Transferring scents over a communication network

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ABSTRACT

In our work on scent technology, we have come across technology that can be used, in a limited way, to achieve scent transfer. In this paper, we document the scent transfer demonstration that we constructed for a science fair in 2018.

Scent transfer requires a means to measure, transmit, classify, and reproduce scents. First, an ion-mobility spectrometer was used to measure scents. This data was sent to a server on the Internet. From the server, the measurement data was downloaded, baseline-corrected, and classified with an algorithm based on weighted K nearest neighbors and time series measurements. The classification result was used to instruct an olfactory display prototype to reproduce the scent for humans to sense. Our demonstration included two scents. Many more could be included, but a general-purpose scent reproduction is beyond our, and as far as we know, beyond anybody's current capabilities. Image and audio transmission technology are mature, but in the chemical senses such as olfaction and taste, significant challenges remain before they can be routinely included in multimodal interfaces.

CCS CONCEPTS

Human-centered computing → Human-Computer interaction (HCI) → Interaction devices; Interaction paradigms

KEYWORDS

Olfaction, multimodal interaction, sensor and actuation technologies

1 INTRODUCTION

Imagine a lightweight system that allows the user to transfer scents over a distance. The system would be able to sense the scents at location A, communicate the information to location B, analyze digitalized information from the scents, and then reproduce the scent using a scent printer. In an ideal case, the system would be intelligent enough to modulate the scents if needed. For example, the system could sense the other scents in the background and intensify the transferred scent accordingly. With such system, scents could be shared in a similar manner as audio and video can already be shared today. It would have a vast potential for scientific and commercial use.

Present-day technology enables neither temporal nor spatial transfer of any combination of scents. However, for certain scents, it is possible to transfer them over time and space. We demonstrated the state-of-the-art technology at a science fair in Tampere, Finland. Our system was able to sense the scents at location A using an electronic nose (eNose), communicate the digitized sensory data to location B, analyze the data and then produce a synthetic version of the scent using a scent printer similar to how visual scenes are reproduced in digital photography. Achieving this goal required technical development and basic researcher in various miniaturized technologies including sensors (eNose technology) and actuators (inkjet technology and mixing). In addition, in order to reproduce the correct scents at the second location, machine learning techniques had to be used for identifying the scents measured at location A.

This paper describes the different parts of our scents transfer system and their interaction. It furthermore provides a discussion of findings we obtained in the building process and during the demonstration.

2 RELATED WORK

To fully utilize the potential of scents in multimodal communication, there is a need to build systems that enable scent measurement, analyzing the scent, and reproducing it. Real-time transfer of scents over a communication network similarly to video and audio is also desirable. This would enable, for instance, sending the picture and scent of a freshly baked apple pie to family members

to entice them to pay a visit later in the afternoon or to enrich virtual reality environments with scents (e.g. the scent of grass while walking over a meadow).

Scent measurement has been studied for decades [10,20]. It can be done in various ways. In laboratory settings highly sensitive gas-chromatography technology is often used to identify the chemical compounds from a scent sample. Operating with gas-chromatography requires technical expertise and the measurement itself is slow and expensive. Another possibility is using chemical sensors that are sensitive to a limited number of selected scent compounds but age rapidly and require, for example, coating of the sensors regularly. The third potential technology is ion-mobility spectrometry [30] (IMS). IMS devices are relatively inexpensive and sensitive. Perhaps the most valuable properties in the respect of the scent transfer scenario are that IMS devices are mobile and easy to use and that their sensor ages slower than those in alternative technologies (e.g. chemical sensors).

By analyzing the measurements from the IMS device a scent can be classified and identified. Several machine learning methods such as principal component analysis [17], canonical discriminant analysis [27], hierarchical cluster analysis [13], and support vector machines [15] have been developed to correctly identify scents of, for example, fruits, dairy products, and beverages [2,3,14]. However, the used classifiers have, in general, been only tested with a specific measurement device. This means, that we cannot simply adopt the classifier that was successfully tested with device A and expect to get similar results using device B. Furthermore, the choice of the classifier depends on the allowed computational complexity (i.e. what hardware is used for computing the classifier an running it), whether real-time classification is needed and how flexible that classifier has to be (most proposed classifiers work only with a predefined set of scents, and modifying this set requires often time-consuming retraining of the classifier).

Scent production has begun to gain interest in the scientific community and industry only recently. To produce scents for human-computer interaction (HCI), a special scent production device (i.e. olfactory display) needs to be built [31,32]. Existing technologies can release or evaporate a limited number (e.g. 1 to 6) of synthetic scents. Synthetic scents are attempts to reproduce a scent of an authentic scent consisting of hundreds of chemical compounds by mixing only the compounds needed to recognize the scent [9,12,29]. Currently, there are several unsolved issues in scent production related to, for example, the accurate control of scent diffusion (e.g. scent spreading in the environment) and contamination of the materials [32]. Despite these limitations, some scents can already be produced to be smelled, for instance, while watching videos [26]. So far, methods for measuring and analyzing scents are not commonly combined with scent production technologies [21]. Seamless integration of these devices is essential for scent transfer.

Finally, there are some issues related to human scent perception that need to be considered before scent transfer can become a mainstream technology. First, scent perception is highly subjective. For instance, cultural background [1], biological sex [7] and even personality affect the perception of everyday scents [4]. Further, to create the most pleasant and intriguing experiences with the scents should be congruent and synchronized with the audiovisual content [25,26]. Finally, the perception of a synthetic scent produced by an olfactory display depends on multiple factors such as its intensity, chemical composition, and simultaneously presented audiovisual content [26,29].

In this paper we propose a method for scent transfer. We know of two recent implementations for scent transfer. Nakamoto [21] presented an idea of combining scent sensing technologies with scent presentation and using the Internet to transfer the data related to scent identification. Nakamoto's system utilized chemical sensors with perishable coatings, meaning that after each measurement they had to be recoated. This makes the system impractical in real user scenarios. Another study has transferred the partial flavor of lemonade to be tasted [24]. The tested system only transferred the color and the amount of sourness of the drink, but not the other dimensions of the flavor or scent of the drink.

3 METHODS

3.1 Scent selection

We chose lemon and jasmine as the scents to transfer. This was mainly due to our previous work showing that we can both reliably classify authentic versions [19] and reproduce synthetic versions of these scents [23,26]. The authentic scents were grated lemon peel and liquid jasmine oil. The jasmine oil was diluted with propylene glycol (nearly scentless clear liquid that is safe for humans in small quantities) (CAS number 57-55-6) so that the concentration of jasmine oil was 1%.

For reproduction, the scents were synthetized. The synthetic version for lemon peel was created by using 97% limonene (CAS number 5989-27-5). The synthetic version of the jasmine oil was created by using two of its odorous components, benzyl acetate (CAS number 140-11-4) and cis jasmone (CAS number 488-10-8). Benzyl acetate and cis jasmone were diluted using propylene glycol so that the concentration of the odorant was 15%. This was done to reduce contamination of the plastic and metallic parts of the used olfactory display (see [23] for details on the display). For limonene, 100% concentration was used. Propylene glycol, limonene, benzyl acetate, and cis jasmone were ordered from Sigma Aldrich®.

3.2 Scent measurement

An ion-mobility spectrometry device (ChemPro 100i, Environics Ltd., see Fig. 1 left and [30]) was used for scent measurement. Measurements are produced by the ChemPro 100i as follows. The device sucks in air with the help of a rotary vane pump that generates an airflow of 1.3 l/min. The molecules in the air are ionized using a radioactive source (Americium-241) in the ionization chamber. Then the air flow with the ionized molecules is pushed through an electric field where some of the ions attach to one of 14 electrodes, depending on their charge and velocity. 7 of the electrodes attract positively charged ions and 7 attract negatively charged ions. For each scent, the currents measured by all 14 electrodes were used as a sample. The sampling rate of the

device was 1 Hz. The Chempro 100i contains additional measurement technology, which was not used in our work.

In the demonstration, the measurement at Tampere University (TAU) began by measuring at least 60 seconds of room air to get a baseline measurement (i.e. a measurement of the background scent signal) before any scented objects were introduced. Then, a scent source (i.e. lemon peel or jasmine oil) was placed in front of the device so that the distance between the inlet of the device and the scent source was 3 cm.

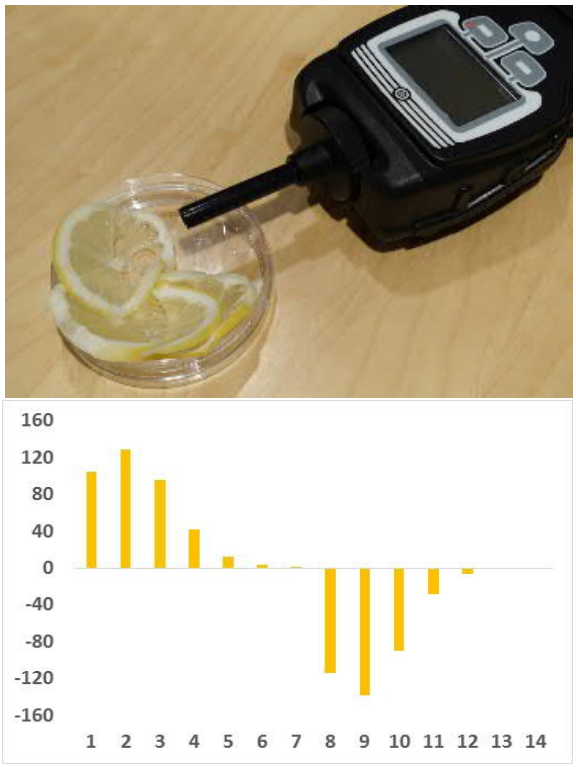

Figure 1: Top: ChemPro 100i measuring lemon. Bottom: An IMS fingerprint of the lemon peel measurement.

Prior to the demonstration, we created a scent database that included jasmine and lemon peel scents as well as several other scents that were measured in the same way as described above. ChemPro-UIP v.1.3.3.3 software was used to record raw IMS data for each scent sample in a text file. In addition, IMS readings of room air were collected before each scent sample. Based on these data the classifier was trained for later use in scent recognition.

3.3 Scent communication architecture

For the scent communication between the measurement site and the reproduction site, we set up a server on the Internet (see Figure 2 for the system architecture). All data communicated over the internet is a simple set of bits making the method of transmission similar regardless of what the data represent. However, the techniques we used are described here for completeness.

Because connecting SSH servers is universally allowed in networks, using SSH tunnels around our HTTP connections was the simplest way of ensuring no outsider access to our server and that no special firewall configurations would be needed at either end of the connection. The server was a simple node.js http server with two functions. One to store new samples and another to retrieve the needed number of latest samples.

Perhaps the most interesting problem to solve in scent server construction is the addressing scheme if we assume that hundreds or perhaps millions of measurement sites would be running and clients could want to receive the data from any one of them. How would they know which is which?

Our solution was that the location of measurement data was encoded in the URL and a corresponding directory structure was maintained on the server so that, if needed, multiple measurement sites could be simultaneously in operation with multiple clients accessing the data. For example, accessing data at http://tuni.fi/PinniB/B2001/1 would connect to the data stream of the first eNose in office B2001 in the Pinni B building at TAU.

While our server utilized SSH tunnel for security and plain http inside the tunnel with open access http server, in production-ready systems a better user authentication and access management system would be needed.

Via the tunneled HTTP connection to the server, the software installed at the reproduction site requested the stored data with the URL of the measurement location. First, to know the baseline scent profile of the room at TAU it downloaded a “room air block” containing sixty seconds of room air before any scent was introduced. After introducing the odorous object at the measurement site, the software at the reproduction site requested blocks of 10 samples. It then compared the average of these 10 samples to the room air block and recognized the differences against the previously created scent database to detect if a known scent was present in the air.

Table 1: Workflow in the demonstration

1	The reproduction scent controller retrieves a block of measurement to detect the baseline scent of the lab.
2	In the laboratory, a scented object is placed next to the IMS device’s inlet.
3	Reproduction computer retrieves a measurement block.
4	Reproduction computer classifies the scent using baseline and IMS measurements with the scent classifier described in Section 3.4.
5	Once the authentic scent has been classified, the trustworthiness of the label exceeds the predefined threshold, and the minimum number of IMS measurements have been evaluated, produce the synthetic scent equivalent to the label from the classifier. Details can be found in Section 3.5.

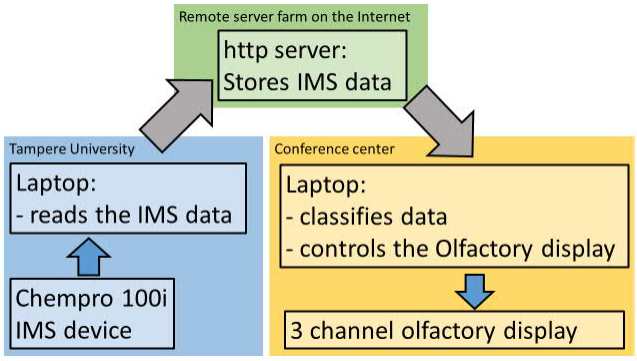

Figure 2: A structural diagram of the scent transfer system. A laptop at TAU reads the IMS data from the ChemPro 100i and sends it to a remote server for storage. A laptop at the conference center (TT) connects to the server and reads data, classifies it, and controls the olfactory display.

3.4 Scent classification

In order to enable fast transmission of scents, it is essential to inform the olfactory display about the scent it should produce; simply providing the IMS data is not enough. Hence a method that classifies the original scent based on the measurements from the ChemPro100i had to be developed. An approach based on K nearest neighbors (KNN) and time series of samples was used for scent classification. The KNN approach [8] compared the 14-dimensional sample $x_{scent} = [x_{scent,1} \cdots x_{scent,14}]$ measured from an unlabeled scent to labeled samples stored in a training database. The Euclidean distance was calculated to find the K training samples in the database closest to x_{scent}. The scent was then labeled (i.e. classified) based on the labels of the K closest training samples using a majority vote. Fig. 3 explains the working principle of a 3NN classifier.

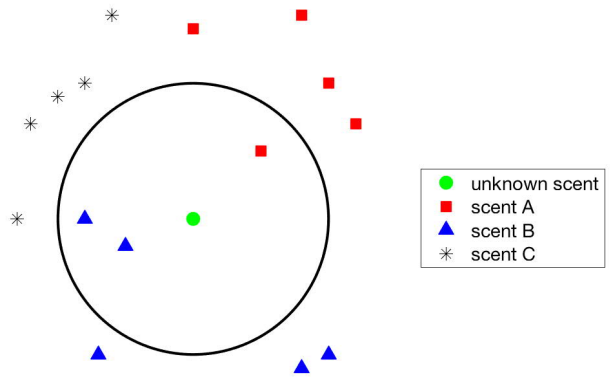

Figure 3: Working principle of K nearest neighbor classifier with K=3. The green dot represents the IMS sample from the scent that is classified. Blue triangles, red squares, and black stars represent IMS samples from three different scents. Based on the 3NN rule the scent will be classified as the same scent represented by the blue triangles because two of the three nearest neighbors are blue triangels and one is a red square (three nearest neighbors are inside the black circle, all other samples are outside the circle).

In the scent transfer demonstration, the unknown scent was either lemon peel or jasmine oil measured from a plate. The training database contained samples from lemon peel, jasmine oil, grapes, and vanilla. Each of the four scents was measured from a sealed flask and from a plate, meaning that there were eight different scents stored in the database. K=3 was used based on the results of our previous study [18]. The classification process is explained in Algorithm 1 (for details see [19]). The minimum trustworthiness level was set to 90% (see Fig 4) and the minimum number of samples was set to 5.

Algorithm 1: Scent classifier

1. Measure the room air for m seconds, average over the m measurements to get a baseline measurement x_{air}.
2. Collect n measurements for the scent to be classified, average over the measurements and subtract x_{air} to get x_{scent}.
3. Find the K nearest neighbors of x_{scent} and classify the scent.
4. Compute the average difference between x_{scent} and the K nearest neighbors.
5. Use the inverse of the difference as trustworthiness level of the sample.
6. Find the label that has the largest overall trustworthiness and use it as the current overall label for the scent. If both the minimum number of samples is reached and the trustworthiness of the overall label exceeds the desired threshold then return label and trustworthiness level. Otherwise return to step 2.

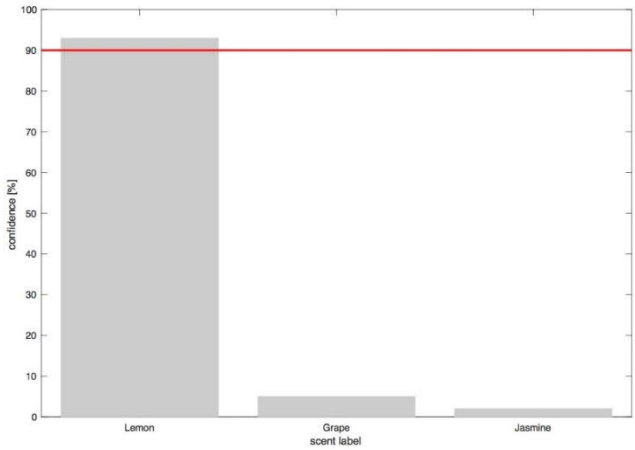

Figure 4: An illustration of the graphical user interface of the classifier. Three bars represent the extent to which lemon scent is classified either as lemon, grape, or jasmine. The red line is the trustworthiness threshold for identification. The confidence

levels for the remaining five scents are zero and therefore not displayed.

3.5 Scent reproduction

Once the scent was classified, its synthetic equivalent could be produced by the olfactory display. We developed the olfactory display ourselves and studied which chemical mixtures are perceived by humans as lemon and jasmine. For details, the reader is referred to our previous studies [23,26].

The classification result initiated a MATLAB R2015b script that was running on a Lenovo laptop PC (Windows 7 Enterprise, 64-bit Operating System). The script controlled an olfactory display (see [23], Fig. 5) for scent reproduction. Clean air used as the carrier gas was produced with an air compressor. The air pressure was regulated to 1 bar and airflow to 5 l/min (calibrated with Sensidyne's Gilian Gilibrator-2 NIOSH). Using Teflon®-coated tubes, the airflow was divided between three uniquely driven channels. Each channel had a syringe filled with odorous liquid (i.e. limonene, benzyl acetate, or cis jasmone). The syringe was attached to a pump which pushed the liquid onto a ceramic heating element that evaporated it.

The pumping speeds and heating elements were controlled using the MATLAB script. Due to varying chemical properties of the odorants, different pumping rates and heating voltages were used. Cis jasmone was pumped with a rate of 108 µl/hr and heating voltage of 1.35V, benzyl acetate with a rate of 108 µl/hour and heating voltage of 1.35V, and limonene with a rate of 185 µl/hr and heating voltage of 1.8V. The pumping rates and heating voltages were chosen based on our previous studies [23,26]. After evaporation, the tubes carrying benzyl acetate and cis jasmone were combined into a single tube to create a synthetic jasmine scent. The tubes were partly covered with Omega rope heaters to achieve stable air temperatures of 35-36 °C that prevented premature condensation of the odorous gases.

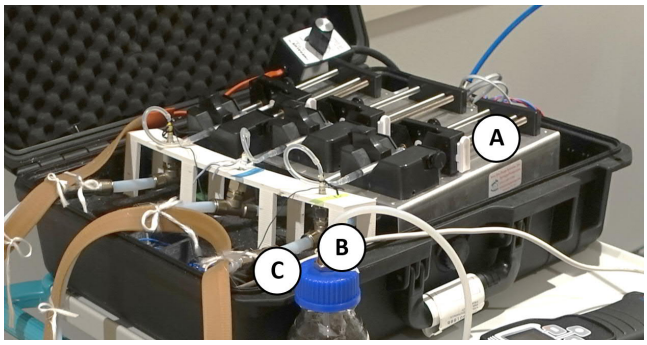

Figure 5: The olfactory display. A) A channel containing a pump and the syringe. B) Heating element for turning liquid to gas. C) Teflon®-coated tube for transferring the gaseous scent to be smelled.

4 DEMONSTRATION EVENT

The demonstration of the scent transfer system proceeded as follows. A Skype video connection between the university (TAU) and the conference center (TT) was formed. At TAU, two researchers measured the scent so that the audience at TT was able to observe it on a screen. The measurement data was automatically transmitted through the server to TT using our scent transfer architecture. The scent was analyzed, and the results were shown to the audience (see Fig. 4 for an example of the visualization). The measurement and classification of both authentic scents were 100% successful during the demonstration. After the classification, the scent was reproduced with our olfactory display prototype for the audience. Dozens of people from the audience took turns in sniffing the synthetic scents from tubes attached to the display that showed the measurement scene from TAU. Since the event at TT was open to the public, the audience was a cross-section of the Finnish society, including pre-school aged children, elderly people and all age groups in between. Due to the event character, it was however impossible to collect precise data such as age or sex for the people that tested our system.

5 OUTCOMES

The scent transfer demo was presented three times during the demo event with two-hour breaks between demonstrations. The system, classification, and olfactory display were functional throughout the day. The main outcomes of the scent transfer event were:

- The transfer process was relatively fast. The time from the beginning of the room air measurement at TAU to smelling the scent at the reproduction site was less than three minutes. The classification of the scent required at least 50s of measurements from the authentic scent at TAU. Theoretically, this time could have been shortened. However, based on our previous experiments in [18], we decided to use at least five average samples for scent classification and demanded minimum trustworthiness of 90% for the scent label before producing the synthetic scent. We were able to shorten the time by measuring room air while the audience at TT was still smelling the previous scent.
- All audience members reported smelling a scent. The spontaneous comments on scent intensity varied. Some said it was clearly perceptible, while others thought it was weak.
- The classifier performed with 100% accuracy, during the demo event.
- The first session of scent transfer demonstration olfactory display functioned perfectly. Later, contamination became somewhat problematic as one of the valves started to emit a vanilla scent that had apparently condensed in it in an earlier experiment in the lab. As a result, olfactory perception of lemon was affected. Therefore, we chose to repeat the scent transfer with synthetic jasmine scent alone in the two later demonstration sessions.

6 DISCUSSION

We were able to measure, transfer, analyze, and reproduce scents for a live audience. However, building a protocol for scent transfer was challenging, even though the devices used to measure and produce the scents were either commercial or our own prototypes

thoroughly tested in previous experiments. We next discuss the benefits and restrictions of the used demonstration setup.

It is commonly recognized that technological development related to olfactory displays is still needed in order to produce scents accurately. For example, the timing of the scent and its strength, scent lingering time, cross-contamination of scents, and even noise of the olfactory display are common problems encountered in the field [5,16]. Our olfactory display functioned reliably in terms of timing and stability of the scent intensity.

6.2 Scent measurement

The scent classifier had to be accurate and rapid during a live event. Therefore, we chose to transfer only two scents, namely jasmine and lemon. In practice, it is possible to transfer any scent in the scent measurement database. During the demo, there were eight scents in the database [19]. Our classifier is known to function reliably with at least fourteen scents [18,19]. The next steps in our research will be adding more scents to the database, test the functionality of the classifier, and develop it when needed. However, it should be noted that scents in daily life are numerous and complex. By using existing mobile scent measurement technologies, it is probably impossible to classify all scents in the environment

It is important to notice that our classification database consisted of samples of the difference that a single scent makes in relation to the background signal present in the laboratory. If multiple scents are simultaneously presented, our classifier probably does not work very well. This is because the ion mobility spectrometers are non-specific measurement devices. They measure the movement tendencies of ions, but cannot distinguish between two ions that exhibit the same movement tendencies. When multiple ions from multiple scents are being measured simultaneously, it will be difficult to recognize any of the scents based on the IMS output. The most prevalent ions will dominate the output regardless of whether they are odorous or not.

6.3 Scent reproduction

Also on the scent reproduction side scaling to multiple scents is difficult. The scents must exist in the selection of scents the olfactory display can reproduce. The use of individual channels in our olfactory display means that the evaporation temperature can be controlled individually for each scent. This further means that scents evaporating in different temperatures can be reproduced and thus, most common scents are usable with our system. However, including the thousands of odorous chemicals we encounter daily is clearly impossible.

To ensure that synthetic scents are associated with the correct authentic scent further studies are required. In our demo, we used limonene as a synthetic equivalent of lemon, and a mixture of benzyl acetate and cis jasmine as a synthetic equivalent of jasmine. This mixture proved to be indistinguishable from real jasmine scent by participants in an earlier study [23]. If other scents should be transferred, the first step would be to study which synthetic versions of these scents are indistinguishable from the authentic scents by humans. An alternative would be to develop techniques that find the synthetic scent that is most similar to the authentic scent without interference from humans. We are currently studying feedback functions that iteratively compare the IMS readings of synthetic scents with the readings of the authentic scent, and then adjust the composition of the synthetic scent accordingly.

In an ideal case, the release of the synthetic scents should start immediately after the classification result is available. In the described demonstration, audience members were able to start sniffing the scents only after approximately 10 seconds when a sufficient amount of material had been pumped and evaporated. Furthermore, the system consisting of IMS and the olfactory display was large. Some miniaturized measurement technologies and olfactory displays exist (e.g. [6,11]), but they do not necessarily function reliably with a large number of scents.

6.1 Contamination

The use of separate channels and tubes mostly prevented cross-contamination of scents in our olfactory display [23]. However, different forms of contamination still became problematic. One of the valves was used to produce vanilla scent earlier and our attempts at cleaning it apparently had failed. Consequently, when the valve warmed up, the vanilla scent was noticeable although vanilla was not being evaporated during the demonstration.

Overall the most significant problem in the scent reproduction technology we employed was the contamination of the parts. The main reason for the contamination was that we heated the scent chemicals to evaporate them, and they were prone to condense as soon as the temperature sank.

The scent production system we used was made for experiments where the goal was to carefully control the concentration of the scent chemicals in the pumped air. With the heating, we were able to guarantee that all the liquid injected was evaporated. As we learned, the olfactory display was not robust enough for use outside carefully controlled laboratory conditions.

6.4 Other issues

It should be noted that at the demo event, no formal questionnaires were presented to the audience. The reason for excluding human tests from the demonstration event was that the event was relatively crowded and the demonstration area was filled with ambient scents like food or perfumery that could have affected the perception of the scent even though the reproduction would be successful. However, from our previous work [23,26], we know that the chosen synthetic scents are perceived similarly to their authentic counterparts in a controlled laboratory environment. Also, the spontaneous reports by the audience members suggested that they were able to smell the reproduced scents.

Finally, there are some general issues related to the scent transfer that need to be considered whilst developing the technology further. Due to the current technical restrictions, scent selection requires extra care. This means that one should consider what are the central scents related to human life or used application (e.g. computer game) that need to be transferred. This task can be complex. Scent preference in terms of intensity and quality is highly subjective. This means that the receiver should be able to

adjust both and even block unwanted scents. Also, because oversensitivity to scents and allergies are common, the scent diffusion should always be designed so that people suffering from those conditions are not exposed to the scents.

To sum up, we built and demonstrated a scent transfer system. We were able to show that a very limited set of scents can be reliably measured, classified, and reproduced in real-time for a live audience. Much work remains to be done in order to make scent technology so practical that it can be utilized in consumer products.

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