Aero-plane: A Handheld Force-Feedback Device that Renders Weight Motion Illusion on a Virtual 2D Plane

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ABSTRACT
Force feedback is said to be the next frontier in virtual reality (VR). Recently, with consumers pushing forward with untethered VR, researchers turned away from solutions based on bulky hardware (e.g., exoskeletons and robotic arms) and started exploring smaller portable or wearable devices. However, when it comes to rendering inertial forces, such as when moving a heavy object around or when interacting with objects with unique mass properties, current ungrounded force-feedback devices are unable to provide quick weight shifting sensations that can realistically simulate weight changes over 2D surfaces. In this paper we introduce *Aero-plane*, a force-feedback handheld controller based on two miniature jet-propellers that can render shifting weights of up to 14 N within 0.3 seconds. Through two user studies we: (1) characterize the users' ability to perceive and correctly recognize different motion paths on a virtual plane while using our device; and, (2) tested the level of realism and immersion of the controller when used in two VR applications (a rolling ball on a plane, and using kitchen tools of different shapes and sizes). Lastly, we present a set of applications that further explore different usage cases and alternative form-factors for our device.

Author Keywords
Weight motion illusion; force-feedback; Virtual Reality; VRcontroller

CCS Concepts
•**Human-centered computing** → **Haptic devices;** *User studies; Virtual reality;*

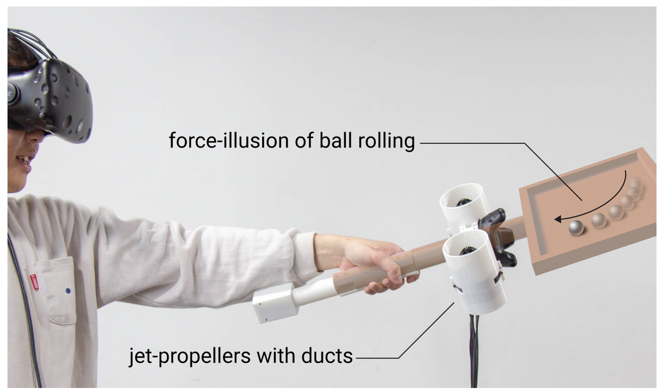

Figure 1. *Aero-plane* is a handheld device capable of emulating a shifting center of mass in 2 degrees-of-freedom by driving two jet-propellers to generate dynamic force-feedback. Here, we demonstrate our device rendering the weight of a virtual ball as it rolls on a virtual box that the user is interacting with.

INTRODUCTION
Haptic force-feedback can significantly enhance the user experience and immersion of Virtual Reality applications [31, 12, 32, 19, 8] by increasing the perceived realism of the virtual world. Recent efforts in the industry and academia have attempted integrating physical proxies that enrich the haptic experience [41, 23, 33]. At the same time, to achieve high realism, users should also be able to freely move without the constraints imposed by grounded hardware such as robotic arms [27], strings [14], or exoskeleton devices [5]. For such reasons, haptic researchers have been working on ungrounded kinesthetic devices that do not trade-off haptic realism for mobility, using techniques based on gyro effect [36], electrical muscle stimulation [18], propellers' thrust [11], weight-shifting [10, 34], transforming the shape [17], changing the center of mass [30, 40], and pneumatic systems [24].

Simulating objects of different weight and center of mass is the latest frontier in this domain. To achieve these effects, previous research employed moving physical parts that can create the illusion of objects with different mass properties. Specifically, two techniques were considered. By mechanically moving weights on a 2D surface, researchers were able to demonstrate that people can perceive *static objects* with different centers of mass, resulting in a *haptic shape illusion* [30]. Other researchers [34, 40], on the other hand, focused on creating one-dimensional *dynamic changes* of the center

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of mass, by mechanically moving a weight (e.g., on a line). However, no previous research was able to achieve dynamic changes of the center of the mass on a 2D surface to represent both the weight of different objects at hand and render changes in weight and center of mass over time. This was mainly due to the mechanical limitations of quickly moving a weight in the space. Therefore, until now, it has not been possible to create applications that, for example, recreate the motion illusion of a ball rolling on a surface.

In this paper we present Aero-Plane, a handheld haptic device that can render in real-time both the illusion of a weight dynamically moving on a virtual plane (e.g., a ball rolling on a virtual plane), and the illusion of handling different static objects with unique centers of mass (e.g., tools width different weight, shape and size). We achieve this by using only two jet-propellers, each of which can create a normal force of up to 7 N with a low latency (from 0 to 7.1 N in 0.3 seconds). By modulating the force of each propeller, our device creates the illusion of an object with a static weight on a virtual plane, and by dynamically adjusting these forces over time, it creates the illusion of a weight *moving* on the plane.

This paper presents the following contributions. We present (1) the conceptual modeling and technical design of the Aero-plane prototype, including an in-depth analysis of the jet-propellers for determining optimal design parameters; (2) a perception study to characterize user recognition of dynamic changes of mass on a virtual plane; (3) a user study with a fully developed Virtual Reality (VR) application to test the immersion and realism of our system with both continuous movements (a ball rolling on a 2D plane) and different static objects with unique centers of mass (lifting kitchen tools); (4) a set of applications that demonstrate further usage scenarios.

RELATED WORK

Our work builds upon the field of haptics, in particular to previous research in haptic force feedback devices designed to render weight or inertial forces.

Rendering weight

Rendering gravity force has numerous applications in Virtual Reality as it enables a more realistic and immersive user experience. Within the existing body of research, some work focused on developing devices that can generate real forces [14, 22, 4, 39], while the others focused on simulating the feeling of weight (haptic illusion) [7, 29, 18, 3]. Both approaches have pros and cons. For example, a device capable of generating real forces can normally provide the user with a more realistic feeling than simulation. However, the trade-off is that such devices often need to be externally grounded. As such, many of them are quite bulky and thus lack in mobility.

An example of this approach is the Virtual Catch Ball [14]. The system uses a number of motor-controlled strings to pull the user's hand downwards to simulate gravity, using a large setup that only works in a cave environment. SPIDER [22], on the other hand, is smaller even using a similar mechanical structure. The device was designed for desktop applications but still lacks mobility. Other works use robots or robotic arms to simulate gravity [4, 39], or even use other participants or passive objects to provide opposing forces [6].

Another line of work simulates the feeling of weight. One approach is to stimulate the user's skin with mechanical deformation. Grabity [7], for example, is a wearable haptic device that simulates the feeling of a gravitational force through asymmetric skin deformation using voice coil actuators. Similarly, Schorr and Okamura's finger-worn device uses skin deformation to simulate the lifting of virtual objects [29]. Another approach is to stimulate the user's muscles with electrical impulses on opposing muscles. For example, Lopes, et al. [18] used electrical muscle stimulation (EMS) to simulate the feeling of gravity while users lift or push against virtual objects. Despite these two different approaches, the resulting devices that simulate feeling a force are all relatively small.

Our work differs from these two groups by not only trying to render the weight of an object, but also by dynamically simulating changes in the object's displacement, which corresponds to perceiving the weight moving on a plane over time. In simple terms, we focus on creating a *weight motion illusion*, so that we can render an object moving on a surface. To achieve this, we attempted to combine the advantages of the different methods explained above, by proposing an ungrounded (hence mobile) controller that uses mechanical actuation to generate real (rather than simulated) forces.

Shape/Weight changing devices

In order to simulate gravity, a device has to be able to generate forces of different magnitudes and in various locations. In this way, objects of different kinds and with various mass properties (e.g., center of mass) can be correctly rendered. This is particularly important for VR applications as the type of objects to be simulated can be enormous. Within the existing research, most systems are capable of relocating the center of mass linearly in a one dimensional space [38, 40, 34, 17].

For example, the gun-shaped game controller developed by Krekhov, et al. [17] can telescope the tube of the controller to simulate the feeling of the user holding different types of guns. Shifty [40] is similar in that the device uses a linear actuator to shift a static weight along the length of a handheld cylinder. The device was developed for VR games to simulate the changes in the length or girth of a virtual object. Torque-BAR [34] has a similar mechanical structure, but the weight is actuated in an orthogonal direction to the handle of the device. The main limitation of these approaches is that they are limited to changes in one dimension.

In fact, changing the location of a static weight in a 1D space is lacking in the ability to realistically simulate virtual objects of a random shape. Transcalibur [30] was developed to overcome this challenge using two movable bars that can open and close on the VR handheld device. Each bar has a moving weight actuated by a linear actuator. This allows the device to create a haptic shape illusion of holding static objects with different 2D shapes. iTorqU [36] adds another dimension to the existing haptic feedback for VR controller by providing directional torques on the device.

The main difference of our work with this literature is that our system is capable of delivering the illusion of a continuous shift in the center of mass in a 2D space. In other words, we focus on creating a dynamic *weight motion illusion* rather than a shape illusion [30]. This allows us to simulate objects that move in a virtual plane and perceive an illusion of the force mapped to such motion. Furthermore, our system is also different in that it was designed to minimize the usage of mechanically actuated moving parts widely used in the existing work, by using only two static propellers to create the illusion of mass changes on a plane.

Force Feedback Using Propellers

Several devices have exploited drones and propellers thrusts to create ungrounded force feedback. BitDrones [9], for example, is a self-levitating display, driven by small aerial vehicles (quadcopters), each representing a 3D pixel. The user manipulates the pixels by pushing each quadcopter, the device in turn can provide a small force feedback to the user's hand. Similarly, Yamaguchi et al. [37]'s mid-air "haptic screen" is a piece of paper hung on the side of a quadcopter. The device was designed to provide mid-air haptic feedback to simulate the presence of a flying object in VR. Tactile Drones [16] are drone-driven flying objects that creates the illusion of game objects bumping into the user's body. HapticDrone [1] and HoverHaptics [2] uses a quadcopter as a kinesthetic haptic interface to simulate objects with different levels of stiffness and weight.

Thor's Hammer [11] is a handheld VR controller, which produces 3DoF force output on the user's hand using six propellers facing outward inside a cubic shaped device. Wind-Blaster [13] is a wrist-worn device using drone propellers to pull the user's wrist for VR applications. LevioPole [28] is a rod-shaped bimanual game controller, featuring a quadcopter on each end. The device was designed to provide resistance forces to simulate kayaking and weightlifting experiences, and its related study and applications does not focus on generating weight illusion for rendering changes in center of mass. Although all these devices can create forces with varying intensities, they have limited control over the perceived location of the stimuli. In comparison to the existing research in this space, our work is different in that we contribute the design and engineering of a dual-propeller system that can precisely create a continuous shift in the center of mass in a virtual 2D space around a VR handheld controller.

AERO-PLANE

Aero-plane creates the illusion of a weighted object moving on a virtual plane by modulating the speed of two propellers. As expected the higher the thrust on these propellers, the stronger the force that the user perceives. The key idea behind our design is that the user holds the device with their hand and thus the user's wrist becomes a pivot point. Thus, the user perceives the change in center of mass through the changes in torque applied to the wrist via the two propellers.

First, we describe the simpler case of creating a 1D force that simulates a shift in weight on a line. When an object of mass M moves from location l_1 to l_2, the user experiences a force change from F_1 to F_2, which is equivalent to the initial force F_1 multiplied by the ratio of change in location $F_1 \times (l_2/l_1)$. Using this simple physical principle, if one generates a force changing from F_1 to F_2, the user will experience the illusion of a mass M moving from l_1 to l_2 (Figure 2.a,b.). In fact, previous research on human perception has shown that for handheld objects, different magnitudes of torque applied to the hand causes the user to perceive objects of different lengths [15, 25, 35].

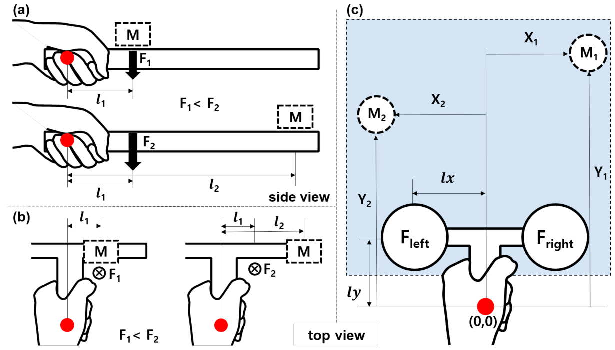

Figure 2. Our device creates the illusion of a shifting weight because (a,b) the thrust of its two propellers generates a force that pivots the device's handle around the user's wrist. Moreover, (c) by modulating the speed of these propellers, it can mimic a weight shift on two dimensional plane (as illustrated by the X,Y coordinates above).

For the 2D case, our device uses two propellers to create the illusion of an object moving on a plane. The user can perceive the weight of a mass (M) located at a position (x,y) from the hand (i.e., the center of mass of the device, indicated in Figure 2 with a red dot) through the *sum* of the forces created by the two propellers. Each propeller is represented as F_{left} and F_{right} (Figure 2.c.). In the formula below we demonstrate how we calculate the force required by each propeller, where l_x, l_y represents the location of the propellers in relation to the user's hand, F represents the weight of the virtual object, and x, y represent the location of the virtual object on the 2D plane.

$$F_{left} = \frac{F}{2} \times (\frac{y}{l_y} - \frac{x}{l_x}) \quad , \quad F_{right} = \frac{F}{2} \times (\frac{y}{l_y} + \frac{x}{l_x}) \qquad (1)$$

For example, if each propeller is located $l_x = 15cm$, $l_y = 7.5cm$ away from the center of mass of the device, and if the virtual object weighs $1.5N(M_1)$ and is currently located at $X_1 = 20cm, Y_1 = 100cm$ on the virtual plane, then each propeller needs to generate the force $F_{left} = 3N, F_{right} = 7N$ to accurately depict this. On the contrary, if the object weighs $1.2N(M_2)$ and is located at $X_2 = -20cm, Y_2 = 60cm$, then each propeller must generate $F_{left} = 4N, F_{right} = 0.8N$. The formula (1) is at the core of our control loop's implementation.

Implementation

We now provide all technical details to assist the readers in replicating our device. Aero-plane is based on two small jet-propeller engines (model *FMS 64mm*). Each of the engine is fitted with 11 EDF blades that are driven by a *KV3900* brushless motor ($\phi 28.4 \times 87.7$ mm, Weight: 100 g, Voltage: 12.5

V, Max Current: 40 A). We use the force of these propellers to generate the haptic force feedback. Each propeller can generate a force between 0.5-7 N. Detailed specifications of the propeller with the duct are described in the next section.

Mechanically, Aero-plane is composed of 3D printed custom parts made of PolyLactic Acid (PLA). Each propeller is housed in a 72 mm diameter × 110 mm height duct with walls of 2.5 mm thickness, located 7.5 cm laterally and 15 cm longitudinally from the center of mass of the device. The weight of the two propellers and connecting parts is 400 g, and 500 g when combined with a VIVE tracker for positional tracking. We set the center of mass of the device in the middle of the handle by attaching cantilevering metal weights onto the other end of the device. The total weight of the device including tracker and counterbalancing weight is 1069 grams. As expected, the weight of the device is directly proportional to the choice of force actuator; in the *Limitations* section we discuss alternative configurations that trade-off haptic performance with weight.

Aero-plane controls the motors using a set of Electronic Speed Controller (ESC) boards (model *ESC, HOBBYWING FlyFun*, rated at 40A), which are controlled via Pulse-Width Modulation (PWM) with an Arduino microcontroller. The PWM signal has a minimum and maximum value of 1.25 ms to 2 ms and a frequency of 50 Hz (20 ms cycle). The device communicates to VR applications via serial commands, either by USB or Bluetooth. The entire device is powered by a Lithium polymer battery (5000 mAh, 11.1 V, 40 C, 3S1P). Finally, the software used for the measurements and for the perception studies was written in Java, while the applications used for the immersion/realism study were developed using Unity3D.

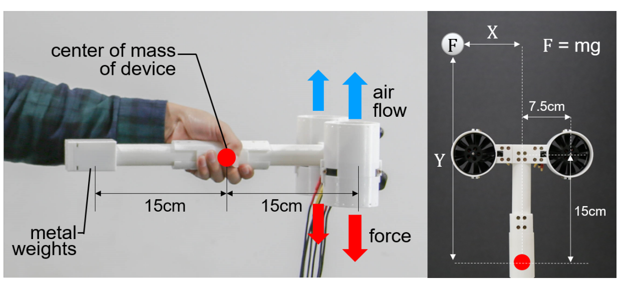

Figure 3. Side and top views with dimensions of our device. User holds the device at its center-of-mass, while the jet-propellers flow air upwards, which in turn creates a downward force (depicted by the red arrows).

TECHNICAL EVALUATION OF JET-PROPELLERS

We conducted a technical evaluation of our prototype to learn about its capabilities and limitations. We were particularly interested in answering four technical questions: (1) what is the minimum force it can reliably produce?; (2) conversely, what is its maximum force?; (3) what is the latency of our device, from propellers off to an actual impulse?; and, lastly, (4) characterize the relationship between the force (in N) and the speed of the propeller's motors (PWM output of the motor drivers). The next sections attempt to answer these questions and better inform the design of the system.

System Identification of the Rotor Actuator

No rotor actuator can produce forces with infinitely high speed and perfect accuracy. Rather, the inherent dynamics of an actuator cause the target force to be transmitted to the user in a distorted fashion. Studies of force actuation in existing VR systems have mainly reported average and standard deviations of forces generated after a step input command and after enough time has passed for the actuator to reach a steady state (e.g., [11]). However, the interactions in a typical VR application can be so fast that the system cannot wait until the actuator reaches the steady state (e.g., a user can move against a target in just 300-500 ms).

In order to ensure our device can actuate quickly and reliably we attempted to characterize its dynamics. We did so by giving a known input to the actuator and observing the forces that arise from it (this standard process is denoted as *system identification* in mechanical engineering). Then, by collecting output sample points (actuator's response) to simple input functions (e.g., a step function) we obtained a general function that can predict the output of the actuator for any other possible inputs (also know as *transfer function*).

Experimental Analysis and Results

To understand the dynamics of our device, we built a testing apparatus, which is depicted in Figure 4. As shown, we fixed the actuator at the center of our measuring cage, which was custom-made from aluminum profiles. Then, we triggered our device by driving the propeller with increasing PWM pulse width. As a result, the propeller creates a pulling force in the upward direction, and pulls on the force sensor (model *VARIENSE-FSE103*) that is attached to the bottom of the cage and connected to the actuator via a steel wire.

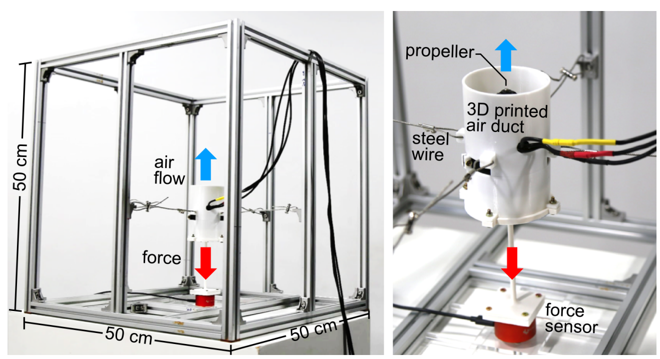

Figure 4. Our measurement setup (left). Close-up of how the propeller pulls on the force sensor (right).

Using this a apparatus, we measured the pull force via the force sensor (sampled at 250 Hz) as depicted in Figure 5. As described above, our rotor produces minimum force at a pulse width of 1.25 ms and maximum force at 2 ms pulse width. In this range, we increased the magnitude of the step input signal by 28 steps at equal intervals, input it into the rotor, and recorded the values measured from the force sensor at each step. This resulted in a total of 28 *step responses* for the rotor system, shown in Figure 6.

Each step response contained also the noise from the force sensor. We removed this noise by means of low pass filter

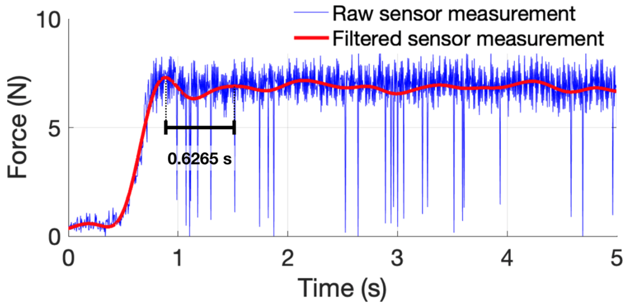

Figure 5. Raw and filtered sensor measurements

with a half power frequency at 5 Hz (Butterworth type zero-phase filtering). Each step response was then analyzed using the *stepinfo* function provided by MATLAB. This function calculates the rise time, settling time, maximum settling force, and minimum settling force for a given step response — in short, it gives us a characteristic behaviour of our actuator for each input point.

The actuator we used required an average rise time of 823.6 ms (SD=1.317 ms), i.e., from fully off to an impulse. This was because the response of the rotor was drastically slowed when rendering a small force of less than 1 N (below the fifth PWM step). The average rise time of the rotor was 338 ms (SD=137 ms) in case of generating a force of more than 1 N; these larger forces are the typical use case for force feedback devices. Also for each PWM value, the minimum and maximum of the settling force (minimum and maximum force once the response has risen) from the sensor are shown in the Figure 6. On average, the force generated from the actuator fluctuates in the range of 0.8837 N (SD=0.3009 N for 28 step responses). It can be also seen that the force output from the input voltages exhibits a strong linear relationship (R^2=0.96 for minimum and maximum settling force); this is ideal as it simplifies controlling our device in interactive cases.

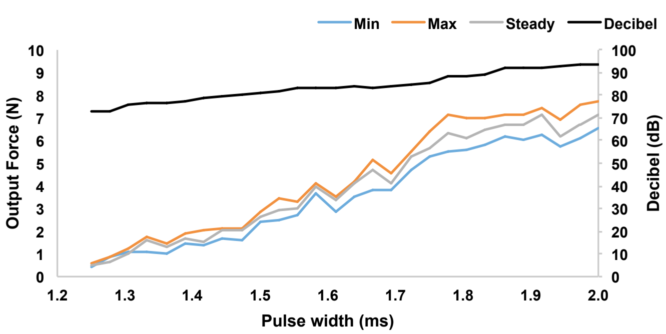

Figure 6. Measured output force (N) and noise level (dB) as we drove our device with increasingly longer pulse widths (ms).

Characterizing our actuator's behavior

To gain deeper insight into our actuator design, we attempted to characterize its physical behavior. This ultimately helped provide a more fine-grained control of its haptic output capabilities. We started by characterizing its transfer function, i.e., model its force output based on the input parameters.

Modelling the transfer function

We approximated the transfer function of our actuator in the form of a spring-mass-damper system (a second order system), which is the simplest model to describe such a typical actuator. The dynamics of a second order system can be determined from its step response. Basically, the damping ratio and the natural frequency of the system should be obtained from the step response. Furthermore, one must add its inherent latency, which as previously described we measured it to be around 300 ms (see Figure 8).

First, the ratio of the maximum overshoot of force exerted by the actuator to the steady state force was obtained (% OS). The mean value obtained for the 10 step response trials in which overshoot was clearly observed was 4.7%. From this, the damping ratio (denoted as ζ) was found to be 0.697, which we obtained using the following equation:

$$\zeta = \frac{-ln(\%OS/100)}{\sqrt{\pi^2 + ln^2(\%OS/100)}} \quad (2)$$

Furthermore, we also obtained the natural frequency (ω_n) of the system from observing the fluctuation in the filtered sensor data; this is useful to better understand the haptic noise that the user will also feel while using our system. Figure 8 shows that the damped natural frequency (denoted as ω_d) of the actuator system is approximately 1.5962 Hz (=1/0.6265, or 10.03 in rad/s); this is relevant because it tells us that such a device produces some inherent haptic noise, which the user might feel. Using the following equation we also obtained the natural frequency of the system, which is 2.23 Hz (14 rad/s).

$$\omega_n = \frac{\omega_d}{\sqrt{1-\zeta^2}} \quad (3)$$

Now, armed with the damping ratio and natural frequency, we can express our device's transfer function (denoted as $H(s)$, and expressed in the Laplace domain):

$$H(s) = \frac{\omega_n^2}{s^2 + 2\omega_n \zeta s + \omega_n^2} \quad (4)$$

Then, we used the identified transfer function to simulate how the system will behave for any given input (thus accelerating our experimentations drastically). Figure 7 shows the the block diagram we constructed in *Simulink*. Using this model we simulated the force output of the propellers by inputting a sine function at various frequencies. The delay of the system was set to 300 ms. As a result, the actuator was able to adequately represent the motion with a frequency of about 1 Hz. We observed in the model that, at higher frequencies, a force of the desired magnitude cannot be generated or an excessively large phase difference occurs.

In summary, each of our jet-propellers are capable of exerting a linear force between 0.5 N and 7.1 N, the average rise time of the rotors is 0.3 seconds for conditions over 1 N up to 7.1 N. Also, we can see that our actuator cannot implement feedback of repeated cycles above 1 Hz. Taking into consideration the maximum force output of each propeller, the length of the

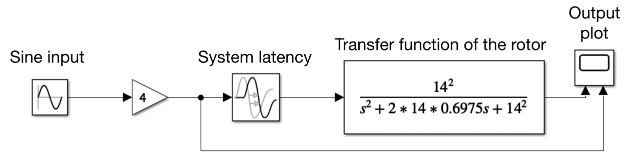

Figure 7. Simulink setup

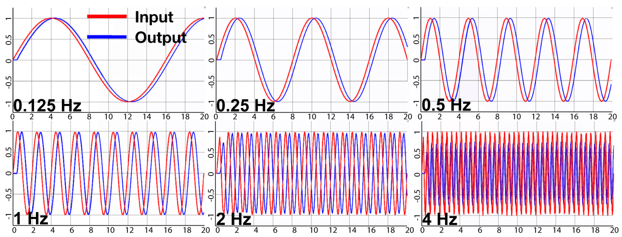

Figure 8. Simulation result of system reaction

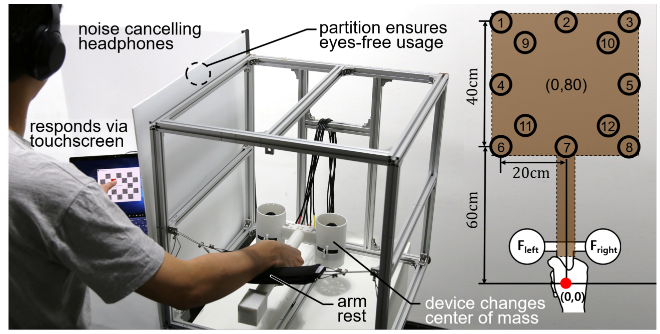

Figure 9. Setup for our user study: participants sat down, without visual contact with the device, and felt the pulling force of the device on their dominant hand. Then, participants used a touchscreen with their non-dominant hand to indicate the perceived weight movement.

virtual handle (0.6 m) and the ratio of the virtual plane (square), the relationship between the weight of the virtual object and the dimensions of the plane are exemplified in Table 1.

We finally investigated the amount of auditory noise, power consumption and vibration generated from the jet-propeller when providing haptic feedback. As done by Thor's Hammer [11], we measured the noise using a decibel meter (TES-1350A) at a distance of 1 meter from the jet propeller. As the force increases, the magnitude of the noise increases, and the maximum magnitude is 93.5 dB at 7.1 N and 83.4 dB at 4 N (Figure 6). In comparison, Thor's Hammer [11] has a maximum noise of 80.7 dB when using 4 N. Lastly, the power consumption for each propeller spinning at maximum speed of 43,290 RPM (7N) is 208.2W, while vibrations amounted to 43 microns (displacement).

PERCEPTION STUDY: MOVEMENTS ON PLANE

User perception of weight shifting and changes of the center of mass have been studied for one-dimensional movements and discrete transformations of objects' shape and structure [40, 34]. Currently, there are no reported studies on the performance of people recognizing continuous weight shifts on a plane and dynamic changes of mass through kinesthetic illusion. Because these two topics are interrelated, in this study we focused on understanding the user perception performance when recognizing *continuous* weight movements *on a plane* through haptic illusion — meaning there are no mechanically moving parts to mimic the weight displacement. Specifically, we considered 16 different one-directional movements on a virtual 2D plane with 8 locations (as in Figure 9). We hypothesized that users can distinguish both the relative motion as well as the absolute location of the starting and ending points.

Weight(N)	Size of Plane (cm)	Min Force (N)	Max Force (N)
1.2	58 x 58	0.16	6.72
1.5	40 x 40	0.8	7
1.8	28 x 28	1.92	6.96
2.1	20 x 20	2.8	7

Table 1. Relationship between perceived weight and plane dimension in force range

Material and Experimental Design

Based on the results of the technical evaluation, we designed a 40cm x 40cm virtual-plane ($L_x = L_y = 40cm$), with the center located at coordinates (x=0, y=80 cm) from the reference point (i.e., the device's center of mass). Eight points are located around the edge. For example, point 7 is placed at the virtual location (0 cm, 60 cm) on the plane, 4 at (-20 cm, 80 cm), and 3 at (20 cm , 100 cm). We then designed 8 symmetrical motion paths of length ($L = 40cm$) as in Figure 10. Paths along the diagonals (hypotenuse) are shortened to match the legs' length. Because we wanted to distinguish between back and forth directions, we considered a total of 16 motions across the plane. Motions on the plane correspond to shifting a mass of 120 grams ($F = 1.2N$ as in [40]) along these paths, at a speed of 16.6 cm/s (i.e., 0.06 second/cm), which is the maximum resolution obtained from Figure 9. Hence, all motion paths take 2.4 seconds, and the forces exerted by each propeller are within the range $0.8N \leq F_{x/y} \leq 5.6N$.

Figure 9 shows the apparatus used for the study. Participants sat down and grabbed the Aero-plane controller with their dominant hand, while placing their wrist on an arm-rest. A divider screen prevented participants from establishing visual contact with the device. To completely cancel out any sound that could inadvertently give away cues, participants wore both earplugs and noise-canceling headphones that emit white noise [20]. During the study, participants felt the force feedback with their dominant hand, while they used their non-dominant hand to make input selections on a touchscreen — e.g., pressing buttons on a GUI indicating the location and direction of the perceived weight motion.

We recruited ten participants (2 female), aged 23-33 years old (M: 26.3, SD: 2.79), who are currently students in our institution. Participants were compensated for their time with 10 USD in local currency.

After debriefing on the experiment, the participants freely experienced movements along the 16 paths as long as they wanted, followed by the experiment testing all 16 motion paths in random order repeated for six blocks, for a total of 96 trials. The first 2 blocks were considered as training and deleted from the analysis. Each trial started with the system placing the object on the virtual-plane in one of the 8 predefined points (e.g., the jet-propellers were set to exert a force mapped to the target point). Then after 2000 ms, the object moved across the path ($40cm \times 16.7cm/s = 2400ms$), and finally was removed/lifted by shutting down the jet-propellers (2000 ms to full stop). A complete trial took 6.4 seconds. Only after the end of a trial does the graphical interface prompt for input from the user. During the experiment, participants took a mandatory two-minute break every 16 trials but they were also able to stretch their wrists at any time. The experiment took approximately one hour to complete per participant. In total, we collected 16 motion paths $\times$ 4 blocks $\times$ 10 participants $= 640$ data points.

Results and findings

For the sake of the analysis, we distinguish between the 16 motion paths as described above, and the 8 *relative directions* (Figure 10 - right) that describe motions with the same direction and orientation regardless of their origin and ending points. For example, the paths between the points pairs 1→6, 2→8 and 3→9 all correspond to the same vertical motion a→e from top to bottom displayed in green in Figure 10. The relative directions are computed by summing the values (e.g., errors) of the corresponding three absolute motions. While paths describe absolute motions (i.e., the user needs to distinguish both the motion and the pair of *origin→end* points), the *relative directions* only require users to discern among the directional motions, regardless of their absolute location on the plane.

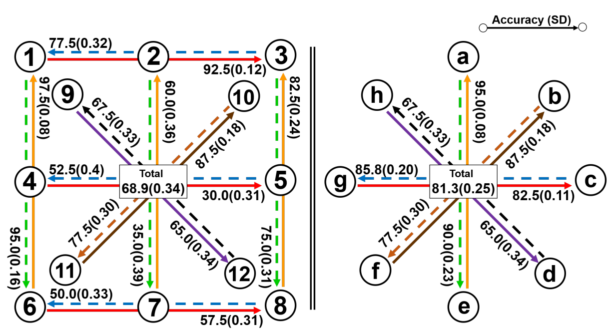

Figure 10. Accuracy % and standard deviations for the 16 motion paths (left), and the 8 relative directions (right). Same directions are represented by the same colors.

16 motion paths \ response	1-3	4-5	6-8	3-1	5-4	8-6	1-6	2-7	3-8	6-1	7-2	8-3	9-12	12-9	10-11	11-10
1 - 3	37		1													2
4 - 5	6	12	8					1	0		1	1	1			10
6 - 8	4	8	23									1	1			3
3 - 1				31	3		1							1	4	
5 - 4				5	21	8								2	4	
8 - 6				1	14	20								3	2	
1 - 6							38			2						
2 - 7						1	1	14	19		5					
3 - 8								6	30			4				
6 - 1										39	1					
7 - 2						1	1			1	24	12		1		
8 - 3									3		4	33				
9 - 12	6	2	5										26			1
12 - 9				6	3	1								27	3	
10-11				4	5										31	
11-10	2	1	1									1				35

Figure 11. The confusion matrix of 16 motion paths. Same directions are represented by the same colors, as in Figure 10.

Figure 10 presents that mean accuracy and standard deviation of sixteen absolute (left) and relative (right) motions. Results were analyzed using one-way ANOVA tests followed by Bonferroni correction post-hoc analysis with $\alpha = 0.05$. We found statistical differences for accuracy across the sixteen motions paths ($F_{(15,144)} = 4.81, p < 0.001, \eta_p^2 = 0.33$), but no statistical difference was found across relative directions ($F_{(7,72)} = 1.967, p = 0.071, \eta_p^2 = 0.16$). The post-hoc comparisons revealed differences between the path 4→5 and the paths 1→3, 1→6, 6→1, 8→3 and 11→10 ($p < 0.05$). Furthermore, 2→7 was found different than 1→3, 1→6, 6→1 and 11→10 ($p < 0.05$).

In a post-hoc interview, participants also gave us qualitative feedback about their experience. All participants responded that, while it was challenging to discern the exact starting and ending location of the motion, they could easily perceive directions and distinguish them. P3, P4, P8, P10 further explained that the left-to-right horizontal motions (e.g., 1→3, 4→5, 6→8) were among the most difficult, while P3, P5, P6, P7, P10 found difficult to distinguish vertical motions (e.g., 1→6, 2→7, 3→9). It is not surprising that people could better distinguish relative motions than absolute positions, very similar to how *haptic shape illusion* can be created by alliterating mass properties of the object without using the actual shape of the targeted object [30].

However, in our experiment we also found that despite difficulties in distinguishing between absolute locations, users can approximately distinguish the distance of the object, adding to the overall realism of the experience. For example, P2 stated that, "it was very fun because I could feel the movement of a virtual object", and P5 remarked that the task "felt like handling an actual ball because I could feel a big change in force". Nevertheless, some users (P4, P7, P10) reported difficulties in discerning motions that were close to each other, such as, for example, 4→5 was easily confused with either 1→3 or 6→8. A further analysis of the data revealed that 51.5% of the errors involved selecting a motion path with the same direction, parallel and immediately close to the correct target, like in the 4→5 vs. 1→3 / 6→8 case.

To summarize, based on the results of our statistical analysis and subjective interviews, we conclude that users could successfully perceive a *weight illusion* of an object moving on a plane. All eight relative directions are equally well recognized with 81.3% (e.g., no statistical difference among directions). Furthermore, users could also roughly distinguish between the location of the object on the plane (e.g., *near vs far*), provided that individual locations are far enough away from each other. Left-to-right motions were more difficult to distinguish, and we hypothesize that this might be related to the uneven twisting capabilities of the wrist in the two directions, and the fact that all but one participants were right-handed. We did not anticipate this issue and did not balance the study for hand dominance — future work might be needed to investigate whether accuracy of motion patterns detection is correlated with hand dominance.

USER STUDY: REALISM AND IMMERSION

We performed a second study to understand the user's perception of realism and immersion when combining the haptic motion illusion with a visual feedback such as in a virtual reality application (Figure 12 - left). We developed two different applications in Unity3D, to exploit dynamic change of mass that creates both the illusion of a moving object (like in the perception study) and the illusion of holding different objects with different physical properties (different weight, length, and center of mass), conceptually similar to the *haptic shape illusion* [30], but achieved through active feedback rather than passive feedback.

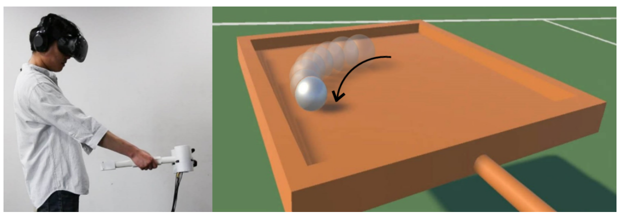

Figure 12. Ball VR application: User shown holding the device and wearing a HMD (left), user point-of-view within application (right).

The first application consists of a metal ball freely rolling in any direction on a wooden board, a setup reminiscent of that in the perception study (Figure 12). Participants were encouraged to roll the ball across the plane in paths of different shape and length. They could also quickly lift the plane resulting in the ball bouncing (implemented as a rapid absence of force, followed by the force of the ball regaining contact with the board).

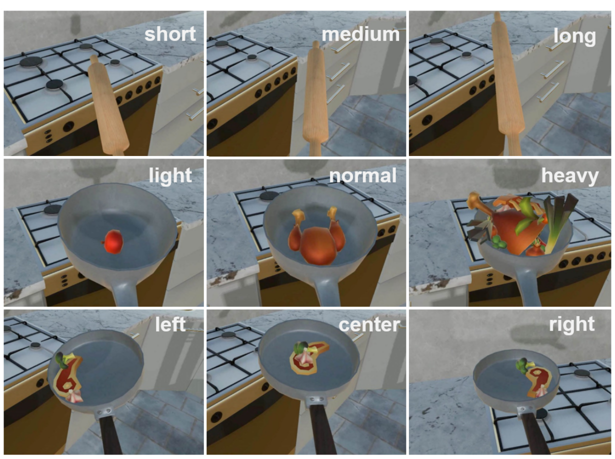

Figure 13. Kitchen VR application: Different haptic feedback is given to the user corresponding to the currently held utensil's length, weight, and center of mass.

The second application exploits the realism of objects with different weights and physical characteristics, similar to [40, 30]. The user experiences holding different cooking utensils (such as frying pans, pots, and a rolling bar) with different lengths, weights, amount of food, and locations of the food (Figure 13). Users can switch utensils by clicking a controller button using the non-dominant hand, and the new kitchen utensil is visually displayed and the haptic feedback immediately updated. Participants could also freely experience the different kitchen tools during the tasks.

Participants experienced the two applications with and without haptic feedback, following a within-subjects design balanced for the visual/haptic conditions. The visual-only condition served as a baseline indicator. We recruited 16 participants (6 female), aged 23-38 (M: 26.8, SD: 3.69), eight of which with prior experience using virtual reality applications. In each application, the users held the Aero-plane device in their dominant hand, while wearing a VIVE head-mounted display and a pair of noise cancelling headphones playing background music. Participants were asked to experience the two applications in two modalities (only visual, haptic+visual) for a duration between 5 to 7 minutes. After each condition, participants self-assessed the level of immersion and realism of the experience (as did Lopes, et al. [18] and Zenner, et al.[40]) by completing a questionnaire with 7-points scale Likert questions. The questionnaire also included questions about the impact of the noise from the propellers on the user experience (is the noise audible? is it disturbing or ruining the immersion?) as well as application-specific questions about the realism of the motion on the longitudinal/latitudinal axes or the rendering of different objects properties (length, weight, location of object on the plane). The experiment concluded with a post-hoc interview. The experiment took about 40 minutes to complete and participants received 10 USD for their time.

Results

The subjective ratings for immersion and realism in the four conditions are displayed in Figure 14.

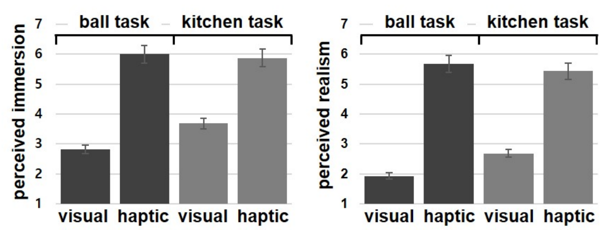

Figure 14. Participants' perceived immersion and perceived realism in both VR tasks (ball and kitchen) for visual-only and visual with haptics condition. We found that our device improves both metrics. The error-bar represents a 95% of confidence interval.

The results were analyzed using the Friedman test followed by post-hoc pairwise analysis with Wilcoxon signed-rank tests. There are statistically significant differences between visual and visual+haptic modalities in both tasks, for both immersion($X^2(2) = 32.473, p < 0.001$) and realism ($X^2(2) = 34.448, p < 0.001$). Post-hocs analysis reveals that the visual+haptic condition was significantly better than the visual-only condition across the two applications for both immersion (ball application: $Z = -3.53, p < 0.001$, kitchen application: $Z = -3.320, p = 0.001$) and realism (ball: $Z = -3.422, p = 0.001$, kitchen: $Z = -3.195, p = 0.001$).

The results from the questionnaire further characterize these results. Participants reported their perceived level of realism (in terms of haptic-visual synchronization) via a 7-point Likert scale (M: 5.31 SD: 1.138), the realism of the ball moving longitudinally (M: 5.38, SD: 1.408) and of the ball moving latitudinally (M: 6.13, SD: 0.806). Similar questions were asked about the kitchen applications. Participants reported the perceived level of visual-haptic compliance (M:6.06 SD:0.771), and the realism of objects with different length (M: 5.38, SD: 1.408), width (M:4.0, SD 0.478), weight (M:6.69, SD: 1.825) and of different positions of the weight on the plane (e.g., different food locations in the pot) (M:6.18, SD:1.328). Finally, participants responded to the perceived noise and distraction level. Participants stated that they heard the noise of the propellers (ball; M:4.44, SD: 1.788, kitchen; M:4.13, SD:1.893), but that it was not distracting or reducing the immersion of the overall experience (ball; M:3.19, SD: 1.47, kitchen; M:3.06, SD:2.143).

Participants' qualitative feedback

At the end of the study tasks, we asked to the participants to provide a feedback regarding their experience. All participants pointed out that they felt immersed and enjoyed engaging with the VR applications using Aero-plane. For instance, P9 stated "There is a large difference between with and without haptics.", similarly P4 stated "When there is only visual without haptics, I feel less immersed"; and P1 said, "It was impressive to receive different haptic feedback depending on the item in the virtual environment.". Several participants, such as P7, P9, P12, added that "It was really fun!".

When asked to provide details on what they liked about the haptic feedback, most participants provided explanations that involved precisely the change of the center of mass. For instance, P13 stated; "I liked the directionality [as the ball rolls]"; similarly, P6 stated; "It was good to be able to feel the movement of the ball as it freely rolls"; P11 stated "I liked that I could feel the weight of this [virtual] ball."; P7 added "The experience in the kitchen was exciting and [the haptic] feedback was appropriate."; P11 added that the "Kitchen was very real"; and lastly, P10 stated that "[I felt the] changes in the location of the steak, and even the amount of meat, it felt realistic!".

When asked which application they preferred, all but one participant preferred the kitchen application. P2 said, "At first, it was awkward because I do not have prior experience of rolling the ball in such a large plate." P1, P15; "When I first feel the force, I felt the ball was heavier than I expected." P11; "The ball moved slower than I wanted." P14; "Kitchen application was mapped well." P12; "In the kitchen, I expected it to be heavy, and I can feel it. It was great!" P1; "It was very realistic that the position of the food in the frying pan changed and the amount changed." P8 who preferred the ball application said, "In the ball application, the continuous haptic change was really awesome!"

Lastly, participants also mentioned possible improvements and suggestions. Seven participants added that when they feel the wind on their face, the immersion was temporarily reduced. Participants also commented that they initially expected the weight of the device to pose problems but it matched well with the virtual scenes; P11 stated,"I expected the device's weight to be a problem, but with the visuals, I perceived this as the racket's weight and was well matched", similarly P5 stated, "I expected the weight of the original frying pan when I lifted it up, the weight of the device felt natural!". Also, four participants indicated that it would have been great to be able to experience the feedback of mixing the food ingredients of the pot filled with food.

DISCUSSION

Aero-plane is the first example of an ungrounded handheld haptic controller that can generate the illusion of a weight moving on a virtual plane (*weight motion illusion*), as well as simulate static objects with different center of mass (*haptic shape illusion*). By directly comparing Aero-plane with prior work, we can further highlight the strengths of our work. Aero-plane, like Thor's hammer and WindBlaster [11, 13], uses propellers to generate a force-feedback on a single hand. Our system exerts a total force of 14 N (7.1 N per propeller), while Thor's hammer deliver a maximum force of 4 N, and WindBlaster of 1.5 N. Furthermore, Aero-plane can render moving weights both faster ($16.7cm/s$ vs the $13cm/s$ of Shifty [40]) and on a larger area ($40 \times 40cm^2$ area vs $48cm$ one-dimensional length of TorqueBar [34]). Finally, our paper is also the first work that present a quantitative analysis of the user's perception of motion in 2D using both absolute and relative motion stimuli.

There are two main findings from our studies. First, from the perception study, it is clear that relative motions can be more easily distinguished than motions between absolute locations on the virtual plane. This is not surprising and echos qualitative results from previous work [30]. However, it is also possible for users to distinguish specific locations, assuming that these locations are not too close. Second, numerical accuracy becomes less relevant when combining the haptic with visual stimuli. All participants reported a high level of realism for both the moving ball and kitchen applications, highlighting the fact that measurement about haptic-visual compliance (e.g., realism, immersion, disturbance, latency) better reflects the real system capabilities.

Based on these results, we developed applications for Virtual and Augmented Reality involving both *weight motion* and static rendering of different center of mass. To fully explore the potential of the idea, we also designed controller attachments with different form factors to expand Aero-plane's original handle design. These applications are discussed next.

APPLICATIONS

Taking advantage of Aero-plane's ungrounded form factor, continuous and dynamic force feedback, and ability to simulate different weights, we developed more examples of scenarios and applications in which our device can be effective. The applications partly reflect the contributions of some related works [11, 34, 30, 17] while showcasing Aero-plane's strengths and competitive advantages.

Shooting Range

We have explored the potential of Aero-plane for simulating different weights and shapes of VR objects. Additionally, considering that our propellers have a short response time, quick bursts of force feedback can be applied dynamically to render the effect of sudden shifts in mass within a simulated object in VR. Furthermore, by actuating the two propellers separately

Figure 15. Gun VR application: User shown holding the device with a gun handle shaped attachment and wearing a HMD (top left). Different haptic feedback is given to the user corresponding to the length of the gun, and muzzle rise feedback is given while the trigger is pressed.

in succession, Aero-plane can generate a quick series of successive feedback, taking only half of the response time of a single propeller. Figure 15 depicts how Aero-plane delivers fast force-feedback at the example of a virtual shooting range scenario. Here, Aero-plane is not only able to simulate the changing weights of the different guns, but also can generate quick bursts of strong feedback to create the illusion of muzzle rise in the user's hands of slow or rapid firing speeds. For this application we 3D printed a simple handle that can be attached to the original Aero-plane and can be held using two hands, mimicking a gun's grip.

Figure 16. Flight control application & Fishing application: Device is attached to a small display running an airplane game, giving the user tilt feedback corresponding to the game (left). User shown holding the device with a fishing rod handle shaped attachment and wearing a HMD (middle). User's point-of-view within the fishing application (right).

Flight Control
Our Aero-plane prototype is a non-grounded haptic device that can generate tilting feedback around its longitudinal axis by changing the force between propellers. In Figure 16(left), we demonstrate this feature by attaching Aero-plane to an existing display (e.g., a tablet) that is running a simple flight simulator game. As a result, Aero-plane enhances the flight simulator game with force feedback. In this game, the tilt of the handles is mapped to and represents the orientation of the airplane's wings. By tilting the handles, the user can control the left and right movements of the airplane to dodge incoming obstacles. A tilting torque is generated by the propellers that serves as haptic feedback for the user and is mapped to the roll axis of the airplane on the screen.

Fishing
Aero-plane can effectively render continuous and dynamic force feedback. Using this feedback actively, the device can provide directional cues to the user simulating the movement properties of an object in motion in VR. In the fishing scenario, depicted in Figure 16 (right), the user holding the fishing pole feels directional pull of a fish on the end of the fishing line as well as the pull toward/away from the user.

CONCLUSIONS, LIMITATIONS AND FUTURE WORK
In this paper we introduced Aero-plane, a propeller-based force feedback handheld controller that can render the haptic motion illusion of an object moving on a plane. To find the optimal design parameter for our design, we conducted a technical evaluation, followed by two users studies to characterize how well users can perceive motions on a plane, and how realistic and immersive are the applications that make use of it. Specifically, in the first user study we found that users can successfully perceive directional movements of a 120 g object on a virtual plane with an average accuracy of 81%. From the second study, we learned that VR graphical applications can strongly benefit from compliant haptic force feedback of dynamic changes of mass, with both realism and immersion rated significantly better than in the non-haptic conditions. Finally, we presented a set of applications that demonstrate further ways to apply Aero-plane to VR and AR.

This work also has some limitations and possible means of improvement. The main issue raised in the experiments' interviews is related with the overall weight of the device. Currently the device weights about 1 Kg, but this figure can be largely reduced by trading-off force for weight. For example, by simply substituting the jet-propellers with two lighter ones (ADF50-300L PLUS, 56g) capable of generating a total force of 5.2 N, we can reduce the overall device weight down to 476 g. Wind and noise from the propellers were both reported to decrease immersion. Wind could be avoided by using gimbals that keep the propellers facing earth, or by better shielding the ducts. Noise is a more serious problem and it is shared across other similar propeller-based devices [13, 11]. However, surprisingly, the users of our applications in the second study reported that noise minimally impacted their experience. Future work will focus on better hardware design for noise reduction [21], though it is currently outside the scope of this paper. Additionally, although not mentioned by the participants, the latency may have influenced the perception of realism and immersion [26] and future work will need to verify this possibility. Lastly, we received several suggestions from users pointing to a device that could render changes of center of the mass in three dimensions: for example, the users commented that it would be interesting if they could feel the feedback of soup stirred in a pot. Future work will attempt to add a third dimension to the system.

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