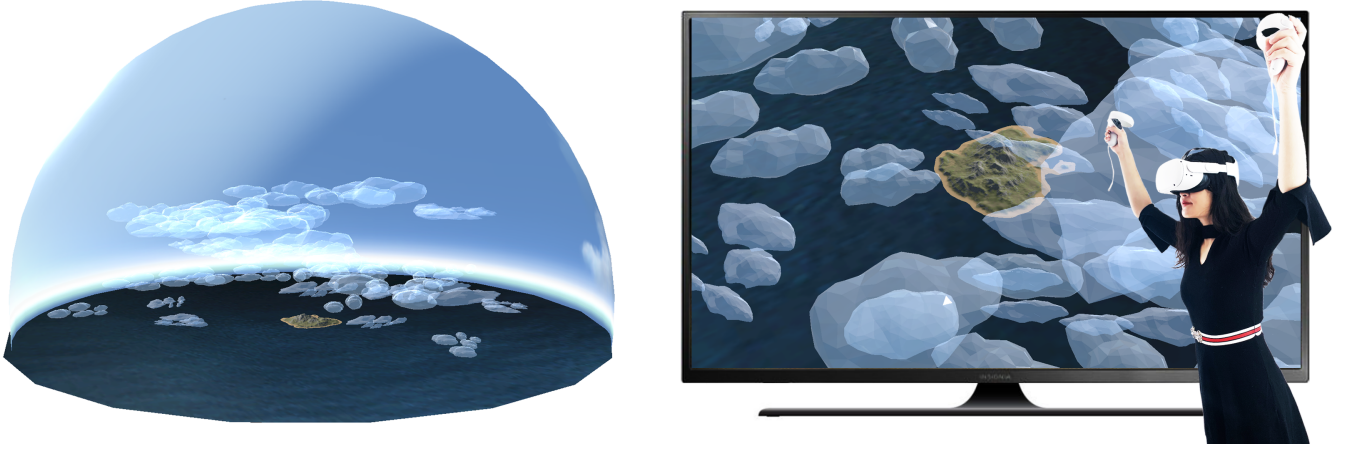*University of South Florida*

Fig. 1: Teaser. This figure shows a manually created virtual natural island scene (left) where a user is skydiving in virtual reality (right). With our approach, the virtual skydiving experience is simulated through aerodynamics laws. In this example, the user is currently free-falling toward an island with a vision displayed in a VR headset and projected onto a TV screen.

Abstract—As one exciting extreme activity, skydiving is gaining popularity in recent years, especially, among the younger group. However, due to the danger raised by skydiving, most first-time players are feared to try. Therefore, indoor VR-enhanced skydiving activities tend to become potential substitutes. Responding to this trend, we propose a stand-alone, easy-to-setup, and physics-based approach to simulate the skydiving experience in virtual reality. With our approach, when users stand in an arbitrary room with two VR controllers held in their hands, their virtual skydiving experiences, such as jumping down from a helicopter, tracking forward, backward, or rotating, deploying the parachute, landing on an island, etc., can be simulated in their VR headsets realistically through aerodynamics laws. Through the numerical experiment results and user study feedback, we validate that simulating virtual skydiving experiences with our approach is realistic compared to real skydiving experiences.

Index Terms—skydiving, physics-based simulation, aerodynamics, virtual reality

I. INTRODUCTION

As Virtual Reality (VR) technologies become more and more intelligent, affordable, and pervasive, simulating sports activity in VR gained growing interest from researchers recently. Due to the immersiveness delivered by the well-designed VR simulation programs, VR exercise or VR sports can achieve even better exercise effects than traditional ones due to the enjoyment, safety, and convenience afforded by VR programs. As a consequence, researchers developed different types of VR simulations that simulates immersive sports activities, such as VR basketball [1], VR soccer [2], VR volleyball [3], VR American football [4], VR badminton [5], VR table tennis [6], VR bowling [7], VR billiard [8], etc. to achieve various kinds of sporting experience in virtual reality.

As one special type of sport and extreme activity, skydiving has been a hot topic for VR researchers. A common feature of extreme activities is the danger behind such kinds of sports. Therefore, different types of VR skydiving simulators have been developed by researchers in recent years for several reasons: First of all, VR is injury free. Secondly, the immersiveness afforded by VR can give users a similar skydiving experience in reality. For example, Eidenberger et al. [9] developed an indoor skydiving VR simulator that has embedded immersive storytelling. But this approach needs the user to be hanging in the room with many steel wires, which requires lots of work for hardware configurations and can not be easily popularized. Also, potential danger can be caused by the malfunction of such hardware systems (e.g., broken wires cause a fall). As another option, iFLY [10] simulates the VR experience for indoor skydiving. But this approach is location-specific, hardware-constrained, and moving space-limited. Therefore, users can never play this VR program at home as a stand-alone app. Most importantly, researchers [11] recently found that indoor skydiving can be an emerging cause of anterior shoulder dislocations.

Therefore, given these limitations among existing VR skydiving simulators, we propose a novel home-stand-alone, simple-to-setup, easy-to-popularize, and physics-based approach to simulate the skydiving experience in virtual reality. More specifically, we propose an approach that takes into consideration the basic aerodynamics rules for simulating immersive skydiving experiences according to the user's gestures. With our approach, the user can skydive virtually with any standard VR headset and controller. As shown in Fig. 1, during the gameplay, the user only needs to stand in the room

(a) Standing.   (b) Free falling and tracking.   (c) Deploying parachute.   (d) Landing on an island.
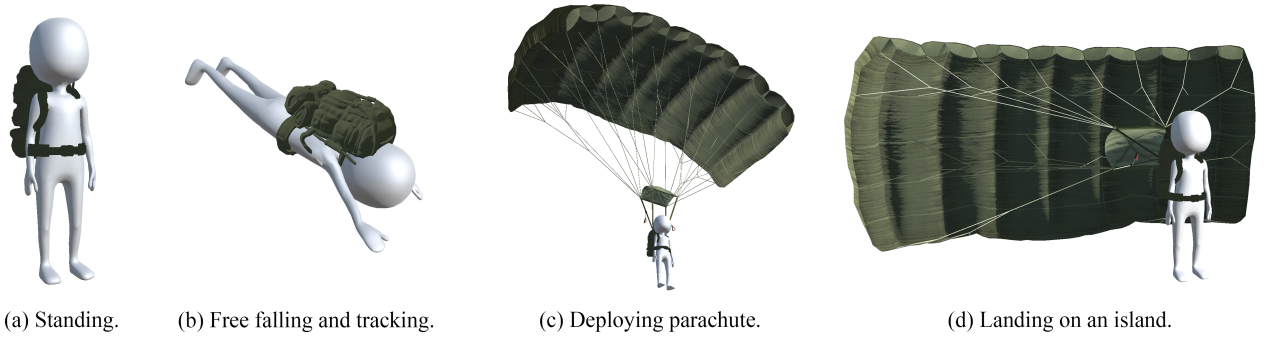
Fig. 2: Overview. This figure shows four stages simulated in our technical approach, they are: (a) standing in a virtual helicopter, (b) free-falling and tracking in VR, (c) deploying a parachute in VR, and (d) landing on the virtual destination island.

and make some simple gestures, such as leaning their arms forward or backward, etc. to control their motion in the infinite VR world. Compared to other's approaches, our approach is injury-free, hardware-regardless, stand-alone, easy-to-setup, and not location-specific. Contributions of our work include:

- We propose a novel research topic about simulating VR skydiving experience on standard VR headsets without any requirement on location or hardware configurations. Demo video is here: https://youtu.be/TLdd7Oj-rG0

- We propose a novel technical approach to simulate the user's VR skydiving experience according to physics rules so as to simulate real-world phenomena.

- We implement this skydiving simulator on a standard VR headset - Oculus Quest 2 - and conduct a series of experiments to validate our proposed approach.

II. OVERVIEW

Fig. 2 shows the overview of our technical approach for the VR skydiving simulator. As shown in subfigure (a), in the beginning, a user wearing the VR headset is standing in a room, correspondingly, that user is standing in a helicopter within the virtual scene. This setting is trying to mimic the full skydiving experience in the real world that generally begins with a helicopter. After the user feels ready to skydive, by moving their bodies forward with one or two steps in the room, the jumping mechanism is automatically triggered in VR (where the trigger's collider is highlighted as blue in Fig. 3(a)). Then, the user starts free-falling and tracking virtually as shown in subfigure (b). During this stage, the user can rotate, tracking forward or backward with different gestures. All these motions are simulated with our approach based on fundamental aerodynamics laws. After the user is approaching a virtual island as shown in subfigure (c), by moving one hand towards a trigger under the virtual backpack (whose collider is highlighted as blue in Fig. 3(b))), a parachute is deployed in VR. This design is trying to help users adapt to a similar action that needs to be taken before throwing a parachute in reality. In the end, after all of the steps shown in previous subfigures are done by the user correctly, the user will land successfully on an island in VR as shown in subfigure (d).

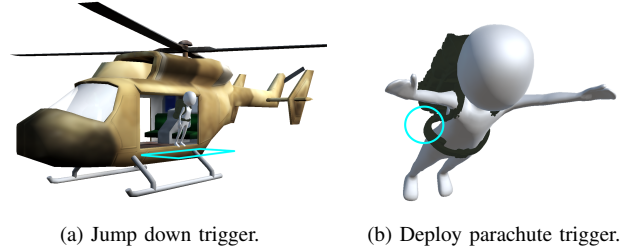(a) Jump down trigger.   (b) Deploy parachute trigger.

Fig. 3: In our proposed approach, there are two types of triggers whose colliders are highlighted as blue including the jump down trigger (a) and the deploy parachute trigger (b).

III. TECHNICAL APPROACH

In order to simulate the user's skydiving experience realistically, we employ the fundamental aerodynamics laws for proposing our physics-based simulation approach. Given the hardware tracking system provided by the VR headset and VR controllers, the positions of the user's head and hands can be captured accurately. Given this background, three time-related variables are important factors considered in our simulation approach, they are: mass center position $\mathbf{p}(t)$, left hand position $\mathbf{l}(t)$, and right hand position $\mathbf{r}(t)$. These three factors will be directly applied to the motion calculation for the user's tracking and rotation during the free falling stage.

Falling Velocity. After the user jumps down from the helicopter in VR, two separate forces acting dominantly on the user which are gravity and drag. The only difference between the free-falling stage and the deployed parachute stage is the drag coefficient $C_D(t)$ and the contact area with air $A_\perp(t)$. Mathematically, we calculate the user's falling velocity $\mathbf{v}_\perp(t)$ by numerically solving a differential equation as shown here:

$$\frac{d\mathbf{v}_\perp(t)}{dt} = \mathbf{g} - \frac{1}{2m}\rho||\mathbf{v}_\perp(t)||^2 C_D(t) A_\perp(t)\hat{\mathbf{v}}_\perp(t), \quad (1)$$

where the average human mass $m = 60$kg, air density $\rho = 1.225$(kg/m^3), drag coefficient $C_D(t) = 0.45/2.3$ before/after parachute is deployed, and $A_\perp(t) = 1.75$(m^2)/20(m^2) is the average vertical contact area before/after parachute is deployed and normalized velocity $\hat{\mathbf{v}}_\perp(t) = \mathbf{v}_\perp(t)/||\mathbf{v}_\perp(t)||$. More intuitively, increasing the drag coefficient or contact

(a) Forward tracking.   (b) Backward tracking.   (c) Left rotation.   (d) Right rotation.
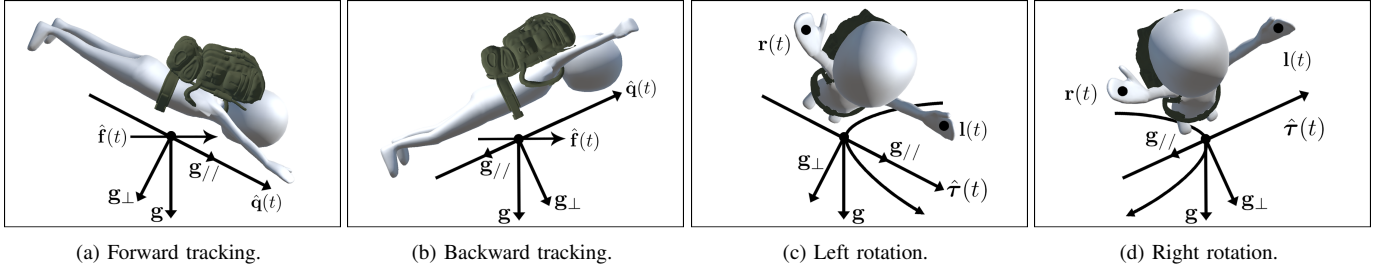
Fig. 4: Mathematics behind the tracking. This figure depicts the aerodynamics rules for simulating the tracking stage during skydiving. (a) (b) show how is forward and backward tracking controlled and (c)(d) show how the rotation is controlled.

area will increase the drag force which is always opposite to the object's moving direction. At the same time, the drag coefficient is related to the object's shape. As a matter of fact, the user's falling speed will be dropped dramatically after the parachute is deployed whose both the drag coefficient and the contact area will increase dramatically.

Tracking Velocity. In our proposed approach, we consider the user's tracking experience during the free-falling stage including tracking forward, tracking backward, rotating left, and rotating right by adjusting their hand positions. Noted that during all stages, users are standing in the room. Therefore, an assumption is made here that the vertical contact area $A_{\perp}(t)$ is a constant and maximized value during each stage as the user's orientation is always facing opposite to the y-axis in VR. This assumption is similar to the reality that when users are skydiving, they can actually track forward or backward through different gestures, this can be achieved by fundamental aerodynamic laws proposed in our approach.

As shown in Fig. 4(a), a user is tending to lean the body forward, in this case, according to the rules of force decomposition, gravity $\mathbf{g}$ can be decomposed into two directions, one is $\mathbf{g}_{\perp}$ which is perpendicular to the user's tracking direction $\hat{\mathbf{q}}(t)$ and another one is $\mathbf{g}_{//}$ which is parallel to $\mathbf{q}(t)$. As the drag is proportional to the content area, the drag along $\mathbf{g}_{//}$ is small enough to be ignorable. As a consequence, there is a sliding force along the tracking direction $\hat{\mathbf{q}}(t)$ to push the user forward along the forward direction $\hat{\mathbf{f}}(t)$. Empirically, we approximate the user's tracking direction $\hat{\mathbf{q}}(t)$ as their arms' direction where $\mathbf{q}(t) = \frac{1}{2}(\mathbf{l}(t) + \mathbf{r}(t)) - \mathbf{p}(t)$. Then, we calculate the user's tracking velocity $\mathbf{v}_{//}(t)$ by numerically solving this differential equation:

$$\frac{d\mathbf{v}_{//}(t)}{dt} = \kappa \hat{\mathbf{f}}(t)(\hat{\mathbf{q}}(t)(\mathbf{g} \cdot \hat{\mathbf{q}}(t)) \cdot \hat{\mathbf{f}}(t)), \qquad (2)$$

where κ is a sensitivity coefficient for tracking. Empirically, we set $\kappa = 0.1$. Forward direction $\hat{\mathbf{f}}(t)$ is calculated as the normalization of user's head position $\mathbf{h}(t)$ subtract user's mass center position $\mathbf{p}(t)$. As shown in Fig. 4(b), when a user is tending to lean the body backward, according to Eq. 2, the angle between $\mathbf{g}_{//}$ and $\hat{\mathbf{f}}(t)$ is greater than $90°$, therefore, the tracking force is opposite to the user's forward direction, which means in this case, the user will track backward.

Angular Velocity. As another phenomenon during the tracking, when user is rolling a angle towards left hand side as shown in Fig. 4(c), there will be a centripetal acceleration $\mathbf{a}(t)$ caused by $\mathbf{g}_{//}(t)$ acted on the user which is pointing towards the user's pitch axis $\hat{\boldsymbol{\tau}}(t)$ where $\boldsymbol{\tau} = \mathbf{l}(t) - \mathbf{r}(t)$. According to the physics rules about centripetal acceleration $\mathbf{a}(t) = \boldsymbol{\omega}(t) \times \mathbf{v}_{//}(t)$ and $\mathbf{a}(t) = \mathbf{g}_{//}(t) = \hat{\boldsymbol{\tau}}(t)(\mathbf{g} \cdot \hat{\boldsymbol{\tau}}(t))$, the user's angular velocity $\boldsymbol{\omega}(t)$ can be calculated as:

$$\boldsymbol{\omega}(t) = \hat{\boldsymbol{\tau}}(t) \times \hat{\mathbf{v}}_{//}(t)\left(\frac{\mathbf{g} \cdot \hat{\boldsymbol{\tau}}(t)}{||\mathbf{v}_{//}(t)||}\right) \qquad (3)$$

As shown in Fig. 4(c), in this example, the centripetal force is pointing towards the left hand, therefore, the user will rotate left around a circle with a radius of $\mathbf{v}_{//}^2(t)/(\mathbf{g} \cdot \hat{\boldsymbol{\tau}}(t))$ at an angular velocity calculated in Eq. 3 and the vision in VR will rotate to right. In the meanwhile, Fig. 4(d) shows a different scenario for rotation. This time, the user is tending to roll an angle towards the right-hand side, according to Eq. 3, the angle between $\mathbf{g}_{//}$ and $\hat{\boldsymbol{\tau}}(t)$ is greater than $90°$, therefore, the centripetal force is opposite to the user's pitch axis, the user will rotate to right and the vision in VR will rotate to left.

IV. NUMERICAL EXPERIMENT

Implementation. We implemented the proposed skydiving VR simulator on Unity 3D (2019v) using the Steam VR 2.0 plugin with the hardware configurations of Intel Core i5 CPU, 32GB DDR4 RAM, and NVIDIA GeForce GTX 1650 4GB GDDR6 Graphics Card. The VR program developed for the skydiving VR simulator is configured on Oculus Quest 2.0 version.

Simulation. Fig. 8 shows the experimental results of simulating the skydiving experience in a virtual outdoor environment where there is an island embraced by an ocean. As shown in Fig. 8(a), in the beginning, the virtual player is standing in a helicopter and preparing to jump down. Once move several steps forward, the virtual player is jumping down from the helicopter and starts the free-falling stage which is captured in Fig. 8(b). During this stage, the virtual player is automatically facing downwards. As shown in Fig. 8(c), by adjusting the arm gestures, the virtual player is able to start tracking during the free-falling stage. Those tracking methods include tracking forward or backward by leaning arms forward or backward, rotating to the left by leaning the left arm forward

(a) Standing in helicopter.

(b) Jumping down.

(c) Free-falling and tracking.

(d) Approaching an island.
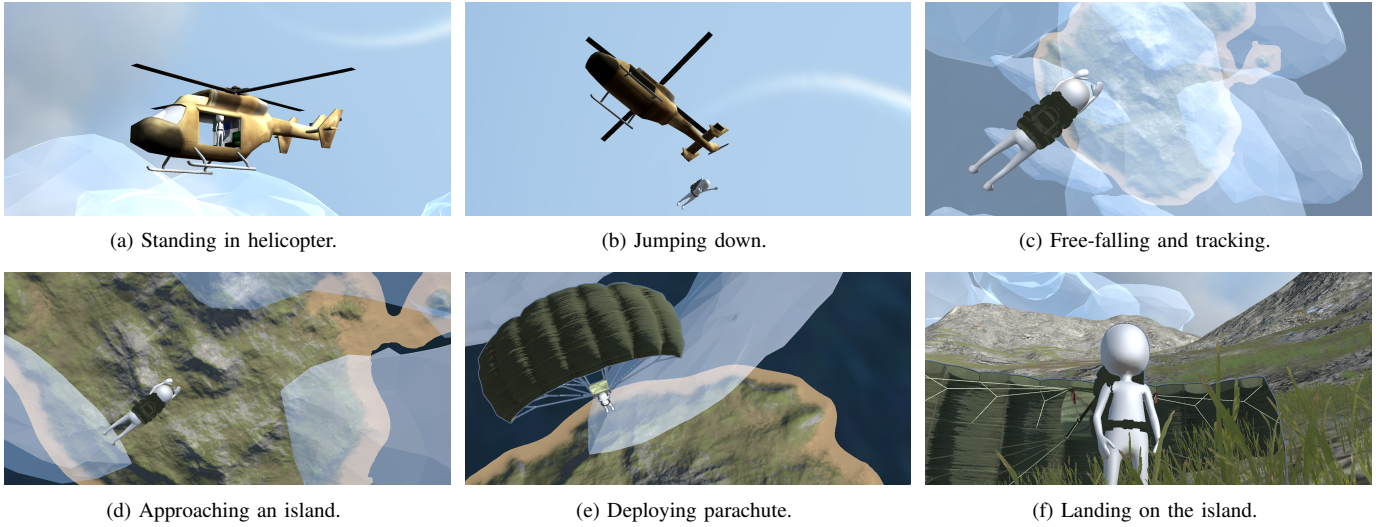
(e) Deploying parachute.

(f) Landing on the island.

Fig. 5: Numerical experiment results. This figure shows different stages of simulating the skydiving experience in a virtual outdoor environment using our proposed approach. Those stages include (a) standing in a helicopter, (b) jumping down, (c) free-falling and tracking, (d) approaching an island, (e) deploying a parachute, and (f) landing on the island.

while leaning the right arm backward, or rotating to the right by doing the opposite. Please refer to the mathematical implementation details in Sec. III. After approaching the island as shown in Fig. 8(d), the virtual player is preparing to deploy the parachute. After the virtual player put the hand near the backpack's bottom, the parachute is deployed as shown in Fig. 8(e). After this stage, the virtual player will face forward automatically as the gravity will drag the body back to the natural position and the speed decreases dramatically. Once the virtual player is colliding with the terrain of the island, the landing stage which is also the final stage starts as shown in Fig. 8(f), during this stage, the parachute will be put onto the ground and the speed decreases to zero automatically.

Numerical Analysis. In order to investigate the correctness of our VR skydiving simulator, we record and plot the virtual skydive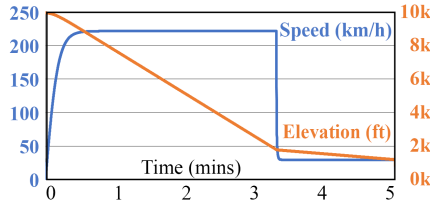r's speed and elevation, as shown in Figure 6, where the x-axis is time (mins), the y-axis (left) is speed (km/h) which is colored in blue, and the y-axis (right) is the elevation (ft) which is colored in yellow. This plot shows three stages, during the first stage for about one minute, the virtual skydiver is accelerating until the drag and gravity are equal to each other, the skydiver reaches the maximum speed and starts the second stage of falling at a constant speed at about 200 (km/h). The second stage lasts for about three minutes, when the elevation is below 2k feet, the virtual player deploys a parachute, then the speed decrease to about 25 (km/h) immediately and starts the third (landing) stage which lasts for about one minute. As we can see, this numerical analysis follows the observations in real skydiving activities.

Fig. 6: Speed and elevation.

V. USER STUDY

Procedure. In order to test the users' experience in our proposed VR skydiving simulator, we conducted a user study including ten users, among whom eight are male, two have learned skydiving before, and nobody has ever tried VR games that are about skydiving. All of the ten users are undergrad students whose ages are between 20 and 25. During the study, we ask the users to put on the VR headset and stand in the center of the room where is no obstacle around. Then, let the user move several steps forward to start jumping down from the helicopter. During the free failing stage, we suggest the users do different gestures for tracking. For example, tracking forward or backward by leaning arms forward or backward, rotating to the left by leaning the left arm forward while leaning the right arm backward, or rotating to the right by doing the opposite. After users play the VR simulator for about 5 minutes, we stop the trial and prompt users to submit a questionnaire about their virtual skydiving experiences.

Questionnaire. In the questionnaire, the questions asking about their virtual skydiving experiences include: (1) Do you agree that the VR skydiving experience is realistic compared to the real-world skydiving experience? (2) Do you agree that the skydiving experience in VR is comfortable? (3) Do you agree that the scene of the VR skydiving looks realistic and immersive? (4) Do you agree that the control of VR skydiving is natural and comfortable? (5) Do you agree that the VR skydiving experience is fun? (6) Do you agree that this VR skydiving experience can help learn skydiving in the real life? All these six questions are prompting users to select a number between 1 and 5 (also called Likert Scale) where 1 stand for disagreeing and 5 stands for agreeing. At the end of the questionnaire, users are asked to provide some suggestions to improve the VR skydiving experience to make it more realistic.

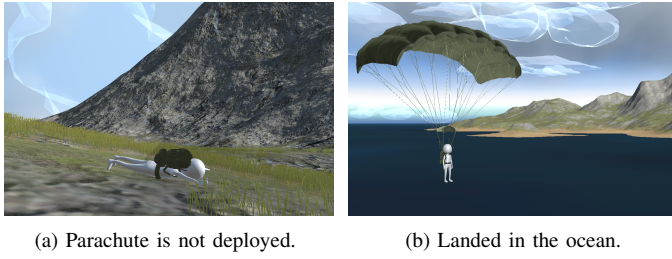(a) Parachute is not deployed.　　(b) Landed in the ocean.

Fig. 7: Examples of common mistakes. This figure shows two types of common mistakes made by users during the study which are failing in deploying the parachute correctly as shown in (a) and failing in landing on the island as shown in (b).

Fig. 8: User study result.

Observations. During the study, we found that most of the users followed our suggestions closely and learned to skydive in our VR simulator very well. For example, they learned how to track with different gestures during the free-falling stage and how to deploy the parachute using the VR controllers when approaching the island. Most of them successfully landed on the virtual island. Interestingly, there are some users who failed to land on the island correctly and make some common mistakes as shown in Fig. 7. But whether succeeded or not, users were relaxed in an atmosphere filled with full of joy.

Result. After collecting the answers from the user's feedback in the questionnaire, we get the scores (1-5) for evaluating our proposed VR skydiving simulator. Fig. 8 shows those scores using the box plots. According to the statistics of the mean scores (M) and standard deviation (SD) for each question (for simplification, here use the abbreviated question) are: (1) Realistic? (M=3.7 SD=0.85) (2) Comfortable? (M=4.4, SD=0.73) (3) Immersive? (M=4.2, SD=0.81) (4) Natural? (M=4.1, SD=0.9) (5) Fun? (M=4.71, SD=0.49) (6) Helpful? (M=3.6, SD=1.07) Therefore, in general, we find users mostly agree that the control of VR skydiving is natural and comfortable (M=4.4) and agree that the VR skydiving experience is fun (M=4.71). However, it seems that users remain somehow conservative when agreeing that the VR skydiving experience is realistic compared to the real-world skydiving experience (M=3.7) and our VR skydiving simulator can help learn skydiving in real life (M=3.7) as only 20% of them have learned skydiving before. But for those two users who have learned skydiving, they both strongly agree that our VR skydiving is realistic compared to the real skydiving experience and is helpful for learning skydiving in real life.

Suggestions. We collected some constructive suggestions from users to improve our VR skydiving simulator in future work such as adding NPCs falling together, adding controls to guide the parachute after it is deployed, making the clouds denser, adding visual effects like air drag lines to simulate falling at a high speed to make the setting more fast-paced, adding external features such as high-speed fan and sound effects, and adding tracking speed control, e.g., slows down when arms are far out and speed up when hands are closer, etc.
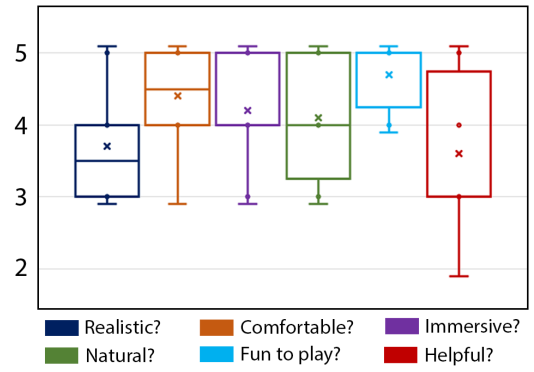
VI. CONCLUSION

In this paper, we propose a novel technical approach to simulate the VR skydiving experience on standard VR headsets without any extra requirements on location or hardware configurations. Through the VR headset and controllers that captures the user's head and hands positions, our approach simulates the motion of users' tracking and rotation during the free falling stage according to the aerodynamics rules. According to the feedback from the users who have tried skydiving using our VR simulator, they agree that our VR skydiving is realistic compared to the real skydiving experience and is helpful for learning skydiving in real life at the same time they believe the VR skydiving experience is natural, comfortable and fun.

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