An open-source Olfactory Display to add the sense of smell to the Metaverse

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As the Metaverse gains popularity due to its use in various industries, so does the desire to take advantage of all its potential. While visual and audio technologies already provide access to the Metaverse, there is increasing interest in haptic and olfactory technologies, which are less developed and have been studied for a shorter time. Currently, there are limited options for users to experience the olfactory aspect of the Metaverse. This paper introduces an open-source kit that makes it simple to add the sense of smell to the Metaverse. The solution is modular, allowing for the simultaneous use of multiple odors and compatibility with both desktop and wearable applications. The details of the solution, including its technical specifications, are outlined to enable potential users to utilize, test, and enhance the project and make it available to the scientific community.

1 INTRODUCTION

There is currently no agreement among the scientific and industrial communities regarding the definition of the Metaverse. The popularity of this technology at the moment further complicates the search for a universally accepted definition. Initially, the concept was introduced in a science fiction book published in the 90s [1]. A recent book defines it as *"a massively scaled and interoperable network of real-time rendered 3D virtual worlds and environments which can be experienced synchronously and* *persistently by an effectively unlimited number of users with an individual sense of presence..."* [2]. To a certain extent, it can be argued that this definition encompasses a virtual environment that is collectively accessible through immersive Virtual Reality (VR) technology.

Despite several years of attempts to fully utilize the multisensory potential of VR, most examples still rely on a limited set of senses, namely vision and hearing. However, incorporating the sense of smell can significantly enhance the user experience by providing an additional dimension to the traditional senses of sight and hearing [3]. Looking back at one of the earliest examples of VR technology, the Sensorama, it is evident that the device was outfitted with an olfactory display [4]. Burdea and Coiffet in a popular book define VR as *"A high-end user-computer interface that involves real-time simulation and interaction through multiple sensorial channels (vision, sound, touch, smell, taste)"* [5]. So, to fully leverage the potential of the Metaverse when accessed through VR technologies, we need to dedicate efforts towards exploring and developing the less mature sensory modalities.

In particular, smells play a significant role in creating a more immersive, realistic, and engaging experience. Many studies demonstrate that when people smell something in real life, it can help to trigger memories [6] and emotions, and can also give them important information about their surroundings. For example, the scent of something burning may alert people to the presence of a fire [1]. Similarly, in VR settings, appropriate smells can add to the realism and immersion of the experience.

Smells can also influence an individual's behavior and mood, as they have a strong connection to memories and emotions [7, 8]. For example, lavender has a calming effect, while peppermint can improve focus and alertness [9]. However, the impact of smells on mood and behavior varies significantly from person to person, depending on cultural background and individual experiences with specific scents. Additionally, individual emotional responses to the same scent can vary, and personal experiences with certain smells can shape their emotional associations [10].

Overall, incorporating the sense of smell in VR is a challenging task that requires a comprehensive understanding of fields like biology, psychology, and engineering. Numerous efforts have been made to create Olfactory Displays (ODs) to stimulate the sense of smell, addressing various difficulties.

Initially, the sense of smell is mediated by an intricate system of receptors situated in the nose. These receptors detect odors in the surrounding and transmit signals to the brain, which interprets these signals and enables us to recognize various scents. Artificially replicating this process is challenging due to the intricate interaction between the odor molecules' physical properties and the olfactory system's biological mechanisms [11].

Factors such as the minimum threshold for scent perception, the distance from the source emitting the scent, and the persistence of the scent in the environment are crucial in creating an Olfactory Display. Additionally, the human olfactory system can detect a vast array of scents, and each scent can consist of a mixture of numerous compounds. This makes it challenging to recreate specific scents artificially. Hence, Olfactory Displays developed thus far have the capacity to replicate a limited number of specific odors [12]. For instance, an Olfactory Display can introduce four chosen scents, e.g., mint, orange, lavender, and chocolate, into the VR environment.

Studies have shown the use of various scents in VR environments to improve immersion and realism [13]. Moreover, research has been conducted on applying scents in VR to evoke emotions such as happiness, fear, warmth, and safety.

Researchers in engineering and psychology who want to explore the creation and perception of smells may find commercial odor-generating devices too expensive and rigid, leading them to build their prototypes instead. A DIY olfactory display can offer cost-effectiveness, design flexibility, and the ability to quickly make changes for further exploration and experimentation, offering more innovation opportunities than commercially available products.

We have developed an open-source kit, named Open-O-Kit, for integrating scent delivery into VR applications. The objective is to encourage practitioners and researchers to incorporate the sense of smell into their VR environments, enhancing the overall experience or conducting various tests. The open-source kit can be easily customized and enhanced to cater to specific applications. We provide comprehensive details of the final design along with relevant specifications that can be valuable for developers. Furthermore, we outline the methodology employed to measure these specifications, enabling developers to replicate the experiments on updated designs.

Resources and data are accessible in an open repository [2].

[1] https://spectrum.ieee.org/virtual-reality-smell

[2] https://github.com/virtual-prototyping-lab/olfactory-display-for-metaverse

2 OLFACTORY DISPLAYS

Olfactory Displays (ODs) are computer-controlled devices that produce and deliver scented air to the human sense of smell. This process involves generating scented air from odor materials and conveying it to the user's nose; this aspect sometimes requires specific design solutions as that described in [14]. The devices allow for control over timing and response to events in the VR environment. For example, they can be set to release the smell of baking cookies when the user enters a virtual kitchen.

Various methods for generating and delivering scents have been developed and utilized for a range of applications in the past decade [13]. Numerous research projects have utilized these technologies to create personalized and ubiquitous ODs for specific purposes. For instance, Kim et al. [15] developed an OD using temperature-responsive hydrogel in a container that can undergo reversible changes between sol and gel. Yamada et al. [16] created wearable ODs to convey the spatiality of smells in outdoor environments. Hirota et al. [17] designed ODs for multi-sensory theaters. Micaroni et al. [18] designed a directional olfactory device to study the integration of vision and olfaction in VR. Narumi et al. [19] developed a ”Pseudo-gustatory” olfactory display to produce a gustatory sensation, while Chalmers et al. [20] presented an innovative approach to simulate virtual flavors using food-safe chemicals, effectively replicating the taste, aroma, and mouthfeel of real flavors. More recently, Liu et al. [21] proposed a novel concept of skin-interfaced odor delivery utilizing compact and flexible odor generators, presenting an innovative method for olfactory stimulation. Additionally, some authors have developed applications that use scents to enhance users' attention and immersion in various contexts, such as improving the reading experience [9], enhancing the quality of users' experience of artworks [22], evaluating products [23], improving drivers' attention levels [24], and enhancing the immersion of eXtended Reality experiences. An extensive review of olfactory displays developed in research labs is presented in [12], where different classifications, locations, how the scent is delivered, etc., are proposed.

Some commercial ODs are today available on the market or have been announced. OLORAMA[3] is a device delivering up to 10 different smells in large spaces. inScent is a wearable olfactory display that can be worn in everyday mobile situations and allows the user to receive personal scented notifications, i.e., scentifications. The recent OWidgets digital smell technology [4] allows selecting the smells and their combinations and adjusting the directionality and the intensity.

Previous attempts to develop open-source ODs have been made. [25, 26] describe a cost-effective and simple OD specifically designed for desktop applications, with the capability to emit a single scent. In [27], a different open-source OD known as Hajukone is presented. This device utilizes ultrasonic transducers to enable the emission of multiple scents and can be worn on the chest. Javerliat et al. [28] present Nebula, a novel wearable solution designed to be seamlessly attached to various HMDs and capable of delivering up to two different scents.

However, while all the devices previously mentioned provide viable solutions for low-cost olfactory displays, each one necessitates a trade-off between portability and the number of odors that can be delivered. In our view, the OD introduced in this paper proposes a good compromise between portability and versatility. Its modular design allows for both desktop and wearable applications while offering extensive customization options. Moreover, the proposed OD can accommodate an expanded range of odors based on the specific requirements of the intended use case.

3 OPEN-O-KIT TECHNICAL FEATURES

This Section reports the main components of the open-source kit we designed and shared. It also outlines the instructions for creating this cost-effective, homemade Olfactory Display (OD) and provides all the necessary information for individuals to construct their devices. The device, named Open-O-Kit, is partially inspired by the design solution initially described by Rossoni et al. in [29].

The Open-O-Kit has the following characteristics:

1. Odor sources are essential oil diluted with water.
2. The odor intensity can be adjusted by changing the emission duty cycle.
3. The duration of the odor emission can be adjusted as well.
4. The odor generation technology used is based on piezoelectric atomizers.
5. The odor delivery technology is direct injection, meaning the release of scented particles in close proximity to the user's nose.
6. Type of OD: the version described in this paper is integrated with a VR headset, but the same technology can be used as a desktop version.
7. The current version of the wearable kit only allows using two odors. This limitation does not apply to the desktop version.

[3] https://www.olorama.com/en/
[4] https://ow-smelldigital.com/

3.1 Requirements

To achieve the intended Olfactory Display, the device needs to meet the following criteria:

1. *Portability*: the device should be small and lightweight, so it can be worn or carried around comfortably.
2. *Low power consumption*: the device should consume minimal power, so it can run on a small battery for an extended period.
3. *Controllability*: the device should be controllable to enable users to change fragrances and adjust the scent, intensity, and duration of delivery.
4. *Efficient scent delivery*: the device should be capable of delivering scents with high accuracy, precision, and consistency.
5. *Ease of maintenance*: the device should be easy to clean and maintain to ensure consistent performance over time.
6. *Accessibility*: the device should be accessible and affordable to a large population of potential users.
7. *Safety*: the device should be designed to ensure the safety of the user and others in the surrounding environment.

3.2 Components

The Open-O-Kit device includes a liquid atomizer module that consists of an ultrasonic transducer and a circuit board powered with $5V$ direct current[5]. Additionally, it is equipped with two atomizer sets placed on individual modules, allowing for easy modification to include a different selection and number of scents.

Open-O-Kit uses essential oils that are water-diluted and poured into the vertical component of the module enclosure. For the experiments described in this paper, commercially available fragrance liquids were employed[6]. These fragrance liquids were composed of propylene glycol, and the exact concentration of the scent components was not disclosed by the manufacturer. To evaluate the device, a water solution was employed, consisting of ten drops of the aforementioned fragrance liquid per milliliter of water.

Using this uncomplicated layout, the liquid ratios in the blend stay consistent. Nevertheless, while in operation, the emission pace can be altered to modify the strength of the sensation. This is achieved by transmitting a suitable command to the micro-controller unit, as explained in Section 3.3.

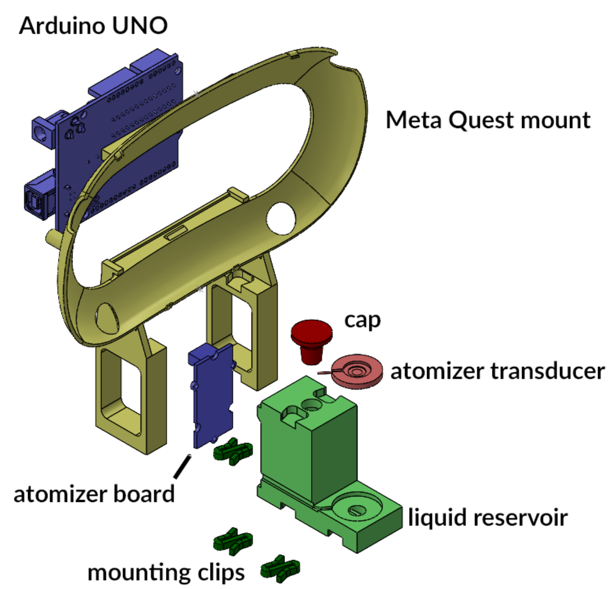

Fig. 1. Exploded view of the main components of the wearable device

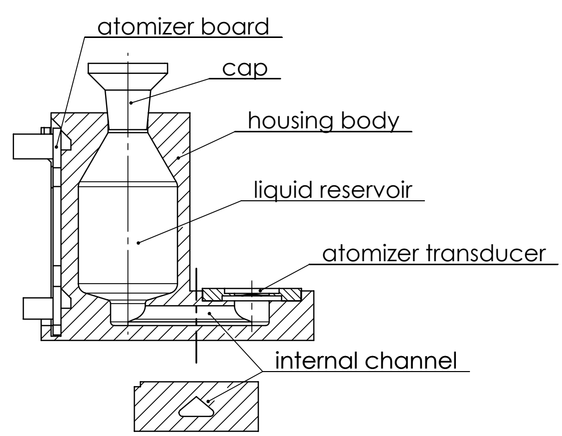

Fig. 2. Drawing of the main module with internal cross-section

The module's configuration is simple, mainly consisting of a 3D-printed piece. The mount for the ultrasonic transducer and the reservoir are merged into one component, which negates the requirement for any bonding or sealing materials that might produce leaks. Figure 1 illustrates the main components of the device, while Figure 2 illustrates how they are mounted.

The socket for the transducer is intentionally undersized to achieve a secure fit with the silicon seal included with the ultrasonic device. The other opening of the reservoir is closed with a cone-shaped cap, which is recommended to be printed with a flexible material such as TPU (Thermoplastic Polyurethane).

[5] https://wiki.seeedstudio.com/Grove-Water_Atomization/#specifications

[6] Products by FlavourArt: "Menta Piperita", "Limone Sicilia", and "Lavanda" https://flavourart.com/

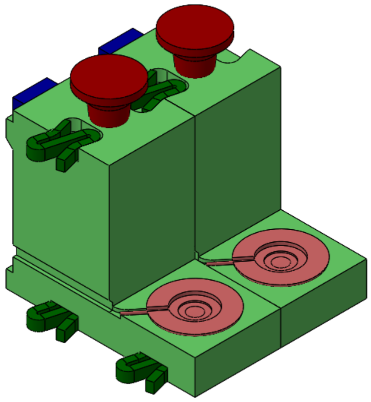

Fig. 3. Isometric view of a pair of two assembled modules. This configuration can be used in the wearable version and as a standalone solution for a desktop configuration

The inner volumes' layout, such as the reservoir and channel, has been fine-tuned to enable printing on a standard FFF (Fused Filament Fabrication) 3D printer. The most important adjustment was limiting most overhanging surfaces to $55\deg$ from vertical in order to print without any internal support structures. The mechanical design also incorporates mounting spring clips that enable effortless parallel connection of the modules without the need for any tools, as shown in Figure 3. A distinctive feature of this design, distinguishing it from other examples in the literature, is its remarkably minimal bill of materials. By utilizing a 3D printer, the only necessary purchases for replicating the device are the atomizer modules and a microcontroller board for their operation.

The module's design features a dedicated mount for the Meta Quest 2 headset, shown in Figure 4, that can snap onto the headset and be further secured with elastic bands. It can accommodate two scent channels placed directly below the user's nose.

3.3 Integration with VR, XR and desktop applications

The atomizers are controlled by an Arduino microcontroller board, which communicates with the computer via a straightforward serial protocol. Manual control is facilitated by sending commands in the form of an ASCII character in a single byte. A '0' digit turns off all channels, while any other digit activates the relevant channel.

The emission duty cycle can be adjusted in 10% increments by sending a letter between 'A' (10% emission time) and 'J' (constant emission). After each command is executed, a plain text response is returned. The device

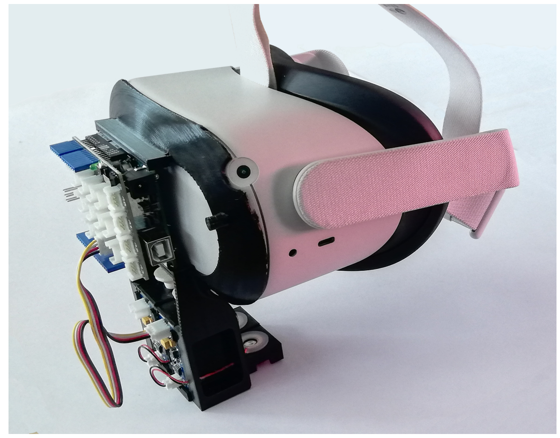

Fig. 4. How the wearable device is mounted on a Meta Quest 2 VR headset

can be managed manually through a serial console, like the Serial Monitor in the Arduino IDE, or a custom-made application, as explained in the user study.

A sample project has been made available for the Unity Game Engine [7], showcasing how to control the Open-O-Kit device from within the application.

The software developed for the project is publicly available as a GitHub repository[8]. The files include "sketch" for Arduino micro-controller [9], a graphical application used in the user study and the Unity example. Mechanical design is uploaded as a full assembly file for Solidworks 2022 [10]. All parts intended to be printed are additionally published on the Thingiverse[11] portal in STL format.

4 VALIDATION AND TESTING

We conducted two different tests, as explained in the following sections. The first test involved a Computational Fluid Dynamics (CFD) analysis to determine whether the design of our prototype allows the emitted scent to reach the user's nose. In the second test, we conducted a user study to investigate the time required for the user to perceive the emitted scent, the time required to detect a change in the odor, and the time required to stop perceiving the smell after this stopped being emitted. It is crucial for VR applications to know precisely when the user perceives the stimulus clearly, even if the scent particles reach the user's nose. Furthermore, it is

[7] https://unity.com
[8] https://github.com/virtual-prototyping-lab/olfactory-display-for-metaverse
[9] https://www.arduino.cc
[10] https://www.solidworks.com
[11] https://www.thingiverse.com/thing:5852014

essential to understand how quickly the user can detect a change in the emitted odor since some VR applications might require an immediate response.

4.1 CFD analysis

Simulating an Olfactory Display necessitates the consideration of a multi-phase fluid domain: the scent particles released from the device interact with the ambient air, which determines the prototype's overall functionality. Simulating a multi-phase fluid domain through Computational Fluid Dynamics (CFD) remains challenging due to the complexity of the phenomena involved. Various methods have been implemented to simulate the inertial response and the interactions among the phases [30]. Although few authors have explored the application of CFD in the realm of Olfactory Displays, the analysis proposed here is based on the authors' prior findings [29].

The simulation framework employs a Lagrange-Euler approach, where the Navier-Stokes equations are used to solve the continuum phase while the discrete particles constitute the second phase. One of the most notable methods for implementing this type of approach is the Discrete Particle Method (DPM) [31]. In this particular case, the particles are dispersed in the fluid phase, and various factors such as heat and mass exchange, collisions, break-up, and turbulence can be taken into account. The mist generated by a mesh atomizer is composed of droplets of liquid water suspended in the environment (in this case, air) [32]: it falls in the category of a gas-liquid "droplet flow" where the dispersed flows volume fraction is much lower than the continuum phase [33]. As the scope of CFD in this work is to predict how the mist propagates from the mesh atomizer to the user's nostrils, the DPM is the one that best suits the purpose of this research.

In order to account for droplet collisions and coalescence, the O'Rourke algorithm has been used [34]. Table 1 summarizes the main settings for the solvers.

Table 1. Main settings of the CFD solver.

Continuous Phase	realizable k-ϵ turbulence model;
	standard wall function
Discrete Phase	two-way DPM;
	unsteady particle tracking;
	stochastic collision, breakup and coalescence enabled
Solving schema	Second order coupled pressure-velocity coupling
	Algebraic Multigrid (AMG) scheme for the discrete phase
	Second order implicit time discretization
	Time step size: 5 ms
	No. iteration/time step: 100

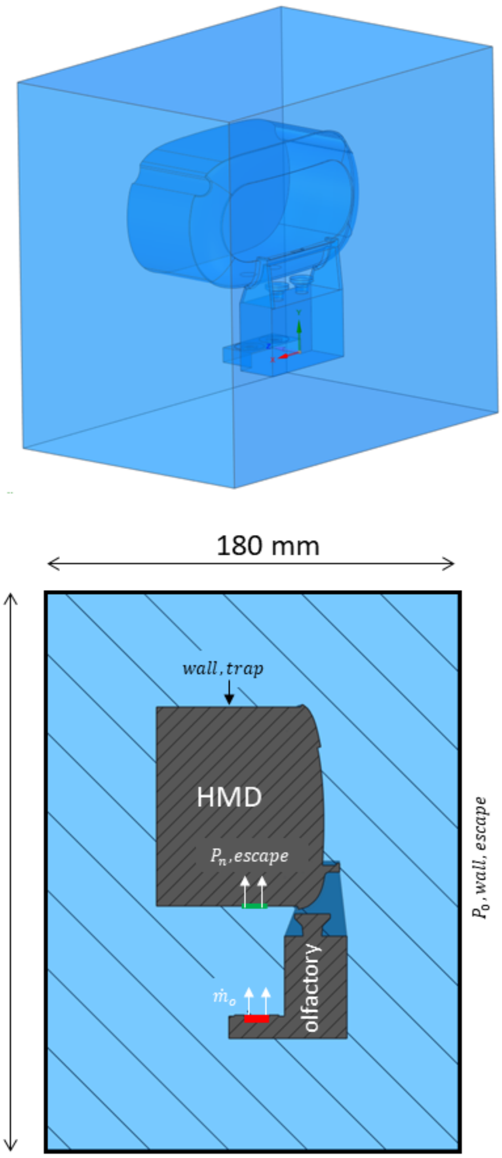

Fig. 5. On the top, Three-dimensional fluid domain. On the bottom, a section view where the fluid domain is depicted by the blue hatching, while the grey hatching represents the solid areas not included in the computational domain.

The fluid domain has been derived from the 3D models depicted in Figure 1. First of all, a defeaturing of the model has been carried out: all the small details that will not influence the results have been removed to facilitate the convergence of the model. The shape of the

HMD (Meta Quest 2) has been added to the 3D model and the nostrils have been simulated with two circular areas on the HMD itself. The fluid domain has been derived with a boolean operation between the 3D model just described and a cubic shape representing the environment. The final fluid domain is shown in Figure 5 by the blue hatching. The gray-hatched areas in Figure 5 - i.e. the HMD and the olfactory - are not included in the computational domain. The volume has been discretized with quadrilateral-dominant quadratic elements of 0,1 mm length inside the fluid region. A 10-layer inflation has been added to the walls: ten layers are generated with a growing ratio of 1.2, and a first-layer thickness of 10 μm. The mesh parameters have been determined after conducting a mesh independence study.

The air has been modeled as a compressible fluid with a density of 1.225 kg/m^3. The particles are injected from the surface of the atomizer (highlighted in red in the Figure 5): the particles have been modeled as inert, liquid water with a diameter is 10 μm [35]. To estimate the mass flow rate of the particle, the olfactory module was placed on a weighing scale and activated. Two atomizers were used to atomize 5 grams of water, which took 12 minutes and 10 seconds. The final estimate for the water atomization rate is 3.55 mg/s per atomizer, with a standard deviation of 0.361 mg/s based on samples taken every time the scale moves down by 0.1 g. In the CFD simulation, the injection has been set to last for 1 s with a total mass flow rate of $\dot{m}_p = 3.55 mg/s$. As one of the assumptions of the DPM model is that the velocity of the inert particles equates to the one of the surrounding flow, the mass flow rate of air at the inlet has been set equal to the particles' mass flow rate. The pressure at the boundaries of the domain has been set at $P_o = 0 Pa$, while in the area representing the nostrils, the pressure has been set at $P_n = -150 Pa$. This is the reference value [36] in the condition of quiet breathing. The rest of the boundaries are stationary walls. Regarding the boundary condition for the discrete phase, the inlet and the external boundaries allow the particle to escape the domain while the walls corresponding to the headset trap the particles.

The analysis was run on a workstation equipped with Intel Xeon E2650-v4 and 64 GB RAM and lasted approximately 8 hours. Figure 6 shows the particle velocity map at different time steps: despite the magnitude should not be taken as accurate, it can be noticed that the first particles reach the user's nose after approximately $25 ms$. Moreover, by estimating the concentration of particles at the atomizer and nostrils locations, the efficiency of the olfactory module can be estimated as the ratio between the particles exiting the fluid domain and the ones injected in. The Area-Weighted Average Discrete Phase

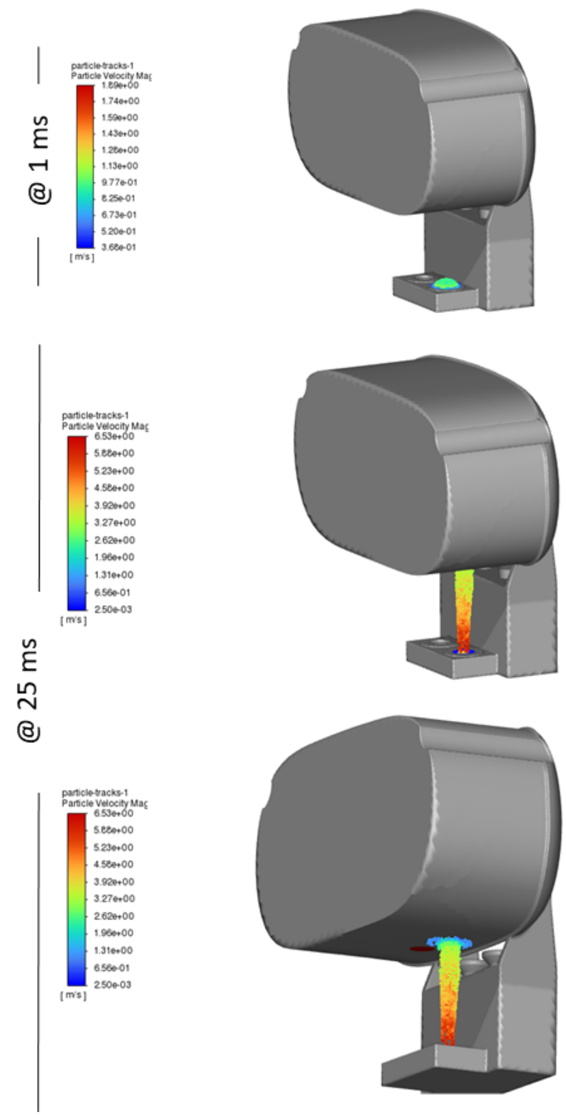

Fig. 6. Particle velocity magnitude at different time steps: the first particles get in contact with the nostrils at $25ms$.

Model Concentration has been recorded at the atomizer and the nostril locations, with values of 0.0445 kg/m^3 and 0.0147 kg/m^3, respectively. By computing the ratio between the two, the efficiency is estimated to be around 33%.

4.2 Device characterization

In order to evaluate the effectiveness of the device, a testing phase was conducted to measure the average users' response times to various aspects of scent emission. This included the time taken to perceive the first scent emission, the time required to detect a change in scent, and the duration it took for the user to stop perceiving a scent after it ceased to be emitted. The purpose of this assessment was to emphasize the advantage of employing a wearable device positioned in close proximity to the user's nose, as opposed to a stationary setup. This advantage lies in the device's ability to rapidly modify the perceived smell. The perceived intensity of a smell can be controlled by adjusting both the concentration of the odor agent in the emitted liquid and the modulation of the emission rate. Therefore, the reaction time was chosen as the most relevant measurement for assessing the capabilities of this device design, rather than the user's perceptual ability.

4.2.1 Procedure

As illustrated in Figure 4, the device was affixed to a Meta Quest 2 headset. The participants were instructed to press a button on the motion controller as soon as they detected a change in scent based on the instructions shown in the headset's view. The fundamental basis of this study was that the response time to scent changes reflects the ease of detection. Every "test cycle" consisted of the following steps:

1. User initiates the test;
2. Scent 1 is switched on;
3. Scent 1 is switched off, and scent 2 is immediately switched on;
4. Scent 2 is switched off.

A random delay, evenly distributed between 5 and 10 s, was inserted before each scent change. The delay started when the participant acknowledged the previous change. Each participant performed 10 cycles. The sequence of scents used for each participant was randomly generated with the constraint that 5 cycles started with scent A transitioning to B, and 5 cycles in the reverse order, making it counterbalanced between participants. During all trials, whenever a scent was emitted, it was done so in continuous mode with full intensity. A faint sound might be audible during device operation in some cases, but it was deemed not to impede its intended use. To limit sensory input to only smell, white noise was played continuously throughout the trial.

A graphical software was developed to simplify the testing procedure, and its source code is available in the project repository. The software can be used with a standard monitor and mouse and does not require a Virtual Reality headset. Participants were asked to provide the following information: gender, age, and their regular tobacco smoking habits. Participants had the option to skip answering each question.

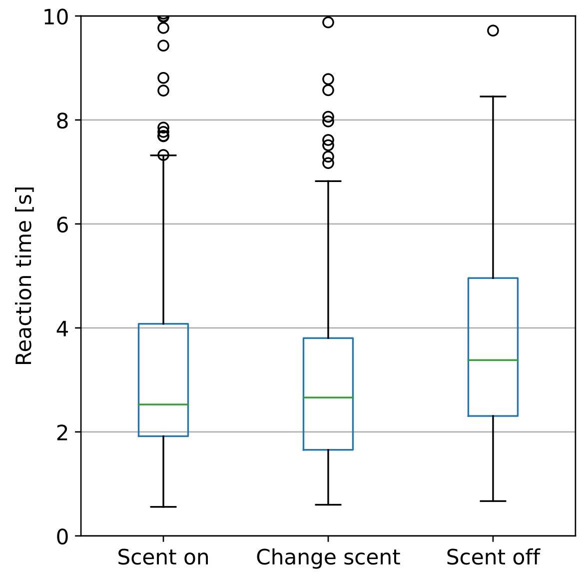

Fig. 7. Distribution of reaction time dependant on the event type. "Scent on" represents the time interval needed to perceive the scent upon initial delivery, "Change scent" represents the time required to detect a change in the scent, and "Scent off" corresponds to the time interval needed to stop perceiving the scent after after the emission has ceased.

4.2.2 Participants

The experiment involved recruiting 20 participants (13 male, 6 female, 1 non-disclosed) aged between 19 and 33 (M = 26.05, SD = 3.79), among university students. Prior to participating, the participants were provided with information about the study's purpose and objectives, and they confirmed they did not have any respiratory-related medical conditions. The same mint and lemon scents were used for all participants. Participation in the study was voluntary, and there was no compensation provided.

4.2.3 Results

In the experiment, only positive reaction times were considered valid for the participants. Any instances where the acknowledge input was pressed before the scent change were considered as mistakes. As such, they are not distributed normally about a central mean and median value but follow more closely a log-normal distribution. The scaled output of Probability Density Function (PDF) calculated for standard [37] log-normal distribution from natural logarithm of reaction time ($M = 1.11$, $SD = 0.742$) matches the samples quite well, as shown in Figure 8.

The bulk portion of experimental reaction time is centered around the median value, however, there are numerous extremely large outliers. For this reason, in this section, the graphical representation of the results will use box plots showing the quartile boundaries. The top end of *whiskers* is drawn to the highest sample falling in 1.5 times interquartile range (IQR) above Q3. This representation was chosen to improve the legibility of plots in presence of numerous high-value outliers.

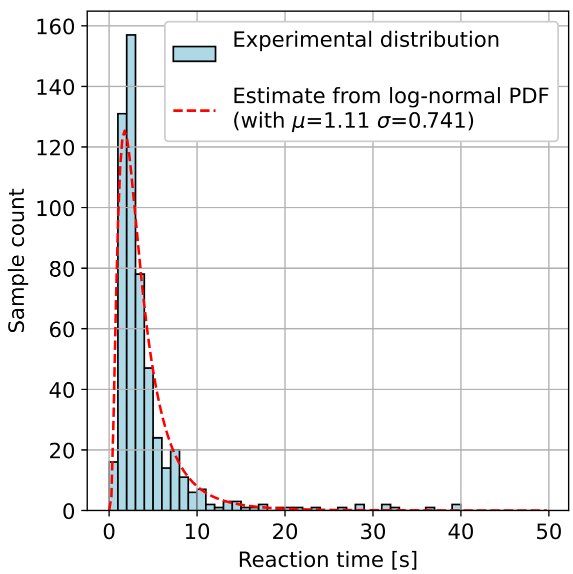

Fig. 8. Histogram of all reaction times with superimposed log-normal density distribution scaled by total sample count

Figure 7 shows that participants' reaction time to the initial olfactory stimulation was located between 0.56 and 39 s, with a median of 2.53 s ($M = 4.44$, $SD = 5.84$). Similarly, the time needed to perceive a change in the scent delivered was a median of 2.66 s ($M = 4.25$ s, $SD = 5.7$ s). Finally, the time interval required to stop perceiving the scent was around 3.38 ($M = 3.99$ s, $SD = 2.71$ s). However, there were no significant variations observed in the reaction times for the initial olfactory perception, the scent change, and the time it takes to stop perceiving the smell after the emission through the olfactory display is halted. In our testing procedure, we used two different scents, namely mint, and lemon, and we examined whether this had any impact on the participants' perceptions. As illustrated in Figure 9, the reaction times did not exhibit any significant differences based on scent, with only a marginally quicker reaction time observed when detecting mint scent change ($M = 4.09$ s vs 4.72 s, $SD = 4.42$ s vs 9.36 s).

Finally, unlike other reported results [38, 39], the

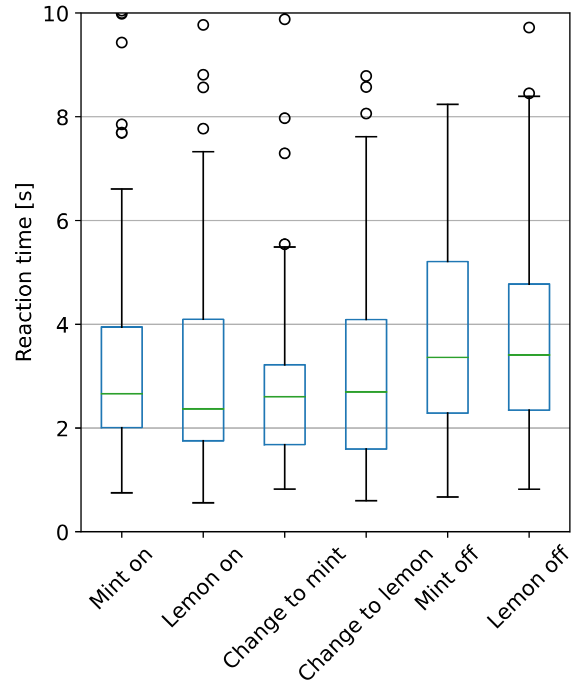

Fig. 9. Comparison of reaction time between scents in the study. No significant differences have been found between the two scents considered in the three stages of the user study (i.e. 'Scent on', 'Change scent', 'Scent off').

results of the user study did not reveal any statistically significant differences in reaction time based on participant characteristics (gender, age, smoking). The aforementioned studies were focused on evaluating the participants' sense of smell, using low concentrations of aromas on the verge of perceptibility. As per the feedback provided by the participants, identifying the scent became more difficult as the testing session advanced. Figure 10 illustrates the variation in reaction time based on the trial's cycle number. This had the most significant impact on the participants' performance and can be explained by a phenomenon referred to as olfactory adaptation or olfactory fatigue [40].

The consistent outcomes observed among different device users indicate that the method and intensity of odor dissemination are effective in consistently eliciting the desired response.

The reported results only consider valid reaction times, which means that participants acknowledged the scent change after it had actually occurred. There were 29 instances (5.11% of all reactions) where participants pressed the button too early. The occurrence of this mistake was fairly evenly distributed across the scents, with

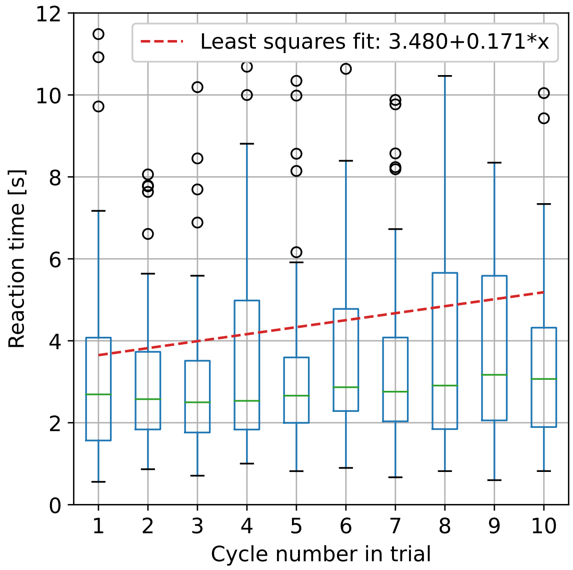

Fig. 10. Distribution of reaction time throughout test session

16 for one scent and 13 for the other, as well as across the types of scent changes to detect (7, 14, 8). The cycle number had the most significant impact on the mistake rate, with 11 (37.9%) of the mistakes occurring in the first cycle of the trial. In contrast, the number of mistakes in cycles 2 to 10 was much lower (M = 2.57, SD = 1.27). This finding contrasts with the measured reaction time, which generally increased as the study session progressed for each participant. Based on these observations, the authors attribute the mistakes mostly to accidental clicks and initial misunderstandings of the task explanation, rather than any perceptual phenomenon.

4.2.4 Limitations

While the overall design of the device successfully achieved its objectives, there are still areas that could be improved. The use of a modular design allowed for easy replacement of scent containers and other parts during prototyping. However, it was found that the design was susceptible to accidental hits when participants reached for their faces. In future iterations, this issue could be addressed by implementing a more robust locking mechanism. Feedback from users was generally positive, but the authors acknowledge the need to include a standardized questionnaire to gather more useful data in this regard. One primary comfort issue identified by users was the deposition of water droplets on glasses and facial hair after several minutes of consecutive scent emission. Future work will aim to address these issues through the modulation of emission rates and the exploration of different essential oil mixes.

4.3 Discussion

The main objective of the testing phase described in the paper was to characterize the key aspects of the device within a hypothetical application context. As the Open-O-Kit is an open-source and affordable device, it is essential to provide reference values on its functionality and effectiveness. This ensures a clear understanding of the device's characteristics for individuals interested in utilizing the Open-O-Kit for their own applications.

Based on the Computational Fluid Dynamics results, it is indicated that the device is capable of delivering olfactory stimuli to the user's nose within a duration of 25 ms. Additionally, the second test offers insights into the average time required for users to perceive a scent, detect a change in scent, and cease perceiving the olfactory stimulus. This type of information is not always readily available in existing research works, as they often focus on measures influenced by the presence of olfactory stimuli (e.g., [25, 26]). However, Iseki and Nakamoto's study [41] offers insights into the temporal perception aspects of three different types of ODs, enabling a comparison with the specific characteristics of the Open-O-Kit described in this paper, particularly regarding the initial perception of odor stimulation. Despite the variations in data collection methods and the devices utilized, our results align with other ODs employing similar technology. This consistency further validates the effectiveness of the low-cost and open-source solution proposed in this study.

5 CONCLUSIONS

In this paper, we have described an olfactory display designed as an open-source kit to add the sense of smell to Virtual Reality environments easily. The aim is to allow researchers and enthusiasts to exploit the olfactory dimension of their VR environments and to exploit it in the Metaverse in the near future. The kit is simple in its design and can be reproduced by anyone with sufficient know-how to assemble the components. We used rapid prototyping tools like the Arduino platform and 3D printing technologies, nowadays broadly available in academia, among makers, and in companies. All the material is accessible on a public repository. In addition to presenting the final design, we have provided the testing protocols we utilized to quantitatively assess its performance. This allows for future testing and validation of redesigned versions of the kit.

To ensure reproducibility and affordability, the device was tested with the widely used Meta Quest 2 headset, which has limitations on the device width due to its tracking cameras. However, the modular design allows for the utilization of additional channels when used with different headsets, with a maximum of four channels possible. In the demonstrated setup, the Arduino Uno is used, which has the drawback of requiring a cable connection to a controlling computer. Exploring solutions for wireless or direct connection to the headset, while still maintaining user-friendliness, would greatly enhance the workflow. Furthermore, investigating the impact of different emission rates on improving the saturation of the sense of smell during the trial and the persistence of odor after the emission has ceased should be considered for potential enhancements.

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