AeroHaptix: A Wearable Vibrotactile Feedback System for Enhancing Collision Avoidance in UAV Teleoperation

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***Abstract*— Haptic feedback enhances collision avoidance by providing directional obstacle information to operators during unmanned aerial vehicle (UAV) teleoperation. However, such feedback is often rendered via haptic joysticks, which are unfamiliar to UAV operators and limited to single-direction force feedback. Additionally, the direct coupling between the input device and the feedback method diminishes operators' sense of control and induces oscillatory movements. To overcome these limitations, we propose AeroHaptix, a wearable haptic feedback system that uses spatial vibrations to simultaneously communicate multiple obstacle directions to operators, without interfering with their input control. The layout of vibrotactile actuators was optimized via a perceptual study to eliminate perceptual biases and achieve uniform spatial coverage. A novel rendering algorithm, MultiCBF, extended control barrier functions to support multi-directional feedback. Our system evaluation showed that compared to a no-feedback condition, AeroHaptix effectively reduced the number of collisions and input disagreement. Furthermore, operators reported that AeroHaptix was more helpful than force feedback, with improved situational awareness and comparable workload.**

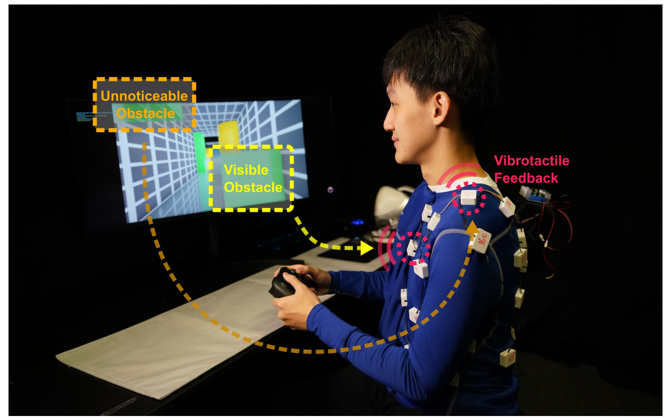

Fig. 1: AeroHaptix assists UAV operators with collision avoidance by delivering on-body spatial vibrotactile feedback about obstacle directions. Operators not only see and feel visible obstacles (yellow), but also perceive obstacles out of view (orange).

I. Introduction

[1]Unmanned aerial vehicle (UAV) teleoperation enables operators to pilot UAVs beyond their visual line of sight, enabling task completions in remote and hazardous environments. However, teleoperation is challenging due to the physical separation between the operator and the UAV, which limits the operator's ability to perceive obstacles and avoid collisions. To solve this problem, researchers have utilized haptic feedback and collision avoidance algorithms to convey obstacle information (e.g., parametric risk fields [1], time-to-impact [2], dynamic kinesthetic boundary [3], and control barrier functions (CBF) [4]).

Despite advancements in algorithms, the devices used to render haptic feedback are primarily haptic joysticks with three degree-of-freedom (DoF) force feedback [5]–[7]. While proven effective for collision avoidance [8], [9], they are rarely adopted for real-world operation due to the high cost of transitioning from standard radio control (RC) controllers. Their usage is also constrained to indoor settings as haptic joysticks must be surface-mounted to provide accurate feedback. Moreover, their limited information bandwidth confines force feedback to a single direction [4], [10], compromising situational awareness in multi-obstacle environments. Since haptic joysticks exert force feedback on the hand, the direct coupling of input and output channels impairs control precision, causing oscillatory behavior [9] and low user acceptance [11]. Alternative devices such as cable-driven exoskeletons [12]–[14] address mobility constraints but have limited degrees of freedom and introduce physical fatigue. Wearable devices like haptic gloves [15] and waistbands [16] permit intuitive hand-motion control, but have limited numbers of actuators and bandwidth.

To address these limitations, we designed a wearable haptic feedback system, AeroHaptix, that renders vibrotactile feedback at 32 upper body positions to convey obstacle directions. Since vibrations are delivered to the body, they do not hinder hand movement and can be seamlessly integrated with existing teleoperation workflows (i.e., RC controllers). We conducted a perceptual study with ten participants to map body positions to spatial directions and employed a neural network to optimize the layout of the vibrotactile actuators. We also designed *MultiCBF*, a novel collision avoidance algorithm that extends CBF to render multi-directional haptic feedback. Our evaluation showed that AeroHaptix effectively reduced collisions and input disagreements relative to a no-feedback condition. Participants also rated AeroHaptix more helpful than the force feedback method, with improved situational awareness and comparable workload.

II. Related Work

Of most relevance to the present research is prior literature on collision avoidance algorithms for UAV teleoperation and vibrotactile feedback to convey spatial information.

A. Collision Avoidance Algorithms

Collision avoidance algorithms were first used for unmanned ground vehicle teleoperation. In 1998, Hong et al. proposed an artificial force field to compute virtual forces from the potential fields of vehicles and obstacles [17]. Later, Boschloo et al. and Lam et al. adopted this concept for UAVs and developed basic risk field [18] and parametric risk field [1]. These methods reduced collisions but had difficulties navigating through narrow corridors. Brandt and Colton introduced time-to-impact and virtual string algorithms to compute virtual impact forces between a UAV and obstacles [2]. These algorithms reduced collisions and workloads but caused oscillatory movements in cluttered environments [9].

Alternatively, some researchers proposed algorithms that overrode user input with safer commands, such as dynamic kinesthetic boundary [3], [19] and obstacle avoidance system for teleoperation [20]. While these algorithms eliminated collisions, they reduced operators' sense of control and user acceptance. More recently, Zhang et al. proposed using control barrier functions (CBF) [4], which modified an input control signal to closely match the original while adhering to safety constraints. They also designed a haptic shared autonomy control scheme that enhanced operators' sense of control [8]. We extended their CBF algorithm to convey haptic feedback for multiple obstacles simultaneously.

B. Vibrotactile Feedback to Convey Spatial Information

Vibrotactile feedback conveys sensory information to humans via actuators that vibrate on the skin. Its utility has been demonstrated in various scenarios where spatial awareness is crucial, including headbands for locating 3D objects in virtual reality [21], [22] and wearable actuators aiding obstacle detection for blind and visually impaired users [23]–[25]. In robotics, vibrations have been used to indicate handover positions and robotic arm trajectories [26], [27], hydrodynamic flow near underwater robots [28], and obstacle positions around UGVs [29].

However, delivering obstacle directions during UAV teleoperation is challenging because it requires numerous actuators to precisely represent obstacle directions. Existing vibrotactile systems like TactJam [30] and VHP [31]) offer customizability but only support up to twelve actuators. In contrast, bHaptics X40 [32]) included more actuators but lacked flexible placement and body coverage. To address these limitations, we developed custom hardware to support high-density actuators with increased customizability.

III. AeroHaptix Hardware Design

To assist UAV teleoperation, AeroHaptix should:

- **R1**: support the fine-grained control of numerous actuators to distinguish obstacles from different directions;
- **R2**: support the reconfiguration of actuator layouts so actuators could be adjusted as needed; and
- **R3**: supports low-latency data communication (i.e., an end-to-end latency of less than 45 ms [33] and a chain communication latency of less than 20 ms [34] to ensure synchronized multi-point feedback).

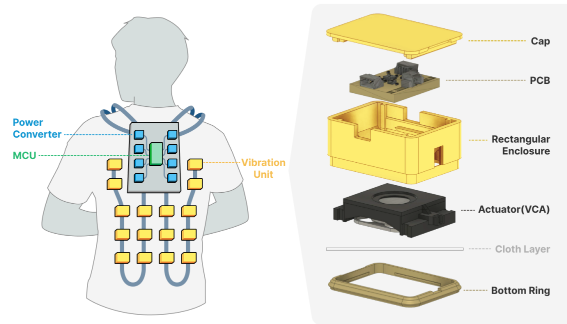

Fig. 2: Aerohaptix's hardware design, with an exploded view of a vibration unit.

AeroHaptix has a central unit and multiple chains of vibration units (Figure 2). Each vibration unit contains a 32 × 22 mm voice coil actuator (PUI Audio HD-VA3222), a custom PCB, and 3D-printed parts. The actuator covers frequencies from 80–500 Hz and reaches a peak acceleration of 2.52 Gp-p at 133 Hz with 1.5 V_{rms}. The PCB features a PIC16F18313 MCU and a DRV8837 H-bridge motor driver. It receives and transmits commands via UART and generates waveforms. Upon receiving a *start* command, the MCU drives the actuator with fine-grained control (**R1**) over 16 intensity levels and 8 frequencies. The 3D-printed parts include a cap and an enclosure for stability, and a bottom ring that attaches vibration units to garments (**R2**) via pressed fit. The garment used herein is an off-the-shelf compression shirt, but the system can be easily adapted to other garments.

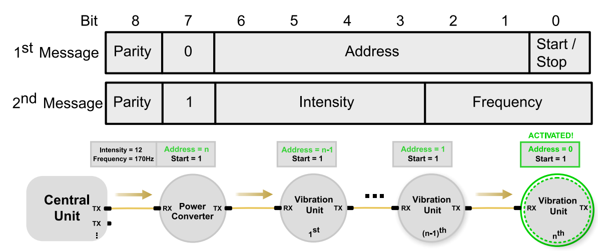

Fig. 3: The data transmission on each chain used a two-byte UART protocol. The central unit sent a command with address n, and each unit deducted the address by 1 until it reached the target unit.

To support low-latency feedback (**R3**), we designed a chain-connection topology and a custom universal asynchronous receiver-transmitter (UART) protocol (Figure 3). Each chain has a central unit, a power converter, and support up to 20 vibration units. The central unit receives Bluetooth commands from a PC, converts them to UART commands, and sends them along the chain. Each vibration unit examines the incoming UART commands to determine whether to execute them or forward them to the next unit. The UART protocol transmits two-byte messages at a baud rate of 115.2 kHz. The first byte contains the target unit address and a *start/stop* bit. The second byte contains vibration parameters (i.e., intensity and frequency). A technical evaluation found 5 ms of controller input latency, 1 ms of system processing latency, 14 ms of Bluetooth latency, and 2.5 ms of chain communication latency. Thus, the end-to-end latency was 23