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Short Papers: Olfactory Display: Fluid Dynamic Considerations for Realistic Odor Presentation

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Abstract

This paper describes some fluid dynamic considerations for attaining realistic odor presentation using an olfactory display. Molecular diffusion is an extremely slow process and, therefore, odor molecules released from their source are spread by being carried off by airflow. Since the flow we encounter is almost always turbulent, the intensities of the odors delivered from their sources to our noses fluctuate randomly over time. Experimental results are presented to show the random fluctuations of odor intensity alleviate olfactory adaptation. When the odor vapor generation from an olfactory display device is randomly modulated, the odor is felt more persistently over time than in the case of the constant release of the odor vapor. The results of computational fluid dynamics simulations are also presented to show that our body temperature affects reception of odor vapors at our noses. Convective air currents in the upward direction are generated by our body temperature. They bring the odor vapor drifting along the floor up to our noses. Without the body temperature, such odor might not be detected. The detailed fluid dynamic considerations thus enable reproduction of realistic odor stimuli that we encounter in real-life scenarios.

Categories and Subject Descriptors (according to ACM CCS): H.5.1 [Information Interfaces and Presentation]: Multimedia Information Systems—Artificial, Augmented, and Virtual Realities

1. Introduction

In an immersive virtual reality system, 3-D graphics and sound are presented to give the user a sensation of being in an artificially created environment. Sometimes, a tactile interface is also provided to allow the user to physically interact with the virtual environment through touching the objects projected in the 3-D image. An olfactory display is a device for generating odor vapors. It is expected to bring a significantly improved sense of reality by presenting relevant odors to the user together with 3-D image and sound [NNHY06].

One of the most difficult technical challenges in the development of olfactory display systems is obviously how to generate appropriate odors. Therefore, most of the research work in this emerging field is directed toward the development of physical devices for odor vapor generation. Generally, vials containing liquid-phase odor samples are set in an olfactory display system, and their vapors are delivered to the user's nose through tubing or as air puffs. However, not much attention has been paid on the adjustment of odor intensity for realistic odor presentation. The appropriate concentrations of odor vapors are extremely different for reproduction of a faint scent drifting in the air and a malodor hitting the nose. A systematic method for determining the appropriate odor vapor concentration needs to be established.

One way to solve this problem is to use physics-based simulation. We proposed incorporating computational fluid dynamics (CFD) simulation into an olfactory display system [IMYN08], [MYIN09]. Diffusion of odor molecules into air is generally an extremely slow process (only 70 mm in one minute) [Dus92]. On the other hand, even the weak convection caused by temperature variation in a closed room is in the order of a few centimeters per second [IMYN08]. Therefore, airflow velocity in most indoor and outdoor environments dominates the slow molecular diffusion. The odor molecules released from their source are carried by airflow, and the odor distribution is thus mainly determined by the airflow field. The flows we encounter in real-life situations are almost always turbulent. This fact adds significant complexity in predicting how the odor molecules are transported from their source to our noses. CFD simulation can provide us with reasonable and realistic estimation of the odor distribution if used appropriately.

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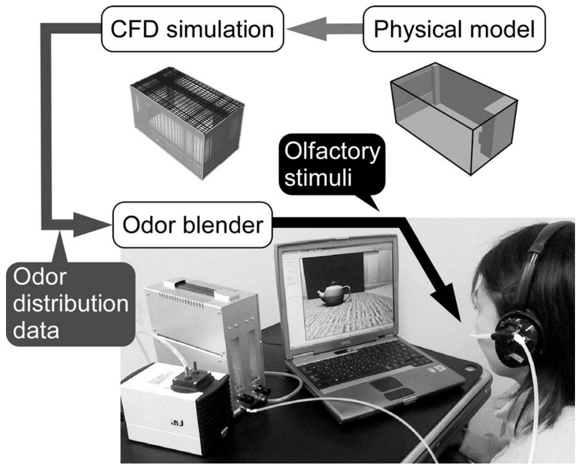

Figure 1: *Proposed olfactory display system.*

Figure 1 shows the structure of the olfactory display system we propose. We start from a physical model of the virtual environment under consideration. CFD simulation is conducted to determine the airflow field and the odor concentration distribution. The odor blender used in our system is based on the same architecture as described in [NY06]. The intensity of the odor stimuli or the concentration of the generated odor vapor is adjusted according to the assumed position of the user in the virtual environment. During the course of our experiments, we noticed some interesting fluid dynamic effects on our perception of odors. In order to provide some insights toward realistic odor presentation using olfactory display systems, here we report the effect of odor concentration fluctuations on olfactory adaptation and the effect of human body temperature on the odor distribution.

2. Related Work

A handful of olfactory display systems can present odors with different intensities. The olfactory display system reported in [NY06] enables generation of various odors by using rapidly switching solenoid valves. Vapors from different vials can be mixed with arbitrary ratios to synthesize new odors. The same technique can be also used to switch the odor to a different one by changing the mixing ratio. The concentration of the presented odor can be adjusted by mixing the odor vapor with clean air. More precise control over the concentration of the odor vapor and the timing for odor delivery is attained in the olfactory display reported in [SOBO09]. Odor vapors are generated by shooting tiny droplets of liquid-phase odor samples into an airstream using inkjet devices. A unique device called a scent projector is proposed in [NNHY06]. The device shoots off vortex rings of odor-containing air and can deliver them to the nose of the user sitting at several meters away from the device.

The wearable olfactory display reported in [YYT*06] allows the user to walk around in an immersive virtual reality

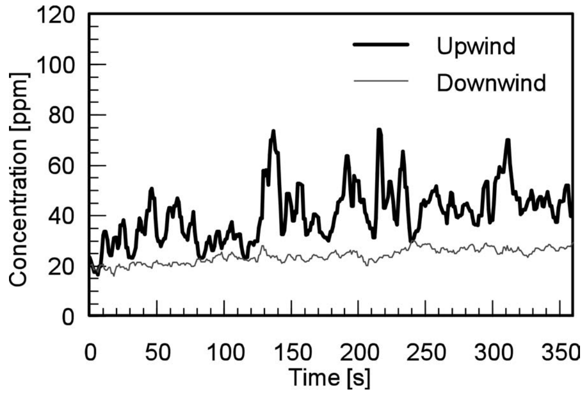

Figure 2: *Fluctuations in the odor concentrations measured with a photo-ionization gas detector in a real room.*

environment. In the experiments described in [YYT*06], the position of the user was measured using RFID tags. The intensity of the odor presented to the user was adjusted according to the distance between the user's position and the virtual odor source. However, the odor distributions in real-life situations can be much more complicated than those expected from the isotropic diffusion model used in [YYT*06].

3. Effect of Odor Concentration Fluctuations

When the odor with a constant concentration was released from the olfactory display, the perceived odor intensity tends to decrease rapidly. However, we sometimes experienced in our experiments that the olfactory adaptation hardly occurs in real environments even if the release rate of the odor vapor from the source was kept constant. We assumed that the persistent odor perception could be attributed to the random fluctuations of the odor concentration caused by turbulence of the airflow. A human sensory test was conducted to confirm the assumption.

3.1. Experiments

One of the distinctive characteristics of the turbulent flow is the random fluctuations in the flow velocity. Since the odor is spread in the environment by being carried by airflow, the odor distribution also shows random fluctuations. Figure 2 shows the time courses of the odor concentrations measured by placing a photo-ionization gas detector at fixed points. A source of ethanol vapor and a large obstacle (90 cm in width, 180 cm in height, and 4 cm in depth) were placed in a real room. The concentration measurements were performed at the upwind and downwind sides of the obstacle. Large concentration fluctuations were observed at the upwind side. At least in our experience, the olfactory adaptation appeared to occur more slowly there than on the downwind side.

In the sensory test, the odor with a constant concentration and that with randomly modulated concentration were

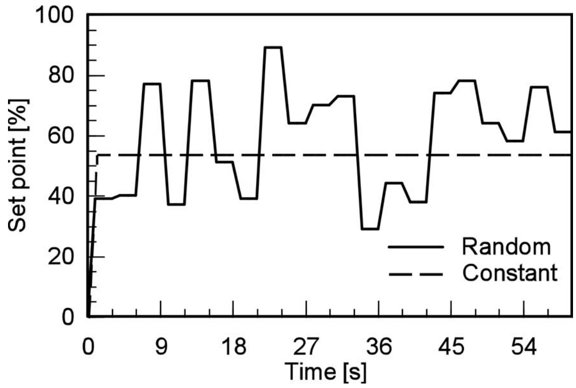

Figure 3: *Changes in the odor concentrations presented to the panelists in the sensory test.*

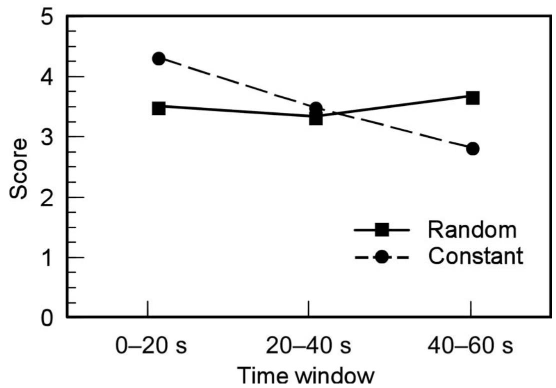

Figure 4: *Result of the sensory test.*

presented to the panelists. In Figure 3, the concentration set points given to the odor blender is shown as the relative concentrations with respect to the maximum concentration attained with the odor blender. The time-averaged values of the odor concentrations were matched for the constant and random odor presentations. In the random odor presentation, the ratio of the standard deviation of the odor concentration over time to its mean value was set based on Figure 2 (the time course of the odor concentration measurement at the upwind side of the obstacle).

3.2. Results

In the sensory test, six panelists tried the constant and random odor presentations. In each odor presentation, the odor vapor was generated for 60 s with either constant or randomly modulated concentration. The panelists were instructed to smell the odor at an interval as short as possible. The 60 s odor presentation was divided into three time windows, and the panelists were asked to score the odor intensities they perceived in each time window with the numbers from 1 to 5.

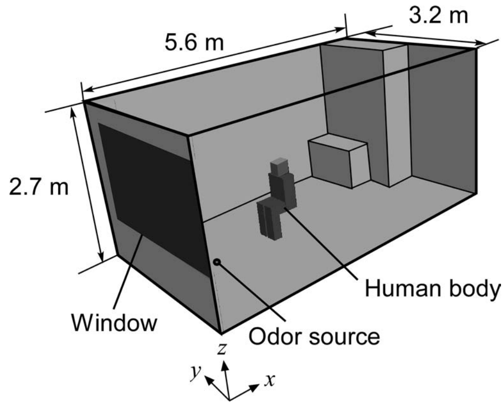

Figure 5: *Room model with a human body.*

The averages of the scores for the six panelists are shown in Figure 4. When the odor was released with the constant concentration, the odor intensities the panelists perceived decreased over time because of the olfactory adaptation. When the concentration of the released odor was randomly modulated, there was no decrease in the perceived odor intensities for 60 s. Even if the olfactory adaptation occurs, the rise in the odor concentration can be still perceived [Dus92]. The result of the sensory test shows that long-lasting perception of odors can be given to the user by randomly modulating the odor concentration. This technique can be used in a variety of applications whenever persistent odor stimulation is required.

4. Effect of Human Body Temperature

When an odor source was placed on the floor in a virtual environment, our initial CFD simulation results showed that no odor could be perceived at the height of our noses. In reality, however, we often feel the odor even if the source is on the floor. The results of the CFD simulations with a human body model showed that this discrepancy can be attributed to the human body temperature.

4.1. Method

The room model shown in Figure 5 was prepared for the CFD simulations. A human facing to the window was assumed to be sitting on a chair in the room. The wintertime was assumed, and the temperature in the room was set to 288 K. The temperature of the window was set to 283 K considering the cooling effect by the outside air. The temperature of the head part of the human model was set to 305 K, and the temperature of the body part was set to 300 K. These values were chosen based on the measurements of the real human body temperature with a radiation thermometer. The room model was divided into $63 \times 43 \times 46$ cells, and the CFD calculation was done using a commercial software package (CFD2000, Adaptive Research). In the CFD

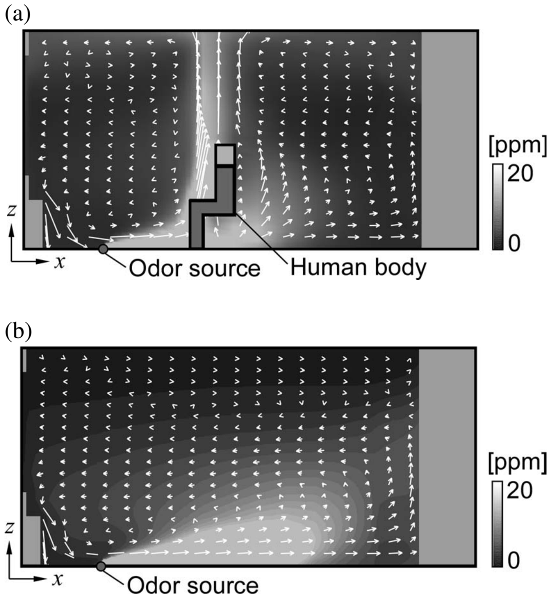

Figure 6: *Results of the CFD simulations using the room models (a) with and (b) without a human body. The airflow velocities shown with the white arrows are in the range of 0–22 cm/s.*

simulation, the development of convective airflow field for 900 s was first calculated. Secondly, to simulate the odor release from a source placed on the floor, odor vapor with the concentration of 50000 ppm was assumed to be released at 500 ml/min from a 5 cm $\times$ 5 cm region of the floor. The odor source was assumed to be 100 cm upwind from the human body. The spread of the odor in the environment for 360 s was then calculated. All calculation was done using the standard k-ε turbulence model with the time step of 0.05 s.

4.2. Simulation Results

The results of the CFD simulations are shown in Figure 6. It shows the distribution of the odor concentration on the vertical cross section at the mid-width of the room. The air cooled down at the window first descended to the floor, and then spread over the floor to the right. As a result, the circulating airflow field was established in this virtual environment. The odor vapor released from the source was carried by the airflow, and was also spread to the right as shown in Figure 6b. Although the density of the released odor vapor was assumed to be the same as that of air, the odor vapor was mostly staying near the floor. In the odor distribution shown in Figure 6b, the odor concentration at the height of our noses is too low for us to perceive the odor.

However, the result of the CFD simulation for the room model with a human body was completely different. As shown in Figure 6a, the convection was created not only by the cold window but also by the human body temperature. The upward air currents generated by the human body was approximately 20 cm/s, and was comparable to the convection caused by the window. The velocity of the air currents caused by the human body was also experimentally validated. The odor distribution in Figure 6a shows that the odor vapor was carried upward from the floor to the head part of the human model by the upward air currents generated around the human body. As a result, the odor concentration in front of the face of the human model was significantly higher than the concentration at the same position in Figure 6b. These simulation results explain the discrepancy we experienced between the real experiments and the initial CFD simulations with the simple room models. The air currents generated by the human body temperature help the odor reception by bringing the odor vapor drifting along the floor or the ground to our noses. Such scenes can be found in many movies, e.g., statding in the field of blooming flowers.

5. Conclusions

Two fluid dynamic considerations for attaining realistic odor presentation were reported. The results of the sensory test showed that the olfactory adaptation can be alleviated by modulating the odor concentration randomly. The results of the CFD simulations with the human body model showed that the convection caused by the body temperature induces significant change in the distribution of the odor concentration. The detailed fluid dynamic considerations thus enable odor presentation of significantly improved sense of reality over the constant release of the odor vapor.

References

[Dus92] DUSENBERY D. B.: *Sensory Ecology: How Organisms Acquire and Respond to Information*. W. H. Freeman & Co., 1992.

[IMYN08] ISHIDA H., MATSUKURA H., YOSHIDA H., NAKAMOTO T.: Application of computational fluid dynamics simulation to olfactory display. In *Proc. ICAT 2008* (2008), pp. 285–288.

[MYIN09] MATSUKURA H., YOSHIDA H., ISHIDA H., NAKAMOTO T.: Interactive odor playback based on fluid dynamics simulation. In *Proc. IEEE VR 2009* (2009), pp. 255–256.

[NNHY06] NAKAIZUMI F., NOMA H., HOSAKA K., YANAGIDA Y.: SpotScents: a novel method of natural scent delivery using multiple scent projectors. In *Proc. IEEE VR 2006* (2006), pp. 207–214.

[NY06] NAKAMOTO T., YOSHIKAWA K.: Movie with scents generated by olfactory display using solenoid valves. *IEICE Trans. Fundamentals E-89-A* (Nov. 2006), 3327–3332.

[SOBO09] SATO J., OHTSU K., BANNAI Y., OKADA K.: Effective presentation technique of scent using small ejection quantities of odor. In *Proc. IEEE VR 2009* (2009), pp. 151–158.

[YYT*06] YAMADA T., YOKOYAMA S., TANIKAWA T., HIROTA K., HIROSE M.: Wearable olfactory display: using odor in outdoor environment. In *Proc. IEEE VR 2006* (2006), pp. 199–206.