Midair Ultrasound Fragrance Rendering

Keisuke Hasegawa, Liwei Qiu and Hiroyuki Shinoda

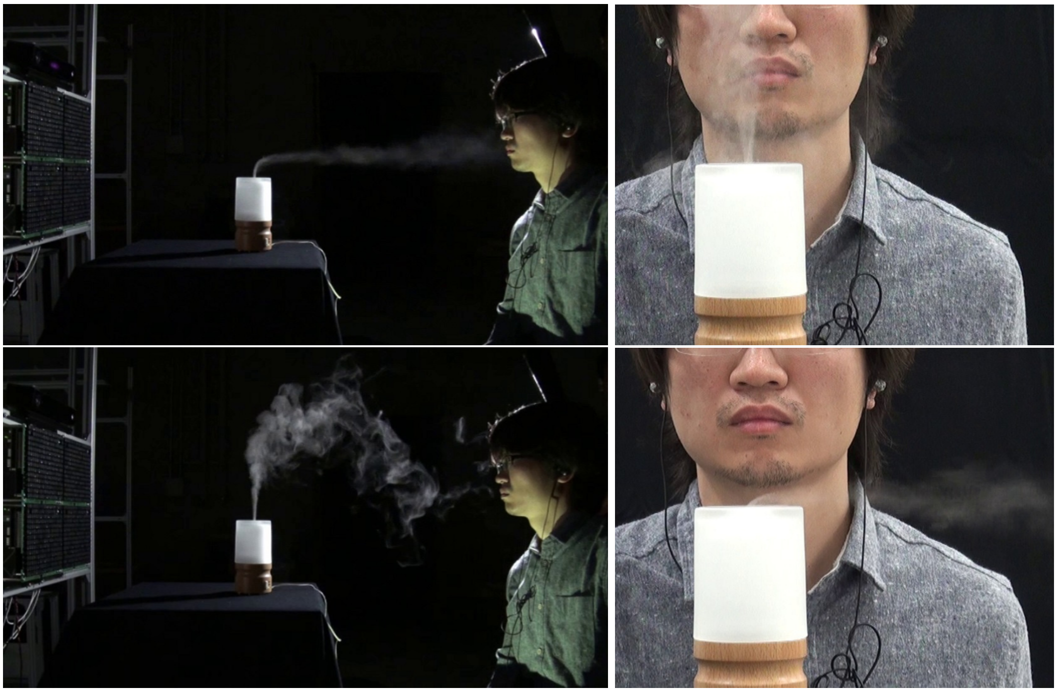

Fig. 1. (a) Scented water vapor guided to the user's nostrils via an ultrasound-driven flow. (b) The vapor simply goes up in the absence of the flow. (c) The proposed system can remove an odor that is emitted from a point-like source by blowing it away.

Abstract—We propose a system that controls the spatial distribution of odors in an environment by generating electronically steerable ultrasound-driven narrow air flows. The proposed system is designed not only to remotely present a preset fragrance to a user, but also to provide applications that would be conventionally inconceivable, such as: 1) fetching the odor of a generic object placed at a location remote from the user and guiding it to his or her nostrils, or 2) nullifying the odor of an object near a user by carrying it away before it reaches his or her nostrils (Fig. 1). These are all accomplished with an ultrasound-driven air stream serving as an airborne carrier of fragrant substances. The flow originates from a point in midair located away from the ultrasound source and travels while accelerating and maintaining its narrow cross-sectional area. These properties differentiate the flow from conventional jet- or fan-driven flows and contribute to achieving a midair flow. In our system, we employed a phased array of ultrasound transducers so that the traveling direction of the flow could be electronically and instantaneously controlled. In this paper, we describe the physical principle of odor control, the system construction, and experiments conducted to evaluate remote fragrance presentation and fragrance tracking.

Index Terms—Olfactory display, ultrasound, nonlinear acoustics, acoustic streaming

1 Introduction

The olfactory sense is one of the essential sensory modalities of human beings. In the realm of virtual reality (VR) systems, the importance of the olfactory modality has been recognized for a long time [2], as seen in a prototype system invented in the early stages of VR research [10]. While it is true that, compared with visual, auditory, and haptic technologies, the number of olfactory technologies is much smaller, there are certain VR experiences that can be accomplished only by olfactory stimulation. Those experiences are often enhanced when combined with the stimulation of other modalities.

The olfactory sense is aroused by fragrant substances that arrive at the nostrils. One straightforward method to realize this is to use a wearable olfactory display that contains a scent-emitting nozzle placed near the user's nostrils. Another approach is to present a scent to the user by using a jet or air vortex cannon containing scented air. These techniques could provide well-structured personalized olfactory experiences.

While these techniques are quite effective, their application range is limited to the presentation of specific prepared fragrances. They are not designed for moving or redirecting odors emitted from generic objects in the environment. Such spatial control of odors would open the door to novel olfactory experiences such as tracking scents, scented tele-existence, or the superposition or replacement of scents on real objects.

We propose a technique for transporting an airborne fragrance by

• *K.H and H. S are with the University of Tokyo. E-mail: (Keisuke_Hasegawa, Hiroyuki_Shinoda)@ipc.i.u-tokyo.ac.jp*
L. Q is with Riken. E-mail: liwei@hapis.k.u-tokyo.ac.jp

Manuscript received 11 Sept. 2017; accepted 8 Jan. 2018.
Date of publication 19 Jan. 2018; date of current version 18 Mar. 2018.
For information on obtaining reprints of this article, please send e-mail to: reprints@ieee.org, and reference the Digital Object Identifier below.
Digital Object Identifier no. 10.1109/TVCG.2018.2794118

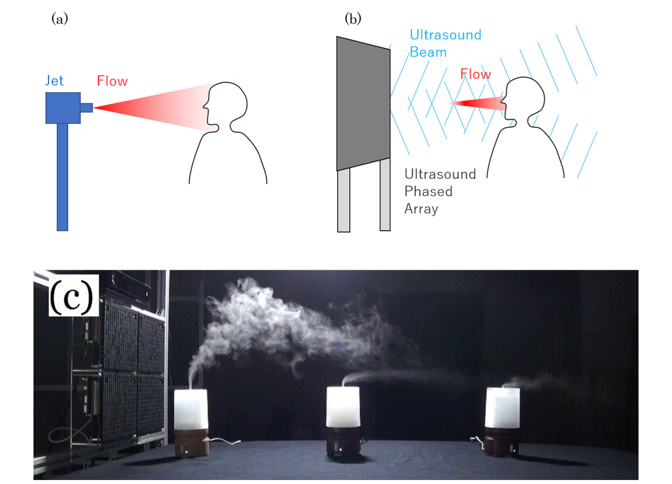

Fig. 2. Schematic depiction of (a) Conventional jet-driven flow and (b) ultrasound-driven flow. (c) Actual generated flow. The vapor source nearest to the ultrasound phased array is not redirected as much as the other two.

generating a straight air flow driven by a midair ultrasound beam. The generation of such straight air flows is known as acoustic streaming [5]. The ultrasound-driven flow is accelerated in the air with the kinetic energy supplied by the ultrasound field (Fig. 2). This mid-air acceleration property is not seen with conventional jet- or fan-driven flows, which merely lose their momentum the farther they travel. The driving force of the flow is proportional to the acoustic energy distribution, which can have a resolution as fine as the ultrasound wavelength. In our setup, the wavelength was 8.5 mm with 40 kHz transducers. By properly controlling the output phases of the transducers, an intense narrow flow was generated at an isolated midair point away from the source. We utilized a phased array of ultrasound transducers so that the position and the orientation of the resulting flow can be instantaneously steered. This electronically steerable air flow is expected to offer midair fragrance control with a spatiotemporal flexibility that is inconceivable with conventional methods (Fig. 3).

The proposed technique is unique in that the source of the fragrance and its airborne carrier are separate. This makes it possible not only to transport a prepared fragrance to the user, but also to redirect an odor that already exists in the environment. As stated above, the fragrance emitted from a generic object in the environment can be controlled with our method.

Odors from multiple sources can be selectively presented to users with a single transducer array. Our method does not require a complicated mechanism such as a switching valve inside a fragrance emitter.

When ultrasound reflection at a wall is utilized to generate a flow that comes from the wall, a flexible spatial setup of the fragrance source and the ultrasound array can be achieved. These properties can be used for removing an odor with a flow generated with a wall-reflected ultrasound beam.

The contributions of the work are summarized as follows:

- We propose a technique that redirects a midair fragrance via an ultrasound-driven air flow with the physical principle described in the rest of this paper.
- We implemented an interactive prototype system that detected a user's face and redirected the fragrance toward it.
- We experimentally evaluated the spatial resolution and operating space of the system. We also assessed the feasibility of utilizing a flow generated by a reflected ultrasound beam coming from a wall, as an airborne carrier of fragrances.

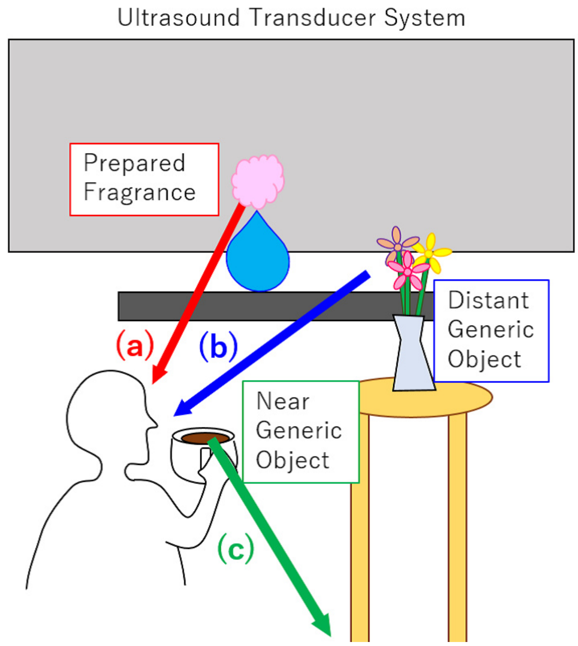

Fig. 3. Possible setups offered by the proposed system. (a) A prepared fragrance can be conveyed to the user. (b) Tele-fragrance display, where the odor of a generic object located away from the user can be conveyed to his or her nostrils. (c) Removal of odor emitted from an object held by the user by blowing the odor away before it reaches his or her nostrils.

2 Related Work

2.1 Near-Field or Wearable Fragrance Displays

Fragrance displays that present ("display") a scent in the near field have been proposed [21] [18] [17]. However, these systems are not intended to display scents in the far field. A common personal olfactory display is a wearable device [27] [9] [1] [3] that is suitable for the immersive VR environments offered by head-mounted displays (HMDs). An HMD can entirely replace the user's viewing field with computer-generated graphics while excluding all wearable devices from the users' viewing field. In these situations, users are less conscious of the devices they wear, no matter how visually bulky they are. Thus, wearable systems have attracted broad interest and have begun to be adopted in VR/AR applications [25].

2.2 Remote Airborne Fragrance Displays

In contrast to the techniques above, a few remote fragrance displays that do not require the users to wear any special devices have been proposed. [28] [22]. The fundamental principle of these systems is the use of an air vortex cannon. An air vortex is a stable "lump" of ejected air that travels over a long distance with suppressed diffusion. Based on this principle, those displays intermittently present prepared scents to users. Although this method is feasible, the cannon must contain fragrant air, which means that the air ejection mechanism and the fragrance source are inseparable. With our technique, on the other hand, they can be made independent, so that more flexible spatial control of odors is possible.

As another example where the fragrance and its carrier are separeted, use of multiple fans are also proposed [11] [12]. They intend to control the direction of the wind by the interference of multiple wind flow. However, in general, it is difficult to expect that fan-based methods offer localized airflows in far field.

Both of fan-based and vortex-based techniques require mechanical movements to change the position of the presented scents. Although some of the fan-based methods control the wind direction by tuning the output velocities of multiple fixed fans, it is expected that only rough direction control would be possible. Our method changes the direction of midair acceleration instantaneously without any mechanical movement of the device [6].

2.3 Applications of Nonlinear Ultrasound

Midair ultrasound phased arrays have attracted the interest of many researchers mostly in the context of potential applications. Those phased arrays consist of an array of ultrasound transducers whose output phases and amplitudes are individually controlled. By appropriately tuning the output waveforms, the array generates an electronically rendered ultrasound field. For example, the ultrasound can be focused at an arbitrary three-dimensional position. So far, many applications have been demonstrated, including a midair haptic display [15] [13] [8] or sensing [4], and particle trapping [19]. These systems all exploit the nonlinear ultrasound effect known as acoustic radiation pressure [5], which is a static pressure arising on the surface of a rigid object, which blocks the propagation of intense ultrasound.

Besides radiation pressure, another major nonlinear acoustic phenomenon is acoustic streaming, which is a mass flow along an intense sound propagation path [5]. The driving force per unit volume in the flow is roughly understood to be proportional to the sound intensity [16].

The generation of such ultrasound-driven air flows in an open space have been reported [6]. In that report, the generation of an ultrasound Bessel beam was also described. In that system, the highest-velocity point in the flow is located away from the phased array, and the beam is as narrow as the wavelength at the most concentrated region. We utilized this type of ultrasound beam for generating narrow extended flows that transport odors in an open space.

2.4 Technical Features of the Proposed Method

If one wishes to remotely present a fragrance to a user, use of ultrasound might not always be the most suitable solution. Nevertheless, an ultrasound-driven flow possesses unique physical properties that are unlike those achievable with jet-based vortex techniques.

An ultrasound phased array can produce an electronically steerable straight flow. This means that no mechanical movement of the device is required for changing the direction and the position of the flow.

The ultrasound field is generated instantaneously, which results in immediate acceleration of the air. The theoretical traveling time of the odor from its emission point to the user depends on the distance between the fragrance source and the user, not on the distance between the ultrasound source and the user. This is advantageous in terms of reducing system latency when the source and the user are located close to each other, while the ultrasound phased array is distant from the user.

With a sufficiently large number of transducers forming a large-aperture array, an arbitrarily long ultrasound beam can be obtained in principle. Therefore, it is expected that we can create a straight air flow in the far field while maintaining a small cross section, which is not the case with conventional air flows driven by jets or fans. This property can be exploited for localized fragrance presentation in a region distant from the device. Although a vortex ring can travel further when its radius is increased, the larger size results in deteriorated spatial resolution of the displayed fragrance.

This paper describes a system that transports a scent to a user on the basis of the physical principle of generation of an ultrasound-driven, steerable, straight, narrow airflow, along with its performance evaluation. In this paper, we do not intend to claim the novelty of the physical techniques employed. Rather, the primary contribution of this work is an investigation of the possibility of airborne odor rendering, including redirection, transportation, removal and selective presentation of odors.

We should note that, in the experiments we conducted, the technical features mentioned above were not demonstrated to be obviously advantageous compared to the other conventional methods. Here we merely mention that those properties are expected in principle and will be practically achieved with a more sophisticated system that includes a greater number of ultrasound transducers in the array.

3 Physical Principle

As described above, intense sound beams entail mass flows in the air in the propagation direction. Our method creates ultrasound Bessel beams that generate a straight air flow carrying odorant substances in the air. Bessel beams were originally discussed in optical or electromagnetic fields as 'nondiffracting beams'. With an infinitely large radiation aperture, a Bessel beam extends over an infinitely long distance while keeping its cross-sectional energy distribution unblurred, which is attractive for generating a straight and narrow stream.

A detailed description of the basic technique and a formulation for generating a steerable Bessel beam with an ultrasound phased array have been described elsewhere [6]. For improved understanding, here we add a concise description of how the flow is physically formed. A Bessel beam is intuitively understood as a wavefront radiated from aggregated coherent linear sources forming a cone shape. The sound energy density takes is maximum on the propagation axis where all emissions collide 'in phase'. The propagation axis is identical to the cone axis (Fig. 4). The cross-section of the beam has an energy distribution in the form of concentric rings, which are described by a solution of Bessel's differential equation.

The ultrasound phased array can form a wide variety of wavefronts by tuning the output phase shifts of individual transducers. It can generate wavefronts that appear to be radiated by a conical source, as described above. A phase shift proportional to the distance between the virtual cone and the transducers should be added to each of them. If the phase calculation is done with a tilted cone, the resulting Bessel beam and flow are oriented toward the cone axis. The traveling axis of the flow can be shifted by moving the cone accordingly. The location of the highest-velocity spot of the flow depends on the depth of the generated beam determined by the apex angle of the virtual cone. By properly placing a designed virtual cone on the radiation plane of the ultrasound phased array, one obtains a straight flow with a desired position and orientation. In our system, a flow that travels through the fragrance source and arrives at the nostrils of the user is created for presenting a fragrance.

The virtual conical source can be characterized with three parameters: the base angle θ, the unit vector axis $\boldsymbol{n} = (n_x, n_y, n_z)$, and the root position $\boldsymbol{r}_b = (x_b, y_b, 0)$. Suppose that the radiation plane faces the z direction. The proper phase shift to be applied at a transducer located at $\boldsymbol{r} = (x, y, z)$ is given as follows. Obtain the root-shifted transducer position $\boldsymbol{r}' = \boldsymbol{r} - \boldsymbol{r}_b$ and find the rotational operation A that redirects $\boldsymbol{n}$ toward the z axis. Then, calculate a corresponding rotated transducer location $\boldsymbol{R} = (X, Y, Z) = A(\boldsymbol{r}')$. Finally, the following phase shift ϕ proportional to the distance between $\boldsymbol{R}$ and the vertical cone whose axis faces the z direction is obtained:

$$\phi = k\left(\sqrt{X^2 + Y^2}\sin\theta - Z\cos\theta\right), \tag{1}$$

where k is the ultrasound wavenumber. The distance here is equivalent to the correspondingly tilted cone and the transducer location $\boldsymbol{r}$ (Fig. 4 (c)).

The beam direction $\boldsymbol{n}$ and its root position $\boldsymbol{r}_b$ are geometrically obtained by the following calculation when the source position $\boldsymbol{r}_s = (x_s, y_s, z_s)$ and the user position $\boldsymbol{r}_u = (x_u, y_u, z_u)$ are given:

$$\boldsymbol{n} = \frac{\boldsymbol{r}_n - \boldsymbol{r}_s}{||\boldsymbol{r}_n - \boldsymbol{r}_s||} \tag{2}$$

$$\boldsymbol{r}_b = \boldsymbol{r}_s - \frac{z_s}{n_z}\boldsymbol{n} \tag{3}$$

By reducing θ to zero, the generated beam can be located more distant from the array. A rough estimation of the depth at the highest concentration of acoustic energy is geometrically given by $\frac{A}{4\tan\theta}$, where A is the array aperture, equivalent to the diameter when the array is circular. Note that since we have a finite aperture, the more distant the beam is located, the more planar the generated wavefronts become. Consequently, the beam becomes broader with less energy concentration. At the same time, a more distant beam extends farther (Fig. 5).

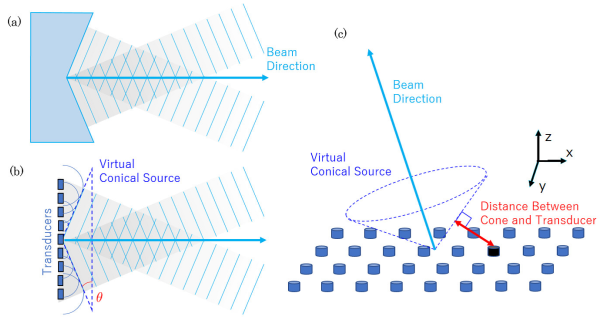

Fig. 4. (a) Concave conical source creating a Bessel beam. (b) The same wavefronts generated by a phased array of ultrasound transducers. (c) The case with a tilted cone yielding a correspondingly tilted Bessel beam.

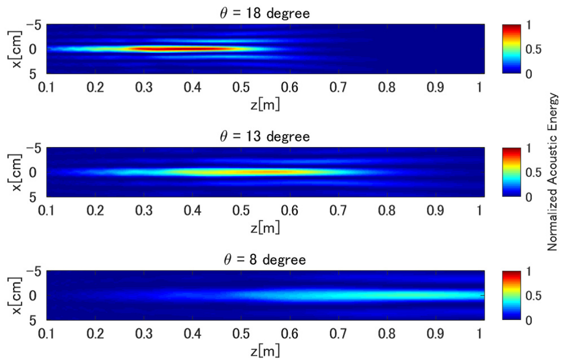

Fig. 5. Numerically simulated acoustic energy distribution of Bessel beams with different depth profiles.

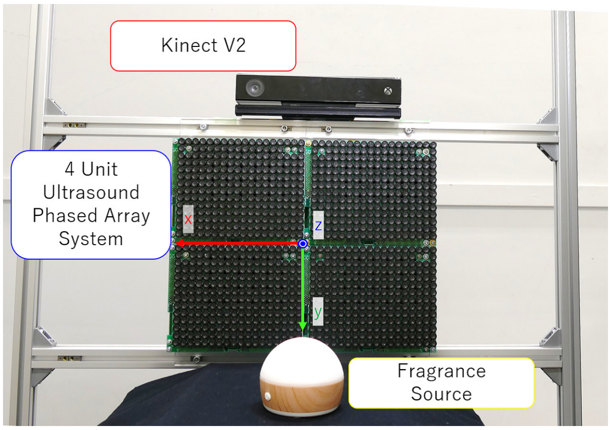

Fig. 6. System setup and the coordinate system used in the experiments.

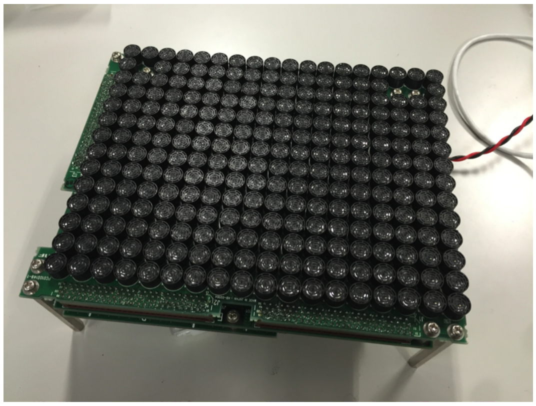

Fig. 7. Single ultrasound phased array unit.

4 System Construction and Implementation

We constructed a prototype system for controlling a spatial odor distribution. It was composed of a synthetic ultrasound phased array, a user tracking sensor, a PC, and a fragrance source. We describe each component below. Figure 6 shows the system setup and the actual fabricated system.

4.1 Ultrasound Phased Array Units

As described, a larger aperture contributes to improved beam generation performance. Hence, we constructed a four-unit synthetic ultrasound phased array system. Each unit (Fig. 7) was governed by the signals transmitted from the PC via Ethercat communication, guaranteeing adequately synchronized real-time communication among units. According to the position and orientation of the desired flow, a set of phase shifts on every transducer was calculated in the PC and was sent to every array unit. Every unit contained 249 ultrasound transducers, each having a diameter of approximately 10 mm, arranged in a lattice. The size of the radiation plane was 192 mm x 151.2 mm. In the radiation plane, one row and one column did not contain transducers, and three transducers in the lattice were replaced with screw fasteners. The power consumption per unit was 50 W at most.

4.2 Fragrance Sources

Our system does not necessarily require a specifically prepared fragrance source. However, there are some desirable properties required of the source. Since our method creates a flow to convey a fragrance, the source should emit or diffuse a fragrance having as small a momentum as possible. When the initial velocity of the ejected gas is higher than that of the generated flow, it will not be precisely redirected. Note that this applies to the vertical direction as well. That is, the method might not be applicable to materials that are too light or too heavy compared with the ambient air. Also, vigorous convection or evaporation might undermine the performance of the proposed method. In user studies, we used a diffuser of incense oil as a fragrance source. Note that this source is different from the water atomizers used in many previously developed systems to visualize the flow. The reason why we did not use the same devices in our experiments is that emitted water vapor hides the users face from the Kinect V2 system used to track the user's face, and deteriorates the tracking performance. The diffuser we used was composed of a sponge pad and a diffusing fan. The emitted fragrance was invisible. The fragrance used was mint.

4.3 User Recognition

We used Kinect V2 for tracking the user's face. Kinect V2 is composed of a calibrated time-of-flight (ToF) depth sensor and RGB camera. In the SDK of Kinect V2, body tracking and facial recognition functions are implemented as usable libraries. We used these to capture the user's face in real time. We defined the position of the nose in the detected user's face as the closest point to the Kinect V2.

4.4 Phase Calculation

Once the conical parameters are determined, the corresponding phase calculation was performed in line with the formulae given in the previous section. For the calculation of the rotational operation, we used Rodrigues's rotational rule. The phase shift was quantized into 256 levels. All of the phase calculations were performed on the PC. The results were sent to each unit via Ethercat.

	x	y
Still	73.27	50.44
Tracking	145.21	74.22

Table 1. Standard deviation [mm] of the obtained points

5 EXPERIMENTS

We conducted several experiments to assess the performance of our system.

5.1 Measurements of Temporal Characteristics

We evaluated the physical latency of the system. It was expected that the ultrasound beam is formed instantaneously after the transducers are driven. On the other hand, it is not self-evident whether the ultrasound-driven flow is concurrently generated or whether there is some delay. We measured this acoustic-fluid delay with a microphone located next to the atomizer. The ultrasound field was sufficiently intense outside of the Bessel beam for the microphone to sense. We visually recorded the redirected flow and the display on an oscilloscope to which the microphone was connected. The video was captured at 30 fps, resulting in a temporal resolution of approximately 33.3 milliseconds.

First, we measured the latency with a fixed beam with θ set to 16 degree. We set the atomizer depths to 0.4, 0.8, 1.2 and 1.6 m from the phased array. Figure 8(top) shows the measured result, revealing that larger latencies were observed with greater atomizer distance. This is because the atomizer was outside of the beam in those cases. The water vapor was guided with the air flow generated by the beam at the speed of the flow velocity, which was much lower than the ultrasound velocity. We then fixed the atomizer at the depth of 0.8 m and performed the same measurements with θ set to 8, 12, 16 and 20 degrees. As explained above, a smaller value of θ enabled the beam to reach further. Figure 8 (bottom) shows the measured latencies against the value of θ. Note that the value of the latency here indicates how long it took for the flow to become stationary, and for initial transient movement of the vapor to be seen immediately after (less than 1/30 second) the ultrasound radiation when the values of θ were 8 and 12 degrees (Fig. 9).

From the results, it can be concluded that 1) the flow was seen both inside and outside the beam, and 2) inside the beam, the flow was formed immediately after the ultrasound radiation, but 3) behind the beam, inevitable latency that originated from the traveling distance between the beam and the observed point was seen. Thus, we demonstrated that the radiated beam promptly accelerated the air at a location away from the phased array. This means that the latency could be minimized with a sufficiently long Bessel beam regardless of the source position. It should be noted that beams reaching farther contain lower energy density and consequently yield slower flows. Therefore, it depends on the position of the user and the fragrance source whether the energy density of the beam should be prioritized over the reaching distance.

5.2 Spatial Evaluation

The purpose of this second experiment was to assess the operating space of the system. We used six male participants (including the author) in the experiments. Their ages ranged from 22 to 32. We instructed them to sit on a chair and continuously move their upper bodies while they breathed. During the experiment, the subjects held a computer mouse and were instructed to click it whenever they smelled the delivered scent. We collected these 'scented points' to assess the spatial properties of our system. We placed the fragrance source at $z = 350$ mm with the emission aperture of the source located on the z-axis. The subjects were seated at around $z = 700$ mm.

We conducted two experiments: one with a still beam and the other with a tracking beam driven by the real-time face-tracking system. First, we had participants smell the scent transported by a vertical beam. From this experiment, we learned how the delivered scent was spatially localized. In the second experiment, the face tracking was

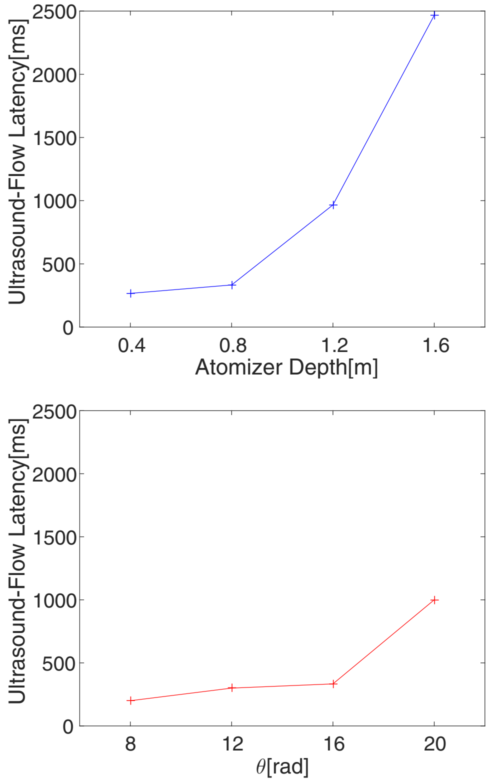

Fig. 8. Latency between radiated beam and formed flow with various atomizer depths (top) and with various virtual conical source angles θ and the atomizer located at z =0.8 m (bottom).

activated. As a result, a Bessel beam was created so that the fragrance source and the subject's nose were both in the path of the beam. Since these procedures were performed in real time, face-tracking scent conveyance was realized. As we described in the previous subsection, there were latencies that that were not negligible. Therefore, we asked the participants to move slowly (less than approximately 1 m/s). The second experiment was conducted to evaluate the effective operating space of the system.

Figure 10 (a), (b) shows the scented points collected from all subjects in the first (still beam) and the second (tracking beam) experiments. Table 1 shows the standard deviation of the collected points on the x and y axes. From the results, it was roughly assessed that the vertical still flow could localize the conveyed flow within a region of 147 mm x 101 mm at a depth of around one meter from the device. The graph shows that the operating space was widened with the face tracking system enabled. From the calculated standard deviations, the operating space was approximately 290 mm x 150 mm x 800 mm. The reason why the y region in the operating space was the shortest is ascribed to the difficulty in guiding the scent downward because the diffuser itself was an obstacle hindering proper downward streaming. Note that the results differed considerably among individuals. Figure 10 (c), (d) show the results for a subject who was relatively more sensitive to the spatial scent distribution, and Figure 10 (e),(f) show those for a less sensitive subject. In (c) and (d) more localized perception with a still beam was observed. Almost all subjects commented that, as the experiment progressed, they gradually lost confidence in their olfactory sensitivity because of the adaptation of the sensory system and the accumulation of emitted fragrance in the environment.

5.3 Flows with Reflected beams

We reflected the generated Bessel beam at a rigid wall and verified that the reflected Beam could form a straight air flow as well (Figure 11). Since the Bessel beam is the physical outcome from the whole

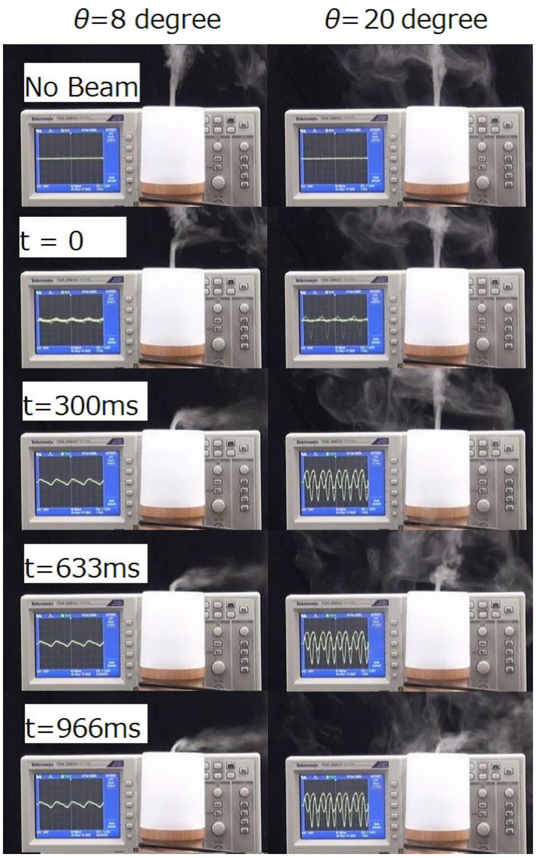

Fig. 9. The movement of water vapor and the captured ultrasound waveform. In the case of $\theta = 8$ degrees, the atomizer was in the beam and the vapor started to move immediately. On the other hand, in the case of $\theta = 20$ degrees, it took almost 633 ms for the vapor to start to move.

ultrasound field, not only that around the beam axis, it was expected that the reflected beam will not be properly produced if the wall is too small. A flow that came from the wall was generated, which indicates that the ultrasound phased array does not always have to be placed behind the fragrance source. Thus, with the use of reflected beams, it will be possible to achieve a higher number of possible paths of the flow with a fixed arrangement of equipment, fragrance sources and users.

5.4 Selective Redirection of Multiple Odorant Sources

Displaying multiple scents in an individual or mixed manner is a topic of great interest and has been achieved with several techniques [26] [24]. We tried replacing an airborne fragrance with our method.

The system we constructed could generate a steerable narrow flow. It can be easily implemented as a selective fragrance display with multiple fragrance sources (Figure 12). We verified that it was possible to sequentially present a set of various fragrances to users at the very front of the users' nostrils. Figure 13 depicts the spatial setup used in a preliminary experiment for alternately presenting two different scents to users. We placed two fragrance emitters in front of the ultrasound phased array. We constructed an 8-unit array system for this experiment. One source emitted lemon-scented vapor, and the other emitted mint-scented vapor. Users sat in front of the array and the fragrance emitters. We alternately generated two flows that corresponded to each scent. Each flow had a path that passed through the corresponding fragrance emitter and reached the nostrils of the user. We used two experimental subjects, both of who answered that they clearly experienced the change of the displayed scent. At two exhibition events, including SIGGRAPH asia 2017, several hundred visitors to our display experienced a system with a similar setup, and almost all of them claimed to notice changes in the fragrances [7].

5.5 Removal of Odor

As seen in Fig. 1, an odor emitted from a relatively small aperture can be blown away. We tested this with canned hot coffee and confirmed that its scent disappeared when the positioning of the can, the nose, and the flow was appropriate.

6 Discussion

The current system produces a single straight Bessel beam that accordingly entails a flow that extends over a certain length. In principle, more complicated flows, such as multiple linear flows, can be generated since systems described in the literature demonstrate the realization of complicated spatial distributions of midair ultrasound energy [20] [14]. By employing a similar technique in our system, for instance, a flow that changes its direction in the middle of the path can be expected.

Currently, the generated flows were perceptible as tactile stimulation.

The flows generated with the system were turbulent, which is not desirable for localization of the conveyed fragrance. Another possible factor that undermines the localization is diffusion, although this is not considered dominant in the case of our system since the flows were much faster than the spreading velocity of freely diffused airborne materials. A Bessel beam contains most of its energy concentrated along the propagation axis. This property is advantageous in terms of increasing velocity; however, it easily causes turbulence because of the radial velocity gradient due to the concentric energy distribution. If we can generate a laminar flow that travels as fast as the flow we generated for the experiments, it might be possible to realize much improved odor localization.

From the perspective of the effective operating space and temporal latency of the displayed fragrance, the current setup is partially successful. As for the spatial operating space, scents can be delivered in the air over distances of around one meter by using vortex-based [23] techniques. It is expected that a combination of fan-based techniques would transport midair scents over distance of one meter [11] [12]. It also has been reported that the vortex-based technique entails a latency of one second when transporting a fragrance over a distance of 1.5 m. These figures are comparable with or slightly better than our current version of the system. The maximum flow velocity was approximately 3 m/s within a small range of depths of several centimeters, resulting in latencies of a few seconds for some spatial arrangements. A larger synthetic aperture composed of a greater number of array units could be used for generating a stronger unblurred beam that travels farther, which would contributes to achieving a shorter traveling time and a wider operating space while maintaining sufficiently localized fragrance transportation.

When the prepared fragrance was presented to users, the concentration of the fragrant material in the environment gradually increased. If one wants to eliminate this, ventilation outlets would be required for discharging the emitted fragrance. Ultrasound-driven flows that convey the fragrance to those outlets would expedite this ventilation. We also described the possibility of removing the emitted odor. This is not the case with an ambient odor that has a uniform concentration in the environment. An alternative method to attenuate this kind of odor would be to override it with a more refreshing scent that is conveyed with our system. The same also applies to odorant sources that are too large for a single narrow flow to thoroughly blow away.

The generated beams were intense. The maximum sound intensity reached over 160 dB in SPL. Sound at this intensity is too loud and might be dangerous at audible frequencies. Since there is no clear evidence to conclude whether such intense midair ultrasound is dangerous or not, we instructed the experimental subjects to wear headsets and glasses. Outside of the beam, the ultrasound energy was much lower. Therefore, appropriately controlled emission of ultrasound would make the system much safer. In practice, it would be advisable to make sure that grating lobes, described below, are also at safe positions.

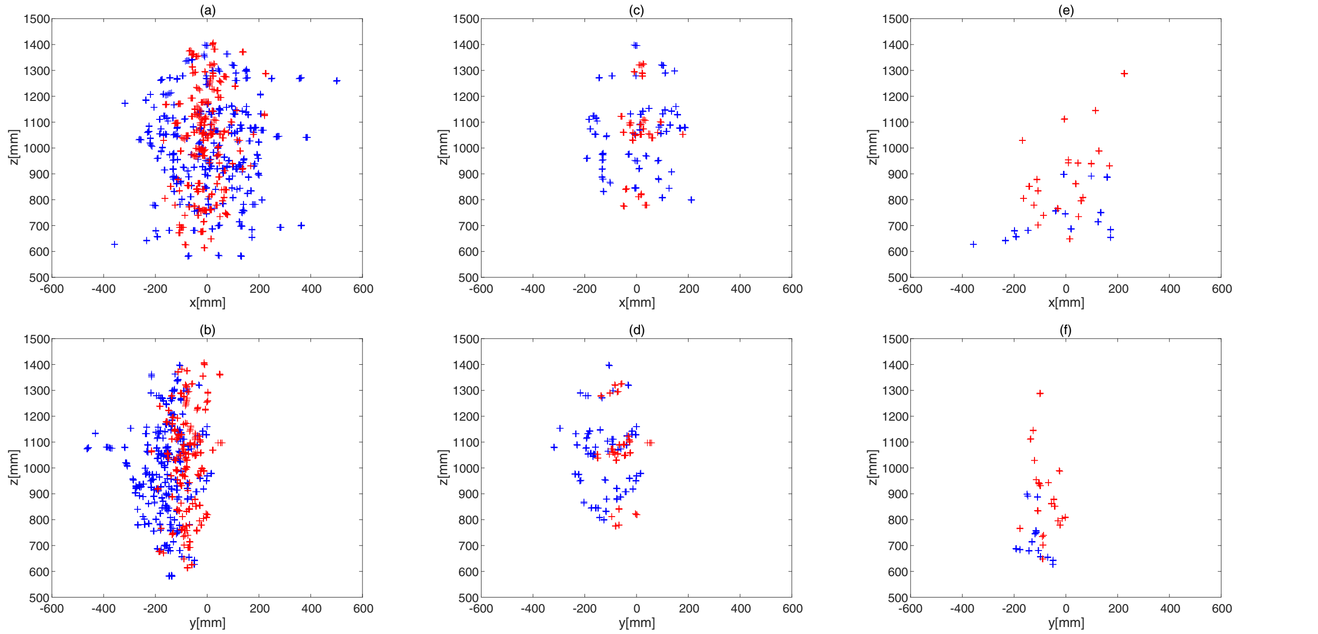

Fig. 10. Collected scented point in three-dimensional space. Red points indicate those with a still flow. Blue points indicate those with a tracking flow. Data from all subjects (a),(b), a relatively more sensitive subject (c), (d), and a relatively less sensitive subject (e), (f).

7 Limitations of the Current System

The current system generates only straight flows. This means that the beam origin, the fragrance source and the user must be arranged in a straight line, in general. This spatial constraint would result in a very limited operating space with a specific spatial setup. As stated above, a wall-reflected beam could be used for widening the operating space in some of those situations. We also plan to construct a multi-array system that surrounds users with several emitting planes. In addition, non-straight beams [29] would be another solution for this problem.

The phased arrays used in the system can be regarded as a set of discrete point wave source, which means that the radiation plane of the array is not continuous. This causes the common 'grating lobe' problem. Here, grating lobes refer to 'ghost' images of the generated beam. These beams of course yield flows along them, resulting in unwanted redirection of scents. Figure 14 indicates the existence of such beams, and we experimentally verified that they do exist. Unfortunately, this problem is inevitable when using a phased source set. However, the interval between the 'genuine' beam and the grating lobes can be increased by reducing the interval between the transducers. The current system contains transducers of 10 mm diameter. If smaller transducers were available and densely mounted on the array unit, the grating lobes would appear farther away from the main beam.

8 Potential Applications

8.1 Anti-Malodor System

We discussed the possibility of removing an odor from objects held by users and concluded that it is possible in principle. Therefore, our technique could be used in shunning harmful or disgusting odors, such as cigarette smoke or unwanted perfume.

8.2 Odor Replacement

In principle, the generation of multiple flows is possible. Hence, by adding another fragrance after removing an existing one, odor replacement would be achieved. This is something that the air-vortex-based techniques cannot handle because they can only present an odor to users. In contrast, our method can remove an existing odor. Thus, it would be possible to have an experience wherein the scent of coffee suddenly turns into that of tea while drinking it. Since olfactory stimuli govern the subjective perception of taste [25], such a system might help children eat vegetables that they do not like by replacing their odor with more enjoyable ones.

8.3 Midair Odor Mixing

We transported two different scents emitted from two different fragrance sources to a specific position. This procedure can be simultaneously performed by generating two flows at the same time. This results in two different scents colliding at a region where mixing of the scents is caused. It is possible to present a wide variety of fragrances by mixing several primitive scents.

8.4 Scent Permeation

Our method would also be applicable to permeating scents to some objects. For example, an airborne perfume presentation system that is embedded in the environment can be realized. With highly volatile materials, users can enjoy many type of perfumes one after another without personally possessing them. Smell is a common sensation among various living organisms. Some chemical substances that are not harmful or even perceivable to human beings can affect specific kinds of creatures. This may be exploited to prevent annoying insects from coming to us or to make pets docile.

9 Conclusions

We proposed and fabricated a midair odor control system that utilizes an electronically steerable ultrasound Bessel beam based on the principle of acoustic streaming. Combined with fragrance emitters, our system could convey a scent to a user located approximately one meter away from the ultrasound phased array. Since the displayed scent was localized within an area that was as large as a human face, it can be said that the presented scent is sufficiently personalized. In addition, our system could generate a flow that tracked the user's face captured with Kinect v2. Although the temporal response of the system still has some room for improvement, we experimentally demonstrated that the tracking system could widen the operating space in which the fragrance is effectively displayed. We also verified that an odor emitted from an object close to the user could be removed by blowing it away with our technique, and that the reflected Bessel beams could generate reoriented flows. These findings will be advantageous for new applications and for flexible system setups. In the discussion section, we

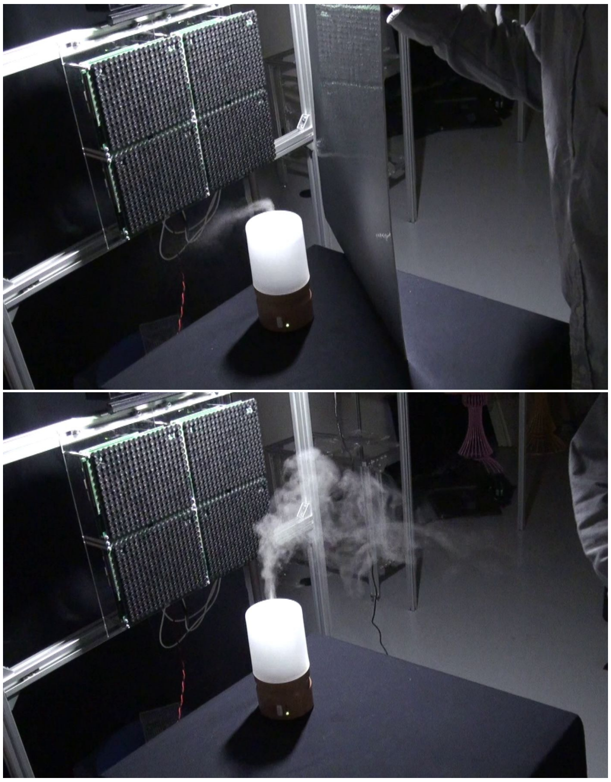

Fig. 11. Flows generated with a reflected Bessel beam (top). When the wall is removed, the flow disappears (bottom).

stated that a larger array aperture would improve the system performance in terms of a larger operating space, faster temporal response and less odor spreading.

We consider the most important contribution of the paper is that we demonstrated the effectiveness of the concept of controlling an air flow with ultrasound radiation. In order to improve the effectiveness further, we plan to develop a system with a larger aperture, as stated above. We will also seek to generate beams that yield sufficiently fast laminar flows with a certain degree of robustness. Another important issue is to demonstrate the practical utility of this system by showing application examples. Last but not least is a thorough evaluation of safety. To make the most of the proposed technique, it is desirable to free users from the need to wear glasses or headphones for the sake of safety.

Acknowledgments

This work is supported by JSPS Kakenhi Grant-in-Aid, 15H05316 and 16H06303.

References

[1] J. Amores and P. Maes. Essence: Olfactory interfaces for unconscious influence of mood and cognitive performance. In *Proceedings of the 2017 CHI Conference on Human Factors in Computing Systems*, CHI ’17, pp. 28–34. ACM, New York, NY, USA, 2017. doi: 10.1145/3025453.3026004

[2] H. Q. Dinh, N. Walker, L. F. Hodges, C. Song, and A. Kobayashi. Evaluating the importance of multi-sensory input on memory and the sense of presence in virtual environments. In *Proceedings IEEE Virtual Reality (Cat. No. 99CB36316)*, pp. 222–228, Mar 1999. doi: 10.1109/VR.1999.756955

[3] D. Dobbelstein, S. Herrdum, and E. Rukzio. inscent: A wearable olfactory display as an amplification for mobile notifications. In *Proceedings of the 2017 ACM International Symposium on Wearable Computers*, ISWC ’17, pp. 130–137. ACM, New York, NY, USA, 2017. doi: 10.1145/3123021.3123035

[4] M. Fujiwara, K. Nakatsuma, M. Takahashi, and H. Shinoda. Remote measurement of surface compliance distribution using ultrasound radiation pressure. In *2011 IEEE World Haptics Conference*, pp. 43–47, June 2011. doi: 10.1109/WHC.2011.5945459

[5] M. F. Hamilton and D. T. Blackstock. *Nonlinear Acoustics*. Academic Press, San Diego, 1998.

[6] K. Hasegawa, L. Qiu, A. Noda, S. Inoue, and H. Shinoda. Electronically steerable ultrasound-driven long narrow air stream. *Applied Physics Letters*, 111(6):064104, 2017.

[7] K. Hasegawa, L. Qiu, and H. Shinoda. Interactive midair odor control via ultrasound-driven air flow. In *SIGGRAPH Asia 2017 Emerging Technologies*, SA ’17, pp. 8:1–8:2. ACM, New York, NY, USA, 2017. doi: 10.1145/3132818.3132833

[8] K. Hasegawa and H. Shinoda. Aerial display of vibrotactile sensation with high spatial-temporal resolution using large-aperture airborne ultrasound phased array. In *2013 World Haptics Conference (WHC)*, pp. 31–36, April 2013. doi: 10.1109/WHC.2013.6548380

[9] K. Hashimoto and T. Nakamoto. Tiny olfactory display using surface acoustic wave device and micropumps for wearable applications. *IEEE Sensors Journal*, 16(12):4974–4980, June 2016.

[10] M. HEILIG. Sensorama simulator, us patent 3050870, 1962.

[11] K. Hirota, Y. Ikei, and T. Amemiya. Olfactory display for multi-sensory theater. In *Proceedings of ASIAGRAPH*, pp. 24–28, 2010.

[12] K. Hirota, Y. Ito, T. Amemiya, and Y. Ikei. Generation of directional wind by colliding airflows. In *2013 World Haptics Conference (WHC)*, pp. 509–514, April 2013. doi: 10.1109/WHC.2013.6548460

[13] T. Hoshi, M. Takahashi, T. Iwamoto, and H. Shinoda. Noncontact tactile display based on radiation pressure of airborne ultrasound. *IEEE Transactions on Haptics*, 3(3):155–165, July 2010.

[14] S. Inoue, Y. Makino, and H. Shinoda. Active touch perception produced by airborne ultrasonic haptic hologram. In *2015 IEEE World Haptics Conference (WHC)*, pp. 362–367, June 2015. doi: 10.1109/WHC.2015.7177739

[15] T. Iwamoto, M. Tatezono, and H. Shinoda. Non-contact method for producing tactile sensation using airborne ultrasound. In *Proceedings of the 6th International Conference on Haptics: Perception, Devices and Scenarios*, EuroHaptics ’08, pp. 504–513. Springer-Verlag, Berlin, Heidelberg, 2008. doi: 10.1007/978-3-540-69057-3_64

[16] T. Kamakura, K. Yasuda, and Y. Kumamoto. Unified description of second-order phenomena in sound waves. *Electronics and Communications in Japan (Part III: Fundamental Electronic Science)*, 82(2):76–82, 1999. doi: 10.1002/(SICI)1520-6440(199902)82:2<76::AID-ECJC9>3.0.CO;2-Q

[17] D. W. Kim, Y. H. Cho, K. Nishimoto, Y. Kawakami, S. Kunifuji, and H. Ando. Development of aroma-card based soundless olfactory display. In *2009 16th IEEE International Conference on Electronics, Circuits and Systems - (ICECS 2009)*, pp. 703–706, Dec 2009. doi: 10.1109/ICECS.2009.5410784

[18] D. W. Kim, K. Nishimoto, and S. Kunifuji. *An Editing and Displaying System of Olfactory Information for the Home Video*, pp. 859–866. Springer Berlin Heidelberg, Berlin, Heidelberg, 2006. doi: 10.1007/11893011_109

[19] T. Kozuka, T. Tuziuti, H. Mitome, F. Arai, and T. Fukuda. Three-dimensional acoustic micromanipulation using four ultrasonic transducers. In *MHS2000. Proceedings of 2000 International Symposium on Micromechatronics and Human Science (Cat. No.00TH8530)*, pp. 201–206, 2000. doi: 10.1109/MHS.2000.903313

[20] B. Long, S. A. Seah, T. Carter, and S. Subramanian. Rendering volumetric haptic shapes in mid-air using ultrasound. *ACM Trans. Graph.*, 33(6):181:1–181:10, Nov. 2014. doi: 10.1145/2661229.2661257

[21] H. Matsukura, T. Yoneda, and H. Ishida. Smelling screen: Development and evaluation of an olfactory display system for presenting a virtual odor source. *IEEE Transactions on Visualization and Computer Graphics*, 19(4):606–615, April 2013.

[22] K. Murai, T. Serizawa, and Y. Yanagida. Localized scent presentation to a walking person by using scent projectors. In *2011 IEEE International Symposium on VR Innovation*, pp. 67–70, March 2011. doi: 10.1109/ISVRI.2011.5759604

[23] F. Nakaizumi, H. Noma, K. Hosaka, and Y. Yanagida. Spotscents: A novel method of natural scent delivery using multiple scent projectors. In *IEEE Virtual Reality Conference (VR 2006)*, pp. 207–214, March 2006. doi: 10.1109/VR.2006.122

[24] T. Nakamoto and H. P. D. Minh. Improvement of olfactory display using

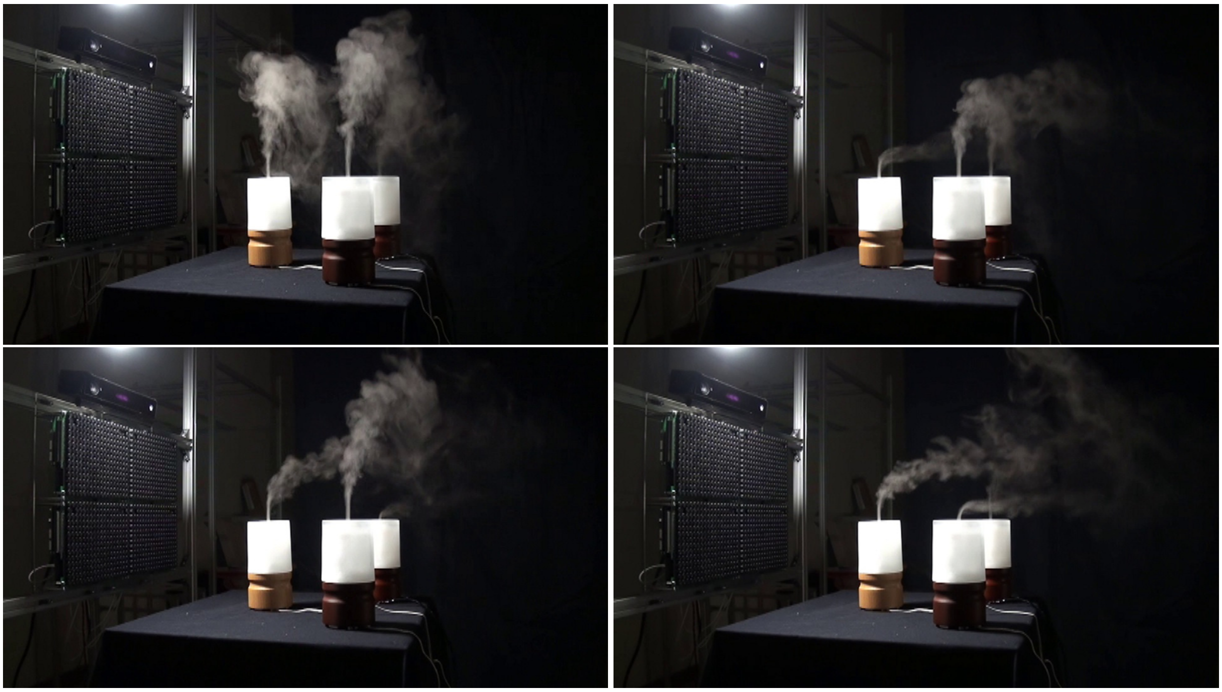

Fig. 12. Selectively redirected water vapor sources.

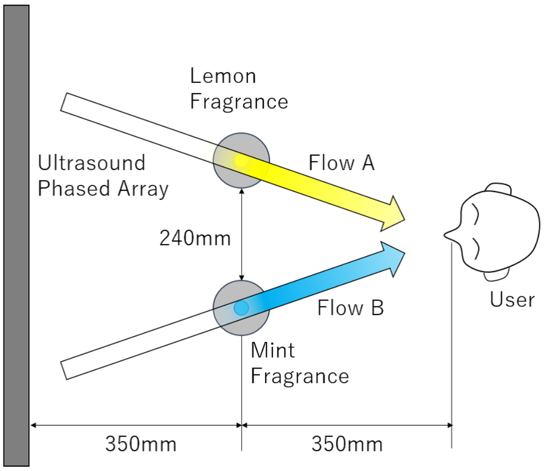

Fig. 13. Spatial setup of the selective scent presentation. A lemon-scented air flow (Flow A) and a mint-scented air flow (Flow B) is alternatively presented to the user's nostril.

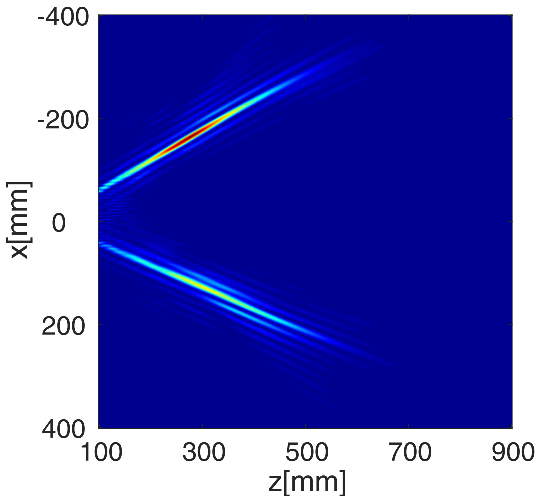

Fig. 14. Grating robe (lower weaker beam) and main robe (upper stronger beam).

solenoid valves. In *2007 IEEE Virtual Reality Conference*, pp. 179–186, March 2007. doi: 10.1109/VR.2007.352479

[25] T. Narumi, S. Nishizaka, T. Kajinami, T. Tanikawa, and M. Hirose. *Meta Cookie+: An Illusion-Based Gustatory Display*, pp. 260–269. Springer Berlin Heidelberg, Berlin, Heidelberg, 2011. doi: 10.1007/978-3-642-22021-0_29

[26] S. Sugimoto, D. Noguchi, Y. Bannnai, and K. Okada. Ink jet olfactory display enabling instantaneous switches of scents. In *Proceedings of the 18th ACM International Conference on Multimedia*, MM '10, pp. 301–310. ACM, New York, NY, USA, 2010. doi: 10.1145/1873951.1873994

[27] T. Yamada, S. Yokoyama, T. Tanikawa, K. Hirota, and M. Hirose. Wearable olfactory display: Using odor in outdoor environment. In *IEEE Virtual Reality Conference (VR 2006)*, pp. 199–206, March 2006. doi: 10.1109/VR.2006.147

[28] Y. Yanagida, S. Kawato, H. Noma, A. Tomono, and N. Tesutani. Projection based olfactory display with nose tracking. In *IEEE Virtual Reality 2004*, pp. 43–50, March 2004.

[29] P. Zhang, T. Li, J. Zhu, X. Zhu, S. Yang, Y. Wang, X. Yin, and X. Zhang. Generation of acoustic self-bending and bottle beams by phase engineering. *Nature Communications*, 5:4316 EP –, Jul 2014. Article.