Implementation and Performance of a Taste Sensing System for Quality Assessment of Agro-based Products

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List of Abbreviation

ADC	=	Analogue to Digital Converter
ANN	=	Artificial Neural Network
CA	=	Cluster Analysis
CFA	=	Common Factor Analysis
GUI	=	Graphical User Interface
Hz	=	Hertz
LDA	=	Linear Discriminant Analysis
PC	=	Personal Computer
PC1	=	Principal Component 1
PC2	=	Principal Component 2
PCA	=	Principal Component Analysis
TSS	=	Taste Sensing System
V	=	Volt

ABSTRAK

Trend dalam pengambilan makanan manusia melihat perubahan dalam permintaan, dari sisi pengguna menuntut peningkatan unsur-unsur kesihatan dalam makanan dan dari pihak pengilang yang menuntut kesedapan yang lebih tinggi. Pada masa ini, kualiti pengeluaran ladang tidak boleh disahkan dan tuntutan kualiti adalah sangat bergantung kepada pengesahan peribadi petani dan rasional yang dibuat oleh ahli panel manusia terpilih. Pengesahan makmal sebaliknya, berkos tinggi dan memerlukan tenaga buruh terlatih untuk mengendalikan namun ia tidak menggambarkan rasa, yang merupakan campuran bahan kimia. Tesis ini membentangkan analisis reka bentuk, pencirian dan prestasi sistem penderia rasa (TSS) dalam menilai kualiti produk berasaskan pertanian. Sistem ini menggabungkan komponen yang sedia di pasaran untuk memastikan keringkasan dalam penghasilkan semula sistem pada harga yang berpatutan. Antara muka pengedalian dibentangkan sebagai antara muka pengguna grafik (GUI) untuk memudahkan pengendalian oleh kakitangan bukan teknikal dalam bidang lain-lain. TSS mempamerkan keupayaan luar biasa (di atas 80%) dalam membezakan sampel rasa kuantitatif dan sempurna (100%) dalam membezakan sampel kualitatif.

ABSTRACT

The trend in human food consumption is seeing a shift in demand, from consumer's side demanding increase of health elements in food and from manufacturer's side demanding higher palatability. Currently, quality of farm production is not verifiable and its quality claim is very dependent on farmers very own personal validation and rationale made by selected human panelist. Laboratory verification on the other hand, is cost prohibitive, requires trained labor to operate and yet does not indicate taste, which is a mixture of chemicals. This thesis presents the design, characterization and performance analysis of a taste sensing system (TSS) in assessing the quality of agro-based products. The system integrates off-the-shelf components to incorporate simplicity in reproducing the system while maintaining affordable cost. Operation interface is presented as graphical user interface (GUI) to allow operation by non-technical personnel in other discipline. The TSS exhibit exceptional ability (above 80%) in discriminating quantitative taste samples and perfect (100%) discrimination of qualitative samples.

CHAPTER 1

1.0 Introduction

Taste is the perception of gustatory sensation when food chemicals (stimuli) enter the human mouth cavity. Pleasant tastes often described as mouthwatering, refreshing, energizing, delicious, tasty, sweet, savory, titillating, appetizing and palatable while foul tastes described as tasteless, distasteful, unsavory, nasty, horrid, inedible and poisonous. The five chemical stimuli identified as being of special significance are acids (sour), salts (salty), alkaloids (bitter), glutamic acids (umami) and sugars (sweet). Sweet and umami tend to be preferred while acids and alkaloids avoided (Frank and Hettinger 2005).

Food essentially is the source of energy, nutrients and fluid for human beings. Human appetite for food is primarily to overcome hunger, nevertheless food are also consumed to sustain growth (in fulfilling energy, nutrient and fluid demand), to attain recreational pleasure and for health related purpose. The human gustatory system associates taste sensations with hedonic attributes (Drescher, Thiele et al. 2008; Lundy Jr 2008). Food preferences and eating habits influenced by its flavor and texture.

In today's urban society, the trend in human food consumption is seeing a shift in demand, from consumer's side demanding increments of health elements in food and from manufacturer's side demanding higher palatability in medicine (Anklam and Battaglia; van Kleef, van Trijp et al. 2005; Mancino, Kuchler et al. 2008). Flavor companies often employed to venture into developing new products to satisfy consumer demand. Taste assessment of the new products will prejudge its acceptance by consumers.

A variety of taste assessment methods exist, human panel and analytical instrument both complements each other in assessing taste. Human panelist (organoleptic) utilizes human to prejudge food samples. The evaluation process employs trained food taster, small-targeted group of people or larger group of random population. The 9-point hedonic scale is one of the many scaling methods use to assess the degree-of-liking in food. Panelists choose which scale represents their preference best. The 9-point hedonic scales are 'Like extremely', 'Like very much', 'Like moderately', 'Like slightly', 'Neither like nor dislike', 'Dislike slightly', 'Dislike moderately', 'Dislike very much' and 'Dislike extremely'(Lawless and Heymann 2010).

Modern machines and automation allow faster testing and more consistent test result. Sensing technological advancement has led to numerous methods developed to complement human panelist. Trace element detection machine often used to 'taste' food. New sensing materials with indicative color codes deposited onto strips further simplify the 'tasting' process and are very easy to use. Although with lower accuracy, this small, lightweight and requiring minimal or no accompanying unit allows portability and provide good screening for *in-situ* assessment.

Nevertheless, the methods mentioned above are not without flaw. Human panelist is labor intensive, require training and prone to fatigue. On the other hand taste detection machines are bulky, require trained personnel to operate and price prohibitive and sensing strip technology (Rahman, Yap et al. 2004) is too application specific and materials prohibitive (Dias, Peres et al. 2009).A taste-sensing instrument may be an alternative to above-mentioned methods (Escuder-Gilabert and Peris 2010).

This research presented the design and performance analysis of a taste sensing system (TSS) for the assessment of agro-based products. TSS implemented using off-the-shelf components integrated onto personal computer, operating in MATLAB's environment. Complexity and cost of implementation and operation of TSS lay in-between expensive analysis instrument and disposable strip, with operating principle mimicking those of human gustation system.

Qualitative and quantitative performance evaluated using sample prepared from selected agro-based samples acquired locally. Selection of multivariate and artificial neural network analysis methods used as pattern recognition. TSS implemented showed correlation to taste chemicals with promising qualitative and quantitative performance.

1.1 Problem statement

Global trend in consumer products is seeing the demand for greener content. Consumer is demanding increase in natural content for healthier lifestyle, food and beverages (F&B) industry is no exception to this trend. Greener products, which translate to healthier lifestyle, are on high demand that need development without compromising good taste.

Biodiversity research increasingly boosts the importance of nature and its wealth of benefits to humankind. Malaysia as one of the 12 mega-diversity countries has a lot to gain from the 'green' trend. Its wet tropical climate with year round sunshine provides conducive environment for cultivation of any of its species of flora and fauna which counts over 170 000. Forgotten, unwanted and uncared for species may soon be cultivated for functional food or cures to fatal diseases.

Nevertheless, the growth in 'green' industry demands for adequate quality control to safeguard its value adding elements. Raw "green" material has numerous parameters influencing its quality. Crops are of numerous cultivars, its produce is influence by soil, weather and seasonal condition, farm practices, geographical location, harvesting technique and post-harvest processing while livestock are of numerous breed and among others, its growth is influence by its feed, farm size and terrain, farm practice and living conditions.

The current quality of farm production is not verifiable and its quality claim is very dependent on farmers very own personal validation and rationale made by selected human panelist which is labor intensive and prone to fatigue. Laboratory chemical analysis machine is bulky, requires trained operator, price prohibitive and does not indicate taste, which is a mixture of a number of chemicals.

This thesis presented design and performance analysis of electronic taste sensing system (TSS) in assessing the quality of agro-based products. The system integrates high-level off-the-shelf components to incorporate simplicity in reproducing the system while maintaining affordable cost. Operation interface is presented as graphical user interface (GUI) to allow operation of the system by non-technical personnel in other discipline.

1.2 Research Objectives

The aims of this research are as listed below:

- To develop a simple taste sensing system (TSS)
- To execute performance analysis of (TSS) for assessment of agro-based products
- To develop graphical user interface (GUI) for operation by non-technical personnel.

1.3 Scope

This research focused on developing an instrument of taste suitable for the use of assessing agro-related products. Electrochemical sensors act as taste buds, commercial data acquisition unit as analogue interfaces and mathematical software, Matlab as signal processing environment.

Electrochemical sensors adopted are of potentiometric nature, supplied by Sensor Systems LLC, St. Petersburg. National Instrument's USB compatible (NiDAQ-6008) provides 8-channel data acquisition with USB connection and signal processing covers selected multivariate analysis and artificial neural network.

This research covers the development of a simple platform for data acquisition from sensor array, optimization of testing parameters for good 'tasting' and exploration of multivariate analysis for taste sensing.

The following assumptions are made during this research.

1) No permanent chemical reaction occurs between analyte and sensing material.

2) No loading (electrical stress) subjected on the sensors.

3) Stable room temperature, pressure, humidity and all other unmentioned parameters during testing.

4) No oxidation happens to analyte while under testing.

1.4 Chapter Outlines

Chapter 2 discussed essential backgrounds of taste sensing system covering from human gustation system to how food is perceive by human and commercial taste sensing instrument.

Chapter 3 discussed the technical (system hardware, software and GUI) implementation of this taste sensing system.

Chapter 4 discussed the methodology and presented the characterization of the developed system.

Chapter 5 presented the performance of developed system in classification of qualitative and quantitative samples using various pattern recognition and ANN methods.

Chapter 6 concludes this research, summarized contribution derived and recommends future works of interest related to this subject.

CHAPTER 2

2.0 Background Information

Food i.e. nutrients are essential ingredients for growth and energy for cells to function and keep the human body alive. Humans are driven to eat by hunger and appetite controlled by the brain. The human digestive system can be visualize as a tunnel from the mouth (ingestion) to the anal (egestion), in between are the digestive organs stomach, small and large intestine.

The human mouth provides the entrance to the digestive system. Human mouth consist the lips, hard and soft palates, cheeks and tongue. The tongue is a muscular flap that occupies most of the mouth cavity when closed. Intrinsic muscles within the tongue change its shape while extrinsic muscles anchored it to the bone allowing the tongue to protrude and retract. The tongue moves and mixes food during chewing process and houses the taste buds.

2.1 Gustation System

Taste and smell are linked senses such that they are located in close proximity, they complement each other and utilizes chemoreceptor sensors. Microscopic hairs present in chemoreceptor detect taste/smell in food, drink or air and triggers nerve impulses that sent to the brain for perception.

2.1.1 Tongue

The human tongue is the organ for taste. This muscularly mobile organ moves and mixed food with saliva when chewed and aids speech process when formatting sounds. The tongue surface covered with tiny projections called papillae which gives it characteristic bumpy appearance. Taste buds housed on the sides of these papillae. Three types of papillae present, spiky shaped Fiilliform papillae covers the main surface of the tongue and provide a rough surface texture to grip food while chewing and swallowing food. Mushroom (round) shaped Fungiform papillae is found near the edges and tip of the tongue while 'V' shaped Circumvallate papillae found at the back of the tongue.

The tongue also contains receptors for touch and pressure that allows determination of heat, cold and the texture of the food. Pain receptors detect chemicals in spicy foods such as chilies and peppers.

2.1.2 Taste Buds

Tiny taste buds housed on the sides of Fungiform and Circumvallate papillae number to some 10000 receptors. Each of the receptor contains 40 to 60 sensors and tiny taste hair called microvilli projects from each sensory cell into the opening of the taste bud on the sides of papillae.

Chemical constituents is dissolved in saliva during chewing process, flows into the taste buds opening and making contact with the receptors on the taste hairs. These then will generate nerve impulses that travel to the gustatory area in the cerebral cortex where tastes perceived. Taste buds can detect just five taste qualities, which are sweet, sour, salty, bitter and umami. The brain can distinguish a wider range of flavors when combined with sensory data from the nose.

2.2 Taste qualities and attributes

All the foods i.e. taste group into a few categories of basic taste. Recently, savoriness (umami) accepted as the fifth taste qualities in human gustation. The taste qualities in human gustation categorized as sweet, bitter, salty, sour and savory.

2.2.1 Sweetness

Sweet taste regarded as pleasurable sensation, produced by the presence of sugar or some proteins. Common sweet substances are saccharin, aspatame, fructose, glucose, sucrose and lactose. The average human detection threshold for sucrose is at 10 mM and for lactose at 30 mM.

2.2.2 Bitterness

Most sensitive and unpleasant of all the tastes, bitterness perceived by many as sharp or disagreeable. Common bitter substance includes Magnesium Chloride and Magnesium Sulphate. Common bitter foods and beverages include coffee, unsweetened cocoa, bitter melon (bittergourd), olives, citrus peel and quinine. The average human detection threshold for quinine is 80 micromoles per liter.

2.2.3 Saltiness

Taste produced by presence of sodium ions. Other ions of the alkali metals group also taste salty, however the further from sodium the less salty the sensation is. Common salty substances are Sodium Chloride, Calcium Chloride and Potassium Chloride.

2.2.4 Sourness

Taste detects acidity. Common sour substances are hydrochloric acid, citric acid and carbonic acid. Natural acids found largely in fruits including oranges, limes, pineapples and mangoes.

2.2.5 Savoriness

Taste sensation produced by glutamic acids such as glutamate. Common substance of savoriness is Monosodium Glutamate (MSG) and L-glutamine. Savory food sources include tomatoes, cheese, mushrooms, seaweeds, fishes and all type of meat.

2.2.6 Other taste sensations

Other sensations also sensed by tongue somatosensories, which informs the brain, the feeling of the food. Somatosensories sense temperature, light-touch, pressure and pain. These translated into sensations that we perceived as fattiness, dryness, spiciness, coolness, numbness, heartiness and warmness (temperature).

2.3 Taste perception

Human food intake influenced by body nutritional balance and appetite for good tasting substances. Sweet and umami tasting foods are preferred, bitter and sour tasting foods avoided. Intake preference for salty foods is more dependent on body electrolyte balance. The human gustatory system codes taste qualities and their hedonic attributes as part of species survival that gives them ability to distinguish foods to poisons and nutrition to toxicity.

Human taste food when chemical stimuli enter the mouth cavity meeting taste sensory on the tongue. Nerve impulse generated by taste receptors travels to gustatory area in the cerebral cortex where the brain will perceive it as taste attribute. Brain perceived numerous taste attributes despite only five taste receptors on the tongue. Therefore, the process of mimicking gustation system includes choosing an array of taste sensory and suitable signal processing algorithm for pattern recognition purpose.

2.4 Taste assessment

Taste analysis and confirmation of food largely done using human taste panel (organoleptic) or expensive laboratory chemical analytical instruments. Chemical analysis concerns determination either identity of chemical substances or amount of particular substance in a sample.

2.4.1 Organoleptic panel

A variety of taste assessment methods exist, human panel and analytical instrument both complements each other in assessing taste. Human panelist (organoleptic) utilize human to prejudge food samples. The evaluation process employs trained food taster, small-targeted group of people or larger group of random population. The 9-point hedonic scale is one of the many scaling methods use to assess the degree-of-liking in food. Panelists choose which scale represents their preference best. The 9-point hedonic scales are 'Like extremely', 'Like very much', 'Like moderately', 'Like slightly', 'Neither like nor dislike', 'Dislike slightly', 'Dislike moderately', 'Dislike very much' and 'Dislike extremely'.

2.5 Tasting Instrument

Modern machines and automation allow faster testing and more consistent test result. Sensing technological advancement has led to numerous methods developed to complement human panelist. Trace element detection machine often used to 'taste' food. New sensing materials with indicative color codes deposited onto strips further simplify the 'tasting' process and are very easy to use. Although with lower accuracy, this small, lightweight and requiring minimal or no accompanying unit allows portability and provide good screening for *in-situ* assessment. A few of the common chemical analysis instruments discussed below.

2.5.1 Gas Liquid Chromatography (GC)

GC is a chemical analysis instrument for separating and analyzing chemical compounds (in a complex sample) that vaporized without decomposition. It also separates pure compounds from mixture. This instrument flows test sample through a small column of very fine particles (stationary phase) to separate its compounds. Progression of the compound depends largely on static phase adsorption to that compound itself and heat applied up the column increases sample movement rate. Selection of oven (column) temperature is a compromise between the length of analysis and the level of separation.

2.5.2 High Performance Liquid Chromatography (HPLC)

HPLC is a chemical analytical instrument for liquid phase. This instrument has a broader use because approximately 85% of known compounds are not sufficiently volatile or stable for analysis by gas chromatography. HPLC separates chemical compounds by injecting the test liquid into its pressurized column. HPLC separation depends on the solvent type, column size, stationary phase size and applied pressure.

2.5.3 Atomic Absorption Spectroscopy (AAS)

AAS is a technique for determining the concentration of a particular metal element in a sample. This technique which is capable of detecting over 70 different metals in a solution, is often use for trace metal analyses (health), heavy metal contamination (environmental) and metal impurities detection (pharmaceutical) can be used to analyze the concentration of over 70 different metals in a solution.

2.5.4 Thin Layer Chromatography (TLC)

TLC is a planar form of chromatography useful for wide scale qualitative analysis screening and used for quantitative analysis. Pipette drops test sample on plate at points indicated the future measurement point. The plate then placed into a chamber with one end dipped into solvent just below the sample spot line. The time required for proper separation to take place 10 to 60 minutes.

Qualitative analysis derived by measuring the distance travelled by chromatographic spot while quantitative analysis is based upon the measurement of optical density of chromatographic spot. High Performance Thin Layer Chromatography (HPTLC) is an enhanced version of TLC, which expedite the chromatographic separation by 10 times. HPTLC utilizes smaller stationary phase grain (5 um compared to 20 um in TLC) and uses pressurized chamber.

2.6 Taste Sensing System (TSS)

TSS is liquid analyzing instrument aimed at mimicking human tongue in term of food tasting and beyond(Toko 2000; Vlasov, Legin et al. 2000). TSS recognizes specific and complex taste qualities. Sensor array made up of a number of non-specific yet complementing sensors assembled to make taste receptor as in the human tongue. Array sensor responses to chemical stimuli specified by its individual sensor and other non-specific chemicals due to the wide selectivity characteristic of each of the sensors(Legin, Vlasov et al. 1996).

Works in developing electronics taste buds have moved from using purely ion-selective sensors to employing them in an array(Vlasov, Legin et al. 1997). Other factors contributing to this change are that (1) taste qualities made up of many different ions and (2) the difficulty in developing a purely selective sensor. Most sensors subjected to interference by other ions(Legin, Rudnitskaya et al. 2003).

Array sensing utilizes a number of different sensors acting as new sensor. Array sensor coupled with pattern recognition tools capable of detecting ions other than those specified for each individual sensor and those specified with better sensitivity.

By grouping a number of sensors in an array, taste quality detection be ascertained using a smaller number of sensors. In an array, the response of all the sensors treated as one, with the wide selectivity engineered into the sensors during its fabrication these sensors are set to response in many types of taste solution.

Electrically, a sensor and a reference electrode combination pair is modeled as a voltage source with internal impedance. Sensor impedance varies with the medium separating the two electrodes and may take a big value in non-conducting taste liquids.

For the purpose of this research, a group of seven Chalcogenide Glass sensors and a Silver/Silver Chloride reference electrode used as an array of non-specific ionic sensor. As an array, the response of each of the seven sensors relative to the reference electrode considered as a group response. The group response will be inputs to training, validation and verification in later stage.

2.6.1 The Taste Electrode

TSS developed to mimics biological gustation system in human. In human gustatory system, taste-producing substance stimulates gustatory cells on the tongue. Electrical signal from taste buds stimulation transmits taste information along nerve line to the brain, where taste perceived.

History of TSS starts in 1990 with introduction of 'taste sensor' by Japanese research group of Kyushu University(Hayashi, Yamanaka et al. 1990). This research collaboration led to commercialization of world's first taste sensing instrument, SA-401 by Anritsu Corporation and establishment of Intelligent Sensor Technology (Insent), Incorporated, which currently supplying newer version 'taste sensor', TS-5000z. Lipid membranes formulated by these researchers forms ISE for 'taste sensor' taste bud.

In 1996, researchers from St Petersburg University presented solid-state ISE array as taste buds to their taste sensing system(Legin, Vlasov et al. 1996). Ever since, number of methods reported in TSS studies rises. In 2004, handheld embedded electronic tongue introduced by Malaysian research group(Rahman, Yap et al. 2004). This group improvised Toko's lipid membrane formulation producing disposable strips with miniature solid membrane.

Most of literature related to TSS studies reports utilization of chemical sensors as system's tongue. Among those reports are potentiometric, voltammetric(Winquist, Wide et al. 1997; Winquist, Lundström et al. 1999; Gutés, Cespedes et al. 2006; Olsson, Ivarsson et al. 2008), amperometric, impedimetric(Riul, Malmegrim et al. 2003; Fort, Rocchi et al. 2005) and conductimetric. Other sensing properties include optical(Martinez-Olmos, Capel-Cuevas et al. 2011), mass(Sun, Mo et al. 2008) and biological sensors(Shimizu, Kanai et al. 1994; Shimizu and Stephenson 2010).

2.6.2 Signal processing and pattern recognition

Actual sensor response includes noise signals. Meaningful data extraction and classification of taste were performed using signal processing tools. Noise filtering software implementing a running average filter gives good signal response in time domain analysis. Data extraction and classification of observation were performed using Principal Component Analysis (PCA), Common Factor Analysis (CFA), Cluster Analysis (CA), Linear Discriminant Analysis (LDA), Self Organizing Map Network, Competitive Learning Network, Curve Fitting Network and Back Propagation Feed Forward Network.

PCA is a dimensional reduction technique use for visualization of multi-dimensional data. Original multi-dimensional data is transformed into orthogonal dimension data called Principal Components (PC). Percentage of original data representation is indicated by the percentage of variance of the new PC over total variance, with PC1 having the highest percentage then PC2 and so on. The transform will gives PCs with similar to the original data with PC1 explaining the original data the most.

CFA is data dimension reduction technique that investigates the interdependence between variables. CFA attempts to simplify complex and diverse relationship that exist among a set of observed variables by uncovering common dimension. CFA can be used as an exploratory tool to uncover behavior patterns of complex variables by means of transforming original multi dimensional data into new axes with indications of direction for each of the variables analyzed. Rotation may change Factors representation without changing the original representation.

CA is an exploratory statistical tool to test the validity of group separation. Data under analysis will be subjected to the test of grouping them into a number of possible groups and a Silhouette plot is use to visualize the validity of grouping.

Other methods reported in TSS studies include partial lease square (PLS), multiple linear regression (MLR), canonical discriminant analysis (CDA), analysis of variance (ANOVA), soft independent modeling of class analogy (SIMCA) and ANOVA -simultaneous component analysis (ASCA).

LDA is a statistical classification tool based on Fisher's discriminant theory. This method maximizes the difference between groups while minimizing the difference within groups. A few classifier variants were used to analyzed TSS data as comparison includes linear, quadratic and Mahalanobis classifier.

2.6.3 Commercial Taste Sensing System

World first commercial TSS, SA-401 developed in 1993 by Anritsu Corporation after four years of collaborative works between researchers then Mr. Hidekazu Ikezaki (Anritsu Corp.), Dr. Kiyoshi Toko (Kyushu University), Mr. Kenshi Hayashi (Kyushu University) and Dr. Prof. Satoru Iiyama (Kinki University). In January 2002, Dr. Hidekazu Ikezaki established a new company named Intelligent Sensor Technology, Inc which to date, sold more than 100 of the fourth generation of the taste-sensing instrument, TS-5000Z. Higuchi Inc. managed sales and deliveries outside Japan.

Customer for this instrument includes National Food Research Institute (Japan), National Institute of livestock and Grassland Science (Japan), National of Institute of Vegetable and Tea Science (Japan), National Research Institute of Brewing (Japan), National