Electronic Taste and Smell: The Case for Performance Standards

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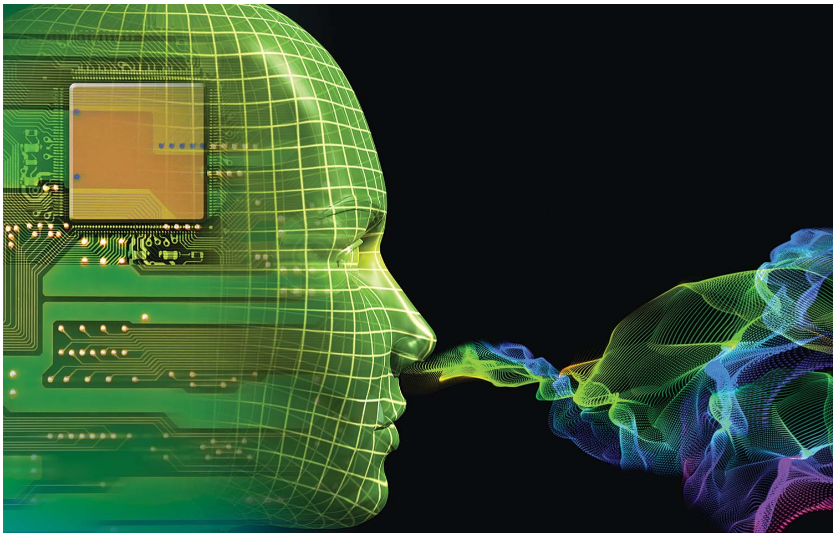

I. IMPORTANCE OF STANDARDS FOR SENSORY DEVICES

International standards have proven invaluable in the technology sector for developing functional and reliable products for the global marketplace. Standards provide performance criteria that technical engineers can use to design products to optimize the reliability and safety of new products. For example, standards have played a decisive role in the development of products associated with the senses of vision, audition, and touch. The design of products that perform automated "visual" tasks including unmanned vehicles, autonomous robots, optical tracking systems, and highway traffic monitoring devices has relied heavily on standards as well as technical regulations. Likewise, standards related to the sense of hearing have played a major role in the development of devices and systems that assist or mimic "audition" including cochlear implants, hearing aids, and voice and speech recognition systems. Standards related to the sense of touch have been seminal in the design of robotic arms and prosthetic hands. Unlike the senses of vision, audition, and touch, there are, however, no formal standards for electronic devices called e-noses and e-tongues that are designed to detect and evaluate odors and tastes. The purpose of this opinion piece is to give a brief background on the senses of smell and taste, to describe why standards for e-noses and e-tongues are needed, and to call for IEEE volunteers to participate and collaborate on technical standards development to ensure that machine olfaction and taste provide reliable and reproducible results that are comparable to human smell and taste.

II. SMELL AND TASTE: BACKGROUND

Smell and taste are chemical senses that play a major role in human health, disease, and survival throughout the lifespan. They prepare our bodies to digest a meal, warn us about tainted food, and alert us to environmental toxins,

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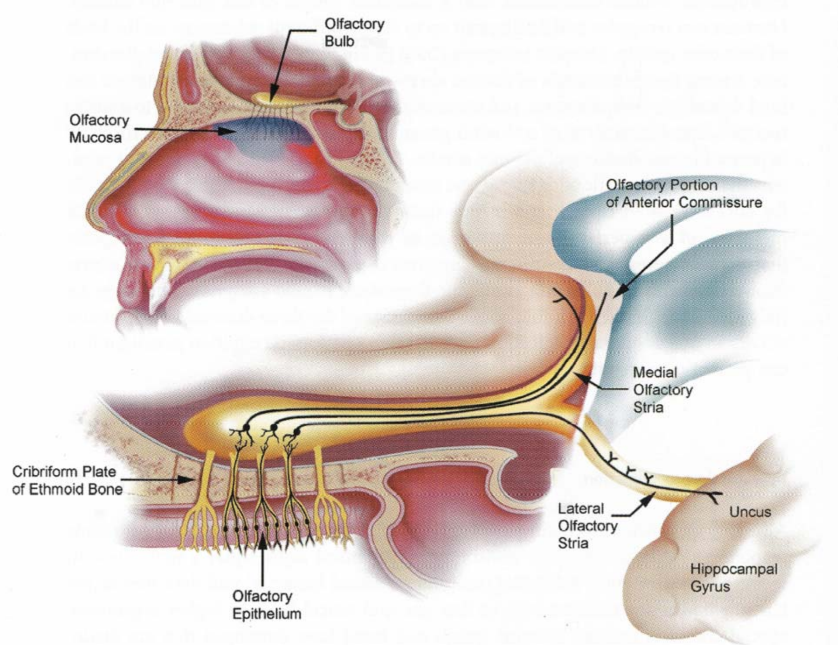

Fig. 1. ***The human olfactory system [1].***

gas leaks, and fire hazards. The human olfactory system is depicted in Fig. 1 [1]. Smell sensations are initiated by volatile compounds that bind to olfactory (odorant) receptors located on sensory neurons in the olfactory epithelium at the roof of the nasal cavity. There are approximately 400 functional odorant receptor types in humans. Odorants typically stimulate multiple receptor types, and the pattern of activation denotes the odor's attributes. The range of odor sensations is vast, and recent research suggests that humans can distinguish differences or patterns among more than one trillion structurally diverse odorous molecules [2]. The human gustatory system is illustrated in Fig. 2 [1]. Taste sensations are initiated when chemical substances dissolved in water or other fluids interact with taste buds located on small rounded structures called papillae on the dorsal surface of the tongue. Taste buds are also located on the palate, pharynx, and upper third of the esophagus. Unlike odor, the range of taste is very narrow and includes five basic qualities—sweet, sour, salty, bitter, and umami (meaty, savory). Several other qualities such as astringent, metallic, chalky (calcium salts),

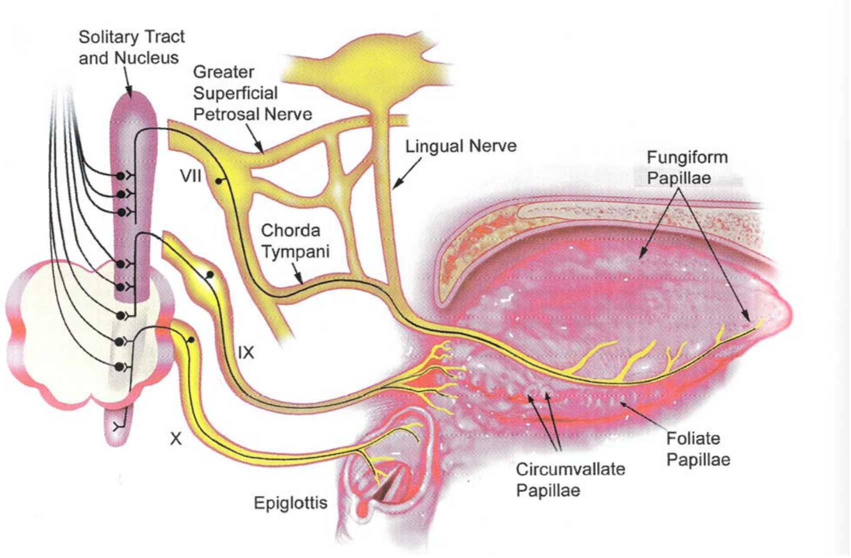

Fig. 2. ***The human gustatory system [1].***

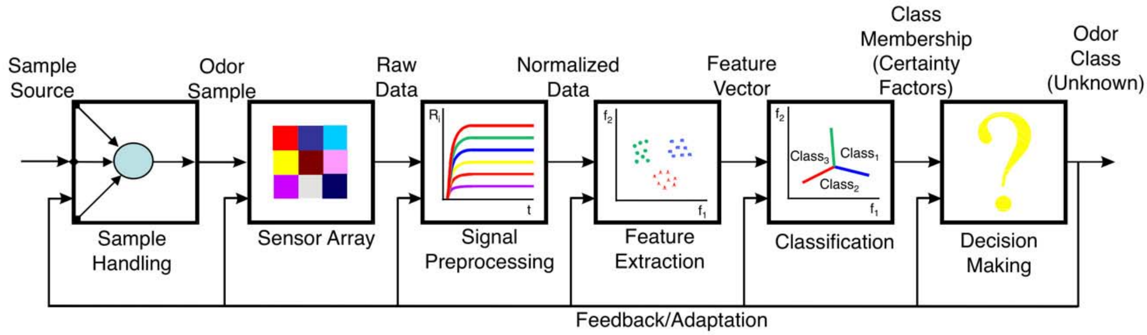

Fig. 3. *E-nose sampling and signal processing (after [5]).*

and fatty have also been considered to be taste sensations.

Throughout history, the sense of smell has played an important role in the fields of medicine, perfumery, culinary arts, agriculture, hygiene, and sanitation. Early medical practitioners utilized abnormal odors emitted from bodily secretions as a diagnostic tool to identify certain diseases such as the sweet, fruity breath in diabetes. Formal sensory testing of products such as olive oil, tea, and wine by professional smell and taste experts became commonplace over time as merchants sold their goods on the basis of sensory quality. Currently, expert human panelists who are trained to characterize and evaluate odor and taste sensations are employed as "measuring instruments" in many industrial settings for quality control and product development. While human smell and taste panels provide important sensory information, there are limitations in their use. First, trained human panelists are not always available when needed or may not safely assess samples such as tainted drugs or malodors from toxic gases. Second, there are learned and genetic differences in the perception of smell and taste that contribute to variability among panelists. Third, the number of samples that can be evaluated by humans at one time is limited due to sensory fatigue that can affect the validity and reproducibility of responses. As a consequence, there has been an impetus to develop fast, reliable instruments for assessing smell and taste that can replace or complement human sensory panels.

III. HISTORY OF MACHINE OLFACTION AND TASTE

The concept of an electronic nose was first introduced to a general scientific audience in an article titled "Now they'll know you by your smell print" published in *Popular Mechanics* in February 1968 [3]. The article described emerging "sniffing" devices

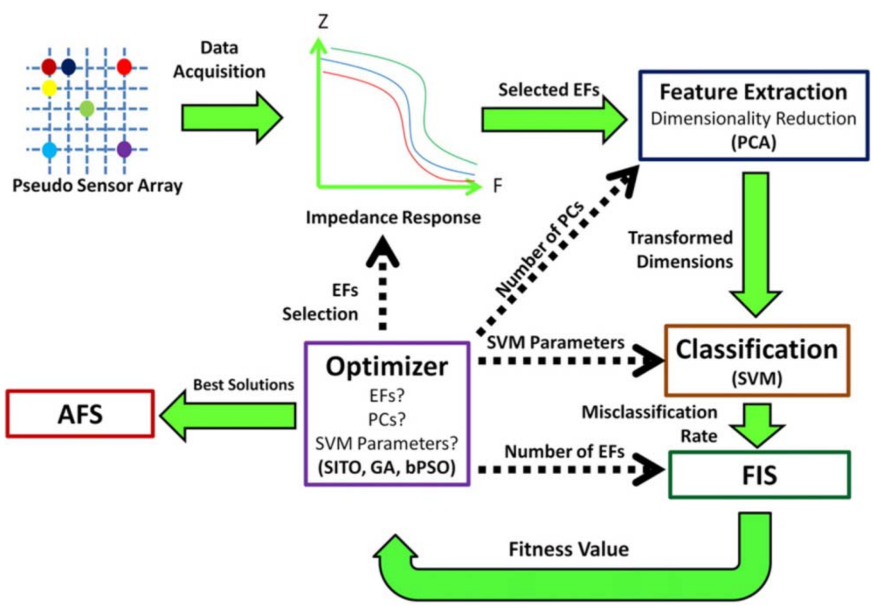

Fig. 4. *An e-tongue sensing and signal processing configuration [12].*

Table 1 Human Detection Thresholds (DTs) of Sulfurous Compounds [13]

Compound	*DT in ppm*
Carbon disulfide	0.21
Carbonyl sulfide	0.055
Dimethyl disulfide	0.0022
Methyl allyl sulfide	0.00014
tert. Butyl mercaptan	0.000029
n-Butyl mercaptan	0.0000028
Isoamyl mercaptan	0.00000077

for diagnosing disease, fingering criminals, and detecting bombs using odor patterns. However, it took over a decade until the first electronic nose based on a chemical sensor array of semiconductor transducers that could discriminate among odors was described in the scientific literature [4]. Since this seminal work, many e-nose devices have been developed using a variety of sensor types including metal oxide, conducting polymer, metal–oxide field-effect transistor (MOSFET), surface acoustic wave (SAW), optical, quartz crystal microbalance (QCM), and chromatographic/spectrometric technologies [5]–[8]. The typical configuration for the various stages of e-nose signal acquisition and processing is shown in Fig. 3. Odor samples are collected and delivered to a sensor array. The sensors convert chemical interactions into analog electrical responses. An analog-to-digital (A/D) converter then provides digitized time responses for signal processing. Preprocessing removes baseline drift and other noise elements. Finally, feature extraction and classification algorithms are applied to identify parameters that distinguish the odor being examined.

Early prototypes of electronic tongues for sampling liquids emerged another decade later during the 1990s. Two early prototypes of an e-tongues consisted of a liquid/polymer membrane for a transducer [9] and a silicon wafer embedded with beads that changed color when contacting simple sugars and acids [10]. Since these early prototypes, e-tongues have been developed using nonbiological technologies including optical, impedance, mass, potentiometric, and voltammetric/amperometric sensors; biological materials including enzymes, lipids, as well as human taste receptor proteins have also been utilized [11]. A typical configuration for the stages of e-tongue signal acquisition and processing is shown in Fig. 4 [12]. This example uses the impedance response of the sensor system to generate its input data set. It then includes feature selection, extraction, and classification algorithms to generate parameters to differentiate the tastant under test.

IV. PRACTICAL CHALLENGES TO E-NOSE AND E-TONGUE RELIABILITY

Despite subsequent decades of innovative e-nose and e-tongue research and development along with introduction of numerous commercial instruments, it is still not possible to reliably identify the odor or taste quality (or intensity) of multicomponent samples over time from profiles generated by e-nose or e-tongue devices. This is due in part to the many practical challenges of machine olfaction and taste that have not yet been solved. First, odorless components of a gaseous mixture such as water vapor (humidity) can interfere with many gas sensor measurements. Second, the selectivity of the device may be inadequate for an application. Third, noise can be amplified as the array size increases. Fourth, sensors undergo contamination and drift with repeated stimulation. Fifth, the sensitivity of the sensors may be inappropriate for the application. Table 1 illustrates that a human odor panelist can detect trace concentrations of some but not others, and the range of detection thresholds varies over six orders of magnitude. Like olfaction, there are significant differences in human taste sensitivity. Table 2 illustrates that human detection thresholds for sweet compounds also varies over six orders of magnitude. In order for an e-nose or e-tongue to mimic human perception, its sensors must perform in a similar manner.

These are just a few of the impediments to developing reliable and accurate instruments. The impetus to find solutions to these and other practical problems has been limited by the fact that there are currently no standards that would guarantee the reliability of these instruments. The development and implementation of formal performance standards would accelerate research that solves general and application-specific issues that limit the efficacy, dependability, and reliability of these instruments.

V. GUIDANCE FROM HUMAN ODOR AND TASTE STANDARDS

Insight and guidance into performance criteria necessary for machine olfaction and taste can be gained by examining standards established for assessment of odor and taste by humans. Hundreds of standards are available from ASTM International and other similar organizations for assessing human responses to odor and taste that include both general and application-specific methods. General standards include those for determining thresholds, suprathreshold intensity, difference thresholds between two stimuli, and classification of odor and taste quality.

A. Thresholds

There are two types of thresholds, detection thresholds (DTs) and recognition thresholds (RTs), that relate to the sensitivity of smell and taste. The DT referred to in both Tables 1 and 2 is the weakest concentration that can be reliably detected while the RT is the weakest concentration that can reliably be recognized. There are many standard methods for determining DTs and RTs but most give equivalent results. The ascending method of limits [14] is an option that can be used to determine the thresholds for e-sensing instruments as well as humans. In this technique, dilutions of odorants and tastants can be presented in triads beginning with the most dilute concentration. Each triad consists of two blank controls along with one odorant (or tastant); the

Table 2 Human DTs for Sweet-Tasting Compounds [13]

Sweetener	*DT in mM*
Fructose	4.39
D-tryptophan	0.109
Sodium saccharin	0.0147
Sucralose	0.00877
Neotame	0.000621
Thaumatin	0.0000716
Monellin	0.0000195

order of three stimuli is randomized over increasing concentrations. The geometric mean of the highest undetected concentration and the lowest detected is the detection threshold. Olfactometers are commercially available to implement this standard [15].

B. Suprathreshold Intensity

The human panelist's perception of the intensity of an odorant or tastant sample changes with increasing concentration. The shape of the concentration-intensity function can be sigmoidal, hyperbolic, linear, and accelerating dependent upon the chemical compounds in the samples under test. Fig. 5 displays an example of a hyperbolic response (the most common function type) for the artificial sweetener aspartame [13]. The ordinate shows perceived sweet intensity relative to sucrose (a value of ten indicates a perceived sweetness equivalent to a solution of 10% sucrose). The figure demonstrated that the maximum sweet intensity for aspartame approaches 15. Thus, at all concentrations of aspartame beyond 3000 ppm, the sweetness of samples is perceived as comparable to 15% sucrose.

In real-world applications, odorants and tastants are rarely single chemical compounds. Therefore, future standards should consider specific mixtures of interest. For human smell, the most common result of mixing two odorants is suppression of intensity (i.e., the mixture is perceived as less intense than the sum of the intensities of the individual components). For mixtures of tastants, the result can be suppression, addition, and synergy. An example is the synergism of the two sweeteners aspartame and acesulfame-K. In mixtures, these two tastants amplify each other and are used together to reduce the cost of sweetening food products. Another example is monosodium glutamate and 5'-ribonucleotides. These two tastants amplify the umani/savory characteristics in Asian noodle soup.

C. Difference Thresholds Between Two Stimuli

A difference threshold for smell or taste is the minimum change in concentration needed to notice a variance between two samples of suprathreshold stimuli. For humans, a change in concentration of 15%–25% is typically needed to notice a difference in intensity between two samples of a suprathreshold tastant [16]. Difference thresholds both lower and higher than the 15%–25% range have been reported for odors in the scientific literature.

D. Qualitative Discrimination

Molecules often have different sensory properties even when their chemical structures are similar. Alternatively, molecules that differ extensively in chemical structure may have similar odors or tastes. For example, hydrocyanic acid (HCN), nitrobenzene ($C_6H_5NO_2$), and benzaldehyde (C_7H_6O) have dissimilar structures but all smell like bitter almonds. Conversely, the three molecules acetophenone (mimosa, almond), styrene (sweet, sharp), and phenylacetic acid (rose, disagreeable, honey) have different odor qualities but have similar molecular shapes and the same basic carbon skeleton. Enantiomers such as S-(+)-carvone and its mirror image R-(–)-carvone have odor sensations described as caraway seeds and spearmint, respectively. These molecules are easily discriminated by humans. Similar issues exist for taste. These are challenges for e-nose and e-tongue devices.

VI. IEEE STANDARDS PROCESS

The IEEE is known throughout the world as a premier technology standards developer. Its standards are developed by sponsors that come from its 43 technical societies and councils. The councils and societies are sponsors of the standards. The standards

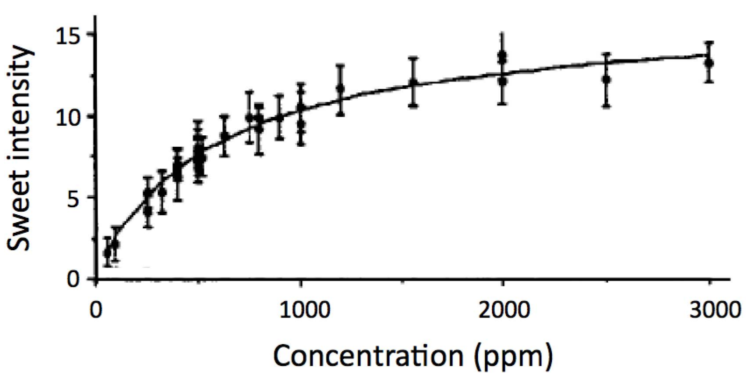

Fig. 5. ***Sweet intensity versus aspartame concentration [13].***

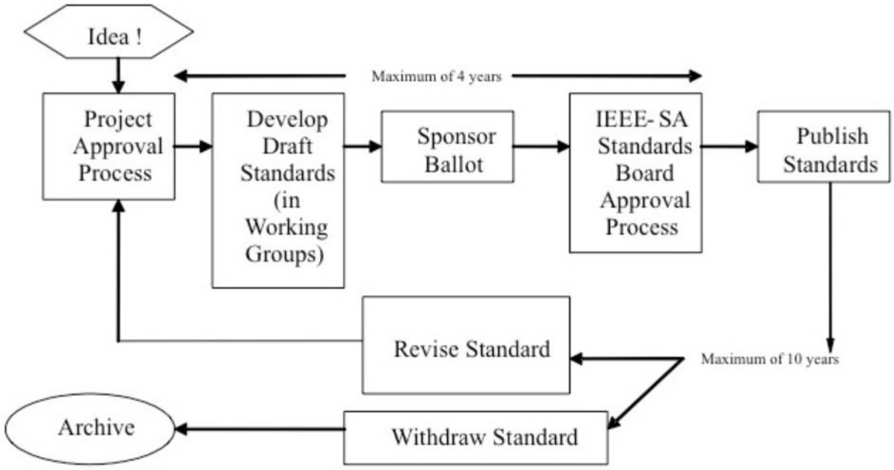

Fig. 6. *How IEEE Standards are made and maintained [17].*

are developed by working groups that adhere to a strict set of guidelines. These guidelines have been developed over the decades and are administered by a quasi-independent organization within IEEE that is called the IEEE Standards Association. The IEEE Standards development process is summarized in Fig. 6 [17]. Note that each standard must be published within four years and revised within ten. IEEE has developed a large number of sensors technology standards in the past and is expanding its work in this important area. Two focus areas that can be applied to taste and smell standards are IEEE 2700 (Sensor Performance Parameter Definitions) [18] and IEEE 1451 (Smart Transducer Interfacing) [19].

VII. HISTORY OF E-NOSE STANDARDIZATION EFFORTS

Table 3 summarizes the two prior odor standardization efforts. First, under the sponsorship of the European Commission in 2001, the Second Network on Artificial Olfactory Sensing (NOSE II) conducted standardization activities by three working groups (WGs) [20]. The final result was that no specific e-nose standards were completed. The reasons given were: 1) the large number of available sensor technologies; 2) the WG goals were too broad; 3) failure by the industry to establish a generic e-nose technology; 4) no broad industry support for a common data format; and 5) fragmented markets with different application requirements. Technical standards commonly add complexity and cost to the system, and thus must bring added value. In addition, IEEE 1451 standard was employed when it was new, and its adoption was subsequently slow.

Second, in 2015, the European Committee on Standardization (CEN) created a Working Group on Instrumental Odour Emissions (WG41) within its Technical Committee on Air Quality (TC 264) [21]. WG41 has established four task groups (TGs). The WG41 standard will specify system requirements for odor monitoring of both indoor and ambient outdoor air. Emission into ambient air will also be considered, including gas sources and odor abatement equipment. Specific focus will be applied to odor sampling, data collection, and measurement uncertainty. Data processing will specify validated sensor metrics to the presence and attributes of an odor. The WG41 standard will not address hedonic tone, odor annoyance, the design of sensors, or specific odor measurement systems. The WG41 activities are continuing, and we look forward to an update at ISOEN 2019 in Japan.

VIII. PLANNED IEEE E-TONGUE AND E-NOSE STANDARDS

Can we now leverage these past and current European standardization

Table 3 Summary of Prior E-Nose Standard Efforts

Sponsor	Development Groups
European Commission (2001)	WG1: Standard data format
	WG2: Testing and calibration
	WG3: Hardware/software interfaces
European Committee of Standardization (2015), TC264/WG41	TG1: Instrumental requirements
	TG2: Target odor metrics
	TG3: Terms and definitions
	TG4: Descriptions and scope of relevant technologies

Table 4 Representative Applications That Have Utilized E-Noses or E-Tongues

Area	Application	Ref
Environmental: air and water quality	Swine confinement facilities	22
	Oil and gas plant emissions	23
	Pathogenic microorganisms in waste water	23
	Microbial count in river water based on VOCs	23
	Dangerous environments monitored by mobile robotic olfactory system	23
	Tobacco	23
	Contaminants in tap water (imidacloprid, dimethyl methylphosphonate, hydrogen peroxide)	23
	Underwater chemicals detected by jet discharge robot	23
	Environmental gases including ammonia, methylamine, and trimethylamine	23
	Molds growing on building materials	23
	Automobile cabin air and parts	24,25
Medical	Lung cancer diagnosis from breath test	26,27
	Creatinine in human urine	23
	Cell culture monitoring	23
	Stem cell differentiation steps	23
	Colon cancer from breath analysis of ethanol and acetone	23
	Volatiles associated with the parasite *Trypanosoma cruzi* that causes Chagas disease	23
	Odor of the anesthetics propofol and sevoflurane	23
Foods and Beverages	Scotch whiskies	23
	Beer production	23
	Parmigiano Reggiano cheese ripening	23
	High potency sweeteners	23
	Oils from lacto-fermented olives	23
	Ham quality	23
	Bitterness, astringency, and odor of tea	28
Product quality, contamination, and forensics	Adulteration of olive oil	29
	Cutting agents in cocaine samples	23
	Okadaic toxin from dinoflagellates that accumulates in shellfish	23
	Off-odors in wines	23
	Hydraulic oil fingerprint contamination on aircraft	23
Military; safety	Vapor analysis of explosives	23

projects to improve the commercial success of the e-nose/e-tongue industry? The IEEE Sensors Council and the IEEE Industrial Electronics Society will sponsor the initial phases of this expanded standardization effort. We note from the earlier standardization projects summarized above that a focus on specific applications is important for future success. E-nose and e-tongue devices have been employed in a large number of interesting and important areas. Table 4 gives an overview of five wide-ranging categories. In our IEEE standards working groups, we will leverage the efforts of the past and apply them to selected applications that are most attractive to industry. Successful standardization projects require strong support from industry. For the selected application areas, we will develop standards that can be used to compare the threshold sensitivity, the intensity of response with increasing concentrations of suprathreshold stimuli, and qualitative responses from e-instruments with those of human panels. There are other parameters that can also be considered, such as adaptation (the reduction in intensity that occurs with repetitive presentation of a stimulus), the time course of intensity (e.g., slow onset or persistent lingering), the impact of temperature including hot or cold stimuli, and hedonic properties (pleasantness or desirability). Standard algorithms for advanced signal processing will be developed for e-sensing instruments that can augment, compete, and/or replace human responses. The development of formal standards for analyte selection, signal processing algorithms, and performance evaluation will empower companies to introduce new generations of e-noses and e-tongues that simulate human chemosensory responses with greater accuracy and precision. Only then will these devices become commercially successful.

IX. CALL FOR E-NOSE AND E-TONGUE STANDARDIZATION VOLUNTEERS

Volunteers are needed for several roles. The most important need is for members and leaders of WGs, the committees that develop new standards. A WG member typically spends about one hour per week over several years. Being a WG leader (chair, vice-chair, secretary, etc.) requires about two hours per week over several years. Volunteers with experience in IEEE standards development can join a sponsoring entity's Standards Committee (IEEE Sensors Council and/or IEEE Industrial Electronics Society) which requires a commitment of about one hour per month (yearly appointments). Persons with expertise in the technology and application area for a specific standard will be invited to join a balloting group (BG). A BG is convened at the end of a standard development cycle (see Fig. 6). BG members devote about two hours per month for six months. If you are interested in learning more about (or joining) this standardization effort, send an e-mail request to t.nagle@ieee.org.

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