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An Integrated Ducted Fan-Based Multi-Directional Force Feedback with a Head Mounted Display

Koki Watanabe[1], Fumihiko Nakamura[1], Kuniharu Sakurada[1], Theophilus Teo[1] and Maki Sugimoto[1]

[1]Keio University, Japan

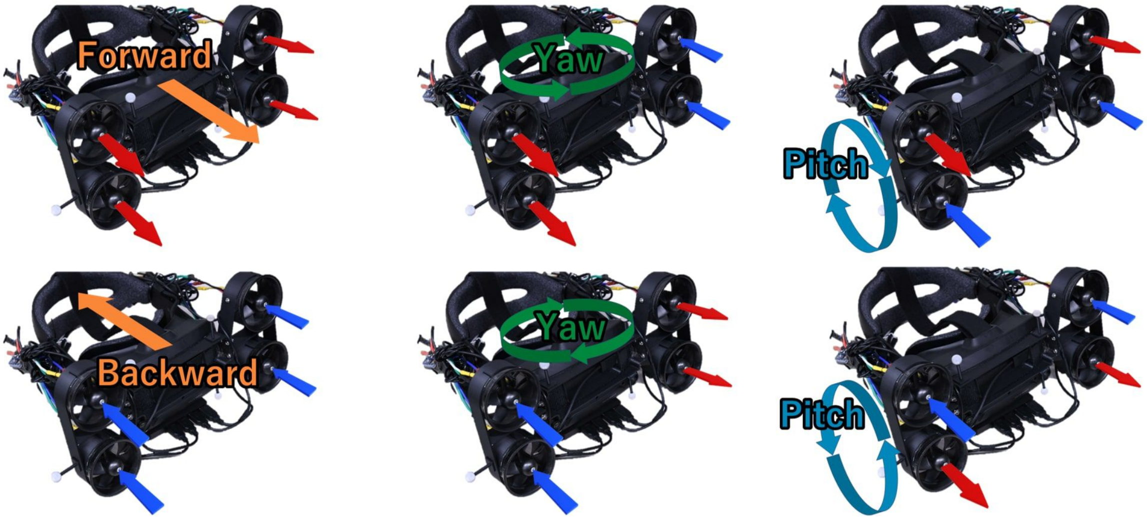

Figure 1: *Force feedback prototype overview. The force is converted into thrust powers by ducted fans on the VR HMD, which converts into multi-directional forces when rotated in specific directions.*

Abstract

Adding force feedback to virtual reality applications enhances the immersive experience. We propose a prototype, featuring head-based multi-directional force feedback in a virtual environment. We designed the prototype by integrating four ducted fans into a head-mounted display. Our technical evaluation of the ducted fan revealed the force characteristics of the ducted fan, including presentable power, sound level, and latency. In the first part of our study, we investigated the minimum force that a user can perceive in different directions (forward/backward force; up/down/left/right rotational force). The result suggested the absolute detection threshold for each directional force. Following that, we evaluated the impact of using force feedback through an immersive flight simulation in the second part of our study. The result indicates that our technique significantly improved user enjoyment, comfort, and visual-and-tactile perception, and reduced simulator sickness in an immersive flight simulation.

CCS Concepts

• ***Human-centered computing*** → ***Haptic devices;*** *Virtual reality;* • ***Hardware*** → *Haptic devices;*

1. Introduction

Force feedback is essential for a Virtual Reality (VR) experience as it can enhance users' enjoyment and presence. While a VR Head-Mounted Display (HMD) can offer immersive visual and auditory feedback, it does not provide force feedback which is important for many virtual simulation experiences. Massie proposed a prototype that applies force feedback to a user's hands [H.94] through mechanical links. However, the prototype needs to be stationary so the actuators can generate sufficient impulsive force for the user. Be-

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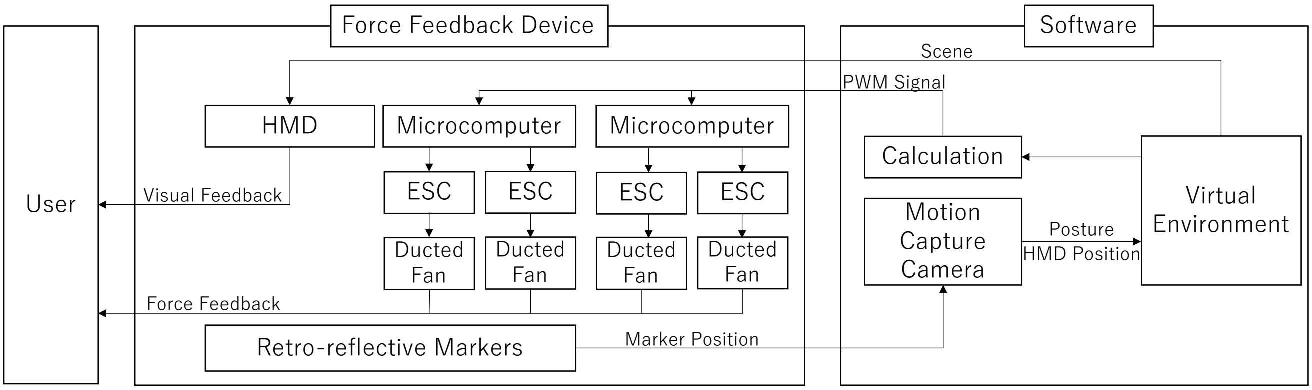

Figure 2: *System Overview*

cause of this, it is undesired for VR applications that require a user to roam freely in a virtual environment.

Although portable force feedback devices were proposed in the past to support room-scale VR, most devices require users to attach significant amounts of haptic receptors to their hands [hap21]. This is because hand-based force feedback is beneficial for VR interactions, such as grasping objects or clicking buttons. Likewise, it is sensitive to feel the difference between a smooth surface. Besides hands, a human head is also sensitive to detecting haptic feedback. Previous works added air-jets [LYM*20] and motors [TC19,CTT*18] to VR HMDs to generate force feedback on a user's head for increasing sensual immersion. However, the former method required large and heavy air compressors to create strong air jets and the latter generates powerful force with small actuators but in fixed directions. These techniques have bottlenecks restricted by the hardware configuration. Hence, we focus our work in this paper to propose a head-based force feedback prototype that is strong and multi-directional.

In this paper we introduce a head-worn force presentation prototype that generates impulsive force power in multiple directions. We use ducted fans to generate force power through air propulsion. The surrounding duct in ducted fans traps and concentrates the airflow in a direction for an intense thrust power. We attach ducted fans to four corners of an HMD (See Fig. 1) and manipulate them using pulse width modulation (PWM) signals. This allows us to rotate each ducted fan in specific directions to produce thrust powers. We added a gap between each ducted fan to output multi-directional forces similar to Leviopole [SHL*18] and ThorsHammer [HCLW18]. Together, our design creates impulsive and continuous thrust forces to a user's head. We demonstrate our prototype by designing a VR flight simulation to stimulate the wind pressure and the event of a bird strike.

Our contributions are below.

- Technique to generate directional forces using ducted fans attached to a VR HMD. We reported the power, loudness, and latency of a ducted fan and monitored available force power and directions by our implementation.
- Evaluation of the threshold to feel a force applied on the head. The results showed that the feedback perceived by the participants differed from the directions of the force.
- A report of the effectiveness of our wind-based force feedback to a head in a virtual experience. Through a study using the flight simulator we implemented, we found that our method improved the virtual experience in terms of user enjoyment, comfort, visuo-haptic match, simulator sickness, and realism.

In addition, this paper is an extended version of XWing [WNS*21].

2. Related Work

Haptic stimuli have been used to enhance experiences and augment human perceptions in VR scenarios. This section reviews previous and related works for using haptic as force feedback by different body parts.

2.1. Haptic Feedback on Human Limbs

Applying haptic feedback on human limbs are common in research works and commercial products because limbs are essential for performing interactions in physical and virtual environments. Among these, Phantom [H.94] is a popular device that generates powerful force feedback to a user's hands thanks to a grounded configuration. It allows a user to feel an object through a pen-type interface that renders the shapes of the virtual object as a repulsive force. In a similar fashion, portable haptic devices were developed to support haptic feedback with an ungrounded configuration. Minamizawa et al. [MFK*07] built a finger-worn haptic feedback device to render weights of virtual objects by applying pressure on fingertips through motor-driven belts. Their device enabled a user to receive haptic feedback as they are walking, but the design was restricted to produce a weak force. To overcome this, Fang et al. developed a wearable force-feedback prototype on a hand with retractable wires mounted to the shoulder [FZDH20]. Although their prototype can render strong forces, the system configuration restricted the direction of forces. Besides direct touch, indirect touch such as wind force was also proposed as a form of haptic feedback to improve the immersive experience. Kuroda et al. [KSKT17] proposed a force feedback device that generates translational and rotational forces to the user's hand by attaching a fan to a grasping device. Similarly, Heo et al. [HCLW18] embedded propellers into a handheld device to generate air propulsion power in multiple directions. Likewise, Sasaki et al. [SHL*18] attached propellers to a handheld rod to generate force feedback on the wearing hands. Similarly, Tsai et al. developed a handheld device that offers directional force with air-jets [TTL*22]. There are also studies implementing propellers as a wrist-worn device [JLKB18] and a leg-worn device [KCGZ22] to enhance virtual presence and VR realism. Obviously, applying force feedback on human limbs can improve the sense of immersion when interacting in a virtual environment. Besides human limbs, the human head is superior and sensitive to spatial awareness, which affects immersion. Despite that, head-based haptic feedback is not well-explored to date.

2.2. Haptic Feedback on Human Head

A human head is also essential for giving and receiving interactions in a virtual environment because of sensitive sensory systems and haptic organs. Simulating haptic feedback on the head is effective for information that is difficult to interpret by human limbs. Attempts in the past have proposed various mechanisms for HMD-based VR applications. For example, Costes et al. demonstrated attaching a grounded robotic arm to an HMD to simulate motion through force feedback [CL22]. Their prototype allowed a user to move within the arm's moveable range. To avoid spatial restriction, haptic actuators are embedded into an HMD for head-based haptic experiences. Several studies succeeded to enhance user's presence in VR applications by adding vibrotactile and thermal cues to specific areas in an HMD foam [WRHR19], or by providing ambient cues such as wind and thermal cues, to a user's mouth [RJTNT*18]. In addition, there were attempts to demonstrate force sensations using actuators embedded into an HMD. As a kind of actuator, flywheels were used to produce kinesthetic feedback [TAM*20]. To generate instant force in five directions, Tsai et al. mounted impactors using a brake mechanism on an HMD [TC19]. However, only instant force could be applied to the limited situation. Chang et al. integrated a belt-pulling mechanism into an HMD to push the display toward the user's face [CTT*18]. However, their approach was limited to producing standard force. Liu et al. employed HMD-integrated air jets to generate persistent 360-degree force [LYM*20]. However, their technique required an air compressor, which restricted the user's behaviour and movement in some ways. Hoppe et al. proposed a helmet-based force feedback device to simulate gravitational force with four propellers in a virtual environment [HOSK21]. They attached propellers to the front, rear, and sides of a helmet to render three-dimensional forces. However, their approach could not produce strong forces. As shown above, embedded approaches have difficulty producing strong force in multiple directions. To overcome these, we propose a technique that attached ducted fans to an HMD to simulate force feedback that is strong and multi-directional.

3. Ducted fan-based multi-directional force feedback to the head

We designed a prototype using ducted fans to simulate powerful forces on a user's head. We chose a ducted fan because it has a surrounding duct that serves as a barrier to trap and concentrate the wind to reduce the aerodynamic loss of the wind force generated by the propeller. Therefore, it emits a higher thrust efficiency than a non-ducted fan.

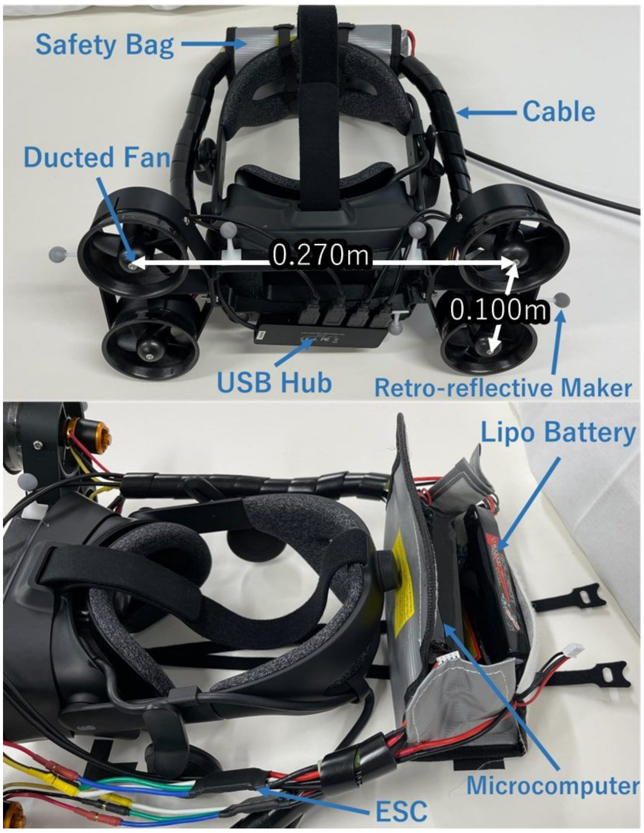

Figure 3: *Force Feedback Device overview.*

We attached four ducted fans to the front of an HMD with some gaps to generate a directional force on a head. Together it produces forces comprising two movement directions: forward and backward; and four rotation directions: left, right, up, and down (See Fig. 1). The rotation speed of ducted fans can be adjusted to output thrust power of different strengths.

4. Implementation

We developed a VR prototype system to present force feedback on the head (Fig. 2). Our system consists of a force feedback device and software.

The force feedback device used four ducted fans (QX-MOTOR QF 2822, 64 mm diameter), four electronic speed controllers (ESC), four lithium-ion polymers (LiPo) batteries (1300mAh, 11.1V, 25C), two microcomputers (Arduino Nano), a USB hub, and retro-reflective markers. Four ducted fans were attached to each corner of the HMD using 3D-printed brackets. The horizontal and vertical distances between the fans were 0.27 m and 0.10 m, respectively. We used ESCs to manipulate the rotation speed of ducted fans via Pulse Width Modulation (PWM) signals. The ESCs were placed on the left and right sides of the HMD for a balanced weight distribution. Each ESC was connected to a ducted fan that translates a pulse width between 1100μs and 1900μs with a delimiter at 1500μs. In other words, the ESC rotates the propeller in a counterclockwise direction if the pulse width is smaller than 1500μs. Likewise, the ESC rotates the propeller in a clockwise direction when the pulse width is larger than 1500μs. We used LiPo batteries to provide power supplies to the ESC. On the other end, we used microcomputers to receive the data from the software and send them as serial data to the ESC. Both microcomputers and batteries were packed in a fire-proof bag and stitched to the rear of the HMD. A USB hub was placed on the front side of the HMD. We used retro-reflective markers attached to the left, right, top, and bottom sides of the HMD to allow the motion capture system to track the markers. The device (including the HMD) weighed 1994g.

On the opposite, we designed a virtual environment alongside software to communicate between the environment and the hardware. (Fig. 3). The software detects action and collision events in the virtual environment and converts them into signal data representing power output and directions of the thrust force. Next, the software translates the power output into the PWM signal and sends it to the microcomputer via serial communication for each ducted fan. We used a motion capture system to track the user's head position and posture because vibrations from the force feedback in our system disrupt HMD tracking. This allows the software to receive positions and postures of retro-reflective markers and generates corresponding body gestures in the virtual environment. The motion capture system also sends these data to the computer via a network connection. The data streaming delay was approximately 5ms, and the virtual environment was built using the Unity game engine (version.2018.4.23f1).

5. Technical evaluation of ducted fan

To explore the force feedback with the ducted fans, we assessed the force characteristics generated by a ducted fan. This includes the force values, noise level and latency. The force values and noise level were measured using the pulse width of PWM signals. This is accomplished by sending values of $1100\mu s + 50 \times n\ \mu s (n = 0, 1, 2, ..., 16)$ to the ESC since it has threshold values of 1100μs and 1900 μs.

For measuring the latency, we tracked the changes in force value for 2.6 seconds since a signal was sent by the virtual environment. We recorded the time taken to receive a signal by the software (communication time), initiate the propeller to rotate (driving delay), reach the maximum rotational speed from zero (peak time), and reach a full stop from the peak speed (fall time). As a procedure, we began by sending 1900 μs PWM signal to produce a maximum force. After two seconds, we reduced the PWM signal to 1500 μs to stop producing a force. We recorded the change of force values throughout time.

5.1. Evaluation setup

Fig. 4 illustrates the evaluation setup. We mounted the ducted fan on a force sensor (Leptrino, PFS055YA251U6) with screws. The six-axis force sensor was installed on a desk with screws and connected to a computer using a USB cable. We measured the sound level by placing a sound level meter (Shinwa, Digital Noise Meter 78588) 10cm away from the ducted fan. The force values were monitored by the computer via USB communication.

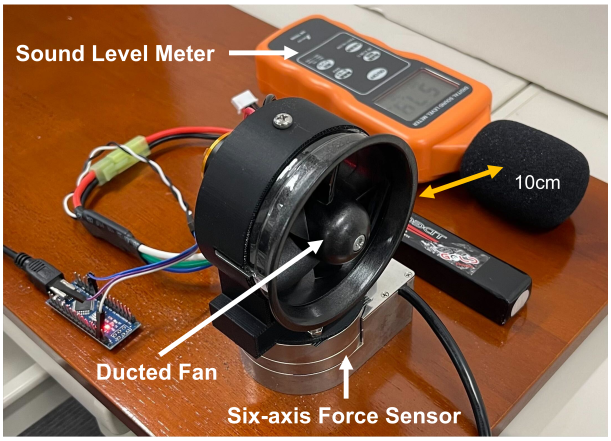

Figure 4: *Setup of technical evaluation.*

5.2. Result

The result of power is shown in Fig. 5. The maximum force was 5.69 N in the forward direction when the PWM signal was 1900μs and 2.35 N in the backward direction when the PWM signal was 1100μs. We realised the ducted fan produced more power in the forward direction than in the backward direction.

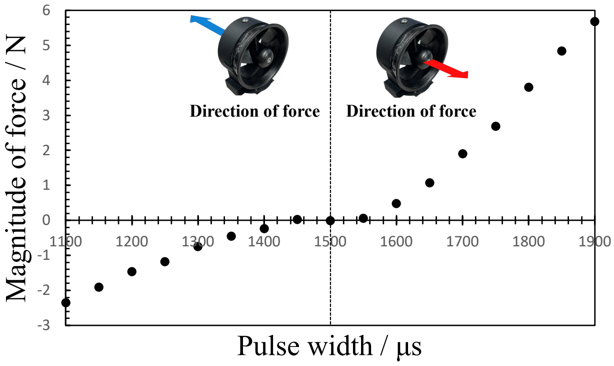

Figure 5: *Result of force generated by a single ducted fan.*

Fig. 6 shows the sound level result. Forward forces produced noise up to 92.6dB, while backward forces generated noise up to 110.6dB. This suggested earplugs should be worn during the experience to protect the user's hearing. Do note that the maximum force within the acceptable limits of the human ears with earplugs is 1.33 N in the forward direction when the PWM signal was 1670μs and 0.23 N in the backward direction when the PWM signal was 1388 μs.

Fig. 7 illustrates the observed response between 0 ms and 2600

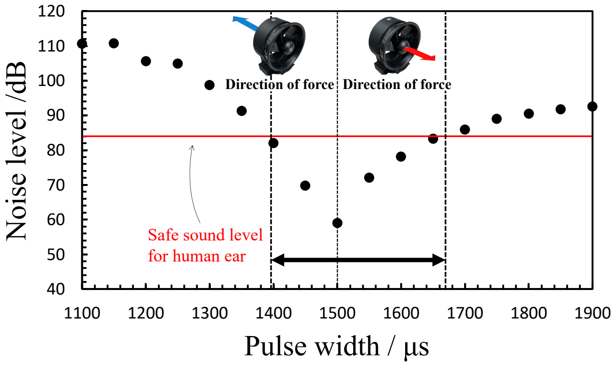

Figure 6: *Result of sound level generated by a single ducted fan.*

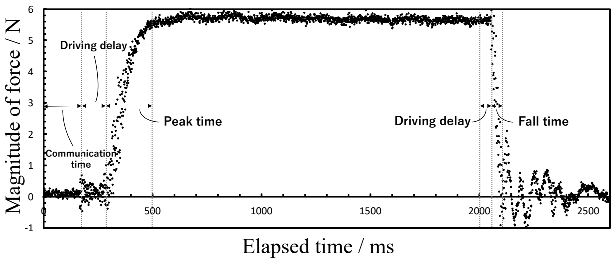

Figure 7: *Result of latency. Monitored force values in generating a power and falling a power. The force values between 0ms and 2600ms were plotted.*

ms. The communication time was 200 ms, the driving time was 100 ms, and the peak time was 200 ms. Thus, it took 500 ms to send a signal from the computer until the prototype exerts a force. The driving time was 60 ms, and the fall time was 50 ms. According to Fig. 7, the force values were unstable after stopping force exertion. This was caused by post-vibration conveyed from the ducted fan.

5.3. Net force with four ducted fans

The net force, which is the sum of force vectors, can be expressed as Table 1. The force measurement result suggested that our prototype with four ducted fans was capable of producing the following force in each direction:

- Backward: 2.35N × 4 = 9.40N
- Forward: 5.69N × 4 = 22.76N
- Yaw: 5.69N × 2 × 0.135m + 2.35N × 2 × 0.135m = 2.17Nm
- Pitch: 5.69N × 2 × 0.050m + 2.35N × 2 × 0.050m = 0.80Nm

Table 1: *Resultant force expression produced by four ducted fans.* $N_{LU}, N_{LD}, N_{RU}, and N_{RD}$ *indicate the forces of the upper left, lower left, upper right, and lower right ducted fans, respectively.*

forward and backward	$N_{LU}+N_{LD}+N_{RU}+N_{RD}$
yaw moment	$(N_{LU}+N_{LD})\times 0.135-(N_{RU}+N_{RD})\times 0.135$
pitch moment	$(N_{LD}+N_{RD})\times 0.050-(N_{LU}+N_{RU})\times 0.050$

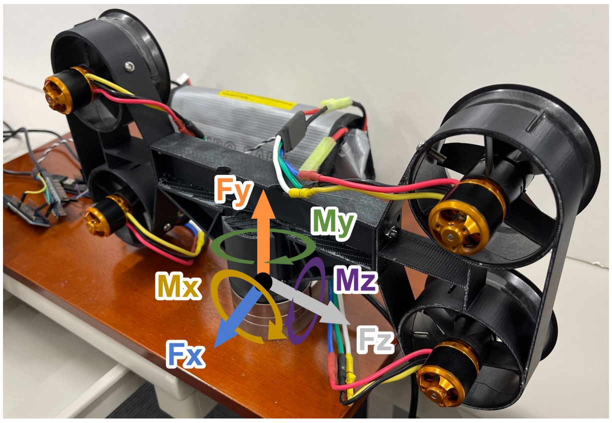

Figure 8: *The force measurement setup. The force presentation device, which was the same as our prototype, was mounted on a six-axis force sensor, Leptrino PFS055YA251U6.*

When the noise is maintained at a safe level for the human ears (< 90 dB), the sound level a fan can produce becomes 84 dB. That being said, a ducted fan at 84 dB or lesser can produce a force magnitude of 1.33 N at 1670 μs and 0.23 N at 1388 μs. The resultant force under the above conditions is as follows.

- Backward: 1.33N × 4 = 5.32N
- Forward: 0.23N × 4 = 0.92N
- Yaw: 1.33N × 2 × 0.135m + 0.23N × 2 × 0.135N = 0.42Nm
- Pitch: 1.33N × 2 × 0.050m + 0.23N × 2 × 0.050m = 0.16Nm

The resultant force was then measured using Leptrino PFS055YA251U6, a six-axis force sensor (See Fig.8). The force sensors were mounted 64.25 mm below the centre of the four fans. Each of the ducted fans could rotate in a clockwise or anti-clockwise direction to generate a forward or backward force. According to our measurements, each fan outputs 1.00 N in the front-back direction; 0.74 N in the yaw direction; and 2.00 N in the pitch direction. Hence, the combined forces are shown in Fig. 1. Based on table 1, the translational force in the front-back direction should be 4.00N and the rotational force in the yaw and pitch directions should be 0.40Nm. The result is shown in Fig. 9.

6. Study 1: Absolute Detection Threshold (ADT)

We designed a user study to investigate the minimum perceivable force when using our prototype. This also includes the ADT of six directional forces (forward/backward forces and up/down/left/right rotation forces). We adopted a two-down, one-up staircase procedure [JT13] to assess the ADT of the force. We recruited 10 participants (8 males and 2 females) with an average age of 23.4 (SD=1.50). Four participants reported using VR at most an hour a week, and six participants at least an hour a week. Participants participated in the experiment individually.

The experiment started with a task briefing. Then the participants were instructed to sit on a chair, wear the earplugs, put on the HMD and prototype, and hold the VR controllers in their hands. Once ready, we launched the software, and the participants were

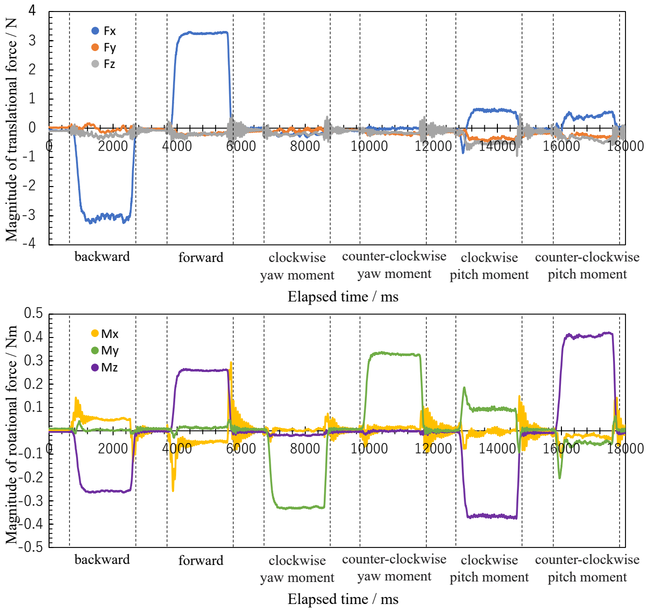

Figure 9: *Multi-directional force presentation. Observed force values generated by the force presentation device. The device produced forward/backward force and up/down/left/right rotational force for two seconds each. (Top) The translational force measurement. (Bottom) The rotational force measurement.*

immersed in the virtual environment. In the environment, an arrow that indicates the direction of the force will appear. The participants had to follow the arrow instructions in front of them to complete the task. The initial force and step values were different by the force directions. For forward/backward forces, the initial value was 5N and the step value was 1N. For rotational forces, the initial force was 0.5Nm and the step value was 0.1Nm. Participants proceed with the procedure as follows:

1. The prototype generated a force over two seconds as a trial.
2. The participants verbally reported whether they felt the force at the end of each trial, following a five seconds interval until the next trial.
3. If the participants did not feel a force, the force will be increased by a step. Otherwise, the force decreased by a step if the participants reported a force in two consecutive trials.
4. If the participants did not feel a force in the proceeding trial once the force was increased or decreased, the force will be adjusted by a half step.
5. We obtained the participants' average force value after repeating the previous step five times.
6. The participants repeated Steps 1-6 for a second time.

The participants repeated the procedure six times to measure each directional force, comprising 12 sessions (6 directions ×2). The experiment took 40 minutes on average.

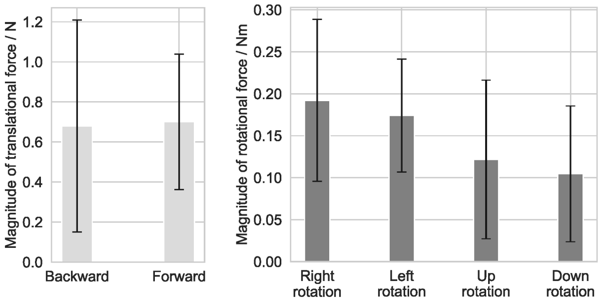

Figure 10: *ADT results in Study 1. The bars indicate the mean ADT in each direction. (Left) The ADT results of translational forces. (Right) The ADT results of rotational forces.*

6.1. Result

Fig. 10 illustrates the result of the trials. The mean ADT of the backward and forward forces were 0.68 N and 0.70 N, and the mean ADTs of the right, left, up, and down rotational forces were 0.19 Nm, 0.17 Nm, 0.12 Nm, and 0.10 Nm, respectively. The Shapiro-Wilk test showed that the ADT results could be assumed to be from a normally distributed population: backward (W = 0.924, p = 0.392), forward (W = 0.977, p = 0.947), right rotation (W = 0.958, p-value = 0.760), left rotation (W = 0.905, p = 0.248), up rotation (W = 0.894, p = 0.190), and down rotation (W = 0.868, p = 0.095).

7. Study 2: Effects of Force Feedback on Flight Simulation

We conducted a follow up study to evaluate the effects of using our prototype to generate force feedback to the user's head in a VR simulation. We developed a flight simulation to simulate two kinds of force feedback: wind pressure and an event of a virtual-physical impact. In the flight simulation, the participants rode an aircraft and travelled on a predefined path for 60 seconds (Fig. 11). During the course, the participants experienced continuous wind pressure from the aircraft movement and periodical impact events by a bird collision. The participants could look around in the environment and that influenced the direction of the force feedback. In other words, the wind direction and force generated during a bird collision changed according to the participants' head movement and the airplane's position. The participants went through the simulation with two conditions: with or without the force feedback. We evaluated the user immersion, enjoyment, reality, comfortable, visuo-haptic match, and side effects of vibration and noise using custom design questions (Table 2). In addition, we assessed the participant's simulator sickness using the Simulator Sickness Questionnaire (SSQ) [KLBL93]. We recruited the same participants as in Study 1.

The experiment started with explanations of the task to the participants. Then the participants were instructed to wear the prototype and earplugs while sitting on a chair. Afterwards, the participants experienced the flight simulator as we launched the software. Towards the end, the participants removed the prototype and answered the questionnaires on a laptop. Once completed, participants wore the prototype and went through a similar procedure for

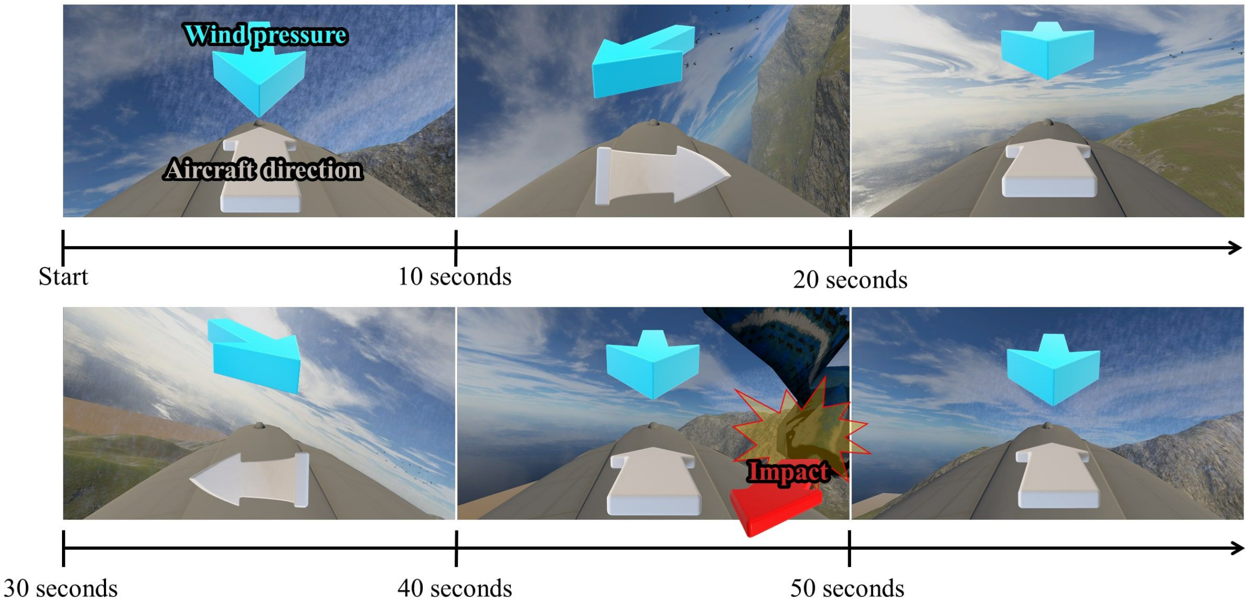

Figure 11: *Snapshots from the flight simulation in Study 2. The flight simulation involved the wind pressure caused by aircraft motion and the impact caused by a bird strike.*

the second condition. The conditions order was counter-balanced to reduce the bias effect.

7.1. Result

Fig. 12 illustrates the result of the questionnaire 2. The force condition reported an immersion score of M=6.37 (SD=0.64), an enjoyment score of M=6.55 (SD=0.89), a reality score of M=4.91 (SD=1.56), a comfortable score of M=5.73 (SD=1.29), the visuo-haptic match score of M=5.27 (SD=0.962), the vibration score of M=2.00 (SD=1.13), and the noise score of M=3.00 (SD=1.71). For the no-force condition, the immersion score was M=5.82 (SD=0.83), the enjoyment score was M=4.82 (SD=1.37), the reality score was M=4.64 (SD=0.979), the comfortability score was M=4.27 (SD=1.96), the visuo-haptic match score was M=3.82 (SD=1.11), the vibration score was M=1.00 (SD=0.00), and the noise score was M=1.00 (SD=0.00). The Shapiro-Wilk test found that the immersion, enjoyment, comfortability, visuo-haptic match, vibration, and noise results could not be assumed to come from a normally distributed population: immersion (W = 0.835, p = 0.003), enjoyment (W = 0.826, p = 0.002), reality (W = 0.918, p = 0.091), comfortability (W = 0.861, p = 0.008), visuo-haptic match (W = 0.871, p = 0.012), vibration (W = 0.574, $p < 0.001$), and noise (W = 0.668, $p < 0.001$). Wilcoxon signed-rank tests revealed a significant difference between the conditions for enjoyment (p = 0.003, Z = 0.86), user comfort (p = 0.011, Z = 0.72), visuo-haptic match (p = 0.001, Z = 0.97), vibration (p = 0.014, Z = 0.69), and noise (p = 0.004, Z = 0.84).

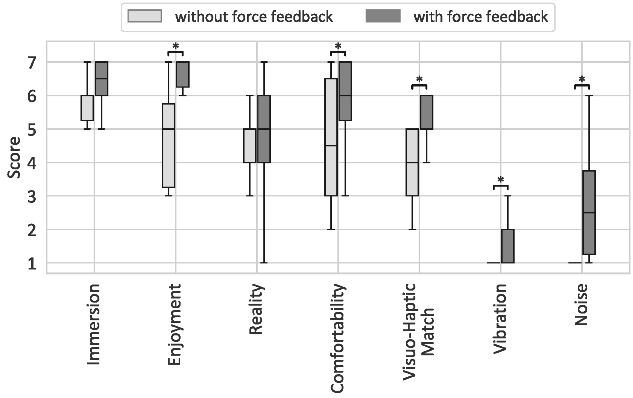

Figure 12: *Questionnaire scores in Study 2. * denotes* $p < 0.05$.

Table 2: *Questionnaire for Study 2*

1	How much did you have a sense of “being there” in the virtual environment?
2	How much did you enjoy yourself during the experience?
3	How real did the virtual world seem to you?
4	How comfortable was the experience?
5	How much did your experience in the virtual environment seem consistent with your real world experience?
6	To what extent did the vibration generated by the ducted fans distract from the virtual experience?
7	To what extent did the noise generated by the ducted fans distract you from the virtual experience?

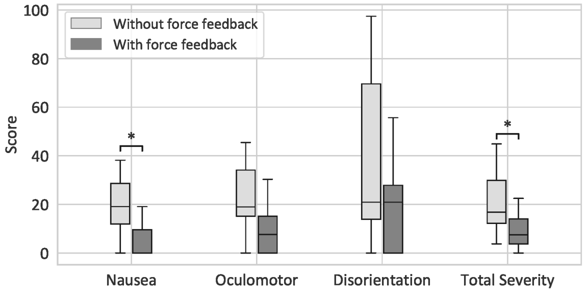

Figure 13: *SSQ subscale results in Study 2. * indicates p < 0.05.*

Fig. 13 illustrates the average SSQ score. Among the subscales, the force condition performed better than the no-force condition. For each subscale, the Nausea was M=4.77 (SD=6.40), Oculomotor was M=10.61 (SD=11.84), Disorientation was M=19.49 (SD=18.88), and Total Severity was M=10.10 (SD=9.32). The sum of the mean subscales was 44.97. In the no-force condition, Nausea was M=20.03, (SD=13.16), Oculomotor was M=21.98 (SD=13.75), Disorientation was M=37.58 (SD=34.13), and Total Severity was M=21.69 (SD=13.36). The sum of the mean subscales was 101.29. Shapiro-Wilk tests found that the Nausea, Oculuomotor, and Disorientation results could not be assumed to be from a normally distributed population: Nausea (W = 0.842, p = 0.004), Oculomotor (W = 0.896, p = 0.035), Disorientation (W = 0.827, p = 0.002), and Total Severity (W = 0.907, p = 0.056). Wilcoxon signed-rank tests revealed significant differences in Nausea (p = 0.005, Z = 0.89) and Total Severity (p = 0.025, Z = 0.71) between the condition with and without force feedback.

Overall, our prototype enhanced the immersion, enjoyment, reality, comfortable, and visuo-haptic match scores than a standard VR simulation without force feedback. We think the reason for the increased comfort in our prototypes is because of a smaller gap between reality and the experience in the virtual environment. One participant reported, "the experience with force feedback felt like an attraction, but the experience without force feedback made me VR sickness." This suggested force feedback provided an attraction-like experience and reduced the gap between reality and the flight simulator, making them feel comfortable while reducing VR sickness. However, the significantly larger vibration and noise scores than the no-force condition indicated possible distractions on the user's focus in a VR experience. Despite that, the low scores implied that the noise and vibration of the ducted fans had little effect on the user experience. For SSQ, all scores in the force condition were lower than the no-force condition. This suggested applying force feedback on the user's head could reduce simulator sickness.

8. Limitations and future work

In the follow up study, the questions on the noise showed that our force feedback had a lower score than just the visual feedback. We used the ducted fans designed for generating forward propulsion. Hence, it requires a higher amount of power and louder noise to generate an equivalent force in the opposite direction. While we instructed participants to wear earplugs, participants felt that the sound generated by the ducted fans was still loud. Likewise, the prototype created strong vibrations when generating the force feedback. In the future, we will investigate a method to suppress the noise and the vibration.

In our implementation, we have the ducted fans on the front side of an HMD to present HMD-centered forces to the user while providing head-centered rotational forces is an ideal design. In future work, we will investigate the effect of this axis misalignment of the rotational force on the experience.

In addition, we will increase the presentable force directions in our prototype. Our current design presents six directional forces. Increasing the presentable force directions could offer more expressive force feedback.

9. Conclusion

We proposed a force feedback system to support directional forces on 3 Degrees of Freedom. We used four ducted fans by attaching them to a VR HMD which generates intense forces on a user's head. By manipulating the fans' rotation speed and direction, our prototype generates six directional forces: Forward, Backward, Yaws and Pitches.

We evaluated the performance of a ducted fan using a force sensor. The result showed that a ducted fan produces a peak forward and backward force of up to 5.69 N and 2.35N at the sound level of 92.6dB and 110.6dB. Moreover, the prototype had a latency of 500 ms for generating a force and 110 ms to degenerate. Hence, our implementation with four ducted fans can produce cumulative forces of 22.76 N in the forward direction, 9.40N in the backward direction, 2.18 Nm in the left/right rotations, and 0.80 Nm in the up/down rotations on a user's head. When adjusted to a safe sound level for the human ear with earplugs (<90 dB), our prototype produces 7.72 N, 1.48 N, 0.62 Nm and 0.23 Nm for forward, backward, yaw and pitch forces.

We conducted a user study to investigate the ADT for six directional forces. The results showed that the average ADTs of the forward and backward directions and left, right, up, and down rotations were 0.68 N, 0.70 N, 0.19 Nm, 0.17 Nm, 0.12 Nm, and 0.10 Nm.

A follow up study was conducted to investigate the effect of our prototype on a flight simulation. The result showed that applying force feedback on a user's head can improve the user enjoyment, comfort, visuo-haptic match of the experience. Furthermore, the SSQ scores indicated that our prototype reduced VR sickness compared to a standard VR experience without force feedback.

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