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Record of Dynamic Changes of Odors Using an Odor Recorder

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We have developed the system called an *odor recorder* for reproducing the smell recorded using the odor sensing system. The recipe of the odor, where the sensor-array output pattern of a target odor matches that of an internally blended odor using multi-input multi-output (MIMO) feedback control, is recorded. It can be reproduced using an odor blender. The odor recorder has the capability of dynamic change in the odor in addition to the ability of recording the static recipe of the odor. Here, several techniques such as a neural network with feedback error learning, the real-time reference method and its modified technique for speeding up are described. The experiments revealed that the real-time reference method had the robustness against the environmental change. Moreover, the recording of the dynamic change of the odor over a few seconds was successfully performed using that method.

1. Introduction

Recently research has focused on communication using five senses. Since the fields of vision and hearing are mature, it is indispensable to open new fields in addition to those senses. The study of recording olfactory information is very challenging.

Although odors have been analyzed using gas chromatograph/mass spectrometry (GC/MS) for long time, odor-sensing systems, often called electronic noses, have been studied for last two decades.(1) An odor sensing system offers a simple, rapid and objective evaluation method in place of GC/MS. Its principle is based upon pattern recognition of multiple-sensor outputs with partially overlapping specificities in the same manner as the biological olfactory system. This principle was proposed in 1982,(2) the concept of similarity was introduced,(3) and then a combination of a sensor array with a neural network was proposed.(4) Thereafter, many researchers came into this field and research on odor sensing systems became popular.(5,6)

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On the other hand, an olfactory display, a device for smell presentation, was recently studied in the field of virtual reality.(7) A computer-controlled scent diffuser connected to the Internet,(8) an odor-source localization in virtual space,(9) and the olfactory display for delivering smell to a single user's nose were studied.(10)

Our group proposed an odor recorder with the capability of reproducing smells as well as recording them in the same manner as in a video cassette recorder (VCR).(11) This is a new field, since the odor sensing system and the olfactory display have been studied independently. There are many consumer products related to smell such as food, beverage, cosmetics, toothpaste, and air refreshners for breath, room and bathroom. It is possible to use an odor recorder in a variety of fields and activities, such as e-commerce, games, virtual reality, cinema.

In the odor recorder, odor quality is represented as a recipe of the multiple odor components. Unlike the primary colors in vision, primary smells have thus far not been discovered, although the stereochemical theory was proposed by Amoore.(12) Thus, the range of smells to be realized is limited at the current stage. However, the range of smells can be gradually extended after information on smells is accumulated using this system.

There are two types of odor recorder. One determines the odor recipe kept constant during recording. The other is the odor recorder to obtain the recipe of the dynamically changing odor. In the actual environment, the odor concentration is rapidly changed due to turbulence. In this report, the latter type of the odor recorder is reviewed.

2. Principle of Odor Recorder

2.1 *Whole system*

Although a sensing system together with an olfactory display has been discussed,(13) only a few reports have appeared for systems with the capability of both recording and reproducing smells. Keller *et al.* proposed the olfactory transmission method in which an odor identified by a neural network was transmitted to a place, where the same odor was generated.(14) However, the range of odors was quite limited because the system did not have the ability to blend odors. Although reproduction of smell was studied using the commercially available sensing system and conventional multivariate analysis, evaluation of the reproduced smell was not carried out.(15)

The principle of an odor recorder is illustrated in Fig. 1. First, the target odor to be recorded is introduced into a sensor array composed of partially overlapping characteristics and its output pattern is memorized. Then, the responses of the sensors to the blended odor made up of multiple component odors given by an odor blender are measured and are compared with those of the target odor. The recipe of the target odor is obtained from that of the blended odor in the case in which the sensor-array output pattern of the blended odor agrees with that of the target odor. Otherwise the recipe of the blended odor is iteratively modified so that the sensor array output pattern of the blended odor approaches that of the target odor using a nonlinear optimization algorithm or adaptive feedback control theory.(16) The recipe of the target odor is obtained after convergence.

Once the recipe is recorded, the smell can be reproduced using the odor blender. The odor blender located remotely from the odor recorder can be used to generate the smell as

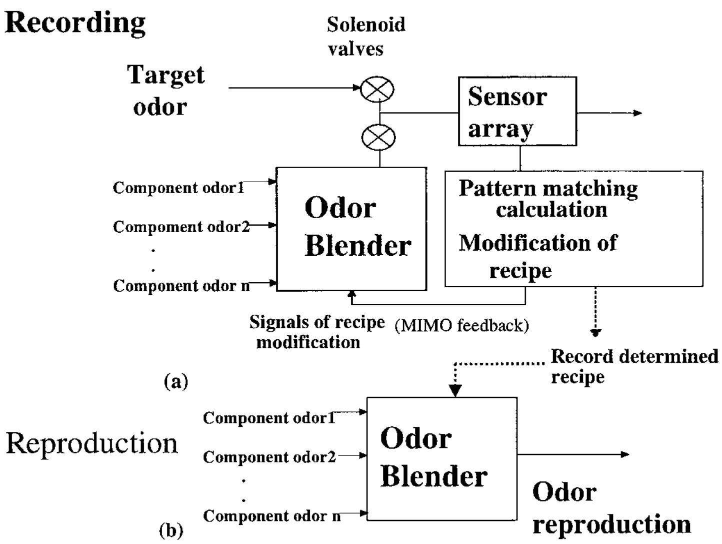


Fig. 1. Principle of odor recorder. (a) Recording and (b) reproduction.

can the blender inside the odor recorder. When the odor blender is located far from the odor recorder, the recipe can be transmitted to it via the Internet.

When the odor is reproduced at a place far from the recording point, there is another way to realize the odor recorder as is illustrated in Fig. 2. First, the sensor array output pattern is recorded. In the reproduction phase, the recipe of the blended odor is iteratively modified so that the sensor responses to the blended odor can match those to the target odor.(17)

In the recording phase, the output pattern of the sensor array is just recorded without the odor blender. However, the sensor array as well as the odor blender is required in the reproduction phase. When the odors at various places are collected, the approach in Fig. 2 seems attractive because no blender is required at the recording place.

2.2 *Sensors*

A variety of sensors are used in odor sensing systems such as metal oxide semiconductor (MOS) gas sensors,(18) quartz crystal microbalance (QCM) gas sensors,(19) surface acoustic wave (SAW) gas sensors,(20) cantilever-type gas sensors,(21) flexural plate wave (FPW) gas sensor,(22) conducting polymer (CP) sensors,(23) carbon-black polymer composite gas sensors,(24) MOS FET gas sensors,(25) mass spectrometry (MS),(26) ion mobility spectrometry (IMS),(27) high-speed GC,(28) optical sensors,(29) and electrochemical gas sensors.(30)

We used the QCM gas sensor since a variety of gas sensors may be easily fabricated. Its characteristics are somewhat similar to the human ones since its limit of detection correlates with human threshold values. Moreover, its output has a digital form and is easily interfaced with a digital LSI.

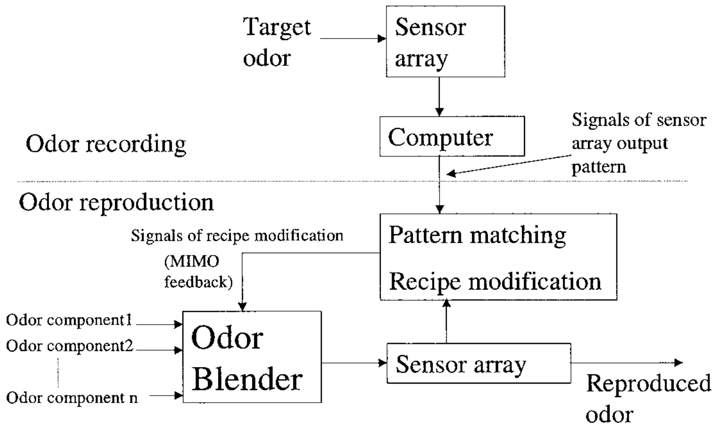


Fig. 2. Another type of odor recorder.

Its typical orientation is AT-CUT with a temperature coefficient of zero at 25°C. Thus, stable oscillation is achieved even if its structure is simple. Its operating mode is thickness shear, in which the particle displacement of the acoustic wave is parallel to the quartz plate surface.(31) It operates even in a liquid phase because of the thickness-shear mode.(32)

Although the typical size of the quartz plate is conventionally 7–8 mm, a recent quartz resonator mounted on a surface-mounted device (SMD) package was very small down to 2 mm. Thus, the SMD type QCM is effective when many sensors are integrated.(33)

The quartz resonator gas sensor consists of a resonator and the sensing film coated over its electrode. There are several methods for coating sensing films such as cast method, spin coating, spraying, Langmuir Blodgett (LB) method,(34) dip coating, plasma deposition(35) and ultrasonic atomizing.(36) The spray coating method is often used because of its simplicity. The sensing film material is dissolved in an organic solvent such as chloroform and is sprayed over the electrode of the quartz resonator. Since the organic solvent soon evaporates, only the sensing film is deposited over the electrode.

When odorant molecules are adsorbed onto the sensing film, its resonance frequency decreases due to the mass loading effect.(37–38) It returns to its original frequency when the gas around the sensor is replaced with clean air. Thus, it is possible to measure the sensor response repeatedly and reproducibly.

The sensitivity of a QCM gas sensor increases when its fundamental resonant frequency is raised. The quartz plate should be thinner as the resonant frequency becomes higher. Thus, it was difficult to raise the fundamental resonance frequency higher than 30 MHz, because a thin quartz plate is easily broken. However, the VUHF band QCM can be used when the active region of the quartz plate is partially etched to support the thin quartz plate by the thick plate around it.(39)

The materials of sensing films are lipids and celluloses, the stationary phase materials for gas chromatography. The materials are characterized using the partition coefficient of the sensing film, the ratio of the vapor concentration in the film to that in the gas phase in equilibrium. We previously studied the responses of many sensors to many vapors using an automated static measurement system to characterize the sensor coatings.(40) We select the combination of sensing films for a given set of samples from the huge number of candidates using the statistic index.[41]

2.3 *Mixture quantification technique*

The problem to be solved is closely related to the quantification of the composition of a mixture. When the linear relationship between the odor concentration and the sensor response and the superposition theorem for all the component odors are valid, only the simple techniques such as multiple linear regression or Partial Least Squares (PLS)[42] are required. However, it is rare that the linear relationship is completely valid. In the case of the quartz crystal microbalance sensor, the linearity is still insufficient even if the characteristics of that sensor are better than the other sensors.[42] Thus, an iterative method together with feedback control was adopted in the odor recorder.

Several methods have been proposed to obtain the composition of a gas mixture using PLS,[42] a typical artificial neural network,[43] a neural network tuned to semiconductor gas sensors,[44] locally weighted regression,[45] extended disjoint principal component regression (PCR)[46] and nonparametric techniques.[47] Other techniques utilized the spectral data for the quantification of mixtures.[48,49]

Our group proposed an active odor sensing system using an odor blender and a numerical optimization technique.[50,51] Our method is flexible, and no model for describing the characteristics of the sensor response to a gas mixture is required because of the relative measurement method, whereas all other methods required a model. Thus the accuracy of the active odor sensing system is high because no error is caused by model building. Furthermore, the proposed system is also robust against environmental change because of the relative measurement method. The odor recorder is based upon this active odor sensing system.

2.4 *Olfactory display*

The olfactory display is a device to present smells to people. It should have the function of blending component odors at an arbitrary ratio in the odor recorder. There are several pieces of equipment to present the smells.

The simplest device to present odors is a scent diffuser. Although it is not possible to mix several components at arbitrary ratios, it is easy to generate a smell. Several types of smells can be generated when the scent cartridge is replaced. The computer-controlled scent diffuser can be connected to the internet and can be controlled remotely to generate smells.[8]

Another method to generate smells is an olfactometer often used to measure the olfaction-induced brain wave potential.[52] The conditions of olfactory stimulus such as concentration, duration and flow rate are precisely controlled using this equipment. However, the equipment is large and expensive.

Several types of olfactory displays have also been developed.[7,13] Hirose developed an olfactory display attached to a head mount display for a virtual environment.[9] It is possible to let people sense how far away the object generating the smell is located. Yanagida *et al.* developed the smell generator to carry smell in a specific direction using an air canon.[10]

The specifications required for olfactory display is summarized in Table 1. First, the number of smells to be generated is important. Since primary smells have not yet been known, no equipment has been developed to emit any kind of smell. However, a variety of smells can be generated if component odors are blended at any composition. Second, the function of the concentration adjustment is required. A large dynamic range of odor intensity is preferable. Third, the speed of the odor variation both in strength and quality is a factor to be considered since the odor in the ambient air changes dynamically and irregularly. Moreover, the direction to the object generating the smell and the area of smell diffusion are important for the virtual environment.

Our group focused on blending aromas. Several methods are available to realize an aroma blender. The principles of olfactory display with the function of blending aromas are shown in Fig. 3. The first method is to use mass flow controller (MFCs). A mixture with any composition can be realized by adjusting the flow rates.(25) The MFC is good equipment for controlling the flow rate precisely and electronically. Although the MFC is typically controlled using an analog voltage, a recent model of an MFC has a digital interface. However, it is not suitable for realizing a blender with many components because of its cost. If a number of MFCs are integrated on a silicon chip using MEMS technology,(53) a sophisticated olfactory display can be realized.

The second method is an inkjet-based olfactory display. The inkjet devices individually controlled by a computer are used to blend aromas of any composition. An organic solvent-free device should be used to generate a smell. When we use the inkjet device, not a vapor but a liquid droplet is expelled from the nozzle. Since an odorant with high odor intensity typically has a high boiling point, it is difficult for the odorant to evaporate completely in spite of the tiny droplet size. Thus, the heater should be used to evaporate it immediately and completely. In our case, a mesh heater was employed. The combination of the inkjet device with a mesh heater enables the rapid change in concentration of the odor with high odor intensity, which often remains inside the plumbing in an MFC system.(54)

The third method is an olfactory display made up of solenoid valves. The solenoid valve is originally a fluidic switching device and could not be used to express fine differences in concentration. However, it becomes possible to express subtle concentration changes using high speed switching followed by a fluidic low pass filter. Our group applied the delta-sigma modulation technique, a 1-bit A/D conversion technique, to switch of the solenoid valves.(55) A photo of that type of olfactory display is shown in Fig. 4. Eight component odors can be blended based on an arbitrary recipe using this equipment. Since

Table 1
Specifications required for olfactory display.

No	Item
1	Number of smells
2	Adjustment of concentration (Dynamic range)
3	Speed of odor variation in quality and intensity
4	Direction to object producing smell
5	Area filled with smell

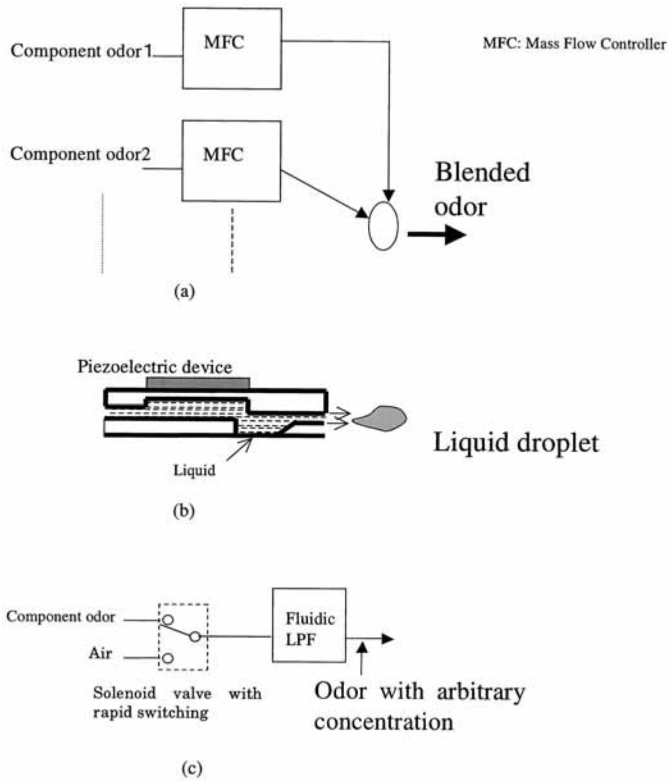


Fig. 3. Principles of olfactory display with the function of blending smells. (a) MFC, (b) inkjet device and (c) solenoid valve with high speed switch.

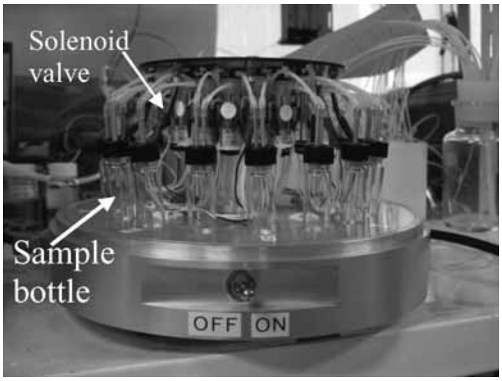


Fig. 4. Photo of olfactory display using solenoid valves controlled by delta-sigma modulation.

the solenoid valve is cheap, robust, and is easily controlled by a computer, it is not difficult to realize an olfactory display equipped with many components using solenoid valves.

3. Odor Recorder for Recording Recipes with Multiple Odor Components

In an odor recorder, multi-input multi-output (MIMO) feedback is used. This section provides a description of the realization of MIMO feedback when the number of sensors is *n* and the number of components is *m*. The response vector and the concentration vector of the blended odor at time *kT* are expressed by

$$\boldsymbol{s_k} = \left[s_1(k), s_2(k), .., s_i(k), .., s_n(k)\right]^T \tag{1}$$

and

$$\begin{aligned}\boldsymbol{u_k} &= \left[u_1(k), u_2(k), .., u_j(k), .., u_m(k)\right]^T \\ &= \left[c_1(k) - c_1(k-1), c_2(k) - c_2(k-1), .., c_j(k) - c_j(k-1), .., c_m(k) - c_m(k-1)\right]^T\end{aligned} \tag{2}$$

where $s_i(k)$, $u_j(k)$, $c_j(k)$ are the *i*th sensor responses, the change in the *j*th component concentration and the change of the *j*th component concentration, respectively. The state-space equation is given by

$$\boldsymbol{s_{k+1}} = F\boldsymbol{s_k} + G\boldsymbol{u_k}. \tag{3}$$

In the optimal feedback control, the index value

$$J = \sum_{k=0}^{p-1} \left\{ \left(\mathbf{s_{k+1}} - \mathbf{s_{target}}\right)^T Q \left(\mathbf{s_{k+1}} - \mathbf{s_{target}}\right) + \mathbf{u_k}^T R \mathbf{u_k} \right\} \tag{4}$$

is minimized by modifying the recipe of the blended odor, where *p* is the number of the concentration change during the odor-recipe exploration.[56] The first term in eq. (4) expresses the difference in the sensor response vector between the target odor and the blended one weighted by the diagonal matrix *Q*, and the second term expresses the difference in the concentration-change vector weighted by a diagonal matrix *R*. The second term is typically used to suppress the oscillation. The recipe of the blended odor is iteratively changed to decrease the index *J*. The method to determine *Q* and *R* is described in reference.[57] Using method described herein, the apple aroma, jasmine scent, spice and citrus aromas[58–60] were recorded.

The experimental setup is shown in Fig. 5. The odor blender was realized using 16 solenoid valves. The number of component odors was at most eight. The solenoid valves were controlled using the second-order delta sigma modulation and were switched every 50 ms. The flow rate at the bottle for each component odor was always kept constant even

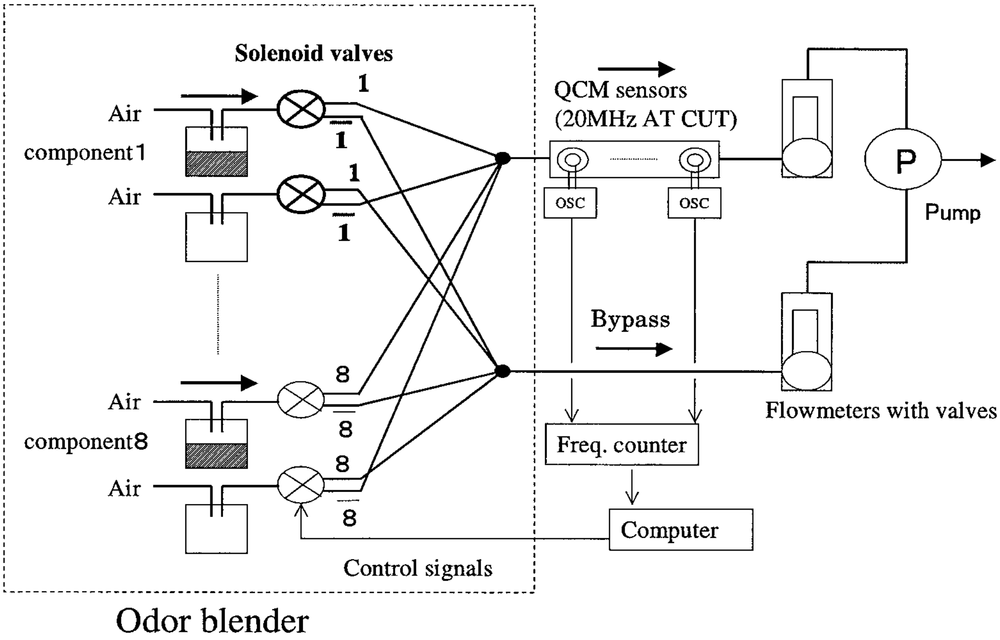


Fig. 5. Experimental setup for the odor recorder.

if that odor component was not supplied to the sensors. Thus, the odor component flowed to the bypass and air was supplied to the sensors instead of that component when the sensors were not exposed to that component. The flow rate through the bypass was adjusted to be the same as that at the senor cell. QCMs (20 MHz, AT-CUT) with different coatings were installed in the sensor cell made of stainless steel. The number of the sensors was at most eight. The experiment was performed at room temperature. The frequency changes of the oscillators connected to the QCMs were measured using a multi-channel frequency counter, with its data transferred to a computer via RS232C interface. Then the recipe was calculated and the solenoid valves were controlled using that information. The recipe modification was repeated until convergence. The target odor was in the headspace of the one of the bottles. It could be also synthesized using the component odors. The apple aroma composed of five main components was successfully recorded when its recipe was kept constant.[57]

4. Odor Recorder for Recording Dynamic Change of an Odor

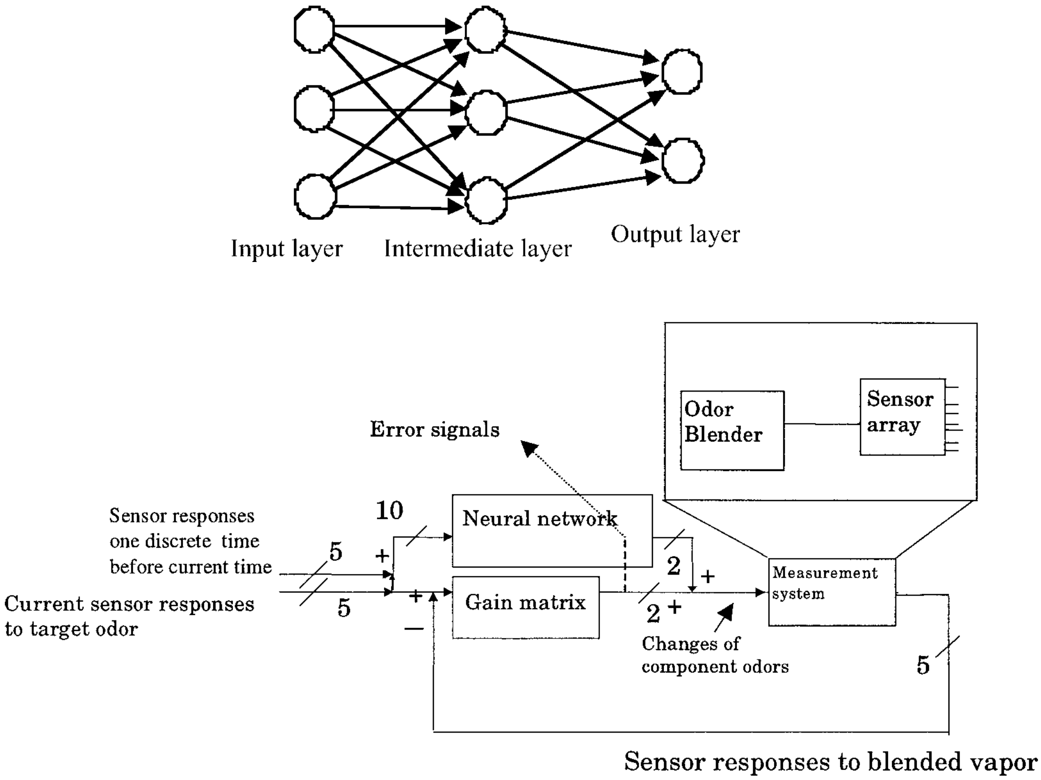
The study of the technique for recording and reproducing smells is becoming more popular in the field of chemical sensors as well as that of virtual reality.[7] People working in virtual reality watch these techniques because they want to include olfaction into five-sense communication.

The eight-component recipe of the apple aroma was successfully determined using the odor recorder.[60] Although a constant recipe was obtained in most of previous studies, the actual odor in the atmosphere is continuously and dynamically changing. Dynamic recording and regeneration are required to have much presence when a system presents smells to people. Therefore, a technique of recoding dynamically changing odor has been developed.

4.1 *Odor recorder using feedback error learning*

The first approach to recording a dynamic change in odor is based upon a neural network using feedback error learning.(61) Although the dynamic change in the composition of the mixture was quantified using a sensor array together with a recurrent-type neural network,(62) the change in the composition was too slow. Therefore, a neural network with feedback error learning was adopted to track the dynamic recipe change quickly.(63) A multilayer perceptron (MLP) with feedback error learning is usually used to control the actuators in a robot. It was reported that it was possible to track the target trajectory quickly when an MLP with feedback error learning was incorporated.

The MLP is a typical neural network shown in Fig. 6(a). The MLP consists of an input layer, an intermediate layer, often called the hidden layer, and an output layer.(64) It typically has target inputs to adjust the weights so that the outputs of the MLP can be the



(b)

Fig. 6. Schematic diagram of odor recorder with feedback error learning neural network: (a) structure of the MLP, and (b) entire system.

same as those inputs. The typical algorithm to adjust the weights is back propagation.(64,65)

The whole system is illustrated in Fig. 6(b). The system to be controlled is composed of an odor blender and a sensor array. The odor blender used here was an old one consisting of several mass flow controllers. The recipe can be determined by the ratio of the flow rates. The sensors were the QCMs coated with sensing films. Both the MFC and the sensor have time constant of a few seconds. The inputs of the system are the concentration changes of the component odors and the outputs are the sensor responses. This is a discrete-time system, since the responses are obtained at discrete time.

First, a target odor with a dynamic recipe change is introduced into the sensor array, and the time-series data for the response pattern are recorded. Then the feedback system controls the recipe of the blended odor so that the response patterns to the blended odor match with that of the target odor. The time-series data of the blended-odor recipe is electronically recorded.

The outputs of the system to be controlled are fed back and the gain matrix is multiplied after those outputs are subtracted from the inputs. The positive and negative signs in Fig. 6(b) mean that each sensor response to a blended odor is subtracted from the current each sensor response to the target odor. The gain matrix determines the concentration changes of the component odors at the next time from the concentrations at the current time. The outputs of the gain matrix are zeros if the response pattern of the target odor matches that of the blended one.

Moreover, the outputs of the neural network are added to the concentration changes of the component odors. There are no target inputs to the neural network, whereas the outputs of the gain matrix are used as the learning signals for the neural network. The neural network was trained simultaneously with the control of the blended-odor recipe in the same way as in the manipulator control of the robot. The learning stops after sufficient training because there are no feedback errors. Then the fast tracking of the target odor is expected, since the feed forward control of the neural network dominates over the feedback control of the gain matrix.

The neural network used in this study was a three-layer MLP. The inputs to the neural network were the sensor outputs at the current time and those one discrete time unit before the current time. The data at different times were used because the delay of the sensor response must be taken into account. Since there were five sensors, there were ten input layer neurons. The output of the intermediate-layer neuron was expressed as sigmoid function plus a constant term, so it can have a value between –1/2 and +1/2. The output of the output-layer neuron was linear with the sum of the weighted outputs in the intermediate-layer neuron, since its output should not be restricted to a certain range in the case of the sigmoid function.

The gain matrix was obtained using the theory of optimal feedback. The sensor dynamics model is described using a first-order state equation that is indispensable to determine the gain matrix. The coefficients of the state equation were determined from the observed data and the least squares method when each component odor concentration was changed according to a certain sequence.(16)

Using this system, the experiment was carried out. The two component odors used here were trans-2-hexenyl acetate (Component odor 1) and isobutyric acid (Component odor 2).

Those are the components of the apple aroma previously described. The five QCMs (20 MHz, AT-CUT) coated with silicone GF SF-96, silicone OV-17, (R)-(+)-2,2’-bis (diphenylphosphine)-1,1’ (BINAP), Apiezon-L and polyphenyl ether.

After the simple concentration profile was studied, the complicated concentration profile was tested. The result is shown in Fig. 7. The concentration changes often occur in an open field where the target odor is spouted in the atmosphere. Since the target odor is usually carried by wind accompanied with turbulence, its concentration changes are complicated. The MLP was initially trained using different concentration profiles, and then the complicated profile was tested. The concentration of each component odor in the blender tracked that in the target odor without any delay. Thus, the dynamic change in the odor was successfully recorded using the MLP with feedback error learning.

4.2 *Odor recorder using a real-time reference method*

Since the odor recorder using feedback-error-learning was somewhat complicated and consumed much time for neural-network training, the real-time reference method for recording dynamic changes of odor was developed.(66) This method is useful for recording dynamic changes of odor as well as for compensating for change in the environment such as temperature and humidity.(67)

The comparison of the real-time reference method with the conventional method is illustrated in Figs. 8(a) and 8(b). Although the multiple component odors and the multiple sensors are actually used, only single component odor and single sensor are shown here for simplicity.

In the previous method, the results from which are shown in Fig. 8(a), a steady-state response to the target odor with constant concentration was measured for the first time.

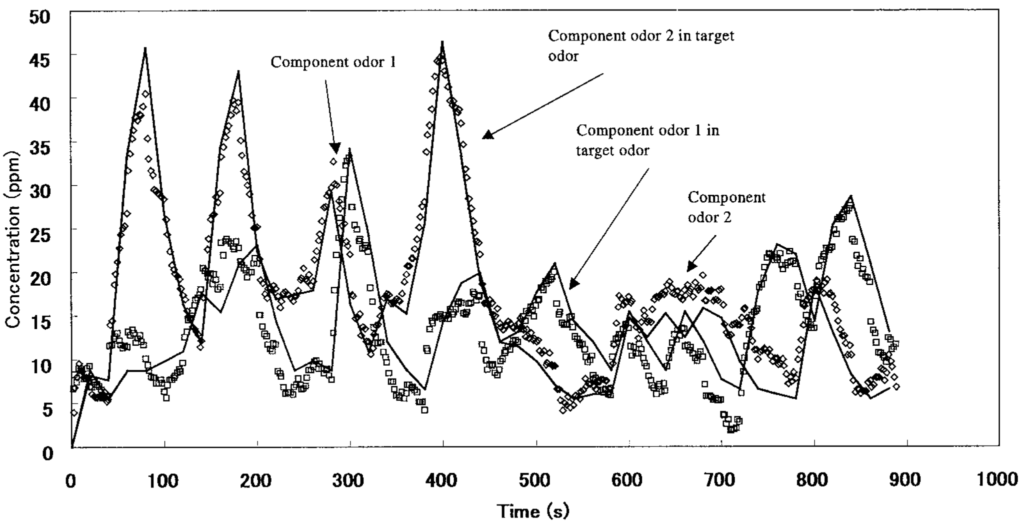


Fig. 7. Experimental results of recording the dynamic change of odor using a neural network.(63)

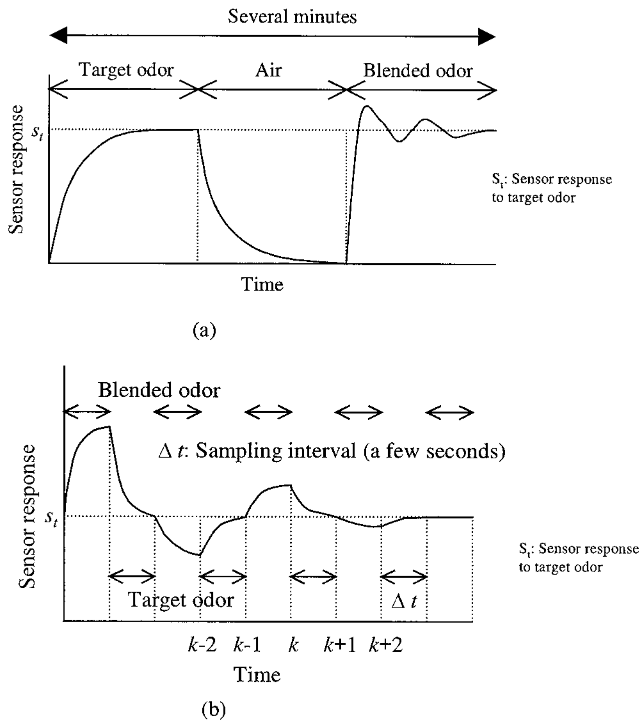


Fig. 8. Comparison of the real-time reference method with the conventional method in the odor recorder. (a) conventional method and (b) real-time reference method.

Then the recipe of the blended odor was adjusted so that the response to the blended odor matched that to the target odor. Since it takes a few minutes to determine the concentration, changes during the process of recipe determination cannot be detected.

On the other hand, the target and blended odors were alternately introduced into the sensor array at every sampling interval (several seconds) in the real-time reference method in Fig. 8(b). Although the sensor response to the blended odor deviates at first from that to the target odor due to the concentration difference, it soon approached the response to the target odor.

In the real-time reference method, the index value J is modified to

$$J = (\boldsymbol{s}_{k+2} - \boldsymbol{s}_{k+1})^T Q(\boldsymbol{s}_{k+2} - \boldsymbol{s}_{k+1}) + (\boldsymbol{c}_{k+1} - \boldsymbol{c}_{k-1})^T R(\boldsymbol{c}_{k+1} - \boldsymbol{c}_{k-1}), \quad (5)$$

where k is an even number. The first term means the difference between the sensor responses to the target odor and those to the blended odor, and the second term minimizes the concentration changes of the blended odor. Once convergence occurs, the blended odor concentration tracks that of the target odor. The real-time reference method achieves a time resolution of a few seconds to record dynamic changes of odor. This method is also effective to compensate for the rapid environmental changes encountered during the process of recipe determination.[67]

The next experiment on recording a dynamically changing odor using the real-time reference method is described in the following. The concentrations of four odor components of the apple flavor were independently changed in the experiment. The odor components used here were trans-2-hexenyl acetate (green note, Comp1), trans-2-hexenal (smell of grass, Comp2), isobutyric acid (sour sweet, Comp3) and ethyl valerate (fruity, Comp4). The sensors used here were four quartz resonators (20 MHz, AT-CUT) coated with polphenyl ether, polyethylene glycol 1000, tricresyl phosphate and Apiezon L. The sampling interval was 4 s. The vertical axis defines the concentration of each component odor relative to the full-scale concentration with the unit [%RC].

The experimental results when the temperature was changed in spite of the constant concentrations of the target odor are shown in Figs. 9(a) and 9(b). The increase in temperature due to heating the sensor cell was 5°C for 100 s. In the conventional method, the convergence was not successful because of the dependency of the sensing-film characteristics upon the temperature given in Fig. 9(a). In the real-time reference method, however, good convergence was achieved in spite of the temperature change given in Fig. 9(b).

Then the temperature and humidity were intentionally changed during the experiment to evaluate the robustness against the temperature and humidity changes. The change in the air conditioner mode (DRY/COOL) caused 2.5°C of the temperature change and 20% of the humidity change during the experiment.

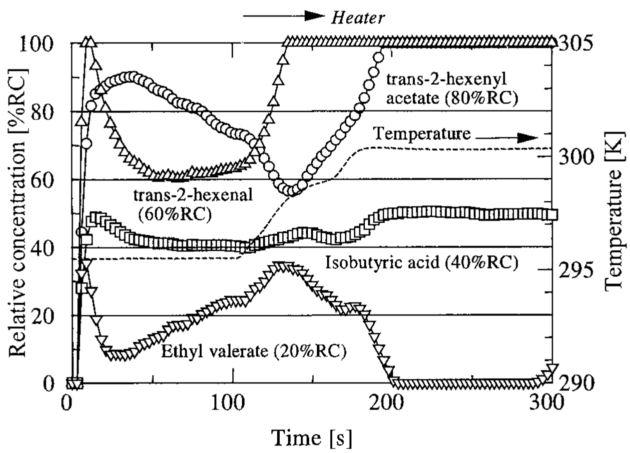
The experimental results are shown in Figs. 10(a) and 10(b). The solid and dashed lines are the concentrations of the component odors in the target odor, and the plots are the recorded concentrations of the component odors. Since the target odor was generated using the odor blender in this experiment, the concentration of each component odor in the target odor is the set point in the odor blender.

Since the recorded concentration of each component odor agreed closely with that of the target odor, the real-time reference method achieves a record of the dynamic change of odor even under an environment of temperature and humidity changes shown in Fig. 10(b). The real-time reference method can be speeded up when the blended odor is measured simultaneously with the target odor using the same two sensor arrays.

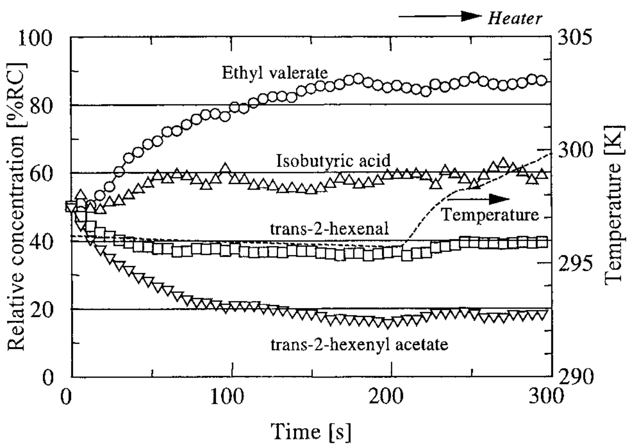
4.3 *Recording odor more rapidly*

In the real-time reference method, the target and blended odors are alternately measured for every sampling interval. When the two sensor arrays are simultaneously used as illustrated in Fig. 2, more rapid changes in odor can be measured.[68] The sensor array response pattern for the target odor is measured by the first sensor array, and the data are immediately transferred to the system for the blended odor. The recipe for the blended odor is adjusted so that the sensor responses to the blended odor in the second sensor array can be the same as those to the target odor in the first sensor array.

The characteristics of the two sensor arrays should be the same with good accuracy. However, it is difficult to fabricate multiple QCM sensor arrays with exactly the same



(a)

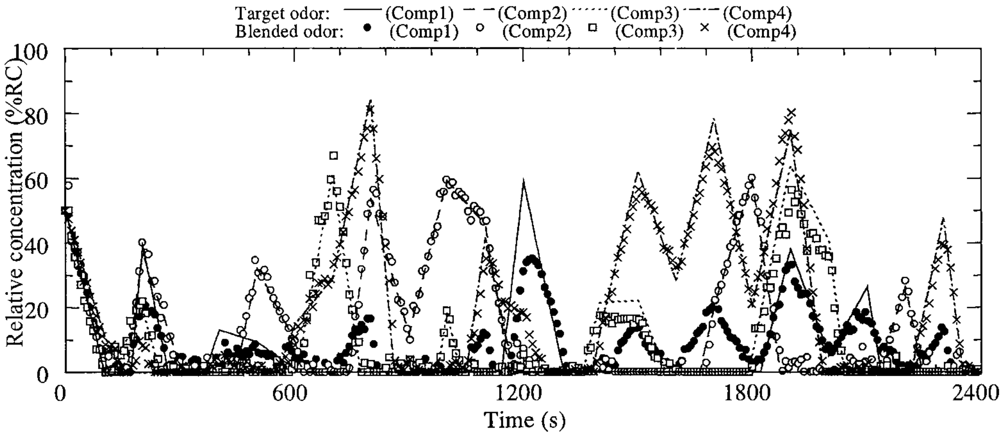


(b)

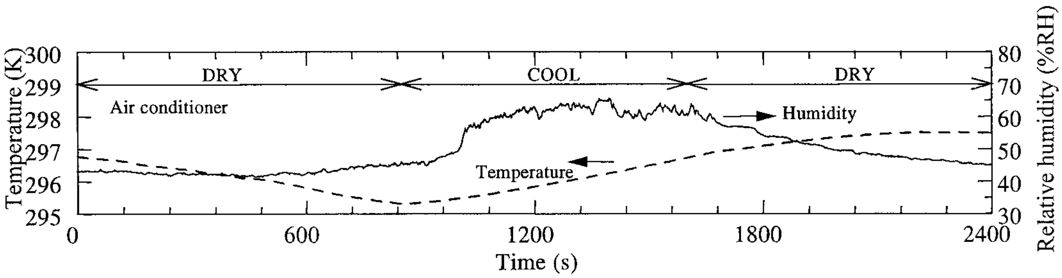
Fig. 9. Influence of temperature change on recording odor. (a) Conventional method and (b) real-time reference method.

characteristics. The spray coating method is often used because of its simplicity. However, it is difficult to obtain a uniform sensing film. Although coating technique using an atomizer may improve the uniformity of the sensing film,(40) one can compensate for the difference using the state equations. The index value corresponding to that in eq. (3) was modified, considering the two sensor arrays for the target odor and for the blended odor are different.(68)

Then the experiment was performed. The two odor samples, trans-2-hexenyl acetate (green note) and isobutyric acid (sour sweet) were used as the odor components of the odor



(a)



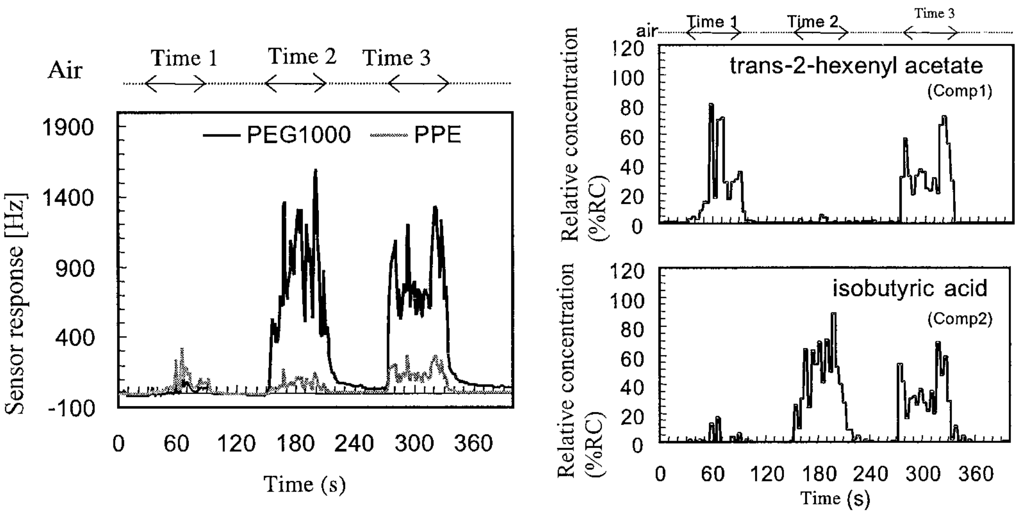
(b)

Fig. 10. Recorded dynamic concentration change of each component vapor in the target odor. Line: concentration of each component vapor in the target odor; Plot: recorded concentration of each component odor. (a) Comparison between target and blended odors, and (b) temperature and humidity changes during the experiment.[66]

blenders. They were also used in the previous section. The sensors used here were the QCM sensors (AT-CUT, 20 MHz) coated with polyethylene glycol 1000 (PEG1000) and polyphenyl ether, stationary phase materials for gas chromatography. The sampling interval of the QCM sensor was 4 s.

The first experiment was to record the dynamic changes of the odor generated by the odor blender. The concentration profile of each component odor was controlled in this case. The increased speed of the system in comparison with the previous method was confirmed, and the recipe change over 10 s was precisely recorded.[68]

Then the experiment to record the recipe change in the atmosphere was performed. The difficulty in recording increases in the presence of turbulent airflows and environmental changes. The odor samples of trans-2-hexenyl acetate, isobutyric acid and a mixture of the



(a) (b)

Fig. 11. Results of recording dynamic odor changes in the atmosphere: (a) Sensor responses and (b) results of concentration-change profile. (time 1) pure trans-2-hexenyl acetate, (time 2) pure isobutyric acid and (time 3) mixture of trans-2-hexenyl acetate and isobutyric acid.[68]

two were prepared in three petri dishes. The odors evaporated from the petri dishes in the ambient air were used as the target odors. The experimental results are shown in Fig. 11.

The first odor sample, trans-2-hexenyl acetate, was placed under the inlet of a Teflon tube connected to the sensor cell from 30 s to 90 s (time 1). After supplying air from 90 to 150 s, the second odor sample, isobutyric acid, was placed under the inlet from 150 to 210 s (time 2). After supplying air from 210 s to 270 s, the third sample, a mixture of the two, was placed under the inlet from 270 to 330 s (time 3). From 330 to 440 s, the air was supplied to the sensor cell.

As can be seen in Fig. 11(a), the sensor responses were rapidly and irregularly changed because of the turbulent airflow in the atmosphere. Moreover, it is clear from Fig. 11(b) that the odors in the atmosphere were successfully recorded, because the reproduced odors during times 1, 2 and 3 were almost pure trans-2-hexenyl acetate, pure isobutyric acid and a mixture of the two, respectively. Thus, the proposed system can be used in recording the dynamic changes in odors even in the atmosphere.

5. Conclusions

The new idea of an odor recorder to record dynamic changes of odor was described. The feedback-error-learning method could be used to record the dynamically-changing odor. Moreover, the dynamically-changing odor was successfully recorded in spite of temperature and humidity changes using the real-time reference method. The rapidly changing odor in an open field was recorded using the two sensor arrays and the feedback control algorithm. The odor recorder can be used to record more complicated odors accompanied with the dynamic changes.

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