Graphical Abstract

HeadiCopter: Providing 6DoF Sustained Propulsive Force on Head in VR

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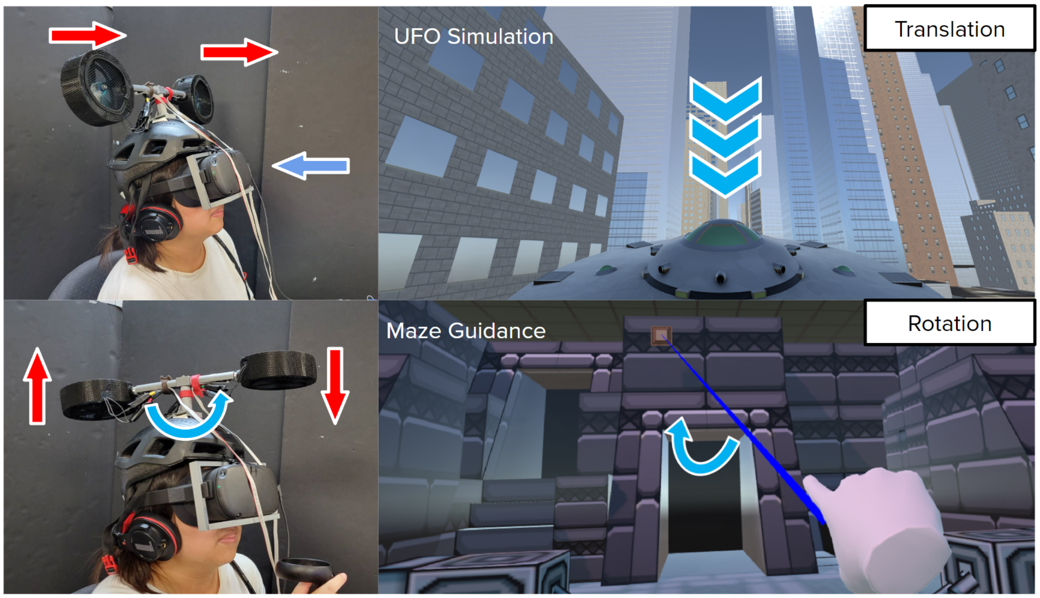

Highlights

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- Proposing a head-worn device, HeadiCopter, equipped with two rotatable propellers to provide 6DoF sustained force feedback on the head in VR.
- Understanding users' sustained force level distinguishability on the head in 6DoF.
- Evaluating users' recognition ability in identifying 6DoF force feedback directions.
- Observing the potential enhancement of VR experiences through the proposed 6DoF sustained force feedback provided by HeadiCopter.

HeadiCopter: Providing 6DoF Sustained Propulsive Force on Head in VR

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[a]*National Taiwan University, james5190929@gmail.com,*
[b]*National Chengchi University, hsnuhrt@gmail.com,*
[c]*National Taiwan University, robin@ntu.edu.tw,*

Abstract

Force feedback on the head achieves intense and immersive virtual reality (VR) experiences and has been utilized in various VR scenarios. However, prior methods typically provide force feedback within short periods, usually less than 500ms, which is unfavorable for scenarios requiring sustained force feedback on the head, *e.g.* flying experience or guidance in VR. Moreover, since VR headsets are worn on the head, the force feedback applying to the head could represent the force on both the head and the whole body. Therefore, force feedback on the head with high degrees of freedom (DoF) is crucial for realistic and versatile VR experiences. We propose HeadiCopter, a head-worn device equipped with two rotatable propellers to provide 6DoF sustained force feedback on the head in VR. We conducted a just-noticeable difference (JND) study to understand users' sustained force level distinguishability on the head in 6DoF. We then performed a direction recognition study to evaluate users' recognition ability in identifying 6DoF force feedback directions. Based on the results of these investigations, we conducted a VR experience study to observe the potential enhancement of VR experiences through the proposed 6DoF sustained force feedback provided by HeadiCopter.

Keywords: Force feedback; propeller-based feedback; head-worn device; virtual reality.

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1. Introduction

Many studies have explored haptic feedback in common VR simulations, such as racing and flight experiences. Due to the head's reliance on inputs from the vestibular, somatosensory, and visual systems to interpret head and body movements Kandel (2013), devices placed on the head have been employed to provide force feedback. However, current head-worn haptic devices mainly focus on rendering sudden force feedback, which is usually less than 500ms, such as being punched in VR. Furthermore, since the force feedback on the head could represent the force on the head or the whole body, high degrees of freedom (DoF) to enhance expressiveness is also critical. Limited period and DoF of force feedback could not be applied in some scenarios requiring sustained and high DoF force feedback in VR, such as flying experience, and head and body movement guidance. This is a research gap that needs to be further investigated.

Prior studies leverage elastic force (Tsai and Chen (2019); Hung et al. (2022)) and air jets (Liu et al. (2020); Ke et al. (2023a)) to provide force feedback on the head for impact, inertia and guidance feedback. However, the sudden force feedback from these devices is usually less than 500ms or even less than 250ms. On the other hand, to render sustained force feedback, propellers (Hoppe et al. (2021)) and electrical muscle stimulation (EMS) (Tanaka et al. (2022)) are utilized. However, these systems have limited DoF for expressing versatile VR scenarios. Some methods exploit pressing force (Chang et al. (2018)) and the hanger reflex phenomenon (Kon et al. (2017)) to simulate force feedback on the head, but pressing force cannot achieve kinesthetic sensations, which involve body part movement, and the hanger reflex only generates the illusion of force feedback. Therefore, sustained force feedback on the head with high DoF is still not achieved.

We present a head-worn device, HeadiCopter, to provide 6DoF sustained force feedback on the head to enhance VR immersion and experiences (Figure 1). HeadiCopter consists of two propellers on a rotatable T-bar grounded on a helmet. Propellers can generate sustained force feedback on the head. Furthermore, leveraging three motors to rotate the propellers and the T-bar accomplishes 6DoF force directions, including 3DoF translation and 3DoF rotation. Notably, 3DoF translation force not only refers to force in 6 discrete directions (upward/downward/leftward/rightward/forward/backward) but also represents any direction in continuous ranges of 3D space, *e.g.*, 21 degrees leftward and 76 degrees downward, which means omnidirectional translation force, as in GuideBand (Tsai et al. (2021)). We conducted a just-noticeable difference (JND) study to understand users' distinguishability of sustained force feedback on the head in 6DoF. Additionally, we conducted a direction recognition study to understand users' recognition ability in 6DoF

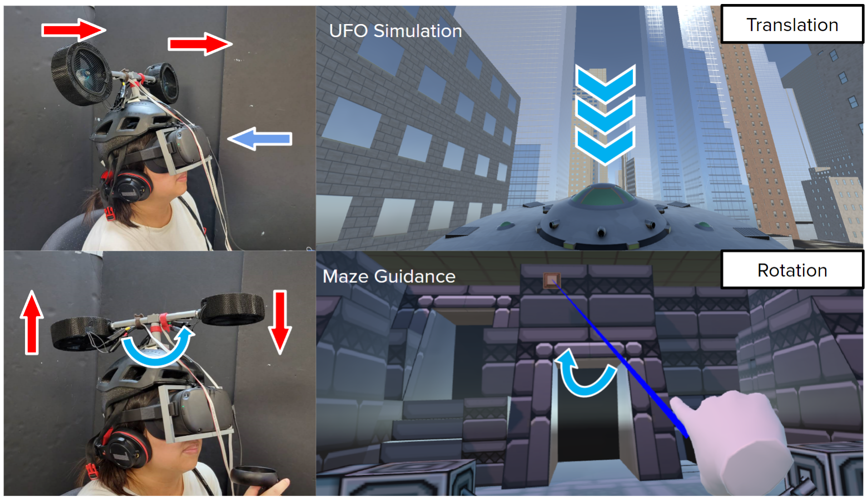


Figure 1: HeadiCopter provides force feedback in three translational degrees of freedom (DoF) and three rotational DoF, delivering 6DoF Sustained Propulsive Force feedback in virtual reality. At the top of the image, the propellers blowing forward simulates the backward inertial force during UFO acceleration. Below, one propeller blowing downward and another blowing upward simulate the upward rotational force feedback during a "pitch up" guidance. The red arrows mean the direction of the propellers blowing air, the blue arrows mean the direction of the force feedback.

force directions. Finally, we performed a VR experience study to verify that the proposed 6DoF sustained force feedback enhances users' VR experiences and demonstrate VR applications of HeadiCopter.

2. Related Work

Our device is inspired by previous research on force feedback devices and haptic feedback on head.

2.1. Force Feedback Devices

Numerous force feedback methods have been proposed. JetController (Wang et al. (2021)) is equipped with five air jet nozzles on a VR controller to simulate the recoil during shooting and the resistive force when slashing objects in VR in 3DoF. AirRacket (Tsai et al. (2022)) is equipped with nozzles at the top of the controller to simulate force feedback when striking a ball using air jets. transPAF (Chen et al. (2023)) uses a semicircular track, a linear track, and an impactor to achieve omnidirectional impact feedback with a dynamic point of force application. Such a design enables transPAF to render both 3DoF translation and 3DoF rotation sudden impact force feedback. MetamorphX (Hashimoto et al. (2022)) uses control moment gyroscopes (CMGs) to generate ungrounded, 3DoF torque feedback with desired inertia and viscosity via impedance control. These methods achieve significant contributions for rendering force feedback. However, air jets might render force feedback for longer periods but require a huge air compressor, or users have to wait for an interval for the next sustained force feedback. Furthermore, due to moment saturation, CMGs system cannot consistently generate torque for sustained force feedback. Therefore, these methods can only render sudden instead of sustained force feedback.

In order to simulate sustained force feedback, a cable-driven system (Kim et al. (2017)) is a feasible mechanism, but it is grounded. Slashed (Ooshima et al. (2008)) employs vibration motors to simulate sensations of being slashed or pierced. Furthermore, Squeezeback (Pohl et al. (2017)) and HapticClench (Gupta et al. (2017)) leverage inflatable straps and shape memory alloys worn on the wrist, respectively, to generate compression feedback. Although these methods can simulate sustained force feedback, they cannot achieve kinesthetic force feedback, which involves the movement of body parts. Virtual Wall (Lopes et al. (2017)) stimulates the user's shoulder, arm, and wrist muscles using EMS to generate a resistive force on arms. Wind-blaster (Je et al. (2018)) leverages two rotatable propellers worn on the wrist to render force in 2DoF for simulating shooting and slashing. Thor's Hammer (Heo et al. (2018)) is a handheld VR controller with six propellers, which allows users to experience force feedback in 3DoF, mimicking effects such as underwater resistance, animal traction, and gravitational changes. Aero-plane (Je et al. (2019)) is a handheld controller that utilizes two miniature jet propellers to emulate a shifting center of mass in 2DoF. PropelWalker (Ke et al. (2023b)) is a pair of calf-worn ducted fans to simulate the buoyancy and the resistive force in 1DoF direction when walking in different fluids. While these works achieve kinesthetic force feedback, they primarily focus on rendering feedback on the body and limbs and do not achieve force feedback in high DoF. Furthermore, EMS alters the body's movement internally, which is different from force feedback externally applying to the body.

2.2. Haptic Feedback on Head

To render haptic feedback on the head, GyroVR (Gugenheimer et al. (2016)) utilizes a rotating flywheel installed in front of the head to generate resistance. It renders the resistance feedback of the inertial force when users turn their heads. HangerOver (Kon et al. (2017)) leverages the hanger reflex phenomenon by incorporating air-driven balloons around the head to generate pressure, generating force feedback illusion in the yaw direction. Elastimpact (Tsai and Chen (2019)) stores power in extended elastic bands to provide 2.5DoF instant impact force feedback on the head. Similarly, OsciHead (Hung et al. (2022)) also controls and stores power in elastic bands on both sides of the head to generate 4DoF impact force and inertia feedback. TurnAhead (Ke et al. (2023a)) uses air jets to produce 3DoF rotation force feedback on the head to mimic the motion of a first-person view (FPV) drone. However, these methods can only accomplish sudden instead of sustained force feedback.

FacePush (Chang et al. (2018)) utilizes tension straps on both sides of the head to render 1DoF compression normal force on the face. Electrical Head Actuation (Tanaka et al. (2022)) utilizes EMS to stimulate neck muscles, allowing for 2DoF head movement in the yaw and pitch directions. Odin's Helmet (Hoppe et al. (2021)) is equipped with four propellers on the front, back, left, and right sides of the helmet to provide 2DoF sustained force feedback in the roll and pitch directions. Similarly, X-Wing (Watanabe et al. (2021)) also attaches four propellers on a head-mounted display (HMD) to render 2DoF rotation force in yaw and pitch and 2 directions in translation force in forward and backward. These methods render sustained force feedback. However, kinesthetic force feedback cannot be achieved using compression and EMS suffers from the internal body overwriting issue. Therefore, propeller-based design is the most proper mechanism to render sustained kinesthetic force feedback, but DoF of Odin's Helmet is limited to 2DoF rotation force and DoF of X-Wing is limited to 2DoF rotation force and two translation directions. This differs from our goal to render 6DoF force feedback, which consists of 3DoF translation and 3DoF rotation force. Especially, for 3DoF translation, it means omnidirectional translation force, as mentioned above, which is much more expressive and versatile than discrete two or six directions. In fact, whether for sudden or sustained force feedback, 3DoF translation force on the head has not yet been achieved. Based on these works, we chose propellers as actuators to build HeadoCopter and generate 6DoF sustained force feedback to enhance the VR experiences.

3. HeadiCopter

We propose a head-worn device, HeadiCopter, to render 6DoF sustained force feedback, including 3DoF translation, upward/downward, leftward/rightward and forward/backward, and 3DoF rotation, yaw, pitch and roll, on the head. The 3DoF rotation force could provide feedback for the head rotation, and the 3DoF translation force could render feedback for the head or even the whole body movement in versatile scenarios.

3.1. Design Considerations

To achieve our goals, it is crucial to factor in the following design considerations.

- *Expressiveness.* For versatile VR scenarios, providing force feedback in multiple directions and levels is critical. Therefore, rendering force feedback with higher DoF for more expressive feedback is our goal.
- *Period of Force Application.* The period of force application could be short or long in various VR scenarios. For the shorter period of force application, usually less than 500ms or even 250ms, the force feedback is called sudden force, which could be used for sudden impact feedback. For the longer one, usually over 1 or 2 seconds, the force feedback is called sustained force, which could be used for skydiving or flying force feedback. The device can render both sudden and sustained force feedback enhancing VR versatility.
- *Comfort and Safety.* To generate force feedback on the head, users' comfort and safety are the premises. Although the intenser force feedback could achieve better immersion and realism, the device should prevent the feedback from hurting users or causing discomfort.

3.2. Hardware Implementation

HeadiCopter consists of two propellers on a rotatable T-bar grounded on a helmet, which is integrated with an HMD using straps and a PLA frame. Each propeller consists of a brushless motor (T-motor FPV V2306 V2.0 with a KV rating of 2400 designed for a 4S battery configuration) and a propeller (Azure Power 3-blade 4838) attached to the shaft of the brushless motor, which are equipped in a 3D-printed propeller case with a fan guard made

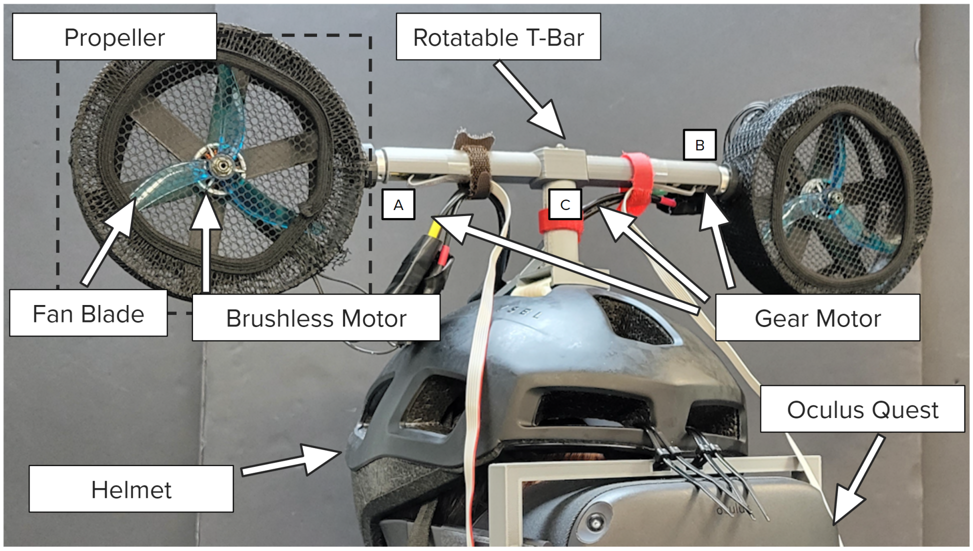


Figure 2: Three DC motors are mounted on the components labeled A, B, and C in the figure.

from a hairnet for safety. The two propellers are equipped on the two sides of the T-bar, respectively. The length of the horizontal bar of the T-bar is 36.9 cm, which serves as the lever arm (18.45 cm) to generate torque for 3DoF rotation force feedback, yaw, pitch and roll. The chosen length is a trade-off among the device size, force magnitude and safety. The length of the vertical bar is 7.1cm, which keeps the propellers a bit away from the head for safety and noise issues and reducing airflow interference. Three DC motors (Pololu Micro Metal Gearmotor with a gear ratio of 1000:1) along with a rotary encoder (Pololu Magnetic Encoder 12 counts per revolution) are mounted on the T-bar, as shown in Figure 2. Two of them are used to rotate the propellers, and the other is used to rotate the horizontal bar of the T-bar. By controlling the propellers in the same and opposite directions, the force in translation and rotation directions can be generated, respectively. Furthermore, by controlling the three motors to rotate the propellers and the T-bar, 3DoF translation and 3DoF rotation sustained force feedback can be achieved (Figure 3).

An FMS Predator 40A brushless electronic speed controller (ESC) is used to control each propeller. The DC motors are controlled by two TB6612FNG DC motor drivers. The motor drivers are connected by an Arduino Mega board. An external 12V power supply is used for brushless and DC motors,

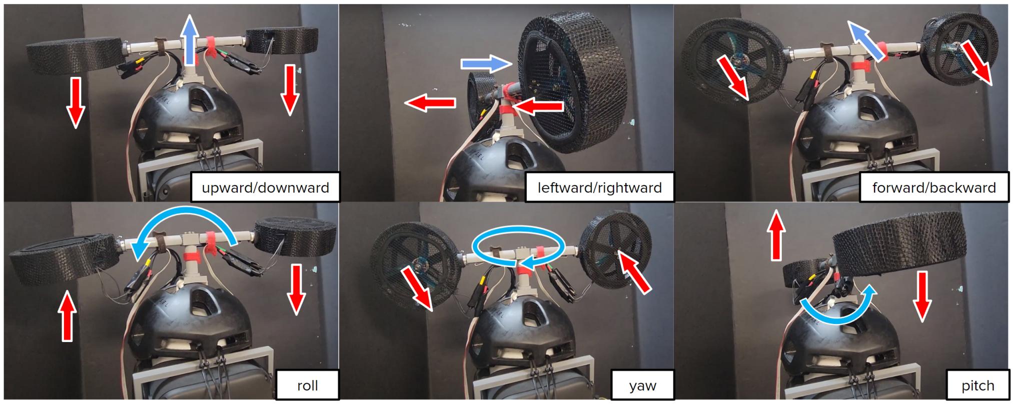


Figure 3: HeadiCopter can provide force feedback in translational directions (the top three images) as well as rotational directions (the bottom three images) across all six degrees of freedom (6DoF). The red arrows represent the direction in which the fan blows air, the blue arrows mean the direction of the force feedback.

which can also substituted by batteries worn on body parts, *e.g.*, the arm, back or waist, to avoid additional weight on the head. The weight of the HeadiCopter prototype, including the propellers, T-bar and helmet, is 613g. HeadiCopter is lighter than X-Wing (Watanabe et al. (2021)) (850g) but renders force in much higher DoF. The DC motors take about 1000ms to complete a half revolution of the propellers and a quarter revolution of the rotatable T-bar. These are the most revolutions for rendering 6DoF force feedback, which means the largest delay in device rotation.

3.3. System Evaluation

We conducted a system evaluation to evaluate the force and noise generated by HeadiCopter to facilitate the control of the propellers and strike a balance between force and noise.

Force Magnitude: We attached a propeller to a force sensor (load cell TAL220 with an HX711 amplifier) on an aluminum extrusion frame (Figure 4 (a)) to measure the force. By gradually increasing the speed of the propeller using PWM signals ranging from 1000 to 1500 milliseconds, we obtained the relationship between the PWM control value and the force magnitude. Measurements were taken in 50-millisecond intervals between 1200ms and 1450ms of PWM signal duration. 1200ms was the lower bound to actuate the propeller. The measured data (Figure 4 (b)) was converted into a regression line: $y = 0.011x - 12.737$ ($R^2 = 0.9862$) to facilitate force feedback control.

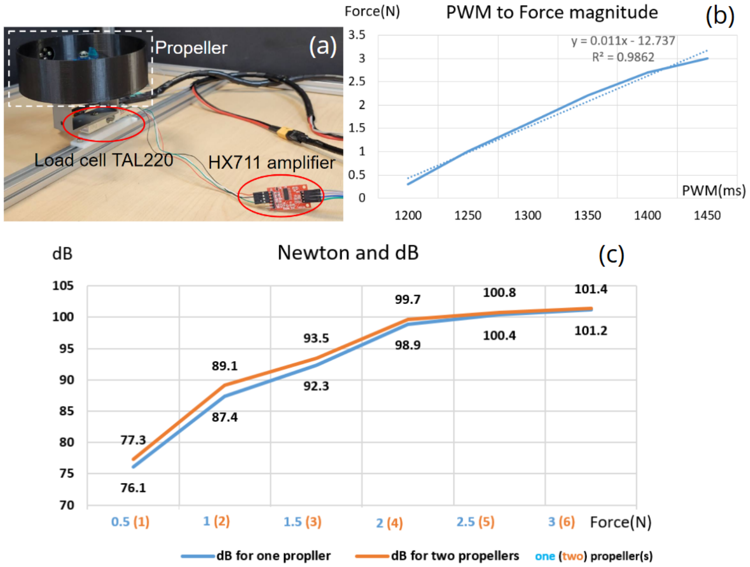


Figure 4: (a) We utilize aluminum extrusions with a force sensor (the load cell TAL220 with an HX711 amplifier) to measure force. (b) Pulse width modulation corresponding to Newton. The regression line is $y = 0.011x - 12.737$ ($R^2 = 0.9862$). (c) The correlation between force and the decibel(dB) generated when one or both propellers are activated.

The maximum force magnitude is 3N for stable feedback. Since two propellers are actuated on HeadiCopter at the same time, the maximum force of HeadiCopter is 6N, which is larger than the maximum force of Odin's Helmet (Hoppe et al. (2021)) (5N).

Noise: Noise has consistently been a challenge for propeller haptic devices. Therefore, we gradually increased the force magnitude of a propeller from 0.5N to 3N with a 0.5N interval to obtain the relationship between noise (dB) and force magnitude (N). We measured the noise for a single propeller and both propellers, separately. Since the distance between each propeller to the closest ear is approximately 20 cm, the decibel meter was placed at a distance of 20 cm from the propeller on the aluminum extrusion frame (Figure 4 (a)) for the single propeller measurement. For measurement of both propellers, the decibel meter was placed at the ear position of a Mannequin head wearing the HeadiCopter device with the helmet and two propellers. The results are shown in Figure 4 (c). Interestingly, when both propellers are activated at the same individual force magnitude as a single propeller, the difference in decibel level is small. For example, the decibel level for a force magnitude of 3N is 101.2dB with one propeller and 101.4dB with two propellers, which means a combined force of 6N for two propellers. Therefore, using both propellers for a wider range of force feedback is not limited by the noise constraint. Compared to the noise level of 106.9dB at 5N in Odin's Helmet (Hoppe et al. (2021)), our device generates only 100.8dB of noise at 5N, with each propeller producing 2.5N. Although X-Wing (Watanabe et al. (2021)) with four propellers can generate stronger force, the noise level for just one propeller can reach up to 110.6 dB.

Latency: The latency issue is not only in propeller and T-bar rotation but also in propeller actuation. We measured the latency by generating force levels of 0.5N, 1N, 1.5N, 2N, 2.5N, and 3N for a single propeller using the setup in Figure 4 (a). The latency in each force level was measured five times, and the average latency of the force levels were 676ms, 680ms, 700ms, 710ms, 726ms, and 740ms, respectively.

4. JUST-NOTICEABLE DIFFERENCE (JND) Study

To understand the users' sustained force level distinguishability in various directions, we conducted a Just Noticeable Difference (JND) study. Since the perception of the head varies in different directions, we intended to examine the six directions from 6DoF sustained force feedback of HeadiCopter, 3DoF translational directions (forward/backward, leftward/rightward, upward/downward) and 3DoF rotational directions (yaw, pitch, roll), separately. Notably, although the six directions were examined in this study, 3DoF translation force refers to any direction in continuous ranges of 3D space, which means omnidirectional translation force, as in GuideBand (Tsai et al. (2021)) and transPAF (Chen et al. (2023)).

4.1. Apparatus and Participants

Participants wore the HeadiCopter device along with an Oculus Quest HMD. The HMD was used to isolate visual feedback from the device and display the interface, and the controller was used to select the items. Participants wore noise-canceling earbuds and listened to white noise to minimize interference from the propeller noise. 12 participants (4 females) aged from 22 to 30 (mean: 24.25) were recruited. The study was approved by the ethics committee of National Taiwan University.

4.2. Task and Procedure

We adopted a two-down, one-up staircase design for the JND study to observe the minimum force magnitude difference for participants to clearly distinguish force stimuli in each DoF, as in Jetto (Gong et al. (2018)). In each trial, participants were presented with three sustained force stimuli, including two reference stimuli (S) and one test stimulus ($S + \triangle S$). All sustained force stimuli lasted 2200ms. They were tasked with identifying which stimulus was different from the others. Since stimuli of HeadiCopter were generated by both propellers, the stimulus magnitude is described as the combined force from both propellers in the following. S was set at 2N, which was clearly perceivable in five directions from a pilot study, and the sixth direction, upward/downward, will be elaborated on later. $\triangle S$ is set at 0.8N, determined adaptively as a positive value, representing the difference in force magnitude between the reference and test force stimuli. Participants used the controller to select the stimulus different from the others, and they could play back to experience the stimuli. Responses were recorded, and the next $\triangle S$ for the trial was determined.

Initially, the step size was 0.2N. If they responded correctly for two consecutive trials, $\triangle S$ decreased by a step size of 0.2N. If they responded incorrectly in a trial, $\triangle S$ increased by a step size of 0.2N. After the first two reversals, which is a transition from decreasing to increasing $\triangle S$, and vice versa, the step size was decreased to 0.05N. Additionally, if $\triangle S$ was beyond the stimulus range, 0 or 6N, the system considered it a reversal. The staircase procedure ended after a total of eight reversals. The average of the last six reversals was calculated as the JND threshold. For the upward/downward translation direction, the force feedback should be about or beyond 6N to perceive due to the weight of the helmet from the pilot study. Since it is about the maximum force magnitude of our device, we cannot increase force magnitude as $\triangle S$ for the JND study. Therefore, only five directions were examined. The orders of translation and rotation, three staircase runs in translation and two runs in rotation, and two directions in each DoF were counterbalanced. The order of the three stimuli for each trial was randomized. The experiment lasted for approximately one and a half hours.

4.3. Results and Discussion

Repeated measures ANOVA and Bonferroni correction for post-hoc pairwise were used to analyze the results (Figure 5). Mauchly's test of sphericity was conducted in advance to check whether the assumption of sphericity

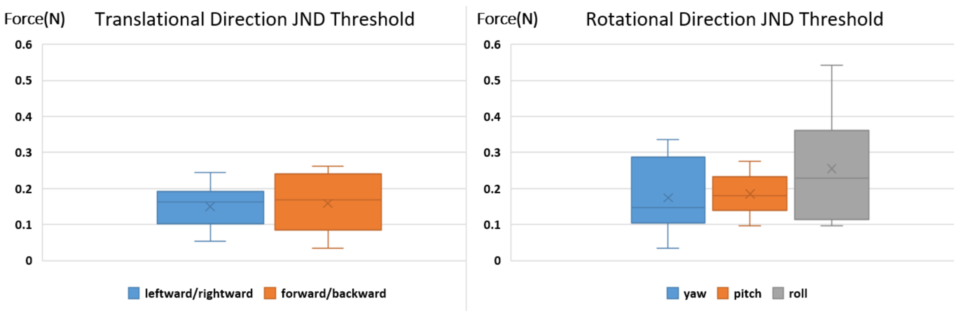


Figure 5: The JND thresholds for translational and rotational direction.

was violated for at least three conditions. No significant difference ($F_{1,11} = 0.23, p = 0.64$) is found in translational directions. Since only two translational directions were examined, the sphericity is met. The thresholds of leftward/rightward and forward/backward are 0.15N (JND = 7.5%) and 0.158N (JND = 7.9%). No significant main effect ($F_{2,22} = 0.77, p = 0.47$) is in rotational directions. The sphericity is also met ($\chi^2(2) = 3.91, p = 0.14$). The thresholds of yaw, pitch and roll are 0.174N (JND = 8.7%), 0.186N (JND = 9.3%) and 0.254 (JND = 12.7%). Notably, although the reference stimulus, test stimuli and step size were the same in staircase runs of all five directions, translation and rotation force feedback are essentially different. Translation force is more like pushing force feedback, whereas rotation force is more like twisting feedback with torque. Therefore, we performed the statistical analyses for translation and rotation force separately, as in transPAF (Chen et al. (2023)). However, we additionally conducted statistical analyses among all five directions to observe the differences between translation and rotation force. No significant difference ($F_{4,44} = 1.63, p = 0.18$) is found among the five directions. The sphericity is met ($\chi^2(9) = 9.17, p = 0.43$).

For the translational directions, no statistical significance is between leftward/rightward and forward/backward. 4 participants (*P3, P6, P7, P12*) mentioned that the neck was more sensitive to lateral movement and the larger contact area on the scalp in leftward/rightward, which made the force stimuli in leftward/rightward easier to perceive and distinguish. However, 7 participants (*P1, P2, P5, P8, P9, P10, P11*) believed that all directions were equally discernible in translation, which is consistent with the results that no statistical significance in translational directions. *P1* described that the helmet seemed to be heavier during lateral movements in leftward/rightward, and there seemed to be resistance in forward/backward.

For the rotational directions, no statistical significance is among yaw, pitch and roll. 7 participants (*P2, P3, P6, P7, P10, P11, P12*) agreed that the stimuli in yaw were the most easily discernible and mentioned that the better mobility of the neck in the yaw direction could cause the force in yaw more obvious. 3 participants (*P1, P4, P9*) thought that it was easy to distinguish the force magnitude in all yaw, pitch, and roll directions.

Although pushing force feedback in translation force and twisting feedback in rotation force with torque are different, an additional statistical was performed, and no statistical significance is among all five directions. However, comparing the directions in translation and rotation, most participants except for *P4* and *P8* subjectively believed that they could more easily distinguish force magnitude in translational directions than in rotational directions. This could be caused by the different pivot positions and lever arm lengths in translation and rotation. In the rotational directions, the pivot is at the bottom of the T-bar with a horizontal lever arm of 18.45cm. However, in the translational directions, based on the reference point around the connection part between the head and the neck mentioned in the works from Ke et al. (2023a); Yip and Jin (2004), the distance between the pivot and the top of the head is approximately 18cm. By further combining the 7.1 cm vertical bar from the T-bar, the total lever arm for translational directions is 25.1cm, which is longer and causes larger torque. *P4* described that the translational force applied towards the center of the head while the rotational force scratched the surface of the head. *P11* further mentioned that the translational force felt like being pushed from the side of the head whereas the rotational force felt like a joystick above the head controlling the head movement.

In this study, we obtained the users' force magnitude distinguishability thresholds in five directions on the head. We chose 3N as the base force magnitude so users can clearly perceive the intense force feedback in the five directions. Furthermore, we chose 0.6N as a unified force magnitude difference, which is larger than all JND thresholds in the five directions so users can clearly distinguish the force differences. Although we could render the maximum force of 6N in HeadiCopter for upward/downward, allowing users to clearly perceive the force feedback, and even all six directions for consistency, the noise level of 101.4dB may be too loud to potentially interfere with users' experiences or even cause hearing damage with long-term use. Therefore, 3N and 3.6N for two levels are used in upward/downward as well as the other five directions. The noise level then ranges approximately from

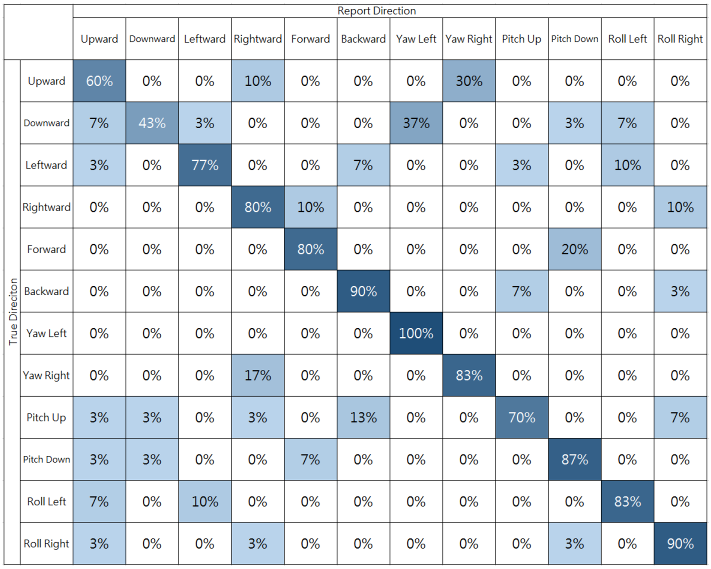
93dB to 97dB, estimated based on 99.7dB at 4N. It is a trade-off between noise level and clearly perceivable force magnitude. In addition, choosing the unified base and difference of the force magnitude can maintain consistency for 6DoF force feedback. Especially for omnidirectional 3DoF translation force feedback, any direction in continuous ranges of 3D space may require a combination of two or three directions in translation, *e.g.*, a combination of leftward, downward and forward. The unified force magnitude simplifies such combinations.

5. Direction Recognition Study

Since 6DoF sustained force feedback is rendered by HeadiCoper, to understand users' direction recognition ability, we conducted this direction recognition study. The setup in this study was the same as in the JND study. 10 participants (3 females) aged from 23 to 30 (mean: 25.7) were recruited. 6 of them had participated in the previous study but more than two weeks had elapsed between the studies. The study was approved by the ethics committee of National Taiwan University.

5.1. Task and Procedure

Based on the results of the JND study, we chose force feedback of 3N for in this study. Two directions are in each of 6DoF force feedback, including forward/backward, leftward/right, upward/downward in translation, and yaw left/right, pitch up/down, roll left/right in rotation. Therefore, a total of 12 directions were examined in the study, and 3 repetitions were for each direction. Participants were introduced to the study procedure in the beginning and wore the HeadiCopter device to experience and be familiar with the force feedback from 12 directions in a training session. During the experiment, they experienced a sustained force stimulus lasting 2200ms and had to answer its force direction. They could ask to play back the stimulus. A total of 36 trials (= (3DoF translation + 3DoF rotation) × 2 (directions in each DoF) × 3 (repetitions)) were examined for each participant. The order of the 12 directions was randomized. Notably, although 12 directions were examined in the recognition study, it did not mean that HeadiCopter can only render force feedback in these 12 directions. It can render force feedback in any direction in 6DoF. The experiment lasted for approximately forty minutes.



		Report Direction											
		Upward	Downward	Leftward	Rightward	Forward	Backward	Yaw Left	Yaw Right	Pitch Up	Pitch Down	Roll Left	Roll Right
True Direciton	Upward	60%	0%	0%	10%	0%	0%	0%	30%	0%	0%	0%	0%
	Downward	7%	43%	3%	0%	0%	0%	37%	0%	0%	3%	7%	0%
	Leftward	3%	0%	77%	0%	0%	7%	0%	0%	3%	0%	10%	0%
	Rightward	0%	0%	0%	80%	10%	0%	0%	0%	0%	0%	0%	10%
	Forward	0%	0%	0%	0%	80%	0%	0%	0%	0%	20%	0%	0%
	Backward	0%	0%	0%	0%	0%	90%	0%	0%	7%	0%	0%	3%
	Yaw Left	0%	0%	0%	0%	0%	0%	100%	0%	0%	0%	0%	0%
	Yaw Right	0%	0%	0%	17%	0%	0%	0%	83%	0%	0%	0%	0%
	Pitch Up	3%	3%	0%	3%	0%	13%	0%	0%	70%	0%	0%	7%
	Pitch Down	3%	3%	0%	0%	7%	0%	0%	0%	0%	87%	0%	0%
	Roll Left	7%	0%	10%	0%	0%	0%	0%	0%	0%	0%	83%	0%
	Roll Right	3%	0%	0%	3%	0%	0%	0%	0%	0%	3%	0%	90%

Figure 6: The results of the direction recognition study are presented in the confusion matrix. The numbers in the matrix represent the accuracy out of 30 data points for each direction. The horizontal axis denotes the directions reported by participants, while the vertical axis represents the true directions.

5.2. Results and Discussion

The results are shown in the confusion matrix in Figure 6. The overall recognition rate is 78.6%. We observed that direction misjudgments usually occurred in some similar head movements between translation and rotation directions, including roll left/right versus leftward/rightward, and pitch up/down versus backward/forward, which were mentioned by all participants in the training session. These phenomena can be explained by the concept proposed by Yip and Jin (2004) that the pivot point of the head is located on the top of the back of the neck, between the neck and the head, and align with the findings in TurnAhead (Ke et al. (2023a)). When translation force pushes the head without passing through the pivot, such as in leftward/rightward and backward/forward directions, it generates torque at the head's pivot point, causing the head to rotate a bit. The leftward/rightward force makes the head rotate in roll left/right directions, and the backward/forward force causes the head to rotate in pitch up/down directions. However, since the upward/downward translation force is close to the head's pivot point, it generates pushing force instead of torque. Therefore, these phenomena are found only in roll left/right versus leftward/rightward and pitch up/down versus backward/forward. Nevertheless, recognition rates of over 70% or 80% in these directions from our results demonstrate that these directions are distinguishable and underscore the necessity of 6DoF force feedback proposed by HeadiCopter.

Another issue is the low recognition rates for upward and downward. The pilot study in the JND study showed that users required at least 6N to perceive force feedback in upward/downward directions, which could explain this issue. This results in their recognition rates of only 60% and 43%, respectively, which is the limitation of the current device. In addition, the confusion rates are notably higher for upward with yaw right (30%) and downward with yaw left (37%). We observed that this could be caused by the gap and backlash between the horizontal bar and the motor on the vertical bar of the T-bar as well as the slightly unequal weight of the two propellers. The left propeller slightly leans toward the rear, while the right one leans forward, which also makes the horizontal bar lean correspondingly in the yaw left direction within the small rotation gap of approximately less than five degrees. In downward, the force direction aligns with gravity, which makes the horizontal bar lean further to the yaw left due to the unequal weight distribution. In upward, the force direction opposes gravity, causing the bar to lean in the opposite direction, yaw right, due to the gap and backlash. Such a gap and backlash are small while essential for the functioning of gears and motors, which usually do not affect direction recognition, as in most directions. However, since 3N in upward/downward is not strong enough for users to clearly perceive force feedback, the effect of the gap and backlash becomes more noticeable. Nevertheless, excluding the recognition rates of upward and downward movements results in an overall recognition rate increase from 78.6% to 84%. This verifies that users can clearly perceive different force feedback directions.

6. VR Experience Study

We performed this VR study to observe whether the 6DoF sustained force feedback from HeadiCopter enhances users' VR experiences. HeadiCopter enables 6DoF sustained force feedback and also can render 6DoF sudden force feedback on the head. Therefore, various VR applications can be achieved by HeadiCopter, including first-person view (FPV) drone videos and 360 videos from TurnAhead (Ke et al. (2023a)), VR flying, surfing, diving and racing games from HeadBlaster (Liu et al. (2020)), FacePush (Chang et al. (2018)) and GyroVR (Gugenheimer et al. (2016)), even boxing games with sudden force feedback from FacePush and ElastImpact (Tsai and Chen (2019)), as well as functional guidance from FacePush and Electrical Head Actuation (Tanaka et al. (2022)). Among these versatile applications, we chose two representative applications in this study to verify and demonstrate the effectiveness of 6DoF sustained force feedback from HeadiCopter. One application, maze guidance, was designed to demonstrate the functional guidance capabilities, while the other, flight simulation, was to showcase the general VR experiences. The setup was similar to the previous two studies. The VR applications were shown in the HMD. 12 participants (7 females) aged from 22 to 30 (mean: 24.5) were recruited. 2 of them had participated in the previous study but more than two weeks had elapsed between the studies. The study was approved by the ethics committee of National Taiwan University.

6.1. Task and Procedure

Two tasks, maze guidance and flight simulation, were examined in this study. High DoF and sustained force feedback were required in these scenarios. Furthermore, three methods were compared in this study, including 3DoF+sustained, 6DoF+sudden, and 6DoF+sustained. 6DoF+sustained was the proposed feedback from HeadiCopter, and the others were based on the concepts of current methods. 3DoF+sustained represented that only rotational force feedback for the yaw, pitch and roll head movements were involved, as in common head force feedback. 6DoF+sudden meant that the force feedback was not more than 500ms in the tasks. Comparing 3DoF+sustained and 6DoF+sustained could observe the necessity of high DoF, while comparing 6DoF+sudden and 6DoF+sustained could understand the essence of sustained force feedback. Actually, both 6DoF+sudden and 6DoF+sustained are achieved by HeadiCopter, since previous methods are not able to render 3DoF translation force on the head, as discussed above. Two force feedback levels, 3N and 3.6N, were used in the study, based on the JND results.

Maze guidance: Participants were in a room with four buttons and five doors (Figure 7). They needed to select the correct button and enter the correct door to complete the task. Force feedback guided them to find the correct button and door. Since guiding force feedback is constantly required to let users know the correct direction or position in 3D space, sustained

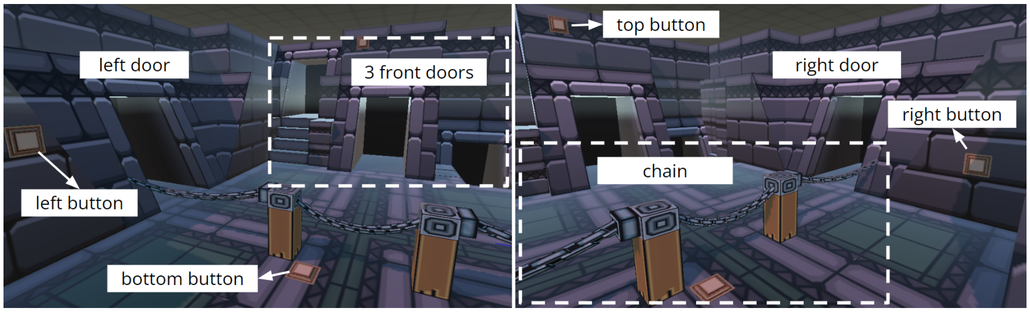


Figure 7: In the maze guidance, there are four buttons: top, bottom, right, and left. There are five doors: left, right, and three in front. The correct button needs to be identified according to the guidance, following which the chain will drop. Subsequently, the correct door is chosen based on the guidance.

and high DoF force feedback are needed in such a guidance scenario. Furthermore, the distribution of up/down/left/right buttons, three front doors with different heights of the locations and left/right doors required high DoF force guidance. Initially, participants were obstructed by a chain. They had to select the target button using raycasting and the trigger on the controller to remove the chain to freely move in the room. Rotational force feedback in yaw and pitch directions were utilized to guide them to search for the button. If the difference between the viewing and target button directions was less than 30°, the force magnitude was 3N. Otherwise, it was set at 3.6N. After selecting the target button, they could move in the room using a joystick on the controller to find the correct door. 3DoF translational force feedback was used to guide them to move to the target door. Translational force feedback was for the whole body movement guidance, and rotational force feedback was for the head direction guidance. If they were close to the target door, the force magnitude was 3N. Otherwise, it was 3.6N. Since there was no translational force feedback in 3DoF+sustained, rotational force directions were used to substitute the translational force directions. Pitch up/down were used to simulate backward/forward force feedback and upward/downward, and roll left/right were for leftward/rightward, due to the similar head movement. Furthermore, since sustained force feedback was not in 6DoF+sudden, sudden force feedback was intermittent instead of keeping rendering force feedback until the target was found. The latency of rendering 3N and 3.6N were about 700ms from the system evaluation, and the sudden force feedback lasted 500ms, so a total of 1200ms was for sudden force feedback rendering and a 500ms cut-off was between sudden force stimuli. After the participants successfully entered the target door three times, the task was completed. The target button and door were randomized in each room.

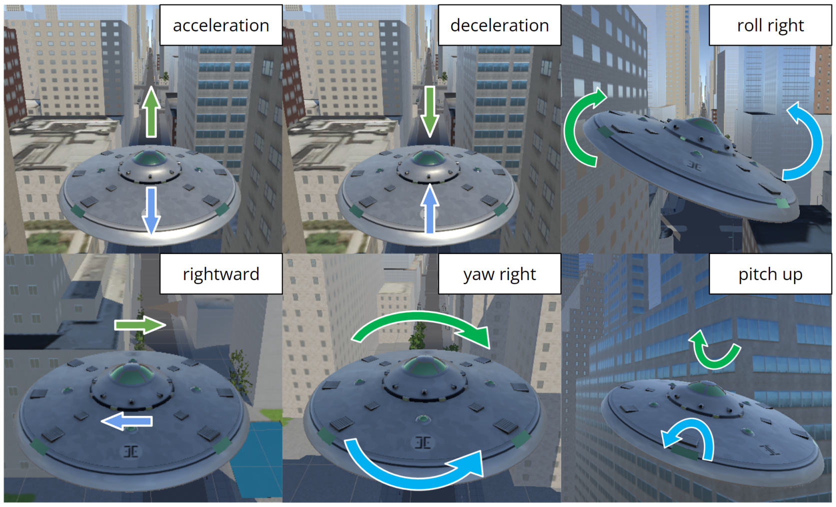


Figure 8: The UFO simulation scenario will involve experiencing acceleration, deceleration, roll rotation, yaw rotation, pitch rotation, and rightward translation. The green arrows mean the direction of travel, the blue arrows mean the direction of the inertia force feedback.

Flight simulation: Participants were in a UFO, and it automatically flew among buildings in a city, so they did not need to control anything in the flight simulation. The force feedback in this scenario represented inertial force feedback, which occurred when the UFO changed its movement (Figure 8), such as acceleration/deceleration, leftward/rightward translation, yaw, pitch and roll. Notably, the inertia force feedback was in the opposite direction of the movement. For example, during forward acceleration, the UFO moved forward, but the backward force feedback for inertia was rendered. For 3DoF+sustained, pitch up/down were used to simulate backward/forward force feedback for the inertia of acceleration/deceleration, roll left/right were for leftward/rightward in the right/left lateral movement. For 6DoF+sudden, sudden force feedback lasted 300ms, and combining it with the 700ms latency, a total of 1000ms sudden force feedback was provided for the inertia. A 500ms cut-off was between two sudden force stimuli.

Participants were briefly introduced to the tasks and procedures and familiar with the three methods. The order of two tasks and three methods were counterbalanced. After the experiment, they were asked to complete a questionnaire with a 7-point Likert scale, and interviewed for some comments. The experiment took approximately an hour.

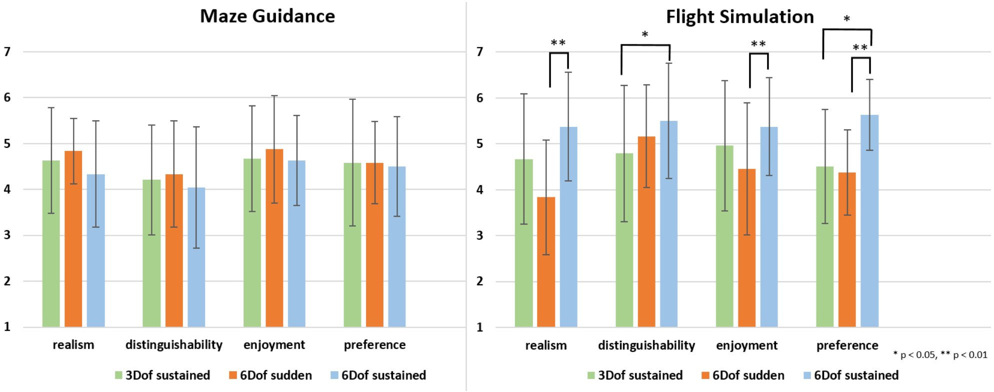


Figure 9: Average rating of realism, distinguishability, enjoyment, and preference on a 7-point Likert scale from the maze guidance and the flight simulation application with three case: 1) 3DoF+sustained, 2) 6DoF+sudden, and 3) 6DoF+sustained force feedback. The error bars represent the standard deviation.

6.2. Results and Discussion

The results are shown in Figure 9. A Friedman test and Wilcoxon signed-rank test with Bonferroni correction for post-hoc pairwise tests were utilized for the analyses. For maze guidance, no significant main effects are found in realism ($\chi^2(2) = 2.46, p = 0.29$), distinguishability ($\chi^2(2) = 0.59, p = 0.74$), enjoyment ($\chi^2(2) = 0.67, p = 0.72$) and preference ($\chi^2(2) = 0.33, p = 0.85$). For flight simulation, significant main effects are revealed in realism ($\chi^2(2) = 16.2, p < 0.001$), distinguishability ($\chi^2(2) = 8.07, p = 0.02$), enjoyment ($\chi^2(2) = 9.94, p < 0.01$) and preference ($\chi^2(2) = 11.49, p < 0.01$). The post-hoc Wilcoxon pairwise tests show that significant differences are between (6DoF+sustained, 6DoF+sudden) in realism, enjoyment and preference, and between (6DoF+sustained, 3DoF+sustained) in distinguishability and preference.

For maze guidance, 6DoF+sudden had slightly better performance in all factors although there was no statistical significance. 7 participants (*P1, P5, P7, P8, P9, P10, P11*) mentioned that sudden force feedback was intermittent so it was clearer to perceive and recognize, but sustained force feedback might cause fatigue in guidance. Although this differs from our expectation, it aligns with the design and findings in GuideBand (Tsai et al.

(2021)), where pulling and releasing force guiding cues could be clearer than maintaining a constant pulling force cue for guidance, as sustained pulling force could numb users. On the other hand, 5 participants (*P2, P3, P4, P6, P12*) preferred sustained force feedback since they could perceive the feedback direction constantly adjusted, while intermittent sudden feedback was less responsive in direction adjustment. Notably, no matter whether it is 6DoF+sudden or 6DoF+sustained, both are enabled by HeadiCopter, as mentioned above, which are both contributions in this paper. Comparing 3DoF+sustained and 6DoF+sustained, half of the participants (*P1, P2, P6, P8, P9, P11*) thought that their feedback for guidance was similar. 4 participants (*P3, P4, P5, P10*) preferred the 6DoF+sustained method since the translational force feedback was more obvious, so it was adequate to the whole body movement guidance. Only *P7* and *P12* believed that the directional feedback in 3DoF+sustained was more distinct and easier to follow. Similar performance between 3DoF and 6DoF sustained feedback indicates that translational force feedback could be substituted by rotational force feedback in certain guidance scenarios. In fact, maze guidance was a scenario more about functionality. The force feedback was used as guiding cues, while no visual feedback corresponding to the force feedback was provided. Participants regarded the feedback as guiding cues and only focused on recognizing and following the cues to move the head and body. Therefore, the primary concerns for guidance were whether the force feedback was distinct enough to recognize and easy to follow, indicating its clarity and intuitiveness, which means that functionality was more important in this scenario. Sudden feedback provided better clarity, and 3DoF rotational force feedback was intuitive enough as body movement guiding cues, while sustained feedback was more responsive, and some participants still believed that translational force feedback was better suited for the whole body movement guidance. Therefore, all three methods demonstrate similar performance in guidance.

For flight simulation, the proposed 6DoF+sustained force feedback generally shows better performance than the others. All participants agreed that sustained force feedback for the inertia force over a long duration was better than sudden force feedback. Therefore, 6DoF+sustained had significantly better performance in realism, enjoyment, and preference, compared to 6DoF+sudden. However, no statistical significance between them in distinguishability might be caused by the fact that both 6DoF sustained and sudden force feedback could clearly render the force directions. Furthermore, comparing 3DoF+sustained and 6DoF+sustained, most participants, except for *P2*, believed that they could clearly distinguish force feedback from translation (only in 6DoF) and rotation (in both 6DoF and 3DoF). This is consistent with the statistical results that the feedback of 6DoF sustained is significantly more distinguishable than that from 3DoF sustained, as well as the results of the recognition study. The visual feedback in VR flight simulation could further improve the recognition. In addition, most participants, except for *P7*, commonly agree that using translation force feedback in 6DoF sustained for acceleration/deceleration and leftward/rightward translation of the UFO was better than using rotation force feedback in 3DoF sustained to simulate these. Two common reasons were mentioned. *P1, P4, P6* and *P9* stated that translation force feedback for UFO acceleration/deceleration and leftward/rightward translation felt more natural, realistic and consistent with their daily experiences of being on flights or in vehicles. *P3, P5, P8, P10, P11* and P12 mentioned that translational directions were more suitable for the whole body movements due to stronger force feedback and the sensation of linear propulsion, while the rotational force feedback only weakly scratched the head. This aligns with the findings from the JND study, which indicate that translation force could generate stronger torque than rotation force due to the longer lever arm from the pivot between the head and the neck, as mentioned in works from Ke et al. (2023a); Yip and Jin (2004). Interestingly, even though *P2* thought that they could not clearly translation and rotation force feedback, they still supposed that the rotation force feedback from 3DoF sustained for UFO movement simulation was not realistic. *P7*, the only participant who preferred 3DoF sustained, mentioned that they could distinguish between translation and rotation feedback but still preferred the sensation of head rotation for simulating UFO movement. These could be the reasons that 6DoF sustained is significantly more distinguishable and preferred than 3DoF sustained. However, no statistical significance in realism might be caused by the fact that they had similar neck movements. This task shows that sustained force feedback is more proper than sudden force feedback in scenarios with sustained inertial force feedback, such as flight navigation 360 videos. Furthermore, translational force feedback offers users a more comprehensive sensation of force feedback throughout the body. Besides, *P9* specifically mentioned that the airflow from the propellers in flight simulation further enhances the realism.

By comparing two tasks, we observed that most participants, except for *P2*, were able to distinguish the difference between 3DoF and 6DoF force feedback in flight simulation, including 5 of 6 (*P1, P6, P8, P9, P11*) participants who had previously thought that feedback from 3DoF and 6DoF was similar and two participants (*P7* and *P12*) who had believed that feedback from 3DoF was more distinct in maze guidance. This interesting finding shows that participants were actually able to the directions in 6DoF feedback, as proven in the recognition study. Especially when corresponding visual feedback was provided in flight simulation, the proposed 6DoF force feedback could enhance their realism and VR experiences. For functional scenarios, such as guidance, clarity and intuitiveness instead of immersion were primary concerns. Based on these results and the comments, we obtain that the proposed 6DoF sustained force feedback from HeadiCopter significantly enhances users' VR experiences for typical VR scenarios with consistent visual and haptic feedback, such as the abovementioned 360 videos and VR games. In addition, 6DoF sustained force feedback can also serve functional scenarios, *e.g.*, guidance, as haptic cues with better responsiveness.

7. Limitations and Future Work

The 6DoF sustained force feedback from HeadiCopter achieved good performance in some VR scenarios and was appreciated by users in the studies. However, there are still some limitations. The noise issue is a potential drawback in propeller-based devices. To prevent the loud noise from interfering with users or causing hearing damage, we limited the force levels to only 3N and 3.6N with noise range between 93dB and 97dB, even though the HeadiCopter propellers can generate the maximum force of 6N, which is a trade-off mentioned above. The noise level of 97dB from HeadiCopter is much lower than that of similar previous works with propellers on the head, including 106.9dB from Odin's Helmet (Hoppe et al. (2021)) and 110.6 dB from X-Wing (Watanabe et al. (2021)). Furthermore, earmuffs can be additionally worn over the earbuds on the ears to further reduce the noise and protect users' hearing during future use. Another limitation is the weight issue. Although HeadiCopter with a weight of 613g is lighter than some other force feedback devices for the head, including X-Wing (Watanabe et al. (2021)) (850g) and OsciHead (Hung et al. (2022)) (955g). Furthermore, unlike most force feedback devices for the head that add uneven additional weight on the HMD, the weight of HeadiCopter is on the helmet, evenly supported by the head. The even weight distribution alleviates the heaviness typically associated with other heavy head-mounted devices or HMDs. Certainly, replacing the off-the-shelf helmet in the current prototype with a custom-fabricated helmet, *e.g.*, by carbon fiber material, can further reduce the weight. In addition, since applications of HeadiCopter allow users to remain seated or move in a small range, using a pulley system on the ceiling to reduce the weight, as in ElastImpact (Tsai and Chen (2019)), is a viable alternative.

Another limitation is that users still cannot clearly perceive and recognize the force direction in the upward/downward translational directions even when the maximum force of 6N of the device is rendered. This could be improved by using more powerful motors, larger fans or fans with more blades on the propellers to provide stronger force. Certainly, these substitutions could increase the noise level and/or weight. Therefore, the current prototype is actually the result of a trade-off among force magnitude, weight and noise level. However, if the abovementioned weight and noise alleviation approaches are implemented in the future for practical use, the substitutions can generate stronger force to make upward/downward force feedback more clearly recognizable. Besides, the latency issue in the propeller and T-bar rotation and the propeller reaching its maximum speed still limits our device for some real-time applications. The airflow issue is inevitable for haptic devices actuated by air jets and propellers. Although the T-bar design of the HeadiCopter is also used to reduce its influence, users could still perceive some airflow. However, the findings in the VR study shows that airflow could enhance users' realism if it corresponds to the visual feedback.

8. Conclusion

We propose a propeller-based device, HeadiCopter, to render 6DoF sustained force feedback on the head. HeadiCopter is capable of generating both sustained and sudden force feedback in 6DoF, including omnidirectional translation force in continuous range of 3D space. Therefore, it can comprehensively render force feedback in versatile VR applications, including 360 videos and VR games. A JND study was performed to obtain a unified force magnitude JND threshold of 0.6N for the 5DoF directions, except for upward/downward in translation. Two force levels, 3N and 3.6N, were chosen for VR applications, which was a trade-off among the noise level, device weight and force magnitude. A direction recognition study was conducted and shows that the average recognition rate is 78.6%, and could be 84% by excluding upward/downward. A VR study was performed to compare between 6DoF and 3DoF force feedback as well as between sustained and sudden force feedback and verify that the 6DoF sustained force feedback from HeadiCoper enhances users' VR experiences in typical VR scenarios with consistent visual and haptic feedback, such as VR games or 360 videos, which are popular for exercise and extreme gaming. HeadiCoper also can serve as representative haptic cues for functional scenarios, such as guidance.

9. CRediT authorship contribution statement

Chi-Chun Su: Conceptualization, Data curation, Formal analysis, Investigation, Software, Validation, Visualization, Writing – original draft. **Hsin-Ruey Tsai:** Formal analysis, Methodology, Project administration, Validation, Writing – review & editing. **Bing-Yu Chen:** Funding acquisition, Formal analysis, Project administration, Resources, Writing – review & editing.

10. Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

11. Data availability

Data will be made available on request.

12. Acknowledgments

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