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Extension of Wearable Olfactory Display for Multisensory VR Experience

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Abstract

An olfactory display is a device that allows users to experience a range of olfactory stimuli. Despite its potential to enhance user experience, challenges remain, including limited odor variety, unwanted odor persistence, constraints on continuous operation, and a restricted range of scent generation. We propose a novel wearable olfactory display that incorporates up to eight odor components to expand the variety of generated scents. Additionally, the device integrates an airflow control system, deodorant filtering, and optimized electrical and mechanical structures. This design aims to provide a more immersive user experience in virtual reality (VR) environments by significantly improving the generation of olfactory stimuli.

CCS Concepts

• ***Human-centered computing*** → ***Systems and tools for interaction design;*** • ***Hardware*** → *Displays and imagers;*

1. Introduction

It has been revealed that olfaction is closely linked to human emotion, memory, etc. [SLM*11]. However, unlike the widespread use of diverse human-computer interface devices in the visual, auditory, and sometimes haptic fields, olfactory interaction remains relatively uncommon. As one of the key human senses, it is believed that the integration of olfactory stimuli into VR environments could significantly enhance user experience and immersion [Nak25]. To facilitate the delivery of olfactory information, the concept of olfactory display has been proposed, which is a gadget that can release one or more target odors to the user. Although the first attempt to present odor could date back to the 1960s with the early work of Heilig et al., several obstacles still hinder their practical application [Hei62].

The primary challenge is the complexity of odor generation due to unclear perception mechanisms stemming from intricate chemical reactions. Unlike visual displays, which can blend primary colors to create arbitrary stimuli, olfactory devices often rely on pre-stored scents with limited capacity for generating new scent. Lukasiewicz et al. introduced an integrated wearable olfactory display, but it was limited to two odor sources [LRS*24]. Covinton et al. extended this capacity to eight in their device, but it still lacked the ability to generate new scents [CAT18]. Addressing this limitation, some researchers indicated that a wide range of scents could be produced by precisely mixing a small number of odor materials according to a specific recipe [PN24]. Building on this concept, we propose a multi-channel device capable of covering a broader range of target odors beyond the initial ingredients.

Even with extended blending capabilities, olfactory displays are still constrained by the small number of stored odor materials, limited by internal space and redundant channel designs. Desktop olfactory displays can store more odors due to their larger size, such as the 20-channel system by Iseki et al. [IPYN22]. However, they are unsuitable for VR due to their longer scent delivery delays and the stationary nature that restricts user's movement. In contrast, wearable designs, like Niedenthal's graspable device [NFL*23] and the HMD-integrated display developed by Nakamoto [NHH20], typically can reduce scent travel time [BML*22]. However, these wearable solutions accommodate only four odor channels, continuing to face storage constraints. This limitation arises from that every odor channel needs separate storage, delivery, and generation items, without any shared items. Although Liu et al. proposed a mask-type olfactory display capable of accommodating up to nine odor materials [LYZ*23], each channel required a separate heating generator, which risked desynchronization in odor delivery and compromised the ability to blend scents effectively because of the varied distance between the heater and user's nose. In contrast, our proposed device uses a centralized, shared odor generator, reducing space requirements and improving blending accuracy. While the current prototype supports eight odor components, it allows room for further expansion in the future.

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Furthermore, olfactory displays often face the challenge of odor persistence, where remnants of a previous scent linger after switching, causing unintended mixing and user confusion. Ideally, each scent should dissipate immediately before the next is released. Prior research suggests that actively suctioning scented air across the nose can minimize this persistence [KN19]. Our proposed system enhances this approach with stronger suction capabilities, ensuring reliable performance even with high-concentration scents. Heat management is another critical challenge, especially in wearable devices where components are densely packed. The accumulation of heat restricts continuous operation times and risks device reliability. In this study, we optimize heat dissipation structures and electrical systems.

This paper introduces a wearable olfactory display capable of blending up to eight ingredients, addressing limitations in blending capability—a feature lacking in most existing wearable olfactory displays, odor persistence, and heat management. This innovation enhances immersive VR experiences by enabling more complicated olfactory interactions.

2. System concept

The schematic diagram of our system is illustrated in Figure 1. This system includes eight liquid odor components, carefully selected to cover as wide a range of target scents as possible. In addition to determining the initial odor ingredients, precise control over the proportions of each ingredient is also a crucial factor that influences the accuracy of the generated scent. To achieve this precision, our design incorporates electroosmotic pumps (EO pumps) and micro dispensers. Their coordinated action enables nanoliter-level control over the volume of each blended odor component. The mixing process takes place on the surface of a surface acoustic wave (SAW) device, which can atomize the mixture instantaneously.

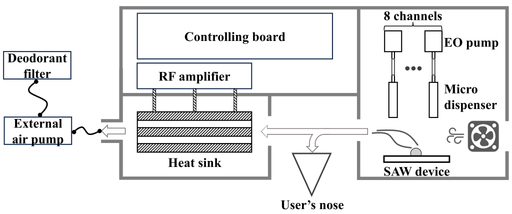

Figure 1: *Schematic diagram of the proposed wearable olfactory display. The PC communicates with this system is not shown in figure.*

Once the target odor is generated, an airflow control system, including a DC fan and an air pump, ensures the timely delivery of the generated odor to the user's nose while also directing any uninhaled scented air to a deodorant filter. This design effectively prevents odor persistence and diffusion. Additionally, an RF amplifier powers the SAW device; however, since it generates significant heat during operation, it is placed within the airflow path and paired with a heat sink to help dissipate the heat and avoid the overheating problem.

All the action above is controlled by a field programmable gate array (FPGA) board, which communicates with a PC via universal asynchronous receiver transmitter (UART) connection. To support the hardware, a debug tool based on MATLAB and a VR application developed in Unity were created. The controllability and feasibility of the proposed device were validated using these software tools, demonstrating its potential for a wide range of VR applications.

3. Technologies

3.1. Micro dispenser

The micro dispenser is a type of solenoid valve that ejects droplets in several nanoliter volumes through the reciprocating motion of an internal plunger. Figure 2 illustrates the three steps of this motion: moving backward, holding on momentarily, and moving forward. This motion is typically driven by a 24V pulse with a 1ms duration as illustrated in Figure 4. By manipulating the frequency of the driving signal, we can achieve the control over the proportion and the intensity of each odor component.

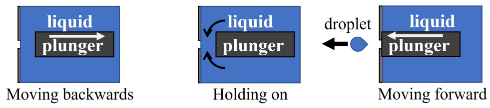

Figure 2: *Ejection steps of the micro dispenser.*

3.2. EO pump

The volume of the droplet ejected by the micro dispenser is related to its flow rate as well as the ejection frequency. The EO pump is adopted to regulate the flow rate and also serves as the containers for the odor components. This pump operates based on the electroosmotic effect, in which fluid movement is induced by an electric field applied across a charged capillary surface, causing ions in the fluid to move and generate bulk flow. Consequently, the flow rate of the EO pump varies with the applied voltage. By connecting the EO pump and the micro dispenser with a Teflon tube and carefully matching the flow rate to the ejection frequency, we can achieve stable and precise control over the droplet volume.

3.3. SAW device

The SAW device is one of the representative methods for odor generation, consisting mainly of a pair of interdigital transducers (IDT) formed on a piezoelectric substrate (128° rotated Y-cut LiNbO3) which generates SAW with high power owing to its high electromechanical coupling coefficient. When driven by an RF E-class amplifier with small heat dissipation due to its high efficiency, the IDT emits a SAW that interact with the liquid on the substrate's surface and atomizes it forcibly using the acoustic streaming effect, as shown in Figure 3. Compared with heater or wind evaporation methods, the SAW device offers high controllability and odor releasing performance even in case of low-volatile odors effectively. Here we need a 9.6MHz SAW device because the atomization efficiency for low-frequency SAW device is high.

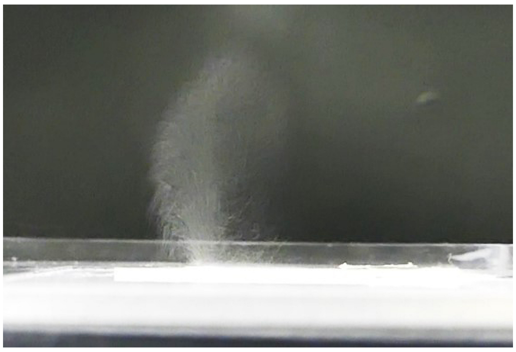

Figure 3: *The atomization process of 3ul ethanol. The contrast of the image was increased by 40% to enhance the visibility of the atomized ethanol particles.*

4. Setup and optimization

4.1. The driving signal of the micro dispenser

In typical operation, the micro dispenser is driven by a pulse signal. To evaluate the concentration control capability of the proposed device, in a preliminary experiment, a photoionization detector (PID) (ppbRAE3000 by RAE Systems) was utilized to measure the odor concentration of the released substances. The result shows that by adjusting the ejection frequency and ejection duration, it is feasible to effectively control the intensity of the emitted odor.

However, during high-frequency ejection operations, significant heat buildup was observed around the core part of the micro dispenser. This thermal accumulation can potentially affect the volume of the ejected droplets and, in some cases, may even cause damage to the device due to overheating.

To mitigate this issue, we replaced the pulse signal with an h-type signal as illustrated in Figure 4 by developing a dedicated driving circuit. The h-type signal consists of two voltage levels: 24V for the backward motion and 5V for the holding on step. Experiments demonstrated that this modification maintained consistent droplet ejection performance while significantly reducing heat generation by 42.7% during 6-minute tests at an ejection frequency of 100 Hz.

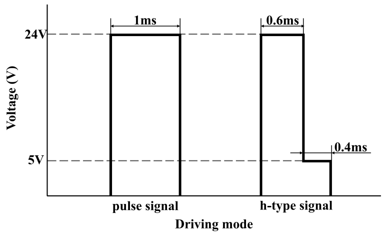

Figure 4: *Pulse signal and h-type signal for driving the micro dispenser.*

4.2. Heat dissipation of the RF amplifier

The RF power required to drive the SAW device in our wearable olfactory display is approximately 30W, supplied by an RF amplifier. While this power level ensures effective atomization, it also causes significant heat buildup within the amplifier circuit. This overheating poses a risk of damaging electronic components, even when a heat sink is utilized. The challenge is further compounded in wearable applications due to spatial constraints that limit the size of conventional heat sinks.

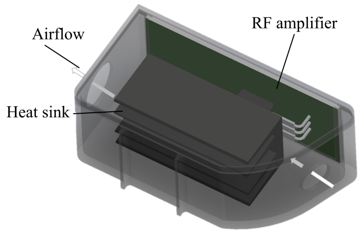

Figure 5: *Combination of the cooling system and the air flow system. The box is set to semitransparent to show the internal structure.*

To address this issue, we developed an exhaust chamber that integrates the airflow system for odor removal with the cooling system for the RF amplifier, as shown in Figure 5. By positioning the amplifier's heat dissipation component in the airflow path, the temperature rise was reduced by 52.6% during a 10-minute continuous operation, as shown in Figure 6. The initial test was terminated at 10 minutes in the absence of forced air cooling due to excessively high temperatures that could damage the circuit. In contrast, in case where forced air cooling was employed, the circuit was driven for an additional ten minutes. After a total of twenty minutes, the temperature was even lower than that reached without forced air cooling within three minutes. Therefore, with the optimized structure, the system is well-suited for olfactory content with frequent smell release, which typically requires for a long-time continuous operation.

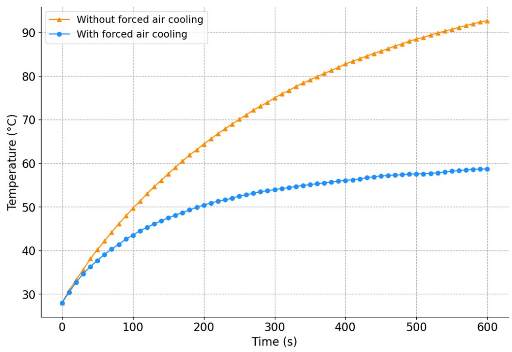

Figure 6: *Temperature rising of the RF amplifier circuit with and without the forced air cooling structure, measured by an infrared thermometer (THI-301S by TASCO).*

4.3. Prototype

We developed the structure of the wearable olfactory display as shown in Figure 7. A prototype was manufactured and attached to an HMD using a hook-and-loop fastener system, as illustrated in Figure 8. This attachment method allows the wearable olfactory display to be adapted for use with different types of HMDs by simply replacing the attachment structure. The weight of the prototype is around 360g. In current case, the liquid odor source containers are located in the extended part in front of the HMD, which can be opened separately. This design allows for easy replenishment of odor liquid without removing the entire wearable olfactory display from the HMD.

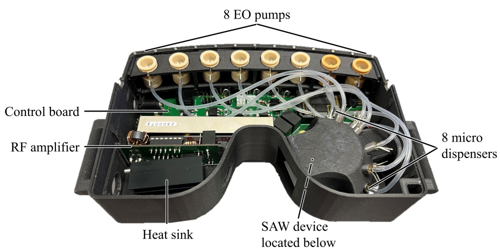

Figure 7: *Internal structure of the proposed wearable olfactory display. For clarity, all electrical connections are hidden, and only tube connections are shown in the figure. The lower right corner depicts the atomization chamber, which houses the SAW device and the DC fan.*

Figure 8: *The olfactory display integrated with an HMD. The external air pump and deodorant filter are not shown here.*

4.4. Application

A debug tool and a VR application were developed to evaluate the performance of the device. The VR application consists of multiple scenes, each containing several designated odor spots, as illustrated in Figure 9. When users focus their gaze on these spots, odors of specific types and intensities are released, synchronized with corresponding visual and auditory cues, to create a multisensory experience. In a preliminary experiment, users were able to perceive changes in odor intensity as well as the transition between different odors.

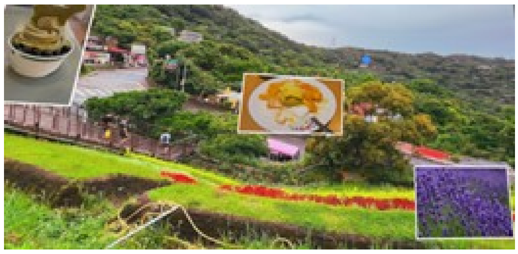

Figure 9: *One scene in the VR application includes odor spots marked by small icons representing scents such as oolong tea, mango, lavender, and others. The user can select and perceive these odors along with the visual and auditory stimuli.*

4.5. Limitations

During a series of preliminary tests, most participants reported perceiving the olfactory stimuli; however, some users were unable to perceive the stimuli effectively. This individual variation may be attributed to differences in olfactory thresholds. To ensure broader perceptibility, the intensity of each odor needs further adjustment. Additionally, the selection of the initial eight odor components requires careful consideration to balance a broader range of target odors with the accuracy of each generated scent.

5. Conclusion

In this paper, we propose a novel wearable olfactory display with odor blending capabilities. By incorporating multiple odor channels and precisely control the ratio of each odor components, the accuracy and range of generated odors can be effectively improved. Furthermore, we also addressed the overheating issues of both the RF amplifier and the micro dispenser through optimized design strategies, significantly enhancing the device's performance and reliability.

Base on the proposed hardware, we can make a variety of olfactory contents using a wearable olfactory display after optimizing odor components, which are currently prepared for odor reproduction by desktop olfactory display [IPYN22]. By integrating the merits of the wearable device, which allows users to move freely without being confined to a fixed position or posture, and the odor reproduction recipe that covers a wide range of generated odors using a limited number of odor components, we can offer a more flexible and immersive VR experience.

While a series of preliminary tests have been conducted, providing initial confirmation of the system's performance, the next step involves conducting a set of systematic experiments. As the first wearable olfactory display capable of blending up to eight odor ingredients, this device has the potential to significantly enhance user perception by delivering a broader range of generated odors within an immersive environment.

6. Acknowledgement

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