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Synchronized presentation of odor with airflow using olfactory display †

Haruka Matsukura[1], Hitoshi Yoshida[1], Takamichi Nakamoto[2] and Hiroshi Ishida[1,*]

[1]*Department of Mechanical Systems Engineering, Tokyo University of Agriculture and Technology, Tokyo, 184-8588, Japan*
[2]*Department of Physical Electronics, Tokyo Institute of Technology, Tokyo, 152-8552, Japan*

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Abstract

This paper reports on an olfactory display system that enables the synchronized presentation of odors with airflow in a virtual reality environment. In the proposed system, computational fluid dynamics simulation is conducted to calculate how an odor released from its source is spread in a given airflow field. An odor vapor with an appropriate concentration is generated and delivered to the user's nose. A sensation that an odor is coming from a specific object is created even though the object per se is not releasing the odor. Experimental results are presented to show the potential of the proposed system.

Keywords: Computational fluid dynamics; Olfactory display; Smell; Virtual reality

1. Introduction

Advancements in virtual reality systems have been so far made mostly on the technologies for visual and audio outputs. The sensation of total immersion in a virtual reality environment is created with three-dimensional images and surround sound. In some virtual reality setups, users receive tactile feedback when they touch objects presented in the virtual world. However, Nakaizumi et al. stated that an experience of a virtual world without smells is like being in a space suit with no contact with air in the virtual world [1]. It is expected that the sense of reality can be significantly improved by introducing olfactory stimulation devices, that is, olfactory displays, into virtual reality systems.

Currently, various types of olfactory display systems are being developed. Generally, one mixture of chemicals in liquid form is prepared for the generation of each specific odor. The vaporized odorant is delivered to the user's nose through tubing [2, 3] or the odorant is vaporized by injecting small droplets of a liquid sample into an air current using an inkjet device [4]. A device that shoots vortex rings of air can also be used to deliver odor to the user's nose [1].

Although these olfactory displays are made solely for odor generation, our sensation of odors is often affected by the sense of airflow. When we perceive airflow on our faces together with a certain odor, we feel that the odor is coming from the direction of the airflow. For synchronized presentation of an odor with airflow, strong influence of the airflow on mass transport must be considered. As molecular diffusion is an extremely slow process, odor molecules released from their source are carried by airflow [5]. The distribution of the odor is thus mainly determined by the airflow field.

In our previous work, we proposed the use of computational fluid dynamics (CFD) simulation in an olfactory display system [6]. The CFD simulation is conducted to calculate the airflow field and the odor distribution in a given environment. The intensity of the odor presented to the user is adjusted considering the relative location of the odor source with respect to the user's nose. Here we report the results of applying the proposed system to a synchronized presentation of an odor with airflow.

2. Method

The schematic diagram of the proposed olfactory display system is shown in Fig. 1. A computational model for the scenario under consideration was first prepared. The airflow field in the given environment and the resultant odor distribution were calculated using a commercial CFD software package (CFD2000, Adaptive Research). The odor with the exact concentration was generated using an odor blender based on the simulation results. The concentration of the odor vapor was adjusted by diluting the odor vapor with clean air at a specified ratio using rapidly switching solenoid valves [3]. The generated odor vapor was delivered to the user's nose through the tube attached to the headset.

Sensory tests were conducted to evaluate the soundness of

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*Corresponding author. Tel.: +81 42 388 7420, Fax.: +81 42 385 7204
E-mail address: h_ishida@cc.tuat.ac.jp

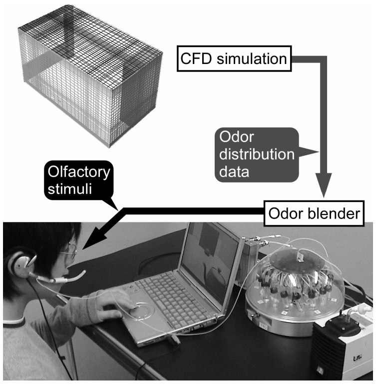


Fig. 1. Schematic diagram of presenting odor stimuli based on CFD simulation.

the proposed method. The scenario assumed in the sensory tests is shown in Fig. 2. An electric stand fan is set behind a teapot filled with peach tea. When the fan is turned on, it starts to oscillate periodically. The airflow generated by the fan brings the odor molecules from the teapot to the nose of the panelist, and therefore, he/she periodically perceives the smell of the peach tea. In the sensory tests, the smell of the peach tea was released not from the teapot but from a peach flavor installed in the odor blender to reproduce the assumed scenario. The smell of the peach tea was released with the intensity specified by the CFD simulation results, while the fan provided the panelist with the real oscillating airflow.

3. Experiments

3.1 CFD simulation

The results of the CFD simulation are shown in Fig. 3. It was assumed that an odor source was placed in a room of 5.8 m in width, 3.2 m in depth, and 2.7 m in height. A real room in our laboratory was used as a model. The black regions at the lower left corners of Figs. 3(a) and (b) represent a kitchenette installed in the room. To imitate the odor release from the teapot, odor vapor with a concentration of 50,000 ppm was released from a 0.10 m × 0.086 m region of the floor at 8.3 ml/s. The diffusion coefficient of the odor vapor was set to 1.0 $\times 10^{-5}$ m^2/s, while its density was set to be the same as air. Typical volatile organic compounds have similar diffusion coefficients.

A fan oscillating by ±35° with a period of 14 s was placed at 0.93 m from the odor source. Airflow was assumed to be generated at a square region of 0.20 m × 0.20 m placed at 0.3 m from the floor. In the fixed grid calculation, the orientation of the square region needs to be fixed along the grid. To reproduce the oscillation of the fan, the direction of the airflow coming out from the square region was oscillated rather than changing the orientation of the square region with time. The airflow velocity at the square region was therefore set to

$$U_{\perp} = 2 \cos \left[\frac{7\pi}{36} \sin\left(\frac{2\pi}{14} t \right) \right] \tag{1}$$

(a) (b)

Fig. 2. Images seen from the panelist's point of view. (a) Fan is pointing towards the panelist. (b) Fan is pointing away from the panelist.

$$U_{//} = -2 \sin \left[\frac{7\pi}{36} \sin\left(\frac{2\pi}{14} t \right) \right] \tag{2}$$

where t is the time in second, $U_{\perp}$ is the velocity component perpendicular to the fan, and $U_{//}$ is the velocity component parallel to the fan. In these equations, a positive value of $U_{\perp}$ means that the airflow is coming out from the fan, and a positive value of $U_{//}$ means that the airflow is directed to the left of the fan.

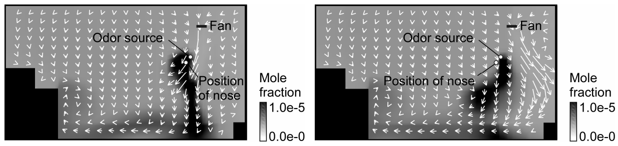
The number of cells for the CFD calculation was 45 × 47 × 32. It was assumed that there was initially no movement in air. The development of the airflow field and the odor distribution for 360 s was calculated using the standard k-ε turbulence model with a time step of 0.05 s. The airflow velocity and the odor concentration were recorded in the hard drive at a 1 s interval. The total time required for the calculation of the 360s time period was approximately 11 h.

The panelist was assumed to be at the point 0.16 m from the teapot as shown in Fig. 3. The CFD calculation was done without introducing the body of the panelist in the room model, although the presence of the body might affect the airflow field and the odor distribution in real scenarios. In Fig. 3(a), the airflow coming out from the fan is pointing to the position of the panelist's nose. Therefore, the concentration of the odor at the position of the nose is high. In Fig. 3(b), the airflow is pointing to the side, and the odor concentration at the position of the nose is low.

The time-series data of the odor concentration and the airflow velocity at 0.1 m from the floor are shown in Fig. 4. The oscillation of the fan causes the periodic changes in the odor intensity and the airflow velocity. In this scenario, a panelist feels the airflow from the fan on his/her face when the airflow is directed to him/her. At the same time, the panelist feels the odor as the airflow brings the odor molecules from the teapot to the nose of the panelist. On the other hand, the intensity of the perceived odor decreases when the fan is pointing away from the panelist.

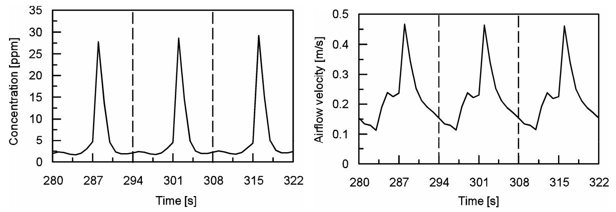
3.2 Sensory tests

In the sensory tests, each panelist was asked to sit in front of a real electric fan at a specific distance and angle. A teapot was placed in front of the panelist to reproduce the assumed scenario. Due to the distance between the fan and the panelist,



(a) (b)

Fig. 3. Results of CFD simulation for the scenario assumed in the sensory tests. Top view of the odor distribution and airflow field in the horizontal cross section at 0.1 m from the floor are presented. (a) and (b) are the snapshots of the odor distribution and airflow field at 288 s and 293 s, respectively. The velocity vectors shown in the figures are in the range of 0 to 0.75 m/s.



(a) (b)

Fig. 4. Time courses of (a) the odor concentration and (b) the airflow velocity at the assumed position of the panelist's nose after 20 cycles of oscillation of the fan. The values were extracted from the CFD simulation data. Periodic changes in the odor concentration and the airflow velocity were observed.

there was a delay of a few seconds between the time when the fan directly faced the panelist and the time when the panelist felt the airflow from the fan. Generating odor vapor with the time course of the odor intensity specified in Fig. 4(a) enables the synchronized presentation of the odor with the changing airflow as the delay is reproduced in the CFD simulation.

The panel of the sensory tests was comprised of university students. Firstly, we let each panelist experience the real odor from the teapot by placing some peach flavor in the pot. It was confirmed that the airflow and the peach smell were felt in phase. The odor with a high concentration was perceived when the airflow from the fan was felt. Each panelist was then asked to try in-phase and out-of-phase odor presentation. In the in-phase odor presentation, the intensity of the odor delivered from the odor blender to the nose of the panelist was changed according to the curve shown in Fig. 4(a). In the out-of-phase odor presentation, the odor intensity was changed with a half-cycle delay. We asked the panelist to close his/her eyes during the experiments to concentrate on the sensation of the odor and the airflow.

In the first set of sensory tests, we told the eight panelists to pay attention to the temporal change and the timing of the olfactory stimuli. All the panelists answered in the questionnaires that the in-phase odor presentation was better than the out-of-phase presentation. The change in the odor intensity they felt in the in-phase odor presentation was closer to the odor intensity change they felt when the odor was released from the real teapot. In the second set of sensory tests, the same experiment was repeated for another eight panelists without instructing them to pay attention to the timing of the olfactory stimuli. Six out of the eight panelists answered that the in-phase odor presentation provided a more realistic odor sensation. This result suggests that the synchronized presentation of the odor with the airflow is effective in enhancing the sense of reality.

4. Conclusions

We proposed the use of a CFD simulation in an olfactory display system. Synchronized presentation of an odor with airflow was enabled by adjusting the intensity of the odor based on the CFD simulation. Sensory tests were conducted to evaluate the effectiveness of the proposed system, and encouraging results were obtained. Future work will be addressed to the development of an artificial airflow generator to be used with an olfactory display.

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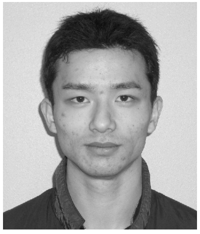
Haruka Matsukura received her B.E. degree in Mechanical Systems Engineering from the Tokyo University of Agriculture and Technology in 2009. She is currently pursuing her M.E. degree in Mechanical Systems Engineering. Her research interest is on olfactory display systems and their applications.



Hitoshi Yoshida received his B.E. degree in Mechanical Systems Engineering from the Tokyo University of Agriculture and Technology in 2008. After completing his undergraduate work, he joined Hitachi, Ltd.

Takamichi Nakamoto received his B.E. and M.E. degrees from the Tokyo Institute of Technology in 1982 and 1984, respectively. In 1991, he earned his Ph.D. degree in Electrical and Electronic Engineering from the same institution. He worked for Hitachi from 1984 to 1987. In 1987, he joined the Tokyo Institute of Technology as a research associate. He has been an associate professor at the Tokyo Institute of Technology since 1993. His research interests cover chemical sensing systems, acoustic wave sensors, olfaction in virtual reality, and LSI design.

Hiroshi Ishida received his M.E. and Ph.D. degrees in Electrical and Electronic Engineering from the Tokyo Institute of Technology in 1994 and 1997, respectively. From 1997 to 2004, he was a research associate at the Tokyo Institute of Technology. In 2004, he joined the Department of Mechanical Systems Engineering at the Tokyo University of Agriculture and Technology as an associate professor. His research interests are in chemical sensors and their applications in robotics.