Biometric Person Authentication: Odor

Zhanna Korotkaya

Department of Information Technology, Laboratory of Applied Mathematics,
Lappeenranta University of Technology
Zhanna.Korotkaya@lut.fi

Abstract. In this overview, a problem of human recognition through the odor authentication is presented. This is the perspective technique and still under development. There are no available commercial applications on the market yet. While human odor recognition is not still available odor recognition is widely used nowadays. Odor recognition is realized by the electronical noses (ENoses). Main components of ENoses are considered in this review. Both types of applications, current and future, are analyzed.

1 Introduction

1.1 Introduction to Biometrics

The task of human recognition is a very old and at the same time quite actual. Nowadays this problem is solved by the application of biometrics. From the technical point of view, biometrics [1] is "the automated technique of measuring a physical characteristic or personal trait of an individual and comparing that characteristic to a comprehensive database for purposes of identification".

Biometrics consists of [2]:

- Physical characteristics:
  eye's features (iris, retina), facial features, hand geometry, ear shape, fingerprints, wrist/hand veins, DNA, chemical composition of body odor.
- Personal characteristics:
  handwritten signature, keystrokes/typing patterns, voiceprint

All these physical and personal characters are measured and integrated into computer system for the following person recognition. Thus biometrics is used for two major purposes [2]: identification and authentication.

The Biometrics Glossary [1] says that the identification, the first main purpose of the biometrics, is “the one-to-many comparison of an individual human biometric sample against the entire database of biometric templates. It allows to determine whether it matches any of the templates and, if so, the identity of the enrollee whose template was matched.” Thus, identification tries to answer the question: "Do I know who you are?", involving one-to- many comparison.

Authentication is the second purpose of the biometric technique. This is the action of verifying information such as identity, ownership or authorization [1]. Question to be answered for the authentication is: "Are you who you claim to be?". One-to-one comparison is used for it.

1 . 2 Significance of Olfaction (Smell)

Olfaction has an extremely high importance in the human being. It is one of the five main senses: Sight, Smell, Taste, Hearing and Touch [3]. Many philosophers and scientists has been trying to comprehend the sense of the smell for several thousand years. It is difficult task, because people often have problem with finding words even to describe their smell sensations. However, odorants influence deeply our life, mood. Reactions like discomfort, attraction, and etc. sensation are hard to extinguish since neurons of the nose are connected straight to a part of the brain, so-called olfactory bulb, and the olfaction mechanism is still unknown [4].

The main problem, associated with odor perception is there is no physical continuum as sound frequency in hearing or Newton's circle in color vision [5]. From this point of view, stimuli based only on the intuitive experience must be chosen. Therefore there is absolutely no guarantee that the chosen stimuli span the whole olfactory perception space [4]. It is possible to say even more that there are no tests to appraise the quality of the smell during experiments.

The main purpose in human odor recognition is try to build an electronic system as much sensitive as it is possible. Such kind of electronic system is assumed to be created on the human olfactory model. Thus before to create this device the human olfactory model must be comprehend entirely.

2. Human Olfactory Model

Anything that has an odor constantly evaporates tiny quantities of molecules that produce the smell, so-called odorants. A sensor that is capable to detect these molecules is called a *chemical sensor*. In this way the human nose is a chemical sensor and the smell is a chemical sense [4].

The human's ability to smell is not so perfect in comparison with animals. Human brain devotes only 4,8 cm^2 to the entire olfactory apparatus [6]. At the same time a dog uses 65 cm^2 and a shark utilizes 2,3 m^2

Despite of its inferiority, a human has about 40 million olfactory nerves. This allows detecting even slight traces of some chemical components. Some odorants can be detected even if the concentration in the air is only one part per trillion [4].

Odor information processing in human model is tremendously complicated task. It has been discussed in a huge amount of works (see for example [7], [8], [9]). Humanity knows much about the functional characteristics and structure of the brain and can comprehend at least some of its information processing mechanisms [10]. However, overall dynamical properties of the brain are still unknown. If we can catch the behavior of the olfactory system it can be helpful to understand how other parts are involved.

Diversity of different methods has been used to understand olfaction. The most exciting methods have been proposed by Freeman (see [11], [7], [8]). He has shown that in the olfactory bulbs each neuron participates in the generation of olfactory perception and no one receptor type alone identifies a specific odor [12].

Main operations [12] of olfaction can be divided roughly in five parts: sniffing, reception, detection, recognition, and cleansing.

The olfaction begins [12] with *sniffing* that mixes the odorants into a uniform concentration and delivers these mixtures to the mucus layer in the upper part of nasal cavity. Next these molecules are dissolved in this layer and transported to the cilia of the olfactory receptor neurons. *Reception* process includes binding of these odorant molecules to the olfactory receptors. Odorant molecules are binded temporarily to proteins that transport molecules across the receptor membrane with simultaneous stimulation of the receptors [12]. During this stimulation the chemical reaction produces an electrical stimulus. These electrical signals from the receptor neurons are transported to the olfactory bulb. From the olfactory bulb the receptor response information is forwarded to the olfactory cortex (*detection*). Odor *recognition* part takes place namely in the olfactory cortex. Then the information is transmitted to the cerebral cortex. Remind that there are no individual receptors or parts of the brain capable to recognize specific odors. The brain is key component associated the collection of olfactory signals with the specific odor [12]. *Cleansing* finishes the olfaction process. For this purpose the breathing fresh air removing of odorant molecules from the olfactory receptors is required.

To grasp the mechanism of olfactory perception the model of our nose can be considered. The schematic view on the human nose is presented in Figure 1.

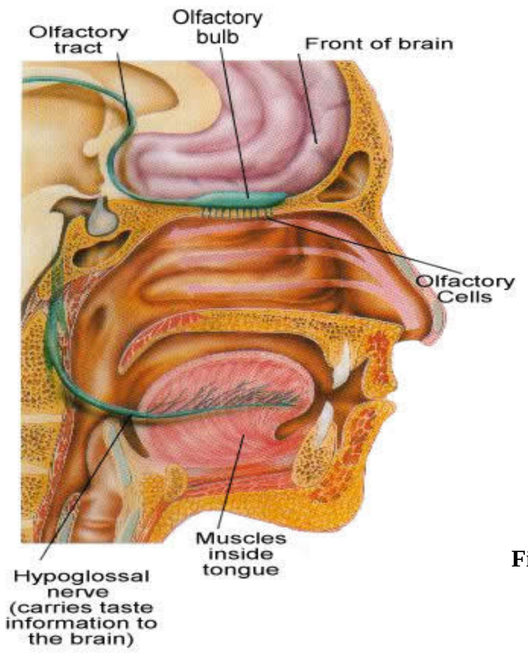

Figure 1: Human Olfactory Model [3]

As it follows from Figure 1 inside each side of the nose is an air chamber, the nasal cavity. Air including odorants inhaled through the nostril and flows down. During the sniffing, air swirls up into the top of the cavity. Here is a small patch of about 10 million specialized olfactory cells. They have long micro-hairs, or cilia, sticking out from them. Odor particles in the air stick on to the cilia and make the olfactory cells produce nerve signals, which travel to the olfactory bulb [3]. This is a pre-processing centre that partly sorts the signals before they go along the olfactory tract to the brain where they are recognized as smells.

3 Electronic Olfactory Model

Remind that the main task in odor recognition to create a model as similar to the human model as it is possible. From this point of view electronic/artificial noses (so-called ENoses) are being developed as a system for the automated detection and classification of odors, vapors, gases [13, 14].

ENose is represented as a combination of two components [12]: sensing system and pattern recognition system. The schematic representation of ENose can be found in Figure 2.

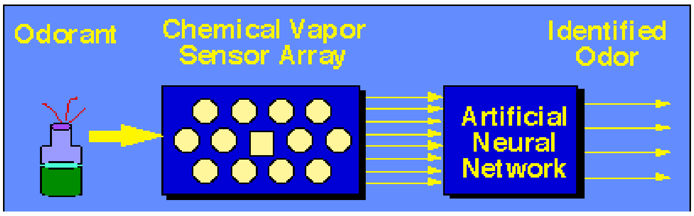

Figure 2: Schematic Diagram of ENose [12]

Sensing system is represented as an array of chemical sensors where each sensor measures a different property of the sensed chemical, or as a single sensing device or as a hybrid of both. The major task of this component is to catch the odor. Each odorant presented to the sensing system produces a signature of characteristic pattern of the odorant [12]. Database of signatures is built up by presenting many different odorants to the sensing system. It is used further to create the odor recognition system.

Pattern recognition system is utilized to recognize procedure. The goal of this process is to train and create the recognition system that will be capable to produce unique classification or clustering of each odorants so that an automated identification can be implemented [12]. This process incorporates several approaches: Statistical, ANN, Neuromorphic.

Creating of a mathematical model of the dynamics in the olfactory bulb is arduous problem. Modeled after the human nose, the ENose relies on the interactions of sniffed chemicals with an array of sensing films that create an identifiable pattern.

Two components of ENose are described in details below.

3 . 1 Sensing System

Sensing system allows tracing the odor from the environment. This system can be single sensing device, like gas chromatograph [12], spectrometer [15]. In this case it produces an array of measurements for each component. The second type of sensing system is an array of chemical sensors. It is more appropriate for complicative mixtures because each sensor measure a different property of the sensed chemical. Hybrid of single sensing device and array of chemical sensors is also possible.

Each odorant presented to the sensing system produces a characteristic pattern of the odorant. By presenting a mass of sundry odorants to this system a database of patterns is built up. It is used then to construct the odor recognition system.

There are 5 available categories of sensors. A brief description of all these types is given hereinafter.

Categories of Sensors

1. Conductivity Sensors

There are two types of conductivity sensors [16]: metal oxide and polymer. They exhibit a change in resistance when exposed to volatile organic compounds. Both these classes are widely available commercially because of its low cost. These sensors respond to water vapor, humidity difference, but not too sensitive for specific odorants. Currently, a lot of research groups work under enhancement of this type of sensors. Conducting polymer sensors are commonly used in electronic nose systems [17]. Because conducting polymer sensors operate at ambient temperature, they do not need heaters and thus are easier to make. The electronic interface is straightforward, and they are suitable for portable instruments

2. Piezoelectric Sensors

The piezoelectric family of sensors (quartz crystal microbalance, surface acoustic-wave devices) can measure temperature, mass changes, pressure, force, and acceleration. During an operation, a gas sample is adsorbed at the surface of the polymer, increasing the mass of the disk-polymer device and thereby reducing the resonance frequency. The reduction is inversely proportional to odorant mass adsorbed by the polymer. In the electronic nose, these sensors are configured as mass-change-sensing devices [18], [19].

3. Metal-oxide-silicon field-effect-transistor (MOSFET)

MOSFET odor-sensing devices are based on the principle that volatile odor components in contact with a catalytic metal can produce a reaction in the metal. The reaction’s products can diffuse through the gate of a MOSFET to change the electrical properties of the device. Operating the device at different temperatures and varying the type and thickness of the metal oxide the sensitivity and selectivity can be optimized [20].

4. Optical Fiber Sensors

Optical-fiber sensors utilize glass fibers with a thin chemically active material coating on their slides or ends. A light source at a single frequency (or at a narrow band of frequencies) is used to interrogate the active material, which in turn responds with a change in color to the presence of the odorant to be detected and measured [21].

Arrays of these devices with different dye mixtures can be used as sensors for an ENose. The main application for such kind of ENoses is medicine [22].

5. Spectrometry-Based Sensors

Spectrometry-Based sensors use the principle that each molecular has a distinct infrared spectrum [15]. Usually devices based on theses sensors are quite big and expensive.

3 . 2 Pattern Recognition System

Pattern recognition system is the second component of electronic nose used for odor recognition. Its goal [12] is to train or to build the recognition system to produce unique classification or clustering of each odorant through the automated identification.

Unlike human systems, electronic noses are trained to identify only a few different odors or volatile compounds. This is very strong restriction to use these noses for human recognition. State-of-the-art does not make possible to identify all components of the human body precisely.

Recognition process incorporates several approaches: Statistical, ANN, Neuromorphic [23].

Many of the *statistical* techniques are complementary to ANNs and are often combined with them to produce classifiers and clusters. It includes PCA [24], partial least squares, discriminant and cluster analysis. PCA breaks apart data into linear combinations of orthogonal vectors based on axes that maximize variance. To reduce the amount of data, only the axes with large variances are kept in the representation.

When an *ANN* [25] is combined with the sensor array, the number of detectable chemicals is generally greater than the number of unique sensor types. A supervised approach involves training a pattern classifier to relate sensor values to specific odor labels. An unsupervised algorithm does not require predetermined odor classes for training. It essentially performs clustering of the data into similar groups based on the measured attributes or features [4].

Neuromorphic approaches center on building models of olfaction based on biology and implementing them in electronics. Unfortunately, there is a lack of realistic mathematical models of biological olfaction. Thus the area of neuromorphic models of the olfactory system lags behind vision, auditory, motor control models [12]. Olfactory information processed in both the olfactory bulb and in the olfactory cortex. The olfactory bulb performs the signal preprocessing of olfactory information including recording, remapping and signal compression. The olfactory cortex performs pattern classification and recognition of the sensed odors.

There are two competing models of olfactory coding [23]. The selective receptor comes from recent experimental results in molecular biology. It can be thought of as an odor mapper. This approach is similar to visual system with the idea of receptive fields of olfactory receptors and mitral cells in the olfactory bulb. The second approach is a non-selective receptor, distributive-coding model that comes from data collected by electrophysiology and imaging of the olfactory bulbs.

Neuromorphic approach has an advanced feature consisting in incorporation of temporal dynamics to handle identification of combinations of odors [23].

3 . 3 Olfactory Signal Processing and Pattern Recognition System

The goal of an electronic nose is to identify an odorant sample and to estimate its concentration (in human recognition case). It means signal processing and pattern recognition system. However, those two steps may be subdivided into preprocessing, feature extraction, classification, and decision-making [26]. All these subparts can be viewed in Figure 3. But first, remind, a database of expected odorants must be compiled, and the sample must be presented to the nose's sensor array.

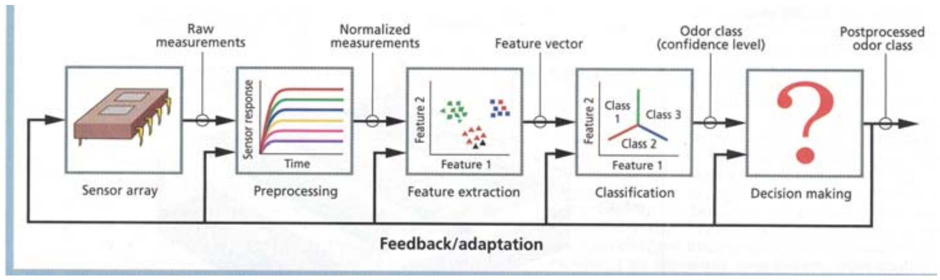

Figure 3: Signal Processing and Pattern Recognition systems stages [26]

Consider all signal processing and pattern recognition stages (from Figure 3) more particularly.*A. Preprocessing*

Preprocessing compensates for sensor drift, compresses the response of the sensor array [27], and reduces sample-to-sample variations. Typical techniques include: normalization of sensor response ranges for all the sensors in an array; and compression of sensor transients.

B. Feature extraction

Feature extraction has two purposes: to reduce the dimensionality of the measurement space, and to extract information relevant for pattern recognition. Feature extraction is generally performed with linear transformations such as the classical PCA.

C. Classification

The commonly used method for performing the classification task is artificial neural networks (ANNs) [25]. An artificial neural network is an information processing system that has certain performance characteristics in common with biological neural networks. It allows the electronic nose to function in the way similar to brain function when it interprets responses from olfactory sensors in the human nose. A typical ANN classifier consists of two or more layers [26].

F. Decision Making

The classifier produces an estimate of the class for an unknown sample along with an estimate of the confidence placed on the class assignment. A final decision-making stage may be used if any application-specific knowledge is available, such as confidence thresholds or risk associated with different classification errors. The decision-making module may modify the classifier assignment and even determine that the unknown sample does not belong to any of the odorants in the database [26].

3 . 4 Prototype of Electronic Nose

Electronic nose research groups have developed a number of prototype electronic noses [28]. Some of them are presented in Figure 2.

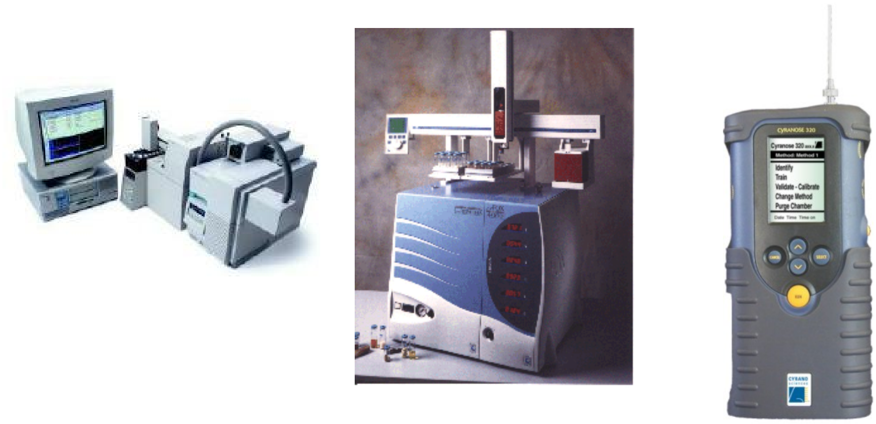

Figure 4: The 4440B (Agilent technologies),
Prometheus (Alpha Mos) and A320 (Cyrano Sciences) electronic noses [28]

Usually, during operation a chemical vapour is blown across the array, the sensor signals are digitized and fed into the computer. Then ANN (implemented in software) identifies the chemical. This identification time is limited only by response time of the chemical sensors, which is on the order of a few seconds [29].

4 Human Odor Recognition

Biometrics tools are becoming more popular as a form of identification as the technology needs becomes increasingly sophisticated and less expensive. Already, vendors are selling fingerprint recognition technology on computer keyboards or iris recognition for automated teller machine manufacturers.

Can we identify people by the odor? Sound like a snorter? It's not. Medical researcher Lewis Thomas first suggested a link between immunity and body smell in the middle of1970s [30]. Scientists already have linked a collection of immunity genes with unique human body odor. And with ENoses now sensitive enough to test beer, perfume samples and uncover pollution and disease, it may be only a matter of time before an ENose will be possible to identify persons.

4 . 1 Problems

Now it’s absolutely clear that people with differing immunity genes produce different body odors, but scientists do not know how that happens. And even if researches knew exactly which compounds to look for, artificial noses are not yet sophisticated enough to do this job.

First of all, today's smell sensors are not sensitive to a wide variety of compounds. Daniel D. Lee, a bioengineering scientist at the University of Pennsylvania said [30]: "We have cameras that can see outside the spectrum of the human eye and microphones that can detect a vibration a mile away, but in terms of chemical sensing, we are far away from what biology can do."

Computers are not as smart or flexible as dogs or humans or other biological creatures. “If I get a brand-new scent that I've never smelled before, I can learn what that means and recognize it the next time I encounter it. Machines aren't very good at being able to adjust to new conditions, “ Lee said.

Thus, scientists must fill big holes in both research and technology

4 . 2 Electronic vs. Human nose

How electronic noses work? Let's compare our nose with the electronic version [31]. Most substances contain volatile chemicals. Due to them we can smell something. Sensors in our nose, which are about 10.000 in number [32] and are non-specific-task in nature, react to those complex chemical vapours (which may consist of 670 chemicals as for coffee) and send the appropriate electric signals to our brain, which has about 10 million sensory neurons. The set of signals transmitted by these set of sensors give a pattern. Our brain records the pattern and, if it cannot match the pattern to any pattern already stored, the new one will be added to its already large library of patterns. Variation between this smell and the already stored pattern will highlight any difference in the constituent of vapour from the known pattern. The next time we encounter this smell, our brain will be able to recognize it.

Human nose is very much needed in many jobs, for example in coffee grading process where a human panel of smell experts will smell out a batch of beans to determine its grade. However, this process prone to give incorrect results as human olfactory system is sensitive to environment, health diet, as well as fatigue [31].

ENoses, however, are much simpler than the biological version, and able to detect only a small range of odors. ENose utilises much smaller number of volatile chemical sensors, usually between 12 and 20, and proportionate number of artificial neurons. [31].

Conventional method for odor identification is both expensive and complicated [31]. There must be a huge sensor array, where each sensor is designed to respond to a specific odor. With this approach, the number of sensor must be at least as great as the number of odors being monitored. Apart from that, the quantity and complexity of the data collected by sensor arrays will trouble this approach when it comes to automated fashion. As such, this method is not feasible.

However, nowadays trend seems to look to artificial neural networks (ANNs). When an ANN is combined with a sensor array, the number of detectable odors is generally greater than the number of sensors. Also, less selective sensors (thus, less expensive sensors) can be used for this approach. Once the ANN is trained for odor recognition, the operation will consist of propagating the sensor data through the network. With this approach, unknown odors can be rapidly identified in the field.

Due to limitations of current technology, many ANN-based ENoses have less than 20 sensors and less than 100 neurons. These systems are designed for odor specific applications with a limited range of odors. Systems that mimic more of the functionality of the human olfactory system will require a larger set of sensing elements and a larger ANN [31].

4 . 3 Who works with it?

Unfortunately, state-of-the-art in ENoses does not allow using these devices for such perspective task as the human recognition task. Work under development system for person authentication is extremely expensive thus not each laboratory can deal with it. However, there are at least two companies who work under creation a device for person recognition.

The first company is the U.K. *Company Mastiff Electronic Systems* [33]. This company is said to be in development of Scentinel, a product that digitally sniffs the back of a computer user's hand to verify identity. Senior engineer Stephen McMillan, however, says the product won't be ready for another three years [34]. So, it is still 3 years away from commercial release. This product is still too expensive ($48,600) but there is interest in its implementation from the British embassy in Buenos Aires, Saudi Arabia's National Guard, and private Indian and Japanese companies.

The second group working under identification people by body odor using artificial noses instead of dogs' is the *Pentagon's Defense Advanced Research Projects Agency*. This agency [30] is planning to pass out some $3.2 million this year, with the expectation that a people-sniffing electronic nose will be available in the next five to six years as specific milestones are met along the way. In Figure 3 the prototype awaiting installation of its electronic nose at a laboratory at the University of Pennsylvania.

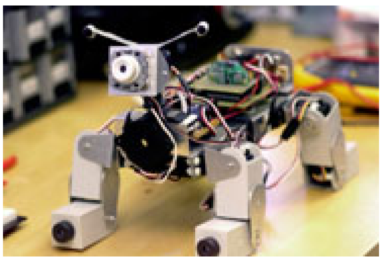

Figure 3: Prototype of electronic nose, University of Pennsylvania [30].

5 Applications

5 . 1 Future Applications

Except of human authentication as a computer’s user there are a number of other perspective applications. As it was said above, the real olfaction mechanism is still unknown for the science. However many scientists, research groups and entrepreneurs are trying to understand it and even to approximate it. It is important from the possible applications point of view.

- The first of them is the *fight against crime*, recognition of terrorists. There are already orders on the human recognition system already from the British embassy in Buenos Aires, Saudi Arabia's National Guard, and private Indian and Japanese companies [30].

- Absolutely new application can be *virtual reality and virtual environment* [35]. The main idea of this application is limited nowadays only by 3D sound and stereo vision, thus users' immersion into Virtual Environmental is restricted only by two of five available senses. The virtual reality including smell is expected to promote training perilous duties. A lot of real-life dangerous situations require more physical conditions than just visual and aural inputs. Among such application, that relies strongly on the smell: fire-fighter training, dangerous gas discharge.

- Another important application is detection of humans buried in rubbles [36]. It is actual task, for example, in earthquakes or damages on coalmines. To detect human body odor an electronical nose is applied. In principle, this ENose can be considered as an alternative to the dogs' work. Unfortunately, dogs can go up to a depth 50 meters and work only with the couple of his master. Another disadvantage that the long maintenance of the handler-dog team is too expensive. From all these points of view an electronical nose for humans’ detection will be suitable replacement of the dogs. Of course this nose is not too sensitive as the dog's one, but it can be used perfectly for these specific applications.

- A more futuristic application of ENose has been recently proposed for *telesurgery* [46]. The ENose would identify odors in the remote surgical environment.

All these applications are expected to appear in the next 5-6 years.

5 . 2 Current Applications

During the last decade, a dozen companies have developed over a hundred electronic nose prototypes and a number of commercial applications are expected in the next five to ten years. A global market of 3000 units annually is predicted annually by 2005. From 10-15 million USD the market is expected to grow to nearly 50 million USD in the next decade [37].

Inline electronic noses cost about 40,000 to 50,000 USD a piece, while hand-held units are available for 5000 USD. As the gas sensor costs only about 5-10 USD, the major chunk of the cost lies in the odor recognition system. This is expected to reduce with improvements in Pattern Recognition Software and advancement of ANN technology [37].

- The most important application nowadays of ENoses is in *medical diagnostics*. Odors in the breath can indicate gastrointestinal problems, sinus problems, infections, diabetes, and liver problems. Infected wounds and tissues give off odors that can be detected by the electronic nose [38]. Odors coming from body fluids can indicate liver and bladder problems. An electronic nose has also been used to track glucose levels in diabetics, determine ion levels in body fluids, and detect pathological conditions such as tuberculosis [22].
- *Environmental applications* of electronic noses include identification of toxic and hazardous wastes [39], analysis of fuel mixtures [40], detection of oil leaks, and identification of household odors, monitoring factory emission, and testing ground water for odors.
- The biggest market for ENoses is the *food industry*. Application in this area includes quality assessment in food production [41], inspection of food quality by odor [14], control of food cooking production, verifying if orange juice is really natural [42], grading whiskey, inspection of beverage container, classification of vintage of wines [43, 44, 45].
- ENoses are used also in *pharmaceuticals* to determine whether stored drugs have already reached the expiry date. This is necessary when we are dealing on a huge scale.
- In *perfumery* to identify counterfeit products [18].

Conclusions

A problem of personal authentication based on the body odor is analyzed in this paper. Now it is absolutely clear that people with differing immunity genes produce different body odors. Each human has unique body odor that is a combination approximately thirty different odorants. The main purpose of human body odor is not just to define these entire components, but also to estimate its concentration.

To identify people by their body odor a special devices, electronic / artificial noses, so-called ENoses must be used. Two main components of these noses: sensing system and pattern recognition system are described in the work. The main idea of ENoses is try to repeat the process of human olfactory model. The problem is the information processing mechanisms of human olfaction entirely is still unknown because of the lack of knowledge about overall dynamical properties of the brain. Thus if for pattern recognition system of ENoses any pattern recognition algorithm can be used, the sensing system represents a stumbling block. It is emphasized in this paper that state-of-the-art in sensors' sensitivity does not allow to estimate the concentration of the odorants within its mixture. All that is possible to do is only to detect whether specific odorant is contained in this mixture or not.

There are no available commercial applications for person authentication through the body odor on the market yet

At least two research groups (U.K. Company Mastiff Electronic Systems and Pentagon's Defense Advanced Research Projects Agency) work under development of the device capable to catch the humans' body odor in the future. It is emphasized that such kind of research is extremely expensive and tedious and the first commercial release is still at least 3 years away. Unfortunately there is no available information about both the accuracy of the methods used in devices and exactly numerical algorithms.

Equally with the humans' body odor recognition is still under construction the odor recognition technique is quite useful in real life application. There are a lot of current applications that together with the future ones have been presented in this review. Among current applications the medical diagnostics, food & beverages industry can be mentioned. Amid the future applications, except computer user identification, the virtual reality and virtual environment, recognition of terrorists can be divided.

Thus the body odor humans' recognition is the perspective future (approximately 3-5 years) technique with a number of possible applications.

References

[1] The Biometrics Glossary. Home Page. (cited 29.10.2003) http://www.eyenetwatch.com/biometrics-glossary/biometric-terms.htm

[2] International Security. Homepage. (cited 27.10.2003) http://www.security-int.com

[3] The Senses. (cited 29.10.2003) http://users.tpg.com.au/users/amcgann/body/senses.html

[4] A. Mamlouk. "*Quantifying Olfactory Perception*". Master of Science Thesis, University of Lubeck, Germany, 2002.

[5] G. Wyszecki, W. Stiles. "*Color science: concepts and methods, quantitative data and formulae*". Wiley, New York, 1982.

[6] http://www.health24.co.za/news/Ear nose and throat/1-905,21885.asp (cited 29.10.2003)

[7] W. Freeman. "*The physiology of Perception*". Sci Am 264: 7885, 1991.

[8] W. Freeman. "*Tutorial on Neurobiology: From Single Neurons To Chaos*". Int J Bifurcation Chaos 2, pp.451-482, 1992.

[9] R.P. Lane, T. Cutforth, et al. "*Genomic analysis of orthologous mouse and human olfactory receptor loci*". Proceedings of the National Academy of Sciences of the USA, USA, Volume 98, pp. 7390-7395, 2002.

[10] G.Georgiev, N. Gueorguieva, P.Tchimev, I. Valova. "*Odor Information Processing in Human-Oscillatory Model*". Proceedings of the IEEE Systems, Man, and Cybernetics Conference, October 2001, Tucson, Arizona, USA, pp. 52-58, 2001.

[11] W. Freeman, Baird B. "*Correlation of Olfactory EEG with Behavior: Spatial Analysis*". Behav. Neurosci 101, pp. 393-408, 1987.

[12] P. Keller. "*Overview of Electronic Nose Algorithms*". International Joint Conference of Neural Networks (IJCNN'99), Washington, USA, 1999.

[13] J. Gardner. "*Detection of Vapors and Odors from a Multi-sensor Array Suing Pattern Recognition, part 1. Principle Component and Cluster Analysis*". Sens. Actuator B, Volume 4, pp. 109-115, 1991.

[14] P.M. Schweizer-Berberich, S. Vaihiger, and W. Gopel. "*Characterization of Food Freshness with Sensor Array*". Sens. Actuator B, Volume 18/19, pp. 282-240, 1994.

[15] Stanford University, Department of Mechanical Engineering, Course Introduction to Sensors. (cited 20.11.2003) http://design.stanford.edu/Courses/me220/

[16] A. K. Srivastava, Pyare Lal, S. K. Srivastava. "*Effect of hydrogen plasma treatment on polycrystalline metal oxide gas sensor: An empirical study*". International Conference on Recent Trends in Sensor Development for Monitoring Environmental Quality , India, pp. 112-113, 1997.

[17] P.M. Schweizer-Berberich, J. Goppert, et. al. "*Application of Neural Network Systems to Dynamic Response of Polymer-Based Sensor Array*". Actuator B, Volume 26/27, pp. 232-236, 1995.

[18] T. Nakamoto, A. Fukunda, and T. Moriizumi. "*Perfume and Flavor Identification by Odor-Sensing System Using Quartz-Resonator Sensor Array and Neural Network Pattern Recognition*". Actuator B, Volume 18/19, pp. 282-290, 1994.

[19] Y. Okahata and O. Shimizu. "*Olfactory Reception on a Multibilayer-Coated Piezoelectric Crtstal in a Gas Phase*". Langmuir, Volume 3, pp. 1171, 1987.

[20] H. Sundgren, F. Winquist and I. Lundstrom. "*Artificial Neural Network and Statistical Pattern Recognition Improve MOSFET Gas Sensor Array Calibration*". Tech. Digest Transducers, pp. 574, 1991.

[21] G.F. Fernando, D.J. Webb, and Pierre Ferdinand. "*Optical-Fiber Sensors*". MRS Bulletin, Volume 27 (5), 2002

[22] P. Boilot, EL. Hines et al. "*Detection of eye bacteria causing eye infections using a neural network based electronic nose system*". Gardner JW and Persaud KC (eds.) Electronic Noses and Olfaction, IOP Publishing Ltd, Bristol, pp 189-196, ISBN 0-7503-0764-1, 2000

[23] C. Linster, F. Grasso, W. Getz, "*Olfactory Coding: Myths, Models and Data*". Neural Information Processing Systems Post-Conference Workshop, Breckenridge, Colorado, USA, 1998.

[24] J. Jackson. "*Principal Component Analysis*". John Wiley & Sons, ISBN 0471622672, 1991.

[25] H. Wu and M. Siegel. "*Odor-based Incontinence Sensor*". Proceedings of the 17th IEEE Instrumentation and Measurement Technology Conference, pp. 63-68, 2000.

[26] A. Couto. "*Current Status of the Electronic Nose: Research and Applications*". Report on Microelectronic Sensors, 2000.

[27] K. Kuiqian, T. Maekawa, and T. Takada. "*Identification of Odors Using a Sensor Array with Kinetic Working Temperature and Fourier Spectrum Analysis"*. IEEE Sensors Journal, Volume 2(3), 2002.

[28] The University of Warwick, Sensors Research Laboratory, Home page. (01.12.2003) http://www.eng.warwick.ac.uk/SRL/electronic_nose.htm

[29] S. Hashem, P. E. Keller, et al. "*Neural Network Based Data Analysis for Chemical Sensor Arrays*". SPIE's AeroSense Conference, 1995

[30] M. Wylie. "*An artificial Nose that Can Sniff Out Terrorists? It May Not Be Sci-Fi*"- Newhouse News Service, 2003. (cited 06.11.2003) http://www.newhousenews.com/archive/wylie013103.html

[31] Assoc Prof. Mohd Noor Ahmad, school of Chemical Sciences, University of Malaysia. Homepage (cited 08.11.2003) http://www.chs.usm.my/chem/LECTURER/MohdNoor.htm

[32] M. Bear, B. Connors and M. Paradiso. "*Neuroscience Exploring the Brain*". Williams and Wilkins, ISBN 0683004883, 1996.

[33] Mastiff Electronic Systems Ltd, UK, Home page. http://www.mastiff.co.uk/

[34] A. Davis. *"The Body as Password"*. Wired News. 1997.

[35] J. Cater. "*Approximating the Senses: Smell/Taste: Odors In Virtual Reality*". Systems, Man, and Cybernetics, 1994. Humans, Information and Technology, 1994 IEEE International Conference, Volume: 2, 1994.

[36] A. Teo, H. Garg and S. Puthusserypady, "*Detection Of Humans Buried In Rubble: An Electronic Nose To Detect Human Body Odor*". Proceedings of the IEEE 2nd Joint EMBS-BMES Conference, Houston, TX, USA, pp.1811-1812, 2002.

[37] A. Biyani. "*Electronic Noses a Novel Technology for Industry* ". 2002.

[38] The William R. Wiley Environmental Molecular Sciences Laboratory, Pacific Northwest National Laboratory in Richland, Washington, Homepage (cited 18.11.2003) http://www.emsl.pnl.gov

[39] A. K. Srivastava, K. K. Shukla, S. K. Srivastava. "*On the performance evaluation of hybrid-trained neural classifier for detection of hazardous vapors using responses from SAW sensor array*". Proc. of IEEE - International Conference on Industrial Technology, India, pp. 656-681. 2000.

[40] R.J. Lauf and B.S. Hoffheins. "*Analysis of Liquid Fuels Using a Gas Sensor Array*". Fuel , Volume 70, pp. 935-940, 1991.

[41] S. Hahn, M. Frank, U. Weimar. “*Rancidity investigation on olive oil: a comparison of multiple headspace analysis using an electronic nose and GC/MS*.” Proceedings of the 7th International Symposium on Olfaction and Electronic Nose, , pp. 49–50, 2000.

[42] C. Di Natale, A. Macagnano, E. Martinelli, R. Paolesse, E. Proietti, A. D’Amico. ”*The evaluation of quality of post-harvest oranges and apples by means of an electronic nose*” Sens. Actuators B 78 , pp. 26–31, 2001

[43] J. de Souza, B. Neto et al. “*Polypyrrole Based Aroma Sensor*”. Synthetic Metals, Volume 102, pp. 1296-1299, 1999.

[44] A. Yamazaki, T. Ludermir, and M. de Suonto. “*Classification Vintages of Wine by an Artificial Nose Using Time Delay Neural Networks*.” IEE Electronics Letters, Volume 37 (24), pp. 1466-1467, 2001.

[45] A. Yamazaki nad T. Ludermir. “*Classification Vintages of Wine by an Artificial Nose with Neural Networks*”. 8th International Conference on Neural Information Processing, Volume 1, pp. 184-187, 2001.

[46] P.E. Keller, R.T. Kouzes, L.J. Kangas, and S. Hashem."*Transmission of Olfactory Information for Telemedicine*," Interactive Technology and the New Paradigm for Healthcare, R.M. Satava, K. Morgan, H.B. Sieburg, R. Mattheus, and J.P. Christensen (ed.s), IOS Press, Amsterdam, pp. 168-172, 1995.