DroneHaptics: Encountered-Type Haptic Interface Using Dome-Shaped Drone for 3-DoF Force Feedback

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***Abstract*— This paper introduces a dome shaped haptic drone that generates controllable 3D force feedback as an end-effector. To this end, a hemispherical cage using an aluminum mesh is attached to the drone. The proposed structure of the cage significantly improves the usability of drones in providing 3D force feedback while ensuring the safety of the users. In a set of experiments, the output force of the drone in six directions (upward, downward, forward, backward, right, left) in response to the thrust of the drone is measured. Then, the force-thrust relationship was mathematically formulated, which allows us to render accurate force feedback in an arbitrary direction. The force rendering accuracy of the system was evaluated by measuring errors between the force command and the actual force output in random locations. The force error rate was less than 8.6 %, which ensures that the system can generate perceptually accurate enough force feedback.**

I. Introduction

Haptic interaction enables us to feel the virtual environment via simulated physical signals generated from haptic devices [1]. These devices can be categorized as either grounded or ungrounded. Grounded haptic devices are physically tethered to the environment, providing a fixed point of reference for haptic interaction [2], [3]. Such devices can generate stable and precise haptic feedback, however, the workspace is usually limited to their mechanical design and size. On the other hand, ungrounded haptic devices are generally wearable in nature and use the user's body as reaction support [4]. Ungrounded haptic devices allow users to move freely to interact with the virtual environment. While having freedom of movement, these devices (e.g. haptic gloves [5], handheld controllers [6]) remain in constant contact with the user's body which can cause discomfort or even pain if worn for a longer period. In addition, they provide a limited range of motion with relative force among body parts. The problems mentioned have a negative impact on the device's usability, leading to a limitation in the adoption and implementation of haptic technology on a larger scale.

One possible solution to overcome these limitations is to use encountered-type haptic devices (ETHDs) which are subsets of haptic devices. Oftentimes, these device tracks the user and provides haptic feedback on need bases [7], [8]. In the past few years, the advancements in drone technology have attracted the haptic community to employ them as mechanical actuators in ETHDs. To this end, researchers employed drones with custom-made end-effectors attached to provide tactile and kinesthetic haptic feedback [9],[10], [11]. This concept offers numerous benefits. First, they are not tethered to any fixed surface providing users with large work volumes. Second, they are significant in providing encountered-type feedback by tracking the user's hand and drone position, providing perfect transparency and high usability [9]. Third, drones can generate considerably large and controllable forces [12].

Drone-based ETHDs are relatively new and have mainly been introduced in two kinds of applications. One is for tactile stimulation where the user experiences various touch feedback such as the object's shape and texture [9], [13]. Besides, they are also used as a force-reflecting device to generate kinesthetic feedback by pushing/pulling the user's hand [11], [12]. This study focuses on the latter. Recently, in [12] and [14], we provide a method to generate controllable force in the vertical direction by formulating the relationship between the drone's thrust command and generated forces produced in contrast to them. The system was still immature since the force can be rendered only toward the vertical direction in order to reduce the complexity of the rendering algorithm as a proof-of-concept study. Another system we introduced in [11] tried to render force in the horizontal direction by vertically attaching a flat surface to the drone. The airflow produced by the propellers was used to generate a fixed force (0.118 N). However, the system still could not generate force in any arbitrary direction.

The current study is a continuation of prior work [11] and [12] where we tried to generate force in full 3 degrees of freedom. Our previous prototypes were intended to generate force through a protruding end-effector attached to the body of the drone. This structure inherently generates undesired force, torque, and movement at the end-effector during a lateral movement or a lateral thrust since lateral motion requires tilting of the drone body. Precise control of the position of the drone in accordance with the tilting can be a solution, but this is not feasible since it needs a very complex calculation of kinematics and very precise control of the drone.

To address the above limitations in earlier studies, this study introduces a new hemispherical structure/interface as an end-effector for the drone-based mechanical actuator. Unlike protruding flat interfaces, this dome/hemispherical-shaped structure can naturally provide controllable force feedback in multiple directions without complex kinematics calculation as they are relatively less prone to the tilt of the drone. Nonetheless, this hemispherical shape is also significant in mapping coordinates for accurate control and

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can easily be mapped using two angles such as latitude and longitude. This makes it easier to create algorithms for precisely controlling the haptic feedback provided by the actuator(i.e., drone). This study aims to provide a complete framework to render controllable 3D force using a single drone. To this end, we first performed a set of experiments to record generated force concerning the drone's speed command in multiple directions (i.e., upward, downward, forward, backward, left, and right). In the later step, polynomial models were created for each direction's speed-force data. Lastly, an algorithm to generate desired force in an arbitrary direction using latitude and longitude angles is created from a hovering drone. This algorithm is evaluated and showed significant force rendering accuracy.

This paper is organized as follows. First, we discuss the design of the proposed Dome-shaped cage in Sect. II. The details of force measurement experiments and the illustration of collected data are provided in Sect. III. In Sect. IV methodology of producing force in any arbitrary direction is discussed in detail. The evaluation of the proposed system can be seen in Sect. V. Lastly, Sect. VI concludes this paper.

Fig. 1. Proposed Dome-shaped Haptic Drone (DSHD). A Haptic interface for 3DOF kinesthetic haptic feedback.

II. Dome Shaped Haptic Drone (DSHD)

Fig. 1, dome shaped haptic drone (DSHD) is designed to provide accurate force feedback in an arbitrary direction. Fig. 2 illustrates the interaction scenario of a human hand with our proposed drone design. Fig. 2(a). and (b) demonstrate force feedback along the vertical and lateral directions, respectively. The longitudinal angle controls the vertical force feedback, while the latitudinal angle controls the lateral force feedback. Fig. 2(c) represents the force feedback in any arbitrary direction, which can be achieved by tuning both longitudinal and latitudinal angles simultaneously (more details in section IV). From Fig. 2. it can be observed that the dome-shaped structure is relatively less prone to tilt when generating desired force in lateral and arbitrary directions than flat interfaces [11], [12]. It is also beneficial in strengthening the structure of the proposed 3D interface as hemispherical shapes can evenly distribute the pressure across their surface. Moreover, the DSHD is significant in formulating kinematics concerning user interaction points while touching an object in VR environments with reduced complexity.

In our prototype, we used the Parrot AR Drone 2.0 quadcopter which is used by several researchers in agriculture, mapping, and haptics-related applications [7]. This quadcopter is a lightweight programmable drone that communicates to a PC through WIFI with its embedded DHDC server. A hemispherical shape cage also plays the role of a safety shield for the users not to be harmed by the rotors as shown in figure 1. An aluminum mesh sheet of 0.6 mm thickness is used to give this cage our desired hemispherical or dome-shaped geometry. The meshes of aluminum sheet are Rhombus in shape with 20 mm and 10 mm diagonal lengths. Moreover, in order to make this cage robust we sewed these meshes with 1.5 mm aluminum wire at the top and in the middle. The measured total weight of the designed cage is 170 grams along with Parrot AR Drone indoor hull.

III. Force Measurement Experiment

The drone's ability to generate force in various directions is influenced by its input parameters such as amount of thrust required to produce certain roll, pitch and yaw movements. The integration of proposed dome-shaped structure changes the overall weight of the drone, which in turn affects the correlation between the drone's input parameters and output force in its default state. The employed Parrot AR Drone 2.0 is programmable which enables us to measure the output force by varying its input parameters. Below we describe the experimental setup which was used to measure the output force from proposed DSHD. Later, the results of these experiments and the developed relationships between the input parameters in contrast to the generated force are discussed in detail.

A. Experimental Setup

To determine the output force, we utilized a digital push-pull force gauge, specifically the Wenzhou SF20. This gauge has a force-sensing resolution of 0.01 N. A stand was used to hold the force gauge and its position was pre-calibrated with the direction of the interaction. A lightweight 3D-printed contact plate was attached to the force gauge sensor to ensure consistent contact between the drone and the force gauge sensor during measurement. The size of the plate was 5 cm^2. We used a string to attack the drone's contact point with a force gauge sensor to measure the downward force as it was convenient to measure this force by pulling mechanism in our design. The force in all other directions was measured by the push mechanism.

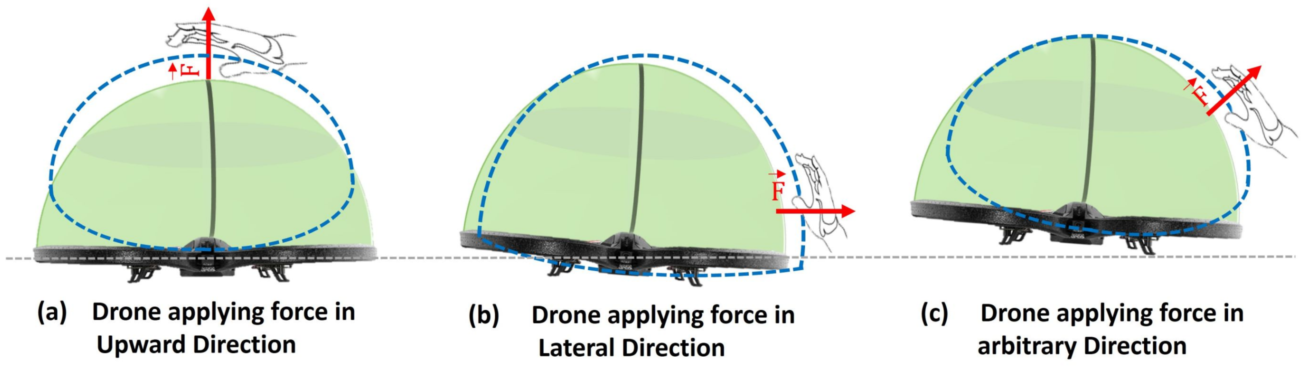

Fig. 2. Illustration of the DSHD generating kinesthetic feedback by pushing the user's hand in the desired direction where the dotted shape shows the drone trajectory to produce force in the desired direction. (a) Applying force in the upward direction by moving the drone in an up direction. (b) The drone is applying force in the lateral direction. (c) Force in an arbitrary direction while moving it in the up and lateral direction.

B. Force Measurement

The programmable Parrot AR Drone comes with its own Software Development Kit (SDK). This SDK provides four normalized movement commands ranging from -1 to +1. These four movement commands are up/down thrust (Vertical), forward/backward thrust (pitch), left/ right thrust (roll), and azimuthal rotation (yaw). During the measurement experiment, we moved the drone in six directions i.e., up/down, forward/backward, and, left/right. We did not consider azimuth/yaw movement as it was not required in our scenario. For our experiments, we employed drones as a black box with these normalized commands as input and their respective measured forces as output. In order to measure force in all six directions we used values from -1 to 1 with an increment of 0.075. The measurement of force in the forward/backward direction was carried out within the range of -0.825 to +0.825, as the drone becomes unstable beyond this limit. However, for the other four directions, the force was measured between -0.9 to 0.9, as the drone remained stable within this range. The force reading was recorded after the drone remained in contact with the force sensor for at least 2 seconds. This time limit was set to ensure a stable contact point for collecting force data. For each data sample, we took 10 measurements and then averaged the response and stored the force data for each sample.

C. Results

The experimental results of measured forces are presented in figure 3. The maximum stable force that our prototype can generate in six directions can be observed in table I, where the negative sign denotes the direction. It can be seen that the maximum forces in the corresponding opposite direction are similar in lateral directions, whereas the maximum force in the downward direction is higher than upward due to the gravity component. Furthermore, we selected a polynomial curve fitting to model the force-thrust relationships, given its suitability for our data's patterns. As can be seen in Fig. 3, the patterns are not excessively complex, and the third-order polynomial offered a suitable balance between simplicity and accuracy. Our analysis demonstrated that the third-order polynomial was appropriate for most force-thrust combinations, leading us to adopt it consistently across all cases.

Mathematically, third order polynomial equation can be represented as follows:

$$T_i = A_i F^3 + B_i F^2 + C_i F + D_i \tag{1}$$

Where F is the desired force and T represents the thrust to render the desired force. i represents the direction in which particular thrust T is required to render desired force F. A, B, C, and, D are the coefficient of the polynomial model (see Table II).

TABLE I
THE MAXIMUM VALUE RECORDED IN EACH DIRECTION ALONG WITH THE MAXIMUM AND MINIMUM CONTROLLABLE THRUST COMMAND VALUES.

Direction	min_thrust	max_thrust	Max_Force
Up	0.15	0.9	1.57
Down	-0.15	-0.9	-2.82
Forward	0.15	0.825	2.3
Backward	-0.15	-0.825	-2.39
right	0.15	0.9	2.19
left	-0.15	-0.9	-2.16

TABLE II
THE POLYNOMIAL COEFFICIENTS AND THEIR RESPECTIVE R^2 VALUES FOR THE RECORDED FORCES IN SIX DIFFERENT DIRECTIONS.

Direction (i)	A	B	C	D	r2
Up	0.825	-1.929	1.77	-0.3271	0.9971
Down	0.0043	-0.082	-0.00472	-0.134	0.9947
Forward	0.0181	0.0057	0.214	0.0015	0.9959
Backward	0.0295	0.0223	0.2016	-0.087	0.9948
right	0.005	0.1445	0.0497	0.058	0.9906
left	0.024	-0.0595	0.1542	-0.04	0.9965

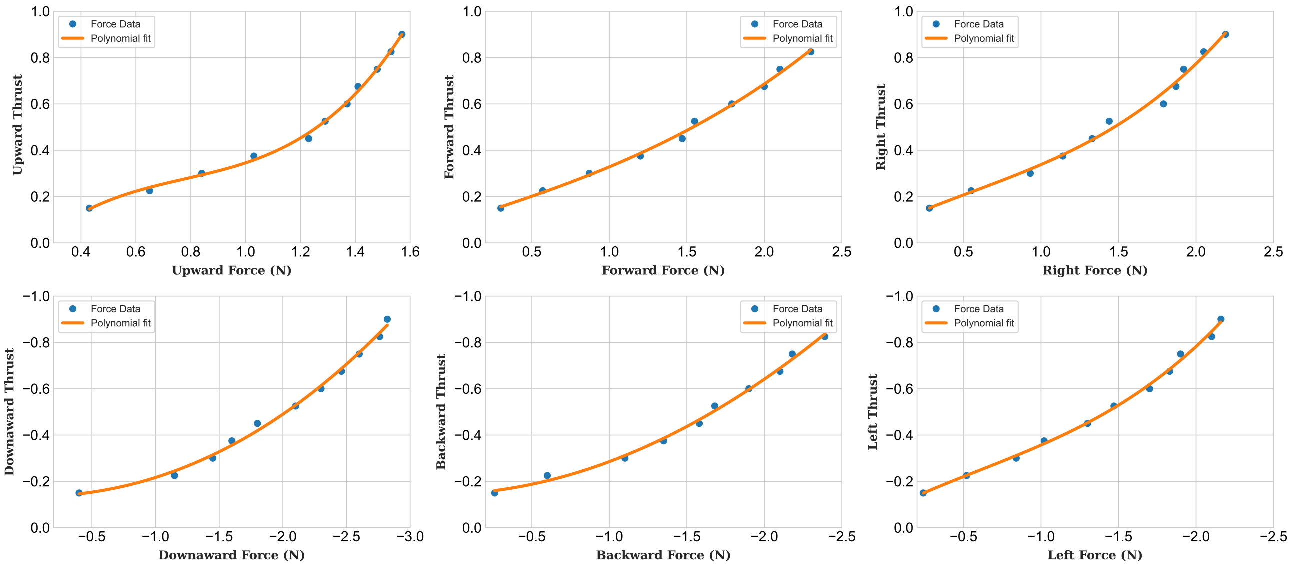

Fig. 3. The results of recorded force in upward, downward, forward, backward, left, and right directions. These forces are recorded while giving the thrust command as input to the drone ranges between (-1 to +1) for each axis pair (e.g., 0 to +1 for upward while 0 to -1 for downward control). Polynomial curve fitting is used to establish a relationship between the drone's thrust and generated force feedback which we used

IV. Force Feedback in any arbitrary direction

We derived equation 1 to establish a relationship between the desired force and the drone's thrust. To apply force in any arbitrary direction, it is necessary to comprehend the geometrical features of the drone's movement in 3D space. We have illustrated this concept in Figure 4 where the geometrical representation of a scenario where force is applied in an arbitrary direction is shown.

In fig 4(a), point O shows the origin/current location of the drone, and point P is an arbitrary point in the 3D space where we want to render our desired force F. $\vec{F}$ is the force vector which shows the amount of force needed to be rendered. In our 3D space, the force vector $\vec{F}$ has its three components i.e. $F_{up/down}, F_{forward/backward}, F_{right/left}$. These force vector components are required to be computed before we plug them into equation 1 to calculate the amount of thrust needed for each axis to reach an arbitrary point P from the origin O. Figure 4(b) explains the methodology to decompose $\vec{F}$ into the three axis-aligned vector components in the 3D space. The point P lies in a 3D space, and its projection can be observed between the backward-right section of our drone's horizontal surface. The projected vector $\vec{OA}$ creates an azimuth angle (latitudinal) α with respect to the origin. In addition, the point P is present above the horizontal plane, which creates an elevation angle (longitudinal) β with respect to the plane.

By using force vector $\vec{F}$, α, and, β, we can calculate force vector components. Equation 2, 3, and, 4 shows the mathematical form for the computation of three vector components in 3D space.

$$F_{up/down} = |F| \cdot \cos(\beta) \tag{2}$$

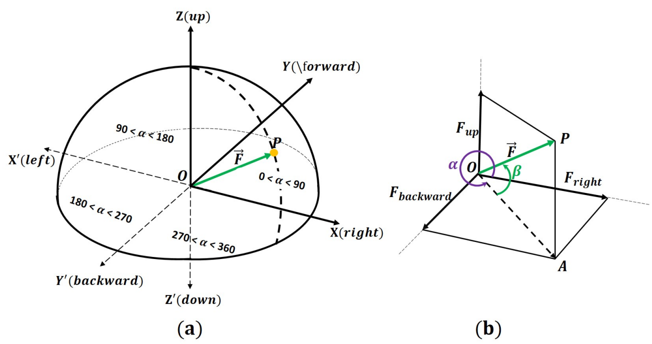

Fig. 4. Geometrical illustration of force decomposition using azimuthal and elevation angle to generate force in an arbitrary direction.

$$F_{forward/backward} = |F| \cdot \cos(\beta) \cdot \cos(\alpha) \tag{3}$$

$$F_{righ/left} = |F| \cdot \cos(\beta) \cdot \sin(\alpha) \tag{4}$$

Each vector component gives us the amount of force required to exert along the axis in 3D space. Once we calculate three vector components, we can use equation 1 that gives the amount of thrust required to push DSHD from point O to point P. Hence, making DSHD capable of navigating in any arbitrary location in 3D space.

V. Evaluation

The established mathematical relationship in the previous section provides force feedback in 3D space. Equation 2, 3, and, 4 calculate the force feedback needed to render along each axis. In order to evaluate the performance of DSHD, a force measurement experiment is conducted. The experimental setup used for evaluation was the same as

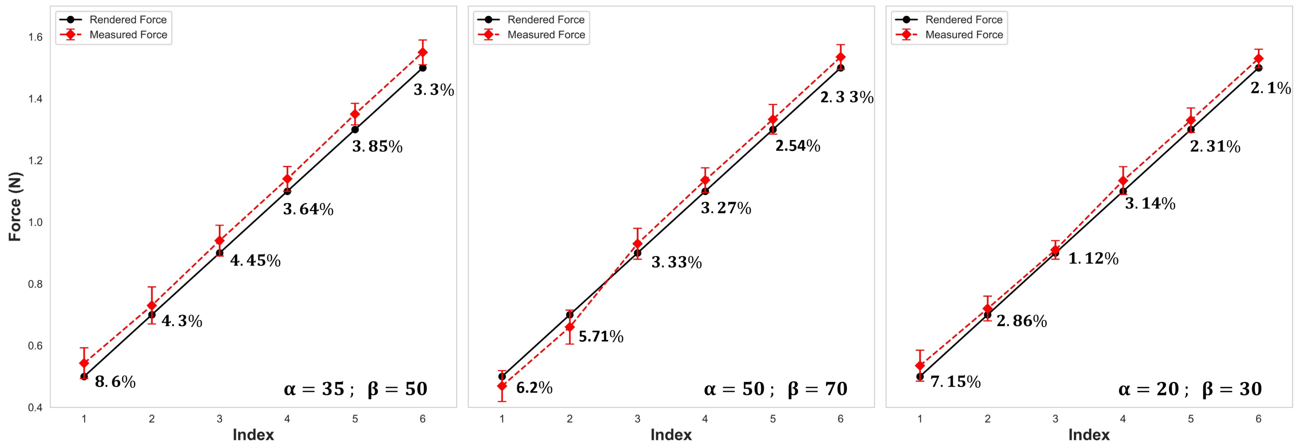

Fig. 5. The comparison between rendered and measured force in three arbitrary directions. The forces were rendered between 0.5N and 1.5N with 0.2N increments in these directions. Percentage error for a mean of recorded values at each instance is also reported.

explained in III, however, the force measurement was done in arbitrary directions in this experiment instead of navigating the drone only along the axes of the 3D coordinate system.

A. *Force measurement procedure*

The DSHD can be navigated by varying the values of α and β in 3D space. α controls the lateral movement in four directions and β is responsible for the upward/downward movement. For evaluation, we choose three arbitrary values of α and β in pairs (i.e. $\alpha = 35$, $\beta = 50$; $\alpha = 50$, $\beta = 70$ and $\alpha = 20$, $\beta = 30$) to move drone in three different directions. The contact point on the drone's mesh was identified according to the mentioned α and β pairs, and the contact plate was attached to that point on the cage. The force gauge, Wenzhou SF20, was also positioned with respect to the α and β pair so that the contact between the plate and force gauge sensor can occur successfully In each direction, we navigate the drone to render a specific force and the force output was measured with the force gauge. The rendered force ranged between 0.5N to 1.5N with an increment of 0.2N at each trial. During force measurement, a total of 10 readings were recorded and the mean force was calculated for each trial.

B. *Results and discussion*

The results of the force measurement experiment are depicted in figure 5. The comparison between the desired force and the measured force is shown in this figure. There is a slight discrepancy between the desired and measured forces at each trial, however, it is observed that the error decreases as the thrust increases. The maximum error in the system is 8.6 %, while the minimum error is 1.12 %. It is worth noting that the maximum error observed in the system is below the just noticeable difference (JND) of human force perception, which is approximately 10 % [15], [16].

In section III, the drone was pushed towards the force gauge in all directions except the downward direction, where the pulling mechanism was used instead. The results showed that the drone provides a consistent push force in the lateral direction, but the upward/downward force was not as consistent due to the influence of gravity. To evaluate the performance of the drone, the experiment was conducted in the forward-right direction ($0 < \alpha < 90$) as it was observed that the drone provides a consistent output force in the corresponding opposite directions in the lateral region. On the other hand, as the evaluation was based on the push mechanism, the drone was moved in an upward direction ($0 < \beta < 90$).

The overall results of the evaluation show that the DSHD can provide force feedback in any arbitrary direction, which can greatly enhance the realism of various applications in virtual reality (VR) environments. For example, the ability to render volumetric shapes with a constant output force can greatly improve the user experience.

C. *Limitations and Future Work*

While the proposed DSHD shows promising results in force feedback accuracy, there are still some limitations and areas for improvement that need to be addressed. One concern arises from using fewer aluminum hard wires to secure the spherical aluminum mesh cage structure and at the same time its robustness. Due to weight constraints, it is challenging to cover the entire mesh with these wires. As a result, when attempting to generate force feedback, the aluminum mesh cage may experience damping, which negatively affects the accuracy of force feedback. Future research could explore alternative mesh cage materials or enhance the drone's design to effectively deliver force feedback, potentially using lighter and more rigid materials. Another limitation is the short operation time of 12 minutes. This could be addressed by incorporating an inductive charging mechanism, which would allow for continuous operation during extended use without needing to replace the drone. Additionally, the noise produced by the DSHD is a concern. While noise-canceling headphones can help, more permanent solutions should be explored, such as adding dampers to the rotor joints or using quieter mechanical parts to reduce drone noise. Moreover, in the future, we would like to develop customized VR applications and conduct user studies to better understand the effectiveness of the proposed approach in different situations and identify areas that need more refinement or improvement. By tackling these limitations and focusing on improvements, the DSHD performance can be greatly enhanced, making it more suitable for various applications.

VI. Conclusion

The main objective of this work was to provide an end-to-end framework capable of generating a 3DOF kinesthetic haptic feedback using a single drone. To achieve our goal, a dome-shaped structure is designed for the drone to ensure efficient and accurate calculation of force and high usability as a safe-to-touch haptic interface. Second, relationships between the drone's API speed commands and the generated force are developed through experiments. Lastly, a rendering algorithm is introduced to employ these relationships to generate force in the desired direction with the required magnitude. As a proof of concept, quantitative evaluation is performed by recording generating force in an arbitrary direction. The results show the maximum error between required and generated force is 8.6%, which is below the just noticeable difference (JND) of human perception. Consequently, this approach shows potential for enhancing haptic rendering in VR environments, fostering more immersive experiences in areas such as gaming and education.

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