Drone Rider: Enhancing VR Flight Experience with Dynamic Wind Feedback

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***Abstract*—Wind stimulation has been shown to enhance self-motion perception in virtual reality (VR). Building on our previous work with the Drone Rider simulator, this study investigates how four types of wind feedback—no wind, constant wind, naturally fluctuating wind, and velocity-adaptive wind—affect the VR flight experience. Seven participants experienced all conditions and rated four aspects: sense of flight, sense of being on a flying drone, sense of control, and wind naturalness. Within-participant analysis revealed that velocity-adaptive wind significantly enhanced the sense of flight and wind naturalness compared to no-wind or constant wind conditions. These findings suggest that both the presence of wind and its dynamic modulation are critical for achieving realistic and immersive VR flight experiences.**

***Index Terms*—Extended Reality (XR), wind feedback, VR flight, multisensory integration**

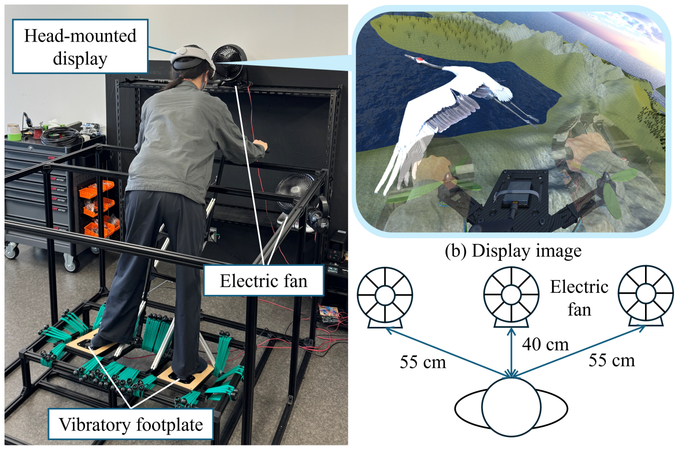
I. Introduction

Wind stimulation, when combined with vection stimuli, has been shown to enhance the perception of self-locomotion in virtual reality (VR) environments [1]–[3]. We previously developed *Drone Rider*, a VR flight simulator that integrates head-tracked visuals, airflow, and foot vibration to simulate drone-like movement [4], [5]. Our earlier work demonstrated that intense wind stimuli increased the perceived flight speed [1].

It is hypothesized that naturalistic wind stimuli may further improve the VR flight experience. Although prior studies [1], [6] confirmed the general benefits of wind feedback, they did not conclusively show the advantages of velocity-adaptive wind—where airflow intensity varies with simulated flight speed—over constant wind. Moreover, the effects of naturally fluctuating wind, which mimics environmental wind variability, have not yet been explored.

This study addresses these gaps by building on our previous work [6], which lacked standardized flight control across participants and failed to reveal significant differences between constant and velocity-adaptive wind conditions. To address this, we introduced an object-tracking task to unify flight trajectories and user interactions.

Additionally, we tested the impact of fluctuating wind, in which airflow intensity changes periodically to simulate natural wind patterns. Through a user study, we evaluate how these more naturalistic wind stimuli affect subjective flight experiences in VR.



(a) System appearance (b) Display image (c) Wind feedback configuration

Fig. 1. Drone Rider. (a) Appearance of the Drone Rider system. (b) Image delivered to operators. (c) Location of electric fans.

II. Methods

A. Participants

Seven participants (aged 21–27) were recruited for the experiment. All participants reported normal or corrected-to-normal vision and no known vestibular or neurological disorders. All conditions were experienced twice in randomized order, and scores were averaged.

B. Ethical Statement

The study protocol was approved by the Ethical Review Board, Hino Campus, Tokyo Metropolitan University (Approval No. R7-006).

C. Apparatus

We used the Drone Rider system [4], a custom-built VR flight simulator consisting of a rubber-suspended platform, Meta Quest 3 head-mounted display (Meta Platforms, Inc., CA), three electric fans for wind stimulation, and a vibration-enabled footplate, as shown in Fig.1. Drone Rider is designed to evoke the sense of flying over scenic landscapes by providing a combination of sensory feedback to the user. A similar approach has been employed in previous work, such as Birdly with specialized hardware [7], Flying Broomstick [8], or Magic Carpet [9] using only a head-mounted display.

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Participants stood on a rubber-suspended platform that could tilt in response to shifts in the user's weight. The simulated drone's motion was interactively controlled by the user's body movements: the pitch angle (forward/backward tilt) of the headset adjusted the simulated drone's forward velocity in real time, while the roll angle (left/right tilt) controlled the horizontal (right/left) movement.

This configuration allowed participants to intuitively control both the speed and direction of flight using natural body gestures, thereby preserving a strong sense of agency over their movements.

D. Wind Conditions

Participants experienced four wind conditions:

- No wind: No airflow was presented.
- Constant: Wind was delivered at a fixed intensity (2.6 m/s at the location of operator's face).
- Fluctuating: Wind intensity varied over a six-second cycle, transitioning between minimum (1.9 m/s) to maximum (2.9 m/s) wind speeds.
- Velocity-adaptive: Wind speed was dynamically modulated based on the simulated drone velocity.

Each condition was presented twice in a randomized order.

E. Data Analysis

Participants rated their experiences on four aspects—sense of flight, self-location (being on a drone), agency, and wind naturalness—using a 9-point Likert scale ranging from 0 (not at all) to 9 (extremely).

A repeated-measures analysis of variance (ANOVA) was conducted for each metric to examine the effects of wind condition. For each participant, the average score across two repeated trials was used for analysis. For sense of flight, agency, and self-location, all four wind conditions (no wind, constant, fluctuating, and velocity-adaptive) were compared. For wind naturalness, however, the no-wind condition was excluded from the analysis.

Following significant main effects, pairwise comparisons between conditions were performed using two-tailed paired t-tests. All analyses were conducted in MATLAB (2024a, MathWorks, Inc., MA) using the 'fitrm' and 'ranova' functions.

III. Results

The results of ANOVAs revealed a significant main effect of wind condition on sense of flight ($p = 0.0039$) and naturalness ($p = 0.0487$), but not on self-location ($p = 0.7243$) or agency ($p = 0.6160$).

Figure 2 illustrates the mean scores for sense of flight and naturalness across the wind conditions. In both measures, the velocity-adaptive wind condition consistently produced the highest ratings, indicating its superior contribution to the overall flight experience in VR.

Pairwise comparisons using two-tailed paired t-tests indicated that the velocity-adaptive condition significantly outperformed the constant condition in terms of sense of flight ($p = 0.0118$) and naturalness ($p = 0.0282$). Similarly,

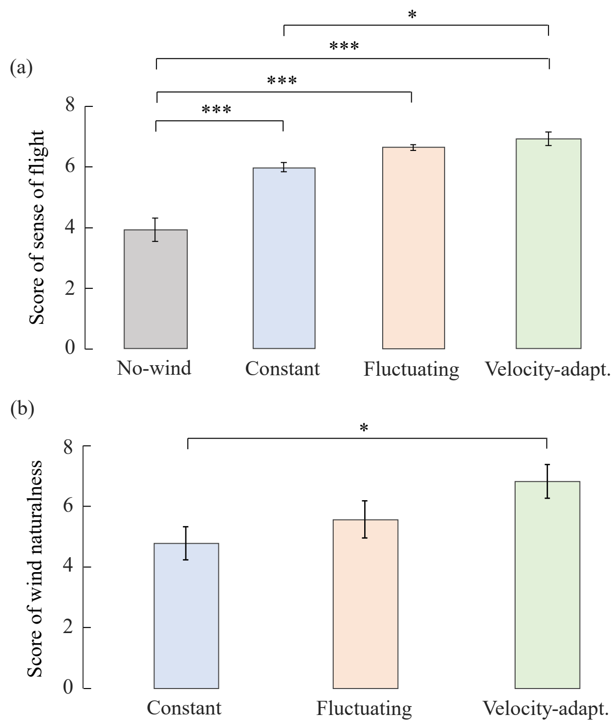

Fig. 2. Mean scores of sense of flight and wind naturalness across wind conditions. Error bars represent standard error of the mean.

fluctuating wind also led to a significantly greater sense of flight than constant wind ($p = 0.0041$). No significant differences were found between the fluctuating and velocity-adaptive conditions.

These results suggest that all wind feedback types can enhance the sense of flight, with velocity-adaptive wind consistently providing the greatest improvements in both sense of flight and wind naturalness.

IV. Discussion

This study investigated how different wind feedback strategies influence the subjective experience of virtual flight. While previous work demonstrated that wind stimuli enhance self-motion perception [2], [3], [6], our results reveal that not all wind types contribute equally to VR experiences.

Among the three wind conditions, velocity-adaptive wind consistently received the highest ratings, particularly for sense of flight and wind naturalness. This suggests that dynamic airflow synchronized with virtual motion more effectively aligns with users' proprioceptive and visual expectations, thereby enhancing realism. In contrast, although fluctuating wind may seem more natural than constant wind, it did not result in statistically significant improvements, indicating that periodic fluctuation alone may be insufficient to create a convincing flight experience.

These findings emphasize the role of temporal congruency in multisensory feedback, especially the alignment between visual and wind cues, for inducing immersive VR locomotion [2]. Our results further support this using a VR flight simulator, the Drone Rider platform, which has been previously applied in studies of embodiment and sensorimotor integration [6].

Taken together, the present study highlights the potential of velocity-adaptive wind as an effective method for enhancing flight realism in VR. Future work could explore the effects of directional wind or investigate additional ways in which wind stimuli can further improve the user experience [10].

Some limitations exist in the current study.

Although the current findings offer preliminary insights into wind feedback effects in VR, the small sample size ($N = 7$) limits the generalizability of the results. Future studies with larger and more diverse participant groups are needed to validate and expand upon these findings.

While the present study relied solely on subjective self-reports, it is important to acknowledge potential methodological biases associated with questionnaire-based assessments.

To strengthen the validity of future investigations, incorporating psychophysiological measurements—such as heart rate variability, electrodermal activity, or respiration via wearable sensors—could provide objective insights into users' immersive experiences and bodily responses to dynamic wind stimuli.

References

[1] H. Yang, K. Shimato, Y. Goto, and S. Okamoto, "Drone Rider: Wind stimulation to enhance speed perception of virtual flight," in *Joint 34th International Conference on Artificial Reality and Telexistence & the 29th Eurographics Symposium on Virtual Environment*, 2024.

[2] S. Park, S. Son, J. Kim, and G. J. Kim, "The effect of directional airflow toward vection and cybersickness," in *IEEE Conference Virtual Reality and 3D User Interfaces*, p. 839–848, IEEE, 2024.

[3] K. Murata, T. Seno, Y. Ozawa, and S. Ichihara, "Self-motion perception induced by cutaneous sensation caused by constant wind," *Psychology*, vol. 05, no. 15, p. 1777–1782, 2014.

[4] K. Shimato, Y. Goto, and S. Okamoto, "Drone Rider: Foot vibration stimuli to enhance immersion and flight sensation in VR," *Applied Sciences*, vol. 14, no. 24, p. 12019, 2024.

[5] K. Shimatoh, Y. Goto, and S. Okamoto, "Drone Rider: Enhanced feelings of flying using a vibratory and passively inclining foot plate," in *IEEE/SICE International Symposium on System Integration*, p. 1217–1218, Jan. 2024.

[6] K. Shimato, Y. Goto, and S. Okamoto, "Drone Rider: Enhancing VR flying experiences via directed wind stimuli," in *IEEE Global Conference on Consumer Electronics*, pp. 755–757, 2024.

[7] M. Rheiner, "Birdly an attempt to fly," in *ACM SIGGRAPH 2014 Emerging Technologies*, p. 3, ACM, 2014.

[8] D. Page, R. W. Lindeman, and S. Lukosch, "Identifying strategies to mitigate cybersickness in virtual reality induced by flying with an interactive travel interface," *Multimodal Technologies and Interaction*, vol. 7, no. 5, p. 47, 2023.

[9] D. Medeiros, M. Sousa, A. Raposo, and J. Jorge, "Magic Carpet: Interaction fidelity for flying in VR," *IEEE Transactions on Visualization and Computer Graphics*, vol. 26, no. 9, pp. 2793–2804, 2020.

[10] A. C. da Silveira, E. C. Rodrigues, E. B. Saleme, A. Covaci, G. Ghinea, and C. A. S. Santos, "Thermal and wind devices for multisensory human-computer interaction: an overview," *Multimedia Tools and Applications*, vol. 82, no. 22, pp. 34485–34512, 2023.