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CrazyJoystick: A Handheld Flyable Joystick for Providing On-Demand Haptic Feedback in Extended Reality

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***Abstract*—We present CrazyJoystick, a flyable handheld joystick allowing seamless interaction methods to change between joystick and hand-tracking while displaying on-demand haptic feedback in extended reality (XR). Our system comprises a quadrotor that can autonomously approach the user when needed, addressing the limitations of conventional handheld and wearable devices that require continuous carrying throughout interactions. CrazyJoystick dynamically reallocates all thrust for haptic rendering during stationary states, eliminating the need to hover while delivering feedback. A customized cage allows users to grasp the device and interact with virtual objects, receiving 3.5 degree-of-freedom feedback. This novel transition method allows us to harvest the aerial mobility from multi-rotor based haptic devices, while having high force-to-weight ratios from being handheld during interaction. This paper describes the design and implementation of CrazyJoystick, evaluates its force and torque performance, and usability of the system in three VR applications. Our evaluation of torque rendering found that users can perceive the direction with an accuracy of 92.2%. User studies further indicated that the system significantly improves presence in VR environments. Participants found on-demand haptic feedback intuitive and enjoyable, emphasizing the potential of CrazyJoystick to redefine immersive interactions in XR through portable and adaptive feedback mechanisms.**

I. Introduction

Haptic feedback is essential for enhancing user experience and immersion in Extended Reality (XR) [1], [2], [3], [4]. However, implementing haptics in XR remains a challenging topic for three key reasons: (1) XR interaction can involve anything. The physical appearance of virtual objects is highly diverse and contextual. (2) XR interaction can occur anywhere. The spatial awareness of XR devices allows users to interact over large areas. (3) XR interaction can happen anytime. Different interaction methods are provided to users for various purposes, such as hand-tracking and joystick controllers.

Research in haptics, human-computer interaction, and robotic teleoperation has explored various physical proxies to provide haptic feedback. These proxies can be categorized based on the grounding of the forces: grounded devices [5], [6], body-grounded (wearable) devices [7], [8], [9], [10], mid-air haptics [11], [12], and air-grounded devices [13], [14], [4], [15], [16], [17], [18], [19], [20], [21].

While different methods of force generation enable a variety of interactions, they also present unique pros and cons due to the nature of their design. Grounded devices can provide strong forces, but they are often heavy and offer a limited workspace, violating the constraint that XR interaction can occur anywhere. Body-grounded (wearable) devices can move with the user and have been extensively studied for VR applications. However, these devices require users to carry their weight, necessitating lightweight and ergonomic designs [22], which limits their applicability for anytime XR interaction. Mid-air haptics use ultrasound to create vibrational sensations. However, the force bandwidth of these devices is generally limited to millinewtons [11], restricting the types of feedback they can provide for rendering in XR.

Air-grounded devices have the advantage of using air as a medium to generate forces, demonstrating promise in meeting the needs of XR haptic interactions. As propellers push air, they generate forces in the direction opposite the airflow. This process eliminates the need for rigid connections to external objects, such as the user's body or the ground. There are two main types of air grounded haptic devices: hand-held propeller based devices [17], [4], and multi-rotors, mainly quadcopters [14], [19], [18], [20], [13], [21]. Among these, multi-rotors have garnered significant interest for XR interactions due to their high mobility, ability to produce a wide range of forces, and flexible control. These features make them well-suited for rendering haptic interactions in diverse XR environments. However, using multi-rotors to provide kinesthetic feedback presents several challenges: (1) instabilities in flight caused by physical interaction with the user, and (2) the significant amount of thrust required for hovering, which drains the battery and limits motor capacity for haptic feedback. As underactuated systems, quadcopters rely on attitude control to achieve position control. This requires orientation adjustments to apply lateral-directional feedback, restricting their haptic interaction capabilities. These limitations also pose challenges in establishing a stable and rigid connection between the device and the user. Secondly, continuous hovering significantly drains the battery of an aerial device, as propeller thrust must combat gravity. This limits the amount of the drone's total thrust capability that could be used towards providing feedback, as most of the drones have a thrust-to-weight ratio between 1.5-3. This indicates that only thrust in addition to the hovering weight can be used towards haptic rendering, which causes fast battery drain and does not utilize the propellers' full capability. To the best of our knowledge, no devices exist that can take advantage of both a quadcopter's actuation capability and handheld device's rigid connection, harvest the flying mobility to provide on-demand interaction, and use all 3.5 degrees-of-freedom (DoF) actuation for feedback when being used as a joystick.

We present CrazyJoystick, a novel system that provides on-demand 3.5 DoF feedback utilizing a customized 3D-printed cage mounted on a quadcopter platform that transitions between no-contact and handheld modes by flying to the user's hand.In real interactions, the quadcopter first uses a standard flight controller to reach the user's hand, then switches off its hovering thrust and uses a customized haptic controller to fully utilize the propellers for haptic rendering. When rendering haptics, it acts as a kinesthetic-feedback joystick, capturing user movements and providing directional torque, upward force, and wind feedback. Our system utilizes an external motion-capture system that tracks both user movements and the quadcopter's position, which is used as input for VR interaction that generates haptic control signals. By dynamically adjusting the thrust of the propeller based on user movements, the system allocates its 3.5 DoF feedback, with torque along three axes and force in one axis. Such capabilities can be used to render sensations such as shifts in the center of gravity, variable torque resistance, or wind perception.

In this paper, we present the following contributions:

- The design and modeling of the CrazyJoystick prototype, a 3.5 DoF handheld haptic device.
- A novel method for switching between handheld and joystick modes in VR without disengaging the user.
- A haptic device with high force-to-weight ratio to provide immersive experience while allowing aerial mobility.
- Three VR environments that demonstrate the haptic feedback capabilities of CrazyJoystick.
- Evaluation of user recognition of directional feedback and the system's ability to enhance presence and realism.

II. Background

Our work builds on the fields of air-grounded XR haptic devices, particularly focusing on previous research in handheld and multi-rotor based devices.

A. XR Handheld Haptic Devices

Handheld devices are a common form factor for both input and output in XR interactions due to the hand's sensitivity and dexterity. Among handheld devices, joystick controllers and gesture control [23] are the most common control methods in modern XR devices. Commercial handheld VR haptic feedback devices offer vibrotactile feedback and adaptive trigger [24], [25]. However, in complex virtual reality scenes, the feedback provided by standard controllers may not be sufficient. To enhance such experiences, researchers have explored various techniques in handheld devices to extend the fidelity of the virtual reality experience.

Torque feedback is a common modality of handheld haptic devices in XR. Flywheels and their gyroscopic effects have been explored to provide such feedback. Moya et al. [26] designed a system that utilizes a flywheel motor and three orientation-control motors to achieve 3-DoF force feedback. Walker et al. [27] presented a dual flywheel system, each mounted on a two-axis gimbal, allowing the system to generate moment pulses that provide directional signals to users. Air-grounded devices have also been studied as a method of providing torque feedback. Heo et al. developed Thor's Hammer [17], which mounts six brushless motors on three different planes enclosed in a handheld hammer-shaped container, capable of rendering 3-DoF force feedback using propellers. Je et al. [4] presented Aero-plane, a handheld device that creates the illusion of a shifting center of weight using two brushless motors and a handheld connector.

This research shows that handheld torque feedback devices can provide meaningful feedback to the user. However, one limitation of these handheld systems is that these devices lack mobility, meaning that the user has to wear such a device for the interaction. The user must either disengage from their XR experiences to put on such devices or put on the devices before the interaction begins and carry the weight of the devices throughout the interaction. This extra weight could be cumbersome. One example is aero-plane [4], which reported that some users perceive arm fatigue after using the device that weighs 1 kg. Our system aims to leverage the advantage of handheld devices' rigid connection to users' hand, without asking the user to put on the device in middle of the interaction which causes disengagement or put on the devices before interaction begins, allowing a more comfortable and intuitive interaction experience.

B. Haptic Feedback using Multi-rotors

Multi-rotors, particularly quadcopters, are well-suited for providing haptic feedback in XR environments because of their ability to exert force, mobility, and flexibility in control. This capability allows them to operate within a large workspace to exert forces on demand, making them versatile tools for XR interaction which could be anything, anywhere, and anytime. Prior research explored using quadcopters to deliver tactile feedback [18] and kinesthetic feedback [20], [19], [13], [28], [29], [30], [14]. Most of these studies adopted direct contact between the drone and the user by equipping a safe to touch cage, where the multi-rotors physically interacts with the user to provide haptic feedback [20], [18], [19], [29], [14]. Other research looked into indirect contact, such as using strings to softly connect users' fingers and multi-rotors [30], [13], or using game proxies to interact with the multi-rotors [28].

Direct contact enables the multi-rotors to act as physical proxies with their cages, enhancing realism and immersion of the virtual experience. For example, Abdullah et al. [20] implemented a vertical force rendering system using Parrot AR 2.0 equipped with cages. Awan et al. [29] also used a half-dome cage with Parrot AR 2.0, capable of generating force in 6 directions. Chen et al. [19] implemented a micro-sized system, using a modified Crazyflie, which weighs only 34 grams with a safe to touch cage, rendering different levels of stiffness to users. Researchers have also studies the use of multi-rotors to provide tactile feedback. Abtahi et al. [18] implemented a texture rendering system by attaching materials to different sides of a quadcopter. Such a system dynamically adjusts its position and orientation according to user interactions, providing different textures for the virtual contents to the users. Yamaguchi et al. [28] demonstrated a system with Parrot AR 2.0 that allows users to use a sword to poke at quadcopters, simulating the haptic proxy. Auda et al. [14] installed different shape proxies on a DJI tello quadcopter, simulating a virtual button, joystick, and other input devices in mid-air.

Although direct contact with multi-rotors provides unique capabilities, it often faces challenges in safety, control, and stabilization [13], [30]. Using soft connections was explored to improve upon these factors, such as using a string to attach the user's finger to the multi-rotors [30], [13], [21].

While previous research utilizes quadcopter's mobility and showed promise in providing haptic feedback, none of the systems could use 100% of its propeller thrust to provide haptic feedback. An example is the Parrot AR 2.0 quadcopter, which was used in three projects [20], [29], [28] and weighs 380 grams without protective cages. The weight of the quadcopter with safe-to-touch cage is 469 grams, and the maximum force delivered by such a device is 1.5N [20], [29], meaning that 4.6N out of the 6.1N thrust (75.4%) was used to combat gravity rather than perform haptic rendering.

Drawing from the advantage of handheld devices and multirotors, we have designed an on-demand handheld device that can fully utilize the propeller thrust. We implemented a system that weighs 41.3 grams (8.8% of the Parrot AR 2.0) and can generate 0.71N (47% of its force output), a 5.34 times increase in force-to-weight ratio. Our device is also capable of using its propellers to generate torque, with 10.4Nmm torques on the X and Y axes, and 1.4Nmm on the Z axis.

III. System Design

CrazyJoystick offers on-demand haptic interaction by transitioning between a flying robot and a handheld device, providing the ability to fly to the user upon a virtual trigger. Our system is designed to fit with both MR and VR workflows, with different activations to summon the joystick. In MR applications, users navigate menu systems through hand-tracking until specific interactions require enhanced input fidelity or haptic feedback. The system then autonomously deploys to provide precise control and tactile response. In a VR game-like scenario, the user could start the game with an empty hand. As the game progresses, they could get items such as picking up a weapon. The user could use hand-tracking at the beginning of the interaction, then summon joystick when virtual interaction is needed. A common approach with virtual objects is to summon them by pressing a button or clicking on the object, attracting it to the user's virtual hand. In both scenarios, CrazyJoystick could fly to the user's hand upon the summon process, augmenting the interaction in XR. After securing user contact, it shuts off hovering thrust and acts as a handheld haptic feedback and input device. CrazyJoystick generates haptic feedback through the control of four propellers on a Crazyflie 2.1 quadcopter (Bitcraze). It has 3.5 DoF output, providing force in positive z direction and torque in the x, y, and z axes. Such capabilities can be combined to create different interaction methods, such as creating the illusion of a weighted object moving along a virtual plane, altering the torque of a virtual object, and simulating virtual wind.

A. System Overview

The system is composed of four main components shown in Fig. 1: (a) Ground station for controlling the drone, tracking, and running Unity. (b) CrazyJoystick for flying or rendering haptic feedback. (c) HMD for visual display. (d) Motion capturing system for tracking CrazyJoystick and user movements. We use the Crazyflie 2.1 (Bitcraze) as the carrier and actuator for our interaction, and created a specialized firmware that enables switching between flying mode and haptic rendering mode with 3.5 DoF feedback. The user experiences haptic feedback as torque and force through a custom 3D-printed grip with thin bars, allowing a stable grip at the minimal weight.

CrazyJoystick is controlled by a ground station, which is also in charge of rendering the virtual environment through Unity 3D. The ground station is connected to a Vicon motion-capture system, receiving high-precision position and orientation information about CrazyJoystick and the user's wrist. When user interaction is triggered, it flies towards the user's wrist, aligning itself with a small offset, and landing into the user's hand. The ground station is also connected to an HMD, which displays the graphics of the virtual environment.

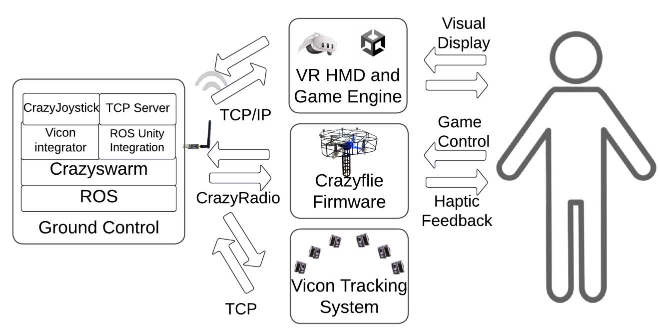

Fig. 1. System Architecture of CrazyJoystick

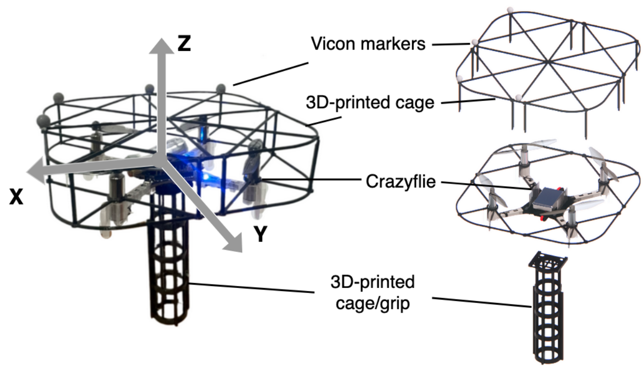

Fig. 2. CrazyJoystick Hardware

B. Hardware Design

The main component of our system is the joystick constructed from a Crazyflie nanocopter equipped with a 3D-printed cage, shown in Fig. 2. The choice of a nanocopter was driven by its compact dimensions, light weight, and inherent safety features. Installed with the high-thrust upgrade package, Crazyflie 2.1 is capable of generating 0.71N of thrust in total. With the quadcopter itself weighing 33 grams (0.32N), additional weight needs to be minimized to maintain stable flight. We iterated our design process to minimize weight due to limited thrust, resulting in a total weight of 41.3 grams including the battery. Besides weight, the cage was designed to be easy to hold and safe to touch for the user. The upper layer was designed with meshes to prevent accidental contact with the propellers. On the bottom, a cylindrical grip was installed to the Crazyflie's body, allowing users to comfortably grip the joystick and enable seamless transitions from flying to balancing modes. The cage, which weighs only 8.4 grams, was fabricated using PLA material and assembles using press-fits.

Four retroreflective markers are attached to the cage to enable motion capture. Such patterns form a rigid body tracked by the Vicon system and used to provide localization input for the VR environment.

C. Software Design

There are three key components of the software system: drone firmware, ground control, and game engine. We modified a Crazyflie firmware to achieve both flight and in-hand haptic rendering. We utilize the ROS-based Crazyswarm [31] to serve as our ground control, which manages the flight mission and communicates with external systems such as Vicon and the Unity application run on Meta Quest 3 HMD. Lastly, we use Unity 3D (version 2022.3.26f1) to render a VR environment that communicates with Crazyswarm through ROS-Unity Integration via TCP. Overall, the user would see the VR environment from Unity through the HMD, and interact with the virtual environment through the CrazyJoystick; the updated position would be captured by Vicon and sent to the Unity application to update the virtual proxy. The updated virtual proxy would then generate the control signal to Crazyswarm ground control, which then controls the propeller's thrust.

To achieve different operation states, we customized the quadcopter firmware's control loop. The standard firmware offers a cascade PID control architecture, consisting of position, velocity, angular velocity, and angular rate controllers. The controllers generate four output signals: x, y, z axes torque, and z axis thrust based on sensor feedback and desired output. These signals are then sent to power distribution, which combines them to generate PWM control for each motor.

For haptic rendering, we modified three major aspects of this controller: (1) We modified the power distribution to allow state switches between flights and rendering by turning off hovering thrust. (2) We create a direct communication to the torque and force controller that allows real-time torque and thrust output. (3) The base thrust and proportional gain for position control is increased slightly to balance the extra weight from the drone's cages.

We provided a generic controller to use the quadcopter's propeller as thrust, mapping movements in each degree of freedom (DoF) as a feedback control signal into the propeller thrust. The 3.5-DoF feedback from the thrust is torque in 3 rotational directions (along the x, y, and z axes) and force in the positive Z direction. From the user's perspective, +x is the front of the quadcopter, +y is to the left of the quadcopter, and +z is pointing up from the quadcopter. We can denote the control of the device as a 4-DoF vector:

$$\mathbf{I}_{\text{control}} = \begin{bmatrix} \tau_x & \tau_y & \tau_z & F_z \end{bmatrix} \tag{1}$$

where $\tau_x, \tau_y, \tau_z, F_z$ are the torque control signals around the x, y, and z axes and the force along the z axis. Each signal is an arbitrary analog command between 0 and 1, controlled on the basis of the interaction from virtual reality.

The thrust output vector for the four motors is given by:

$$\mathbf{T}_{\text{output}} = \begin{bmatrix} \text{thrust}_1 & \text{thrust}_2 & \text{thrust}_3 & \text{thrust}_4 \end{bmatrix} \tag{2}$$

where each motor's thrust can be commanded by a PWM signal between 0 and 2^{16}, and motor_1 being the top-right motor with the number increasing clockwise.

The relationship between the input torques and the thrust outputs is:

$$\mathbf{T}_{\text{output}} = \mathbf{I}_{\text{control}}\mathbf{M} \tag{3}$$

where the transformation matrix $\mathbf{M}$ is:

$$\mathbf{M} = \begin{bmatrix} -c_r & c_r & c_r & -c_r \\ c_p & c_p & -c_p & -c_p \\ c_y & -c_y & c_y & -c_y \\ c_f & c_f & c_f & c_f \end{bmatrix} \tag{4}$$

where c_r, c_p, c_y, c_f are the factor constants controlling the x, y, z axis torque, and z directional force outputs, respectively. Normally the constant is set to either 0 or 2^{16} to cover the range of available actuation. By turning the constant on and off, we can control the degree of freedom of feedback provided in different scenarios.

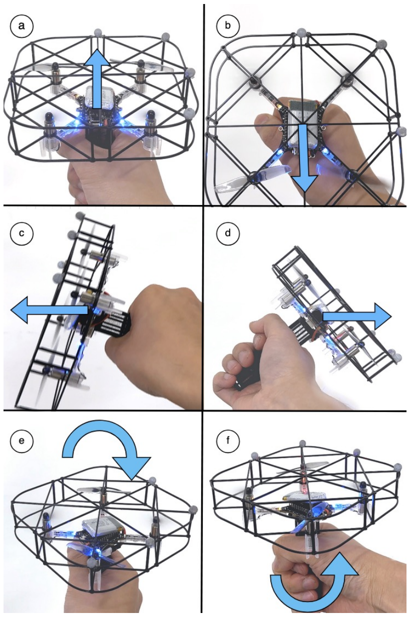

Fig. 3. CrazyJoystick kinesthetic feedback: Directional cues (indicated by blue arrows) illustrating how users perceive directional feedback: (a) Forward, (b) Backward, (c) Left, (d) Right, (e) Clockwise, and (f) Counterclockwise.

D. Directional Feedback Design

Users can perceive six directional cues displayed using torque: forward, backward, left, right, clockwise, and counter-clockwise. Due to the design of Crazyflie, we can only display force in the positive Z direction, hence we did not test the user perception of force. CrazyJoystick's generated torque utilizes the user's wrist as a pivot point to provide directional cues. These effects were evaluated in Study #1.

Forward, Backward, Left and Right. Fig.3 illustrates CrazyJoystick's four-propeller configuration and its directional cue mechanism. We denote $\mathbf{I}_{\text{control}}$ as the control vector, where τ_x, τ_y, τ_z, and F_z represent the torque around the x, y, and z axes, and the thrust force along the z-axis, respectively. Setting c_r, c_p, c_y, c_f to $[2^{16}, 2^{16}, 0, 0]$, the drone outputs torque in the x and y axes according to the control input. Forward cues are created by commanding a positive τ_y up to 1, while backward cues are generated by commanding a negative τ_y down to -1. Left and right cues are created by setting τ_x between [-1,1], where 1 is to the left of the quadcopter.

Clockwise and Counterclockwise. Fig.3 (e) and (f) illustrate clockwise and counterclockwise directional cues, respectively. Setting c_r, c_p, c_y, c_f to [0, 0, 2^{16}, 0], the propellers only output torque around the z-axis. Clockwise and counterclockwise feedback is achieved by commanding the τ_z, where 1 is counterclockwise and -1 is clockwise.

E. Human Interaction Design

1) Interaction Workflow: The CrazyJoystick interaction workflow, shown in Fig.4 and Fig.5, begins with the user putting on a Meta Quest 3 HMD. We implemented two interaction transitions: hand-tracking to joystick in mixed reality (MR) and hand-tracking to joystick in VR. After the user grabs

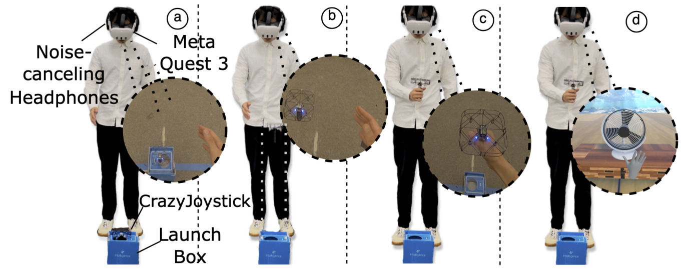

Fig. 4. CrazyJoystick XR interaction workflow. (a) User positioned for CrazyJoystick deployment in XR. (b) CrazyJoystick approaching user's hand. (c) User grasping the CrazyJoystick's 3D-printed cage using XR visualization. (d) VR HMD switching from passthrough to immersive mode, initiating force-feedback interaction game

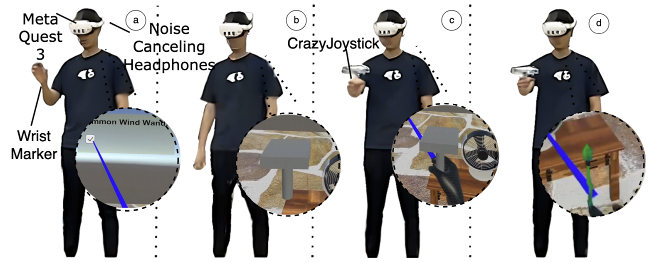

Fig. 5. CrazyJoystick VR interaction workflow. (a) User triggers CrazyJoystick deployment. (b) CrazyJoystick approaching user's hand. (c) User catches the CrazyJoystick using aligned virtual proxy. (d) VR HMD switching from passthrough to immersive mode, initiating force-feedback interaction game

the joystick, the haptic feedback for both interactions is the same, as is returning of the joystick.

The first step in the interaction is to summon the CrazyJoystick. In conventional XR interaction, this could be either transitioning from using handtracking in home menu selection to playing games such as Beat Saber[1], which requires a joystick. In this scenario, the joystick is summoned before the game interaction. In other games, such as Half-Life Alyx[2], the user begins the exploration with an empty hand, transitioning into holding a weapon as the game progresses. In this scenario, the summoning process takes place during the game. We implement summoning for both scenarios, a transition relying on MR for alignment and a transition relying on using motion-capture for alignment.

The user grabs CrazyJoystick upon completion of the summoning process, where it will turn off hovering thrust and begin haptic rendering. Based on the interaction, we implemented three virtual environments with haptic feedback,described below. The user could move the joystick for different interactions with the virtual environment and perceive different sensations from the propeller thrust. Upon completion of the interaction, signaled by the disappearance of the virtual objects, the user loosely holds the CrazyJoystick, which then lifts off from their hand and flies back to its launch box.

Summoning the Joystick. For MR, using hand gestures tracked by the HMD, the user launches a Unity application in

[1]https://beatsaber.com/
[2]https://www.half-life.com/en/alyx

passthrough mode, meaning that the user views their physical environment through the HMD rather than a virtual scene as displayed in Fig.4. The CrazyJoystick then takes off from its launch pad to a height of 1 meter over 2.5 seconds (both parameters are adjustable). Once hovering stably, the user grasps the device's 3D-printed grip attached beneath the quadcopter by looking at it from MR, prompting the application to transition to immersive VR mode. After a brief preparation period, the interactive experience begins, and the joystick begins to provide haptic feedback.

For VR, users rely on a virtual proxy to help them grab the joystick that flies to their hand. Users wear a retroreflective marker that tracks their wrist position as shown in Fig.5. We implemented a virtual button in VR to represent a simplified version of the transition between interaction modes. This trigger can be swapped for other virtual interactions, such as the user summoning a weapon. When the user toggles the button, it sends a signal for the CrazyJoystick to take off and fly to above the user's hand, offset from the measured wrist position by 10 cm vertically and horizontally:

$$P_{\text{takeoff}} = P_{\text{mocap-wrist}} + R_{\text{mocap-wrist}} \cdot \begin{bmatrix} 0.1 \\ 0 \\ 0.1 \end{bmatrix} \tag{5}$$

where $P_{\text{mocap-wrist}}$ is the 3×1 position vector of the user's wrist in the motion-capture coordinate frame, and $R_{\text{mocap-wrist}}$ is the corresponding 3×3 rotation matrix describing the wrist's orientation.

Once the desired target is reached, the drone slowly lands in the user's open hand. The system then detects that the CrazyJoystick is stationary, switching over to the appropriate haptic rendering mode for the interaction.

We conducted a pilot study with three participants (n=3) to evaluate the ease of use of the summoning in the VR interaction. Each participant was instructed on the summoning process and given two sample trials. After completing these trials, participants were asked to perform the summoning process 10 more times, recording the number of successful transitions in each trial. All 30 trials were successfully completed by the three participants, suggesting that our summoning system is user-friendly and requires minimal instruction.

2) Virtual Environment Interaction Implementation: The main interaction consists of three components: user's virtual hand, a visual proxy, and the virtual target. The position of the user's hands inside Unity is tracked by the HMD, $P_{\text{virtual-hand}}$. The user's wrist is tracked through Vicon motion-capture $P_{\text{mocap-wrist}}$. The visual proxy is the game items that the user has summoned, such as a plane with sliding ball $P_{\text{virtual-proxy}}$. The position of the joystick is tracked by the translation and rotation of the quadcopter by the motion capture system, denoted $P_{\text{mocap-drone}}$. We align $P_{\text{virtual-proxy}}$ in Unity space by applying the offset between user's wrist and the drone in Vicon space to the virtual wrist:

$$\begin{aligned} P_{\text{virtual-proxy}} = & P_{\text{virtual-hand}} \\ & + R_{\text{virtual-hand}} * (P_{\text{mocap-drone}} - P_{\text{mocap-wrist}}) \end{aligned} \tag{6}$$

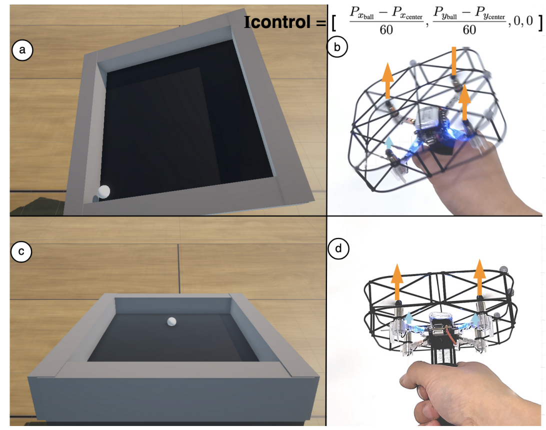

Fig. 6. "Roll the Ball": CrazyJoystick simulates a rolling ball's weight by dynamically adjusting motor thrust: (a) As the ball rolls to the lower-left corner, (b) motors on the upper-right generate torque, creating the illusion of weight. (c) When the ball moves to the mid-upper side, (d) the lower motors increase thrust, continuously adapting feedback to match the ball's position.

Our system uses this virtual proxy pose to simulate interaction with other virtual objects, such as the plane and the ball in "roll the ball". Once feedback is triggered, the quadcopter provides the appropriate feedback to display to the user given the environment and method of interaction. The factor constants c_x, c_y, c_z, c_f are used to control the desired output axes.

We created three example interactions to illustrate three different feedback methods described. This design is part of our efforts to enhance the realism of the interaction by mimicking the physical effort in the real world.

Roll the Ball. We created the "Roll the Ball" application, allowing the user to feel the moving weight of a rolling ball. This interaction, shown in Fig. 6, allows the user to receive directional cues when changing the orientation of a virtual plane with a moving ball by tilting CrazyJoystick. The virtual proxy's pose controls the translation and orientation of the virtual plane. We use Unity's default physics engine PhysX for the physics simulation between the ball and the plane. When the user tilts their hand, the orientation of the virtual plane changes accordingly, which causes the ball to slide. To allow for combining x and y axes of torque feedback, we selected $[c_x, c_y, c_z, c_f]$ to be $[0.6 * 2^{16}, 0.6 * 2^{16}, 0, 0]$. This limits the maximum torque on the x and y axes individually to be 0.6 times the maximum thrust, allowing diagonal feedback (combining two torques on one motor). The control signal for each motor is limited to [0,1]. To compute the torque based on the ball's position, we normalize the position offset from the center by the maximum distance (60). The torque applied is proportional to this offset. Let $\mathbf{P}_{\text{ball}} = (P_{x_{\text{ball}}}, P_{y_{\text{ball}}})$ be the current position of the ball on the plane, and $\mathbf{P}_{\text{center}} = (P_{x_{\text{center}}}, P_{y_{\text{center}}})$ be the center of the plane. The control vector $\mathbf{I}_{\text{control}}$ is calculated as:

$$\mathbf{I}_{\text{control}} = \left(\frac{P_{x_{\text{ball}}} - P_{x_{\text{center}}}}{60}, \frac{P_{y_{\text{ball}}} - P_{y_{\text{center}}}}{60}, 0, 0 \right) \tag{7}$$

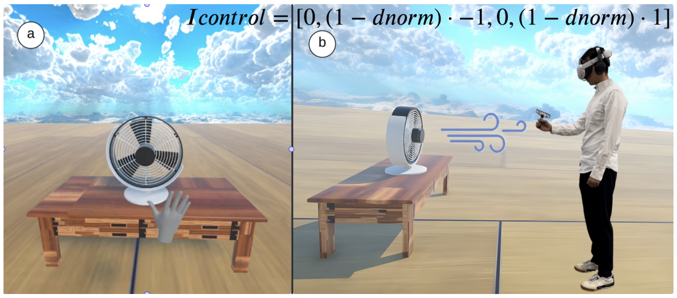

Fig. 7. "Feel the Fan": CrazyJoystick renders wind feedback: (a) First-person view shows the user's virtual hand interacting with a fan. (b) Third-person perspective illustrates how CrazyJoystick's propellers generate force and torque to simulate wind intensity based on the hand's proximity to the fan.

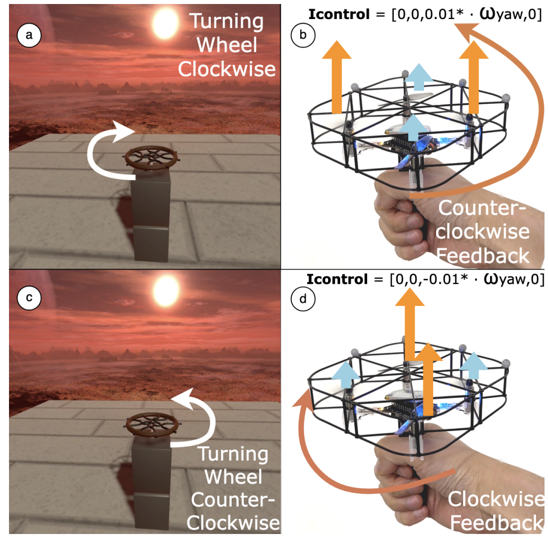

Fig. 8. "Rotate the Wheel": CrazyJoystick simulates rotational resistance of a virtual wheel: (a) As the user rotates their wrist clockwise, (b) CrazyJoystick generates counterclockwise torque to mimic wheel resistance. (c) When the user rotates counterclockwise, (d) CrazyJoystick renders clockwise torque.

This approach simulates the moving weight of the ball by applying torque in the direction of the ball. If the ball slides from left to right, the thrust would first generate torque to the left, indicating a weight to the left of the joystick. Then the thrust changes direction slowly to the right side as the ball slides to the right, the distance from the center controlling the magnitude of the thrust. When the ball is in the center, there is no feedback.

Feel the Fan. In our "Feel the Fan" application shown in Fig. 7, the backward torque cue and overall thrust are employed to simulate the sensation of the user's hand being pushed back by wind from a virtual fan. The participants held CrazyJoystick in front of them, with a virtual hand serving as their virtual embodiment in the scene. The torque and thrust applied to the user's hand are determined by the distance of the virtual hand from the fan. Let $d_{\text{hand-fan}}$ represent the distance between the hand and the fan. The maximum torque and thrust feedback occur at a distance of 0.1 meter from the fan, and the feedback diminishes as the hand moves away, becoming minimal at a distance of 1.5 meters.

The normalized distance d_{norm} is calculated as:

$$d_{\text{norm}} = \frac{d_{\text{hand-fan}} - 0.1}{d_{\max}} \tag{8}$$

where $d_{\text{hand-fan}}$ is the distance between the virtual hand and the virtual fan in meters, 0.1 m is the distance at which full torque and thrust are applied, and $d_{\max}$ is 1.4, calculated by furthest rendering distance 1.5 subtracted by minimum rendering distance 0.1.

The torque and force control vectoris then defined as:

$$\mathbf{I}_{\text{control}} = (0, (1 - d_{\text{norm}}) \cdot \tau_{\max}, 0, (1 - d_{\text{norm}}) \cdot F_{\max}) \tag{9}$$

where $\tau_{\max}$ is -1, representing the maximum torque feedback along the negative y-axis and $F_{\max}$ is 1, representing the maximum wind feedback.

As participants approached the fan, they experienced stronger sensations; conversely, increased distance resulted in diminishing feedback. We also only render feedback if the virtual hand is inside the cylindrical zone in front of the fan.

Rotate the Wheel The third application, shown in Fig. 8, simulates rotational torque associated with wheel rotation in a virtual environment. Our "Rotate the Wheel" application integrates both clockwise and counterclockwise cues to provide resistive feedback as users rotate a virtual wheel. Participants use wrist flexion and extension to rotate the CrazyJoystick, which renders counter-directional torque. The torque is controlled by the yaw angle of the wheel. Let θ_{yaw} represent the yaw angle of the virtual wheel, with θ_{neutral} as the neutral or reference yaw angle. The torque feedback is proportional to the deviation from the neutral angle.

The control vector $\mathbf{I}_{\text{control}}$ is calculated as:

$$\mathbf{I}_{\text{control}} = (0, 0, b_\tau \cdot \omega_{\text{yaw}}, 0) \tag{10}$$

where ω_{yaw} represents the angular velocity of the CrazyJoystick measured in degrees per second (°/s) and $b_\tau = 0.01$ is a constant factor that determines the strength of the torque feedback. The torque τ_z is applied around the z-axis, proportional to the deviation from the neutral yaw angle. This ensures that as the user rotates the joystick clockwise or counterclockwise, a corresponding torque is applied, providing resistance to simulate the feel of rotating a virtual wheel.

Returning Joystick The completion of the interaction is denoted by time in our interaction, but it could easily be swapped with another trigger. Upon receiving the return signal, the ground station initiates a three-phase transition sequence. First, the system switches from haptic rendering to position control mode through a commanded state change. Then the device executes a precise 20cm vertical displacement from the user's hand position, ensuring safe disengagement, before autonomously navigating to a designated launch position using position-based control. We validated this return protocol through a pilot study (n=3) focusing on system reliability during the transition sequence. Participants were instructed in the proper release procedure and completed 10 sequential trials

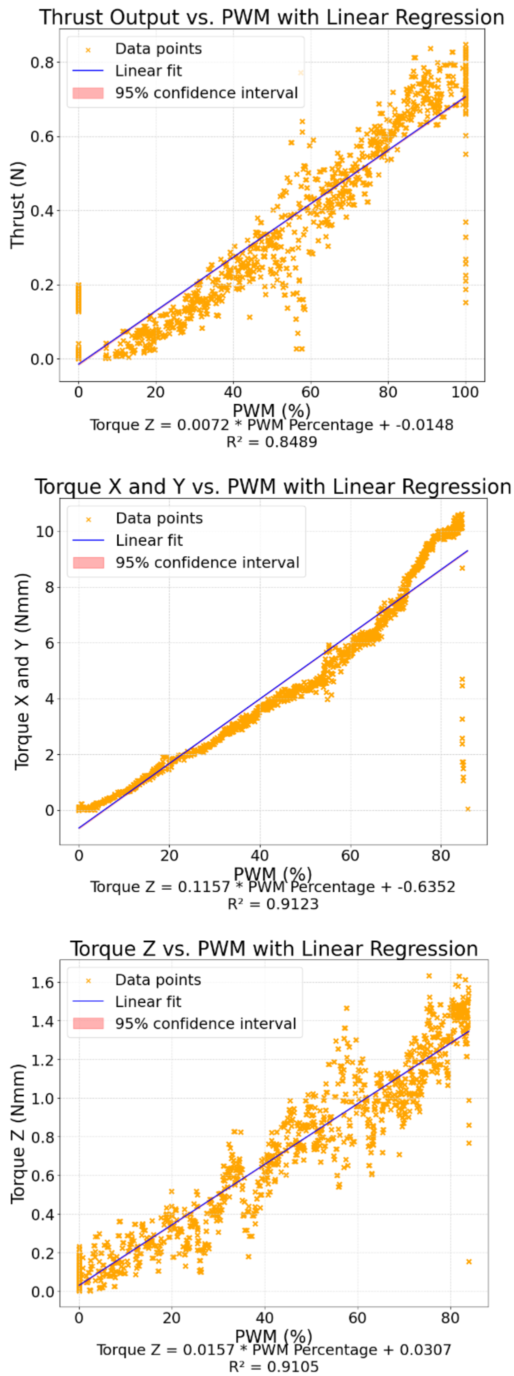

Fig. 9. Thrust and Torque Characteristics vs. PWM Input

each. The study achieved a 100% success rate across all 30 trials (3 participants × 10 trials), demonstrating the robustness and usability of the return mechanism.

IV. Device Evaluation

1) Hardware Evaluation: We measured the force and torque output of the device to determine the magnitude of the torque and force that the user would feel. In a real interaction, the user would hold the device by the gripper, allowing the system to exert force on their wrist joint. We evaluated CrazyJoystick by attaching the gripper to a Nano-17 force-torque sensor (ATI Industrial Automation) and actuated the drone in all 3.5 degrees of freedom. The maximum x and y torques are achieved by turning the thrust of the motors on the other side. The maximum z torque is achieved by turning on opposing motors. The maximum z force is achieved by turning all the motors. From the measurements, the maximum force CrazyJoystick provides is 0.71 N when all four motors use maximum thrust. Note that the weight of our device is only 41.3 grams, meaning that its force-to-weight ratio is 1.7. The maximum torque in x and y directions are measured to be 10.5 Nmm, and 1.4 Nmm in z direction. We performed a linear regression fit on the force and data, mapping the PWM percentage to output force or torque, as shown in Fig.9. Additionally, we evaluated the ramp-up time from a PWM percentage of 0% to 90%, which yielded a ramp-up time of 98 ms. Although the ramp-up time is longer than the human perception threshold for haptic delay [32], we found that the system was very responsive to incremental changes in feedback level. We measured the noise level of the device using a noise meter (Tadeto) positioned 50 cm away, and found that the device produced 64 dBA of noise, compared to a background noise level of 43 dBA.

2) Software Evaluation: The software evaluation primarily focused on device latency on user perception of the interaction. We measured the end-to-end latency of a single update cycle, which includes: (1) user motion capture by the Vicon tracking system, (2) transmission of new data points to our ground control, (3) updating the virtual representation's position and orientation in the Unity application on the VR HMD, (4) sending the package back to the ground station, and (5) commanding propeller thrust to render corresponding feedback. We take the value of (1) to be 7 ms from the work of CrazySwarm [31], which employed a similar software and hardware setup to ours. Our direct measurements encompassed steps (2) through (5), yielding a combined latency of 60.17 ms for these steps. We determined that the estimated total latency for the complete cycle (steps 1-5) was 67.17ms. Although this latency is above the perceptible threshold for haptics [32], we did not notice any negative effects of this latency in our system in terms of stability or responsiveness.

V. Study #1: Perception Accuracy of Directional Feedback

This study assessed participants' ability to accurately identify the six directional cues provided by CrazyJoystick. This study was approved by the University of Southern California's Institutional Review Board under protocol UP-22-01007, and all participants gave informed consent.

A. Study Design

1) Setup: As shown in Fig.10(a), participants used their dominant hand to hold CrazyJoystick while seated in front of a desk. A wooden partition visually blocked the device. To minimize auditory cues from the propellers, participants

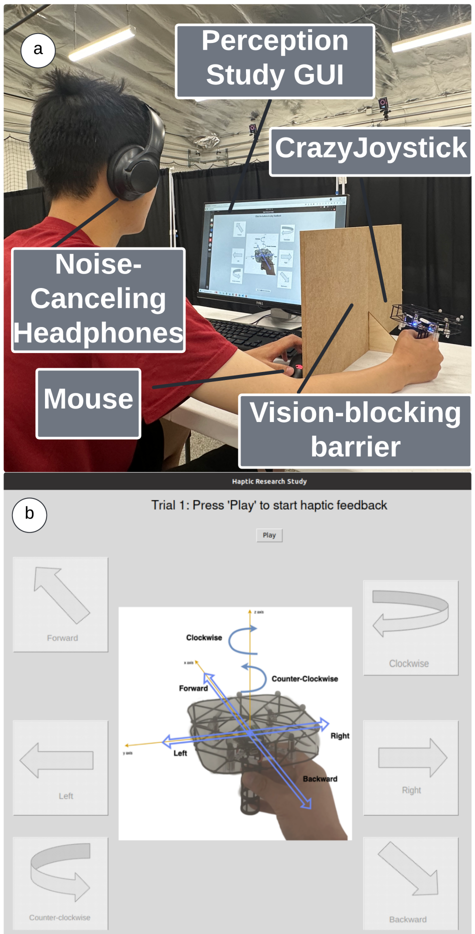

Fig. 10. (a) Perception Study Setup. A participant sits at a desk, holding the CrazyJoystick in their dominant hand while using their non-dominant hand to interact with the perception study GUI. (b) Perception Study GUI: The interface features six directional arrow buttons, a central play button, and a coordinate figure.

wore noise-canceling headphones (Soundcore Anker Life Q20) playing pink noise. They interacted with a graphical user interface (GUI) on a desktop monitor using a mouse with their non-dominant hand. The training session GUI consists of six arrow buttons to play corresponding directional cues. The test session GUI is similar but has one extra button to play directional cues, while the six arrow buttons are used to collect responses from users. In the center of both GUIs, a coordinate image is provided to help participants keep track of the orientation and coordinates of CrazyJoystick (Fig. 10(b)).

2) Task: The experiment consists of two phases. First, participants undergo a training session to familiarize themselves with CrazyJoystick's six directional cues. Following this, the testing session begins, consisting of 30 trials in which CrazyJoystick generates random directional cues for participants to identify.

The training procedure for this study was designed to thoroughly familiarize participants with CrazyJoystick's haptic feedback system. Participants were able to freely experience all six directional cues by clicking the arrow image button on the perception study GUI. Each time participants clicked the button, CrazyJoystick played corresponding directional cues; each cue lasted for 2 seconds. The duration of the training session was flexible, continuing until participants expressed confidence in recognizing all six directional cues.

The test session was designed to evaluate participants' ability to accurately identify the six directional cues provided by the CrazyJoystick haptic controller. The test session consisted of 30 trials. Each trial started when participants clicked the play button on the test session GUI. CrazyJoystick then displayed a random directional cue (forward, backward, left, right, clockwise, or counter-clockwise) for 2 seconds. Participants were allowed to play the cue multiple times before making their decision. Responses were recorded by selecting the corresponding arrow button on the GUI. The study was concluded after completing all 30 trials, with the entire study taking approximately 25 minutes per participant.

3) Participants: The study recruited 19 participants to evaluate CrazyJoystick. Due to technical issues, one participant was unable to complete the study. As a result, 18 participants (13 males, 4 females, 1 non-binary) with ages ranging from 19 to 54 years (M = 26.17, SD = 7.95). successfully completed all tasks. The final analysis and reported results are based on data collected from 18 participants who completed the study.

Seventeen out of 18 participants were right-handed and one participant was left-handed. Participants' prior experiences with VR and robotics varied. Most had limited (10) or no (4) VR experience, while some reported moderate (3) or extensive (1) use. Robotics experience was more evenly distributed, with participants ranging from no experience (4) to limited (7), moderate (3), and extensive (4) experience. Participation in the study was voluntary, and no compensation was provided.

B. Results

Fig.11 shows the mean accuracy and standard deviation for the six directional cues. The overall accuracy across all participants (N = 18) was 92.2% (SD = 7.5%). Fig.11 shows the accuracy and misclassification of six directional cues based on the responses of 18 participants.

VI. Study #2: Presence and Realism

A second study to evaluated the impact of CrazyJoystick's haptic feedback on users' sense of presence and perceived realism in VR applications. The study utilized Unity 3D for application development and a Meta Quest 3 as the VR HMD. Our experiment compared two conditions: CrazyJoystick with haptic feedback enabled (visual plus haptics) versus disabled (visual-only), which served as a baseline. We used the three applications described above: "Roll the Ball", "Feel the Fan", and "Rotate the Wheel" to test different aspects of haptic feedback and presence in VR. Our evaluation focused on: (1) assessing if CrazyJoystick's haptic feedback enhances the overall sense of presence in VR, and (2) determining if the haptic feedback improves the perceived realism of interactions. This study was approved by the University of Southern California's Institutional Review Board under protocol UP-22-01007, and all participants gave informed consent.

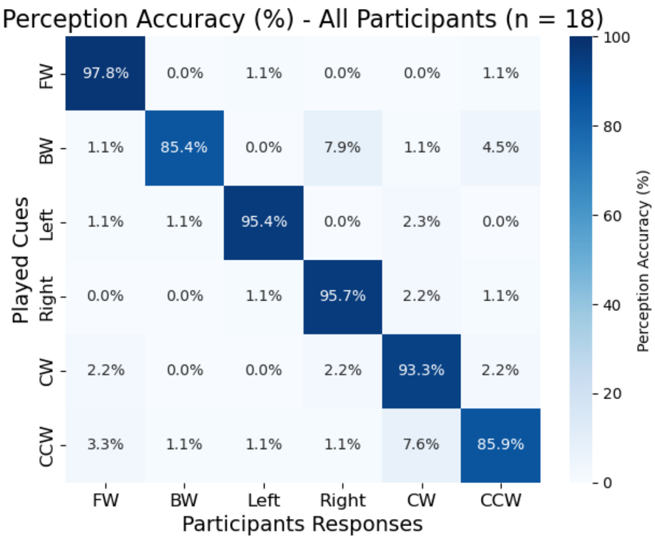

Fig. 11. **Perception accuracy (%) of directional cues (n=18n = 18 n=18).** Confusion matrix showing accuracy rates for Forward (FW, 97.8%), Backward (BW, 85.4%), Left (95.4%), Right (95.7%), Clockwise (CW, 93.3%), and Counterclockwise (CCW, 85.9%) movements. Off-diagonal elements represent misidentifications between directions.

A. Study Design

1) Setup and Experimental Conditions: Participants stood in a designated area wearing a Meta Quest 3 HMD and noise-canceling headphones playing pink noise to minimize distractions. During the study, users interacted with three Unity 3D applications on the HMD. The order of applications and haptic conditions was randomized for each participant, with the conditions counter-balanced across participants. Participants interacted with each application twice: once with haptics and once without. Each trial lasted 90 seconds.

2) Experimental Measures: To determine the effect of haptic feedback on the virtual interaction, we used a revised version of the Presence Questionnaire (PQ) [33], [34], which uses a 7-point Likert scale and measures presence through the six key factors in Table I. We modified the questionnaire by removing the auditory-related items, resulting in 21 questions.

3) Task: At the start of each trial, CrazyJoystick launched and hovered in front of the participant for 2.5 seconds. They then grabbed the 3D-printed grip, triggering the propellers to deactivate and the HMD to enter immersive mode.

In the "Roll the Ball" task, participants rotated their wrist using CrazyJoystick to tilt a virtual box, sliding a ball on the plane. The box's orientation was linked to CrazyJoystick's movement. In the "Feel the Fan" task, participants held CrazyJoystick vertically and received wind feedback based on their distance from a virtual fan. The virtual hand's position corresponded to CrazyJoystick's position. In the "Rotate the Wheel" task, participants rotated CrazyJoystick with their wrist to turn a virtual wheel. The wheel's rotation was directly controlled by CrazyJoystick's orientation.

After each trial, participants removed the HMD and completed a 21-question modified PQ on a touchscreen device.

TABLE I
SIX KEY FACTORS OF PQ

Factors	Number of Q	Description
Realism	7	The extent to which the Virtual Environment (VE) experience is consistent with real-world experiences
Possibility to act	4	The degree of control and responsiveness in the VE
Quality of interface	3	How much the control devices or display interfere with performance
Possibility to examine	3	The ability to closely observe and interact with objects in the VE
Self-evaluation of performance	2	How well users feel they performed in the VE
Haptic	2	The quality of kinesthetic feedback and manipulation in the VE

Each participant completed all three applications under both conditions, totaling six trials. The order of the applications was counterbalanced across participants. The study took approximately 45 minutes.

4) Participants: The participants in Study #2 were the same as those in Study #1. Participants took a mandatory break of 5 minutes between Study #1 and Study #2 to mitigate fatigue.

B. Results

Fig.12 presents the subjective evaluation scores for the six Presence factors across three applications and two conditions. The score range for each factor varies based on the number of questions in the questionnaire and the use of a 7-point Likert scale. For example, Realism, composed of 7 questions, has a potential score range of 7 to 49.

We first conducted a Shapiro-Wilk test on the individual factor scores from the PQ and found that our data was not normally distributed ($p < 0.0001$). Therefore, to analyze the results, we conducted the non-parametric Scheirer-Ray-Hare test on the PQ scores with feedback condition and application as factors. Results showed that the Visual + Haptics condition received significantly higher ratings than the Visual Only condition for several factors, regardless of the application. The addition of haptics significantly enhanced perceived Realism ($H = 23.1954, p < 0.0001$), Possibility to act ($H = 9.5228, p = 0.0020$), Possibility to examine ($H = 7.2443, p = 0.0071$), Self-evaluation of performance ($H = 4.6211, p = 0.0316$), and Haptic ($H = 40.7740, p < 0.0001$). However, the Quality of interface showed no significant effect ($H = 0.2655, p = 0.6064$).

In terms of application type, a significant difference was found only for the Possibility to act ($H = 6.8110, p = 0.0332$). Post-hoc analyses using Dunn's test with Bonferroni correction revealed significant differences between "Roll the Ball" and "Feel the Fan" ($p = 0.032$) and between "Feel the Fan" and "Rotate the Wheel" ($p = 0.240$) for this factor. No significant effects of application type were observed for

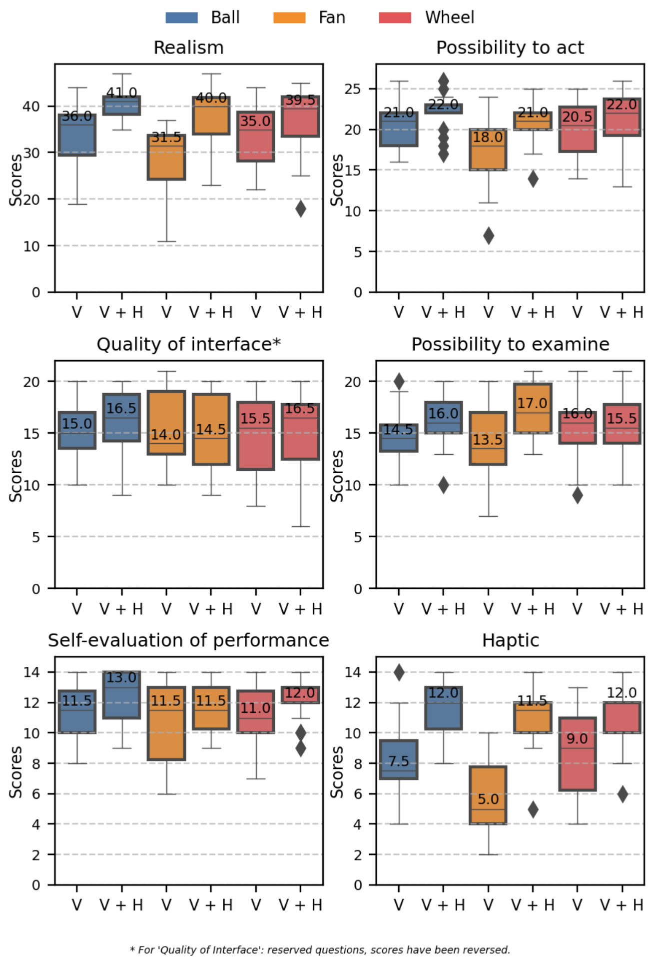

Fig. 12. Participants' perceived presence and realism in all three VR tasks (ball, fan, and wheel) for all six factors, where "V" represents Visual Only condition and "V + H" represents Visual plus Haptics condition. Our device showed improvements across most key metrics, notably in Realism, Possibility to act, and Haptic, with Quality of interface and Self-evaluation of performance exhibiting more variable but generally positive trends.

Realism ($H = 5.8684, p = 0.0532$), Quality of Interface ($H = 0.9603, p = 0.6187$), Possibility to examine ($H = 0.0224, p = 0.9889$), Self-evaluation of performance ($H = 1.2488, p = 0.5356$), or Haptic ($H = 4.5397, p = 0.1033$). These results suggest that, while the nature of the applications influenced the perceived ability of participants to interact, user experiences and perceptions were relatively consistent across the different applications for most factors.

VII. Discussion and Applications

Overall, our results show that CrazyJoystick is an effective haptic joystick interface despite its compact size. On its own, CrazyJoystick can render directional feedback at high accuracy using its propeller thrust. When combined with VR, its haptic feedback significantly enhances the VR experience across multiple presence factors. The device's effectiveness was consistent across different applications, suggesting its versatility in various VR scenarios.

A. Directional Feedback

Study #1 indicated that CrazyJoystick can deliver high accuracy directional cues, with an accuracy of 92.2%. The post-study interviews conducted with participants revealed that the system was generally well-received and effective in rendering directional cues. Most participants reported success in distinguishing most directional cues, particularly for linear movements. As P8 noted, "I felt the left and right motions were very pronounced, and so were the front and back." However, challenges were observed with rotational cues, indicating a need for enhancement in this area. P9 reported, "Rotation about z definitely provided the most confusion," while P18 found that "Clockwise and counterclockwise are a little hard." These difficulties can be attributed to the CrazyJoystick's limited torque capabilities around the z-axis, which are significantly less than those on the x and y axes.

Among the directional cues, forward motion demonstrated the highest accuracy, while backward and counter-clockwise movements showed relatively lower accuracy. The reduced accuracy for backward motion may be attributed to the limited angle of motion in radial deviation. The lower accuracy for counter-clockwise rotation is likely due to the CrazyJoystick's limited torque around the z-axis.

B. Presence and Realism

Study #2 showed that CrazyJoystick is an effective haptic rendering device that increases users' presence and realism in VR. Following completion of all study tasks, participants were asked to rate how easily they were able to detect haptic feedback throughout their experience. Participants reported an average ease of detecting haptic feedback of $5.67 (SD = 0.88)$ on a 7-point scale, indicating that CrazyJoystick's haptic feedback can be easily perceived. Although the latency exceeded the minimum detectable threshold, no participants reported perceiving any delay in the haptic feedback.

Participants were also asked to provide qualitative feedback on their experience with CrazyJoystick in the second study. Overall, users found the device intuitive and effective in enhancing their VR experience. For instance, P2 stated, "I think that it's fairly intuitive. It was easy for me to use. It was something small, lightweight, and offered pretty nice haptic feedback to me." Similarly, P3 remarked, "It can be useful and enhance the game experience."

When asked about the haptic feedback, many participants highlighted its ability to increase presence and realism. P2 noted, "I like the fact that it can fly to the user and be used in diverse applications." while P6 said, "The haptic feedback made the virtual world feel more interactive, improving the experience."

Regarding favorite applications, preferences varied, but many participants found the ball game particularly engaging. P2 explained, "I think that my favorite application is the ball rolling on the square platform. I prefer it because it was very well done within VR and the haptics implementation was very easy to feel." P11 echoed this sentiment, stating, "I prefer the ball games since I can interact with the ball and sense the

Fig. 13. CrazyJoystick in flight simulation. Left: The user pitches CrazyJoystick downward to command a virtual helicopter forward, experiencing a counter-torque pitching upward. Right: CrazyJoystick held in neutral position maintains the virtual jet aircraft's current motion, providing subtle wind feedback to enhance realism.

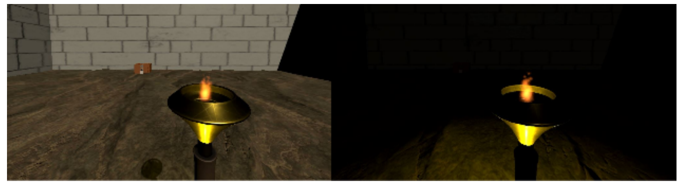

Fig. 14. CrazyJoystick in treasure hunt. Left: Treasure room with lights to showcase the virtual scene. Right: Gameplay view: the magic torch illuminates only the immediate surroundings in the dark environment, while providing torque feedback to guide users toward hidden treasure chests.

haptic feedback much more." The fan application was also popular, with P6 noting, "The feeling of getting closer to the fan in a virtual setting while physically feeling the wind is a surreal experience."

Participants also offered suggestions for improvement. Several mentioned enhancing the strength of the feedback, with P1 suggesting, "If possible, could make more force feedback to me." P4 recommended, "Improve the textures of handle" Some participants noted challenges with specific movements, such as P5 who said, "I think for clockwise and counter clockwise the feedback is not obvious." Some participants stated the noise from propellers might be distracting. P16 stated, "It could be better with less sound from the device."

C. Applications

Leveraging CrazyJoystick's unique capabilities, including its ability to render 3.5 DoF feedback, transition between flying and haptic rendering modes, and provide wind feedback, we developed additional scenarios to demonstrate its effectiveness and potential for future implementations. These applications showcase CrazyJoystick's distinct advantages in providing on-demand, ungrounded haptic feedback. Our applications draw inspiration from related work [4], [27], while showcasing the unique capabilities and strengths of CrazyJoystick in improving virtual reality interactions. CrazyJoystick's existing design allows for these additional applications without requiring any hardware modifications.

1) Flight Simulation: Building on CrazyJoystick's ability to render torque-based interactions and wind feedback, we developed a flight simulation application. CrazyJoystick provides torque feedback that corresponds precisely to aircraft movements in the virtual environment. The system renders torque along all three axes (x, y, and z) by dynamically adjusting the thrust of its four propellers, providing a seamless correspondence between the virtual aircraft's orientation and the physical feedback experienced by the user. Fig.13 illustrates how CrazyJoystick provides kinesthetic feedback in a VR flight game. The system adapts to different aircraft types by modulating thrust output, ensuring that the kinesthetic feedback aligns closely with the virtual plane's response, and creates the illusion of using a real joystick.

2) Navigation: To demonstrate CrazyJoystick's potential as a haptic guidance system [27], [35], we developed a VR treasure hunt game that showcases its yaw-based interaction capabilities. This application highlights the device's ability to provide intuitive directional cues through rotational feedback. CrazyJoystick functions as a magic torch in a dark virtual environment, illuminating only a small area around the player. Users must navigate through the darkness to find hidden treasure chests, relying primarily on haptic feedback from the device (Fig.14). CrazyJoystick provides directional cues through rotational torque feedback, where the intensity of the torque indicates proximity to a treasure chest, and its direction hints at the chest's location relative to the player. This game demonstrates CrazyJoystick's ability to offer intuitive haptic navigation in visually limited environments, enhance immersion by simulating a magical object with kinesthetic feedback, and complement restricted visual information.

VIII. Conclusion and Future Work

This work presented an on-demand handheld haptic feedback system which can provide haptic feedback that significantly increases user's presence in VR and is easy to perceive. Our system effectively delivered haptic feedback and received numerous positive responses from participants. Despite the small magnitude of force and torque, we showed that a nanocopter system could be used to provide haptic feedback, and that such on-demand haptics can increase realism without requiring the user to carry the weight until the game interaction. By allowing the interaction methods to change, we achieved a force-to-weight ratio of 1.72, 5.34 times of previous multi-rotor haptic devices [20], [29]. It demonstrates the possibility of a remote haptic feedback system that can transition the interaction methods in the game, without disengaging the user from their VR experience.

In the future, we plan to improve the system by: (1) Increasing the magnitude of the thrust. Selecting a slightly larger quadcopter could enable higher amplitude of kinesthetic feedback without sacrificing safety and compact factor of smaller multi-rotors. (2) Increasing the degree of freedom of kinesthetic feedback. Quadcopters are limited to 4 DoF kinesthetic feedback, which lacks two DoFs in force output. Using a high DoF UAV such as an omnicopter [36] could increase the diversity of the haptic experience we could render. These changes would further enhance our system's ability to present realistic haptic feedback and diversify the rendering capabilities, making CrazyJoystick even more powerful.

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