

Force-Feedback Through Touch-based Interactions With A Nanocopter

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Abstract—The choice of haptic rendering tools plays a pivotal role in the perception of the simulated kinesthetic feedback. This paper introduces a novel approach using Crazyflie-based quadcopters as haptic rendering devices to simulate virtual stiffness. By designing a specialized cage and implementing control using Crazyswarm and both centralized and decentralized localization techniques, we implemented the smallest drone-based direct-touch encounter-type haptic feedback device. We evaluated three different proportional control levels, with each level simulating a different stiffness based on a distance-to-thrust response. We conducted a user study, which revealed that even with only 21 grams of the force output range, participants could distinguish between the proportional levels, perceiving higher proportional levels as increased stiffness. We also identified distinct vibration characteristics between cages made of different 3D printing materials. Our findings suggest that quadcopters can be effectively used as haptic tools, offering a controllable kinesthetic feedback system.

I. INTRODUCTION

Haptic rendering has become indispensable in fields such as virtual reality, robotics, and teleoperation. By simulating kinesthetic sensations, richer user experiences can be created for various applications. Force-feedback haptic devices can broadly be categorized into grounded devices, body-grounded devices and wearables, and encounter-type devices. The drone-based approach in this paper falls into the category of encounter-type haptic feedback because it provides feedback only when contacted by the user. While effective, traditional haptic devices often have limitations in mobility and dynamic feedback capabilities [1], [2], [3]. This has spurred interest into alternative platforms capable of delivering nuanced and more versatile haptic feedback. Quadcopters have emerged as a potential solution due to their agility and adaptability, and success at providing a stable response in z-directional stiffness rendering [4].

In the rapidly evolving field of robotics, physical human-drone interaction (HDI) has emerged as a pivotal area of research, offering a myriad of applications ranging from appropriate virtual objects [5], [6], [7], to rendering virtual stiffness [4], [7]. Physical human-drone interaction can be categorized by the display methods: interaction requiring a head-mounted display (HMD) [5], [4], [6] or interaction that is self-illuminated [8], [7]. For VR-incorporated systems, VRHapticDrones [5] implemented the presence of a virtual object using a drone installed with different shaped cages, the system by Abtahi et al. [6] rendered texture and grab-and-pull interactions, and HapticDrone [4] simulated virtual stiffness and weights for virtual objects. For self-illuminated

systems, GridDrone [8] and BitDrone [7] demonstrated using swarms of drones installed with LED to render 3D objects.

One previous project [4] has looked at using a medium-sized drone for stiffness rendering and perception, but did not conduct a formal study to evaluate how users perceive different stiffness levels. Other projects [8], [6] discussed how small drones could be used to render a resisting force, but did not present an evaluation on user's perception of these forces. To the best of our knowledge, this paper presents the first user study evaluating the perception of stiffness using small drones. The study in [4] on force perception used a Parrot AR drone, which is 4.47 times larger and 19 times heavier than the one used in our implementation. The disparity in force capability that results from this size difference makes stiffness rendering and perception significantly more challenging with the Crazyflie nanocopter used in this work.

This paper presents a novel approach to haptic rendering using Crazyflie-based quadcopters to simulate virtual stiffness using the smallest drone platform that has been used for direct touch interaction (size: 12.4cm × 12.4cm × 4.0cm). We hypothesize that these quadcopters, when housed within a specially designed cage and paired with advanced tracking and control systems, can provide compelling haptic feedback. We investigate how different control parameters can yield perceivable variations in virtual stiffness. Additionally, we compare the vibration characteristics of two cage materials, carbon fiber PLA (PLA-CF) and PETG, to discern their influence on the interaction.

The **contributions** of this paper are:

- 1) A technical evaluation of a centralized and a decentralized localization technique for haptic interactions. Obtained results show that the centralized technique is more stable for haptic user interactions. Section IV.
- 2) A user study of vertical haptic rendering, demonstrating that participants are able to distinguish between the proportional stiffness levels with 21 grams of force exerted by a Crazyflie quadcopter. Section V.
- 3) A 3D printed cage design that ensures user safety while minimizing the amount of unwanted vibration felt by the user. Section II-B.
- 4) A analysis of the system's force output with data collected from a user study, showing that we can render stiffness between 0.6 grams/cm and 1.2 grams/cm. Section IV-A.
- 5) An open-source control framework for using Crazyflie available to the scientific community ¹.

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¹See the code at <https://github.com/HaRVI-Lab/TouchSwarm.git>

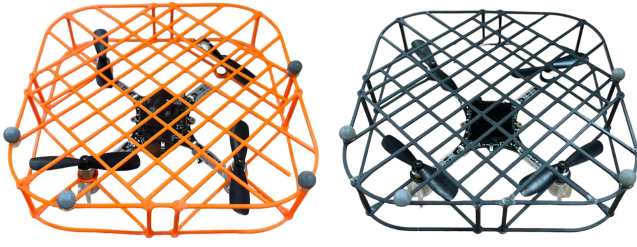


Fig. 1: Left: Orange PETG Cage. Right: PLA-CF Cage

II. HARDWARE DESIGN

A. Crazyflie 2.1

The foundation of our haptic rendering system is anchored on the Crazyflie 2.1 quadcopter. This drone, with dimensions of 92mm x 92mm x 29mm, is not only compact but also packed with features ideal for our study. Its 45mm propellers can generate an instantaneous thrust of up to 60g, providing power for its lightweight frame. Crazyflie 2.1 maintains an approximate flight time of 7 minutes on a full charge. An addition to our setup is the integration of Vicon markers on each drone. In conjunction with our ground station and the Vicon tracking system, this enables us to monitor with precision the drone's position in real-time.

Our choice of the Crazyflie 2.1 was influenced by several of its inherent attributes. The drone's lightweight design ensures user safety. Even if there was accidental contact, the drone's propellers are unlikely to cause harm given their small size and the device's overall weight. Its control mechanisms allow for precise position-based maneuvers, which are key for delivering consistent and nuanced haptic feedback. Another advantage is reduced noise levels courtesy of its petite motors and propellers, ensuring that users experience the haptic feedback with minimal auditory distractions.

B. Cage Design

Previous cages for enabling human-drone touch interaction and hand-made using mesh [7], [6], [5], which not only requires careful fabrication skills, is also difficult to ensure safety as the mesh is often only a thin layer. Our haptic rendering setup employs a specialized 3D-printed cage designed to house the Crazyflie 2.1 quadcopter. The cage, with dimensions of 124mm x 124mm x 20mm, is structured in three distinct layers. Top Cage features a meshed surface, providing a kinesthetic interface for the user. The mesh design, with a spacing of 10mm, ensures that users can interact with the haptic feedback without coming into direct contact with the drone. Bottom Cage integrates with the Crazyflie's four motor mounts, ensuring a snug fit and optimal stability. Twelve connector pins bridge the top and bottom layers, fortifying the cage's structure.

To determine the optimal mesh size for the top of the cage that would prevent direct user-drone contact while ensuring haptic feedback, we analyzed several fingerprint sizes, the average of which was observed to be 1.7cm x 2.5cm. We used a mesh size smaller than this average to ensure safety.

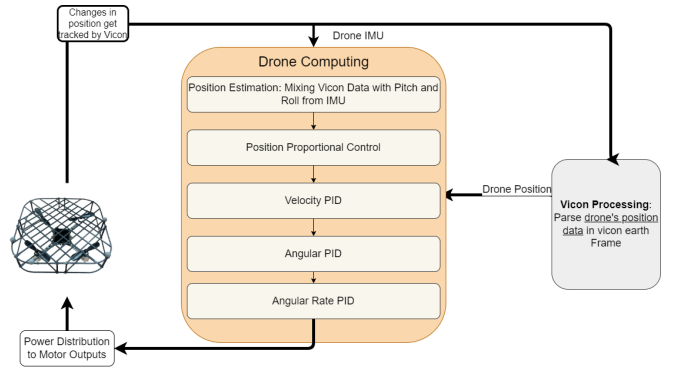


Fig. 2: TouchDrone's system Architecture

To maintain a lightweight cage, the width of the cage's bars is restricted to 1.2mm. However, the thin width of the cage also caused our initial cage designs to break during unexpected crashes. Our design iterations were based on the parts broken during the crashed flights since certain corners and connections are more likely to take the impact during a crash than others. Reinforcements were made by adding additional supports to make the cage stronger for such flights. We created six iterations to find the ideal number of supports for the top of the cage, culminating in a design with 11 and 7 lines intersecting the top plane, creating a 10mm spacing.

Additional strength is achieved by gluing the connection joints, ensuring durability without compromising on weight. Weight is crucial in cage design, since gravity is often the largest force that a drone must overcome, and any weight added to the drone reduces the overall maximum force that the drone can output to the user. We explored a range of commonly used drone materials, predominantly those based on carbon fiber. While carbon fiber PLA is renowned for its strength-to-weight ratio, we observed excessive vibrations, due to harmonic resonance with the drone body. This realization prompted us to pivot towards the softer PETG material capable of damping these vibrations. The finalized cage designs 3D printed in both materials are shown in Fig. 1.

III. SYSTEM IMPLEMENTATION

A. Control Architecture

The system's control architecture is intricately designed as a hierarchical cascaded proportional controller (Fig. 2).

An extended Kalman filter (EKF) integrates data from both the Vicon external tracking system and the onboard gyroscopes. The Vicon system offers high-precision position tracking, while the onboard gyros capture real-time angular rate measurements. The fusion of these data sources within the state estimation ensures that the control loops receive accurate and timely information about the drone's current state, forming the basis for responsive control. High-Level Commander (HLC) dispatches desired position set-points to the proportional position controller, providing a reference for the drone's intended spatial orientation and movements. The proportional Position Controller processes the desired set-points, converting them into specific velocities using velocity

PID controller. Then the commands are output to pitch and roll angles, which are relayed to the attitude PID controller. Attitude PID Controller outputs desired angle rates, which are subsequently processed by the angle rate controller. Angle Rate Controller refines the desired angle rates, and maps the output to the power distribution.

This structured control mechanism, combined with robust state estimation, guarantees that the Crazyflie drone operates with excellent precision and consistency [9], making it appropriate for advanced applications like haptic rendering.

B. Localization Techniques

A localization system is essential to our touch-based interaction model. When a user interacts with the drone through touch, causing a disturbance, it is crucial for the drone to quantify this disturbance so that it can counteract the disturbance by exerting a proportional force. This force determination depends on the desired stiffness to be rendered and the disturbance magnitude. We explored three localization techniques compatible with the Crazyflie ecosystem:

a) *Vicon Motion Capture Cameras*: Vicon operates as an absolute localization system, utilizing a network of infrared cameras. Its mechanism revolves around detecting and tracking the position and orientation of drones based on distinct patterns, each containing four markers. Notably, Vicon boasts millimeter-level precision in its tracking capability. However, one limitation of using this localization method is the possibility of occlusion if the user stands between the drone and the cameras. Additionally, this method requires expensive infrastructure.

b) *Flow Deck*: The Flow Deck (V2, Bitcraze, \$50) is a commercially-available extension for Crazyflies. It has an optical flow sensor and a laser distance sensor. The former measures the drone's lateral movements in the x-y plane, while the latter measures the altitude. Since the optical flow sensor relies on visual data, the floor patterns and the drone's height impact its performance.

c) *Z-Ranger Deck*: Z-Ranger (Bitcraze, \$15) is similar to the Flow Deck without the optical flow sensor. Therefore, it only improves the drone's estimation of its height. A lack of an optical flow sensor causes the Crazyflie to drift.

C. Stiffness Rendering

In the context of haptics, stiffness denotes a system's resistance to deformation. In our quadcopter setup, stiffness is represented as a force opposing a user's touch, realized mainly through the drone's thrust. Traditionally, a drone's position is controlled using a PID position controller. The controller's proportional gain K_p value is instrumental in modulating this response by determining the quadcopter's response to the disturbance applied by the user. During initial testing, we found that the integral K_I term in the controller caused instabilities in the system due to wind-up errors since users applied a constant disturbance preventing the drone from returning to its set-point location. Therefore, we have set $K_I = 0$ in all controllers to remove this instability. The derivative D term can provide optional damping in the

system. For these tests, we set $K_d = 0$. Therefore, our haptic rendering controller follows a simple proportional feedback controller similar to standard haptic stiffness rendering models where the surface is represented as a virtual spring. By adjusting K_p , we alter the slope of the position-to-force function of the quadcopter. A higher K_p value translates to a steeper slope, meaning that for a given positional deviation (e.g., a user's push), the drone will exert a larger opposing force, which is perceived as a higher stiffness by the user. Conversely, a lower K_p value results in a gentler slope, rendering a softer or more compliant interaction.

In this work, we are focusing on rendering forces separately in the vertical and lateral directions, and thus are using separate proportional position controllers for the XY and Z directions. For Z direction rendering, we are changing the K_{pZ} term, while for the XY plane, corresponding changes should be made to K_{pX} and K_{pY} . We conducted several rounds of testing for stability using different K_{pZ} values, finding that a K_{pZ} between 1.25 to 3.5 would keep the system stable. We also found that Z ranger deck and the flowdeck have less stability during touching, leading us to use only Vicon tracking for our user study. We decided to use three different K_p values, 1.25 representing the softest stiffness, 2.5 (default) representing the middle stiffness, and 3.5 being the hardest stiffness. The largest gain of 3.5 and lowest gain of 1.25 were chosen based on a pilot experiment, which determined this to be the largest and smallest gain without the drone losing stability during vertical interaction. The middle gain of 2.5 is the default for our drone's K_{pZ} gain, which was selected as a baseline as a reference.

After accounting for the combined weight of itself and the cage, the Crazyflie drone has approximately 21 grams of available thrust. This thrust reserve is crucial for haptic rendering because it sets a limit on the range of forces that the drone can generate in order to simulate various stiffness levels. The more available thrust, the greater the potential force that the drone can exert in response to a user's touch, and hence, the broader the range of stiffness it can simulate. Since the Crazyflie only has 21 grams of available thrust, it is essential to recognize the limitations of this system. If a user exerts a force that demands a thrust beyond the drone's capabilities, the proportional controller reaches saturation. In such cases, the drone will utilize its maximum available thrust to counteract the force. This results in a consistent upward force, regardless of the incremental force exerted by the user. In other words, once the proportional control is saturated, the drone renders its maximum perceivable force.

Understanding these nuances allows for more informed design decisions, ensuring that the quadcopter-based haptic system provides consistent, reliable, and perceivable stiffness feedback to the user. We provide a technical evaluation of the performance of the drone below.

IV. TECHNICAL EVALUATION

A. Localization Techniques Evaluations

We quantify the behavior of the Crazyflie when the user interacts with it by exerting force on either the top or the side

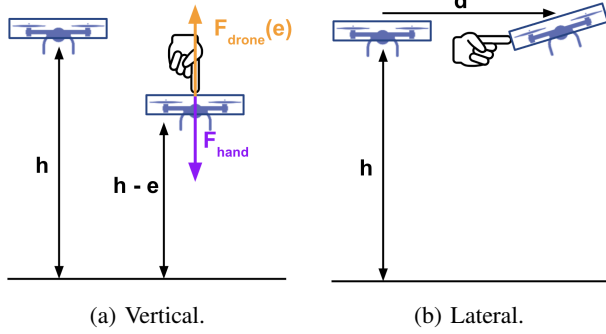


Fig. 3: Types of interaction

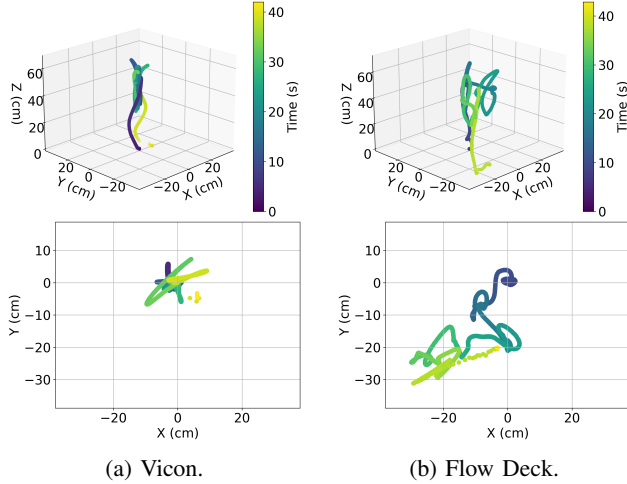


Fig. 4: Flight path comparison in vertical interaction.

of its cage while using two different localization techniques, Vicon and Flow Deck. We call the former vertical interaction and the latter lateral interaction (Fig. 3). We require the drone to hover at a fixed height $h = 50\text{cm}$ in all interactions.

With the vertical interaction, we are interested in the amount that Crazyflie drifts laterally when users interact with it. Figure 4 compares the drone's flight path while being pushed down by the user when using the Vicon and Flow Deck localization. Using Vicon, the drone experiences drifts of 18.7 cm along the x-axis and 14.0 cm along the y-axis. In contrast, with the Flow Deck, the drift is 33.6 cm along the x-axis and 35.1 cm along the y-axis.

Lateral interactions with the drone are more complex and less stable than vertical interactions because quadrotors are non-holonomic and pitch when they apply lateral thrusts, as shown in Fig. 3(b). For these lateral interactions, we evaluate the maximum stable displacement d and duration t of the interaction. In the first test, we provide a steadily increasing disturbance to the drone until it becomes unstable. In the second test, we provide a constant disturbance (half of the maximum disturbance) and measure how long it can hold this position before the drone becomes unstable. The drone pushes back to recover its original position using the chosen localization technique during both tests.

We conducted each experiment ten times, ensuring consis-

TABLE I: Maximum displacement (cm), lateral interaction.

Localization	Mean	Median	STD
Vicon	45.6	44.6	4.2
Flow Deck	95.0	93.1	26.5

TABLE II: Touch duration (s), lateral interaction.

Localization	Mean	Median	STD
Vicon	3.9	3.4	0.4
Flow Deck	6.4	5.3	3.6

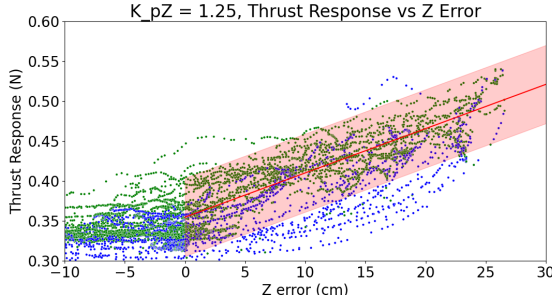
tency between the Vicon and Flow Deck setups. We tried to maintain a constant speed while pushing the drone, but some variations might occur between experiments since they were performed manually.

As shown in the results in Tables I and II, the maximum distance and duration of the lateral interaction were both greater for the Flow Deck than for the Vicon. The Flow Deck primarily detects the drone's motion, not its absolute position. Therefore, given a lateral disturbance, the drone does not attempt to return to its original position as assertively as it does with the Vicon localization method. This allows one to push the drone further before it fails. Vicon, on the other hand, tolerates smaller disturbances because it can pinpoint the displacement more precisely. This precision prompts the drone to exert greater effort to return to its starting position. However, as the drone increasingly attempts to return to its original position, the additional thrust causes it to tilt more, risking a flip and potential instability that results in a crash. Additionally, it was observed that the drone produces a larger counterforce with Vicon compared to the Flow Deck.

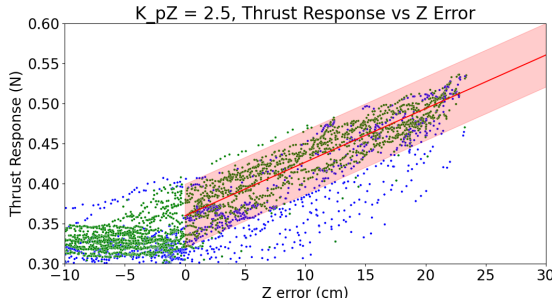
The experiments provide insights into the selection of a localization method and the feasibility of lateral interactions with the drone. Comparing the two localization techniques, Vicon and Flow Deck, the drone's behavior differs under the interaction types. Regarding vertical interactions, the drone experienced less drift with the Vicon system than the Flow Deck, indicating that Vicon provides more stability when users exert force from the top. Specifically, the drift was almost half with Vicon along the x and y axes compared to the Flow Deck. The instability with the Flow Deck caused the drone to crash 8 out of 10 interactions. This suggests that Vicon is the better choice for localization.

B. Vertical Stiffness Evaluation

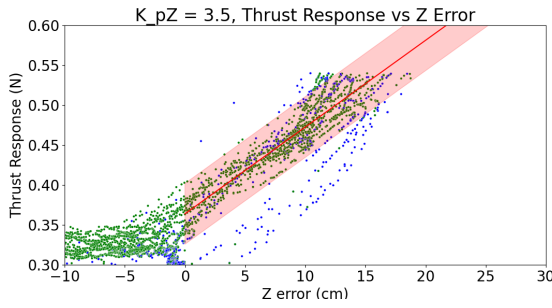
We examined the behavior of the system in terms of the gains of the proportional controller used to render different stiffness levels in the Z direction, K_{pZ} . We evaluated the relationship between K_{pZ} and thrust. Due to a data entry issue, we only have 17 trials of flight data from the experiment. We analyzed 16 trials on vertical interactions with the drone (7 for $K_{pZ} = 1.25$, 6 for $K_{pZ} = 2.5$, and 4 for $K_{pZ} = 3.5$) where the user pushed the drone downwards. For each 30-second trial, we logged the drone's thrust and position, evaluating the distance error from its setpoint location. This



(a) $K_{pZ} = 1.25$, Thrust = $0.0060 \times (z \text{ Error}) + 0.39$, $R^2 = 0.84$



(b) $K_{pZ} = 2.5$, Thrust = $0.0072 \times (z \text{ Error}) + 0.39$, $R^2 = 0.83$



(c) $K_{pZ} = 3.5$, Thrust = $0.012 \times (z \text{ Error}) + 0.40$, $R^2 = 0.85$

Fig. 5: Thrust Response (g) to Z error (cm), blue representing upward movement, green representing downward movement. The red-shaded region is the 95% confidence region from regression analysis.

distance error represents the distance participants pushed the drone away from the set point (0, 0, 1.0).

Our analysis showed a linear regression model could predict the stiffness given by the proportional gain K_{pZ} (Fig. 5). The net force on the drone should be close to zero when stationary unless disturbed, so we treat the thrust that is additional to the hovering thrust during interactions as force rendered to users. During data collection, we noticed that users often quickly removed their hands when the drone was at its lowest point, suddenly changing the dynamics of the system and effecting the relationship between position and thrust. Therefore, we focus our analysis on the drone's behavior during downward motions when the user's hand is guaranteed to be in contact with the drone.

The Crazyflie has a maximum thrust of 60 grams (0.59 N) [10]. Fig. 5 shows the relationship between the distance pushed by the user and the drone's thrust. Hovering thrust

matches closely to the drone's weight (0.39N, 39.7 grams) with only small amounts of noise in this value. We fit a linear regression model to the drone's z-error and recorded thrust during downward motions. Our regression analysis showed that on average, our system exerts 0.60N/m (62 grams/m) for $K_{pZ}=1.25$, 0.72N/m (74 grams/m) for $K_{pZ}=2.5$, and 1.2N/m (121 grams/m) for $K_{pZ}=3.5$.

V. STUDY DESIGN

The study was conducted with a total of 12 participants (7 males, 4 females, one unidentified; ages 21-37). This study was approved by the University of Southern California Institutional Review Board under protocol UP-22-01007, and all participants gave informed consent.

A. Experimental Conditions

To evaluate the effectiveness of the Crazyflie in rendering virtual stiffness, we designed a study to test the user's ability to perceive the stiffness level given different values of proportional gains. We also study the effect of the cage material on the perceived vibration level during the interaction. We tested 3 different K_{pZ} levels (1.25, 2.5, and 3.5) and 2 cage materials (PETG and PLA-CF), resulting in 6 trials for each participant. We randomized the order of K_{pZ} for each participant using a Latin square method to ensure a balanced design. Participants completed all trials for a single cage material before switching. The order of the cage materials was pseudorandom and balanced across participants.

B. Experimental Measures

After each trial, participants were asked to evaluate their perceived stiffness on a 5-point Likert scale with 1="Very Soft" and 5="Very Hard". Participants were given an additional option of 0="Felt no force". The user also reports on their perceived vibration, rated with a 5-point Likert scale with 1="Very Weak" and 5="Very Strong". 0 is also offered if the user did not perceive any vibration.

We also evaluated participants' trust of the system by having them complete the Trust Scale for Human Robot Interaction [11] after each set of interactions with a specific cage material. As the intention of the stiffness rendering system is to directly operate around human and provide feedback to user, we used such measurements to evaluate user's trust on the drone system. This trust scale measures human-robot interaction trust with four components: risk perception, competency, benevolence, and reciprocity. As the interaction is only intended to render a virtual stiffness, we analyze only the perceived risk (i.e., how much risk does user perceive in the interaction) and competency (i.e., how good is the system at achieving its goal).

We also collected participant's ratings of the haptic experience to evaluate the effectiveness of the Crazyflie as a haptic device. Participants completed the Haptic Experience questionnaire [12], which is an 11-item, 4-factor questionnaire that evaluates participants' subjective perception of Realism, Harmony, Involvement, and Expressivity.

TABLE III: Perceived Stiffness

Cage	K_{pZ}	Mean	Median	STD
PLA-CF	1.25	1.92	2.0	1.00
PLA-CF	2.5	2.25	2.5	1.29
PLA-CF	3.5	2.92	3.0	1.51
PETG	1.25	1.83	1.5	1.19
PETG	2.5	1.92	2.0	0.90
PETG	3.5	2.67	2.5	1.44

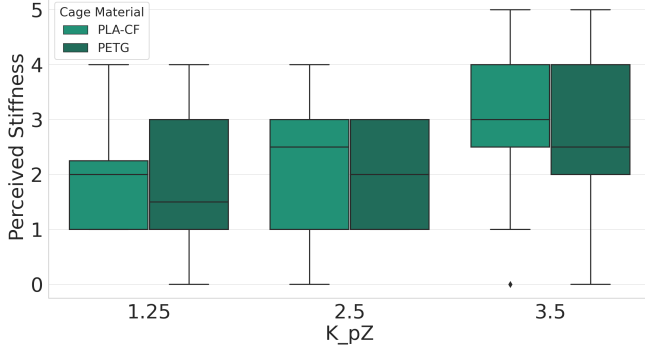


Fig. 6: Perceived Stiffness with proportional level and cage material

C. Experimental Procedure

At the beginning of the study, participants were greeted and presented with the procedure, potential risk, and consent for data collection. Participants then completed a pre-study questionnaire about their demographic information. Next, we demonstrated to the participants how to press down on the drone to perceive stiffness. The participants then interacted with the drone for 10 seconds, allowing us to verify that they were using the correct motions and hand placement.

Each trial consisted of the drone taking off, hovering at a setpoint position (0, 0, 1.0m), and then landing. Participants interacted with the drone during the 30 seconds of flight by pushing the drone in the z-direction for as long as desired and as many times repeated as desired within the 30-second trial. Participants were given a visual indicator showing the maximum displacement to apply, which was 20cm from the hovering position. After each 30-second interaction, they would complete the surveys rating the perceived stiffness and vibration. A video of the user study can be found online².

VI. RESULTS AND DISCUSSION

A. Perceived Stiffness

Table III shows the average perceived stiffness for each K_{pZ} value and cage material. We conducted a two-way ANOVA with K_{pZ} and cage material as factors, and perceived stiffness as the dependent variable. This analysis showed that the K_{pZ} does have an effect on the perceived stiffness ($F=3.61$, $p=0.03$). The cage material did not have a significant effect on the perceived stiffness ($F=0.58$, $p=0.45$) and there were no significant interaction effects ($F=0.06$,

²See the video at https://youtu.be/z_e2M33Gim8?si=-WdKD28YGffZwM-7

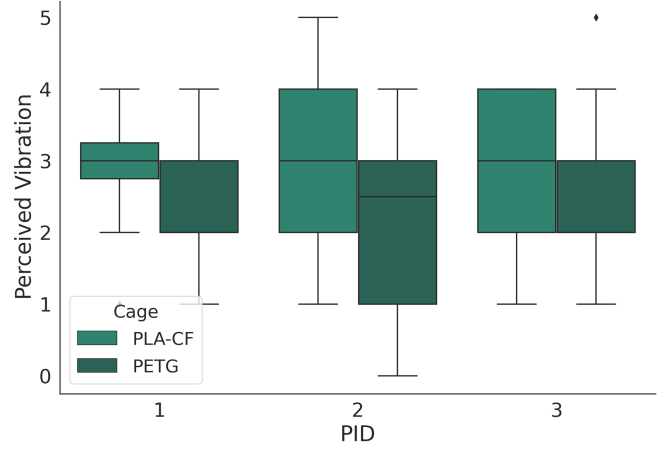


Fig. 7: Results of perceived vibration with cage material

$p=0.94$). Further analysis with Tukey's HSD on K_{pZ} showed that participants could perceive a difference in stiffness between $K_{pZ}=1.25$ and 3.5 ($p=0.0298$). However, there was no significant difference in the perceived stiffness between any other K_{pZ} . This result shows that given the small (21-gram) thrust range of the Crazyflie, participants can only perceive large differences in the proportional controller values as a corresponding difference in stiffness.

B. Perceived Vibration

We conducted a two-way ANOVA with cage material and K_{pZ} as factors, and perceived vibration as the dependent variable. The analysis showed that the cage material has a significant effect on the perceived vibration level ($F=5.55$, $p=0.02$). K_{pZ} did not have a significant effect on the perceived vibration ($F=0.00$, $p=1.00$) and there were no significant interaction effects ($F=0.32$, 0.73). PLA-CF material cage has a mean vibration level of 2.89 , $STD=1.09$, while PETG cage has a mean of 2.28 , $STD=1.06$. A t-test showed that the PLA-CF cage material has a higher mean perceived vibration compared to the PETG cage material ($t=2.41$, $p=0.02$). This confirmed our hypothesis that stiffer material has a higher vibration level than softer material. As of now, this vibration is due to unwanted mechanical noise during the drone's operation of the motors. For our stiffness rendering use case, we believe PETG cage material is better than the PLA-CF material as it shows less mechanical vibration.

C. Human-Robot Interaction Trust

The next part of the analysis evaluates the human-robot interaction trust scales. As discussed earlier, we evaluated only the risk-perception and competency section of the trust scale based on our interaction. We have one lost entry of data for the PLA-CF cage, and the data was analyzed on 11 entries of PLA-Cf and 12 entries on PETG. Risk perception across all trials was rated as 6.92 ± 2.41 and competency across all trials was rated as 9.92 ± 3.06 ; both scales were scored out of 15. We conducted further analysis on the cage materials' effect, with results on both risk perception (PLA-CF: 7.0 ± 2.24 , PETG: 6.5 ± 2.43) and competency

(PLA-CF: 11.0 ± 2.42 , PETG: 9.5 ± 2.94) did not show a significant difference ($p=0.61$ and $p=0.20$, respectively). A risk perception score of $6.92/15$ (46%) indicates that the user associates only moderate risks with our system. The perception of risks could come from lateral instabilities after interactions, loud sounds from the rotors, and the proximity of the user's hand to the rotors during the interaction. Further work is needed to decrease the user's perceived risk. A competency of $9.92/15$ (66%) shows that users largely felt that our system was competent at rendering stiffness.

D. Factor of Haptics Experience

Participants rated the system on the scale factors of realism, harmony, involvement, and expressivity using a set of 11 questions. We conducted a 1-way ANOVA on these scales with cage material as a factor and found that the cage material did not affect the haptic experience along these scales ($p=0.78, 0.62, 0.73, 0.36$ for Realism, Harmony, Involvement, and Expressivity, respectively).

Involvement measures the degree to which users are able to focus their energy and attention on the stimuli or interaction. Our system received high involvement ratings of $(8.00 \pm 2.30)/10$, which shows that participants are able to assign significance to the feedback they receive from the system. Expressivity measures the distinguishability of haptic events based on varying user inputs. Our system received moderate expressivity scores of $(9.46 \pm 1.96)/15$, which indicates that users can distinguish the different stiffness levels. Realism evaluates how convincingly the system conveys the sensations that someone expects to feel in reality. Since we are not trying to match real-world sensations, but rather are just displaying a generic stiffness in the tested interaction, it makes sense that we received moderate realism scores of $(7.69 \pm 2.48)/15$. Harmony evaluates the degree to which the components of the interaction are matched with one another. Our system received the lowest scores within the harmony scale $(4.96 \pm 2.01)/15.00$, which could be due to a mismatch between different modalities. As of now, the only visual and sound of the stiffness rendering is from the drone itself, which could be further improved in future research.

VII. CONCLUSION AND FUTURE WORK

In this paper, we explored and validated the potential of nano-size quadcopters with a 3D printed cage as haptic rendering tools, particularly for simulating virtual stiffness. The research emphasized the role of the proportional controller's gain and the protective cage material in the user's haptic experience. We showed that by using such small drone platforms, we could render different haptic responses from 0.6 N/m up to 1.2 N/m , enabling users to perceive a difference in the rendered stiffness. We also presented a 3-D printed cage design that becomes a part of the drone's body, and showed that the cage material affects the drone's vibration level with users perceiving more vibration with a stiffer cage. This research lays the groundwork for nano-size drone touch interactions that are easily reproduced, allowing future researchers to quickly dive into drone-based haptics.

In the future, we plan on addressing the constraints of nanocopters by: improving the underactuated dynamics of drones, and increasing the force output of the system. With regard to the former, we intend to use an Omnicopter [13], which uses 8 rotors and provides 6 DoF control. Unlike quadcopters or planar drones, an Omnicopter is holonomic, meaning that it can be actuated in all directions and does not require roll or pitch to move in lateral directions. This controllability means that it could have improved performance in balancing human disturbances from all directions. We will also explore the feasibility of employing multiple drones or Omnicopters in tandem to amplify the exerted force [14]. Using a swarm for rendering large forces could overcome the thrust limitation of individual drones.

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