CHAPTER 2

LOW COST PORTABLE E-NOSE

2.0 Introduction

MOS gas sensors have shown promising results in tea aroma assessment correlating with tea taster's evaluation. SnO_2 based gas sensors manufactured by Figaro have shown their substantiate performance in sensing the major chemical constituents of tea. These reliable associations have been demonstrated to be useful for quick and accurate tea aroma evaluation, mostly using a CAT based system. Pioneering work on CAT-based tea aroma classification has been successfully established and it shows good correlation with tea taster's evaluation as well as with that of analytical instruments [1-3, 6, 7, 9].

As mentioned in chapter 1, the CAT-based systems are mostly laboratory type, costly and power consuming, so are not suitable as a field type testing gadgets. Hence, the situation demands for a hand-held portable embedded E-Nose system for tea aroma prediction. Therefore researchers are motivated to develop embedded E-Nose for tea quality prediction. In [4] a tea quality detection system is discussed using an 8-bit microcontroller (µC) PIC 18F4520 with an array of 5 MOS gas sensors in an artificial neural network (ANN) paradigm, where the highest accuracy obtained is 85.7%. Singular value decomposition (SVD) technique has been applied in [8] using 5 MOS gas sensors interfaced to a 16- bit PIC µC to classify tea aroma. However, requirement of various components in odor delivery and refreshing of the sensors makes them power consuming, bulky and costly. Although, the potential of MOS gas sensors for tea aroma classification has been identified, the systems available in literature are inappropriate to be used as a field type instrument due to their large size which in turn has impeded their widespread acceptance. Thus the advance of µC based E-Nose system enabling simple, cost effective, light weight and low power consumption will be of great significance.

In this chapter, a method for developing a novel low cost hand-held electronic nose (E-Nose) for black tea flavor estimation using metal oxide semiconductor (MOS) gas sensors is introduced. In this work, a computer-assisted technology (CAT) based E-Nose system is designed and developed for sensor selection and validation. The results of the first experiment facilitate sensor selection, where only four sensors were selected from twelve MOS gas sensors based on their sensitivity. In the second level a novel hand-held E-Nose is designed and developed for generation of tea aroma, capturing the response patterns and signal processing in a µC (PIC 18F45K22) for tea flavor grading.

In order to verify cluster formation of the multivariate sensor data, PCA and SOFM are chosen due to their widespread use and ease of implementation. Further, they work effectively in low dimensional problems [8]. The Proposed hand-held tea aroma assessment system (HTAAS) can compute tea aroma grading online.

2.1 Properties of Tea Samples

There are varied types of tea manufactured worldwide, but are primarily divided into three categories- CTC (crush, tear and curl), orthodox and green tea. The study is focused on CTC tea as it is widely manufactured in the local tea industries of Assam, India. The various volatile compounds present in Assam tea responsible for its aroma are shown in Table 2.1 [3]. A major chemical constituents contributing to tea flavor are- 2-phenylethanol, Benzaldehyde, B-ionine, Geraniol, Linalool, Linalool Oxide, Terpeniol as discussed in [2] which are shown in boldface in Table 2.1.

Table 2.1 Ratio of major volatile compounds to total volatile compound of Assam black tea

Compound	Var. Assamica
t-2-Hexenal	2.60
cis-3-Hexenal	4.30
t-2-Hexenyl formate	11.80
Linalool oxide (furanoid-cis)	3.20
Linalool oxide (furanoid-trans)	8.80
Linalool	15.50
Phenylacetaldehyde	0.50
Linalool oxide	0.40
Pyranoid-cis	18.80
Methylsalcylate	2.20
Geraniol	1.90
Benzylalcohol 2-phenylethanol	0.90
cis-Jasmone +β-ionone	0.10
t-2-Hexenal	11.80
cis-3-Hexenal	3.20

Dry and fresh tea samples from tea gardens were collected to avoid any discrepancy caused by humidity and adulteration affecting the actual sensor response. Tea samples were put inside coloured plastic containers and stored in a dark place to prevent from sunlight. The air gap inside the sample container is sealed using cotton and then the cap is tightly fixed to provide an airtight seal. A total of 150 CTC tea samples (i.e. 30 samples each of 5 different grades- 0.1, 0.2, 0.8, 2.3 and 2.5) collected from different local tea garden are used to perform the first level experiment in a CAT-based offline classifier. After selecting the sensors, 30 samples each of 8 different grades (0.2, 0.8, 2.5, 5.5, 6.0, 7.5, 8.0 and 9.0) of tea samples originating from three different sources are collected and used to train the handheld E-nose for online testing.

The subjective grading and evaluation of the collected samples are performed by three reputed tea tasters on a scale of 0 to 10. The numeric values evaluated by the tea tasters are the aroma assessment of the tea samples. Tea taster scores thus obtained are assigned to the corresponding sets of tea samples and their responses to the sensor array are measured. Table 2.2 shows of flavor score of tea samples authenticated by different tea tasters.

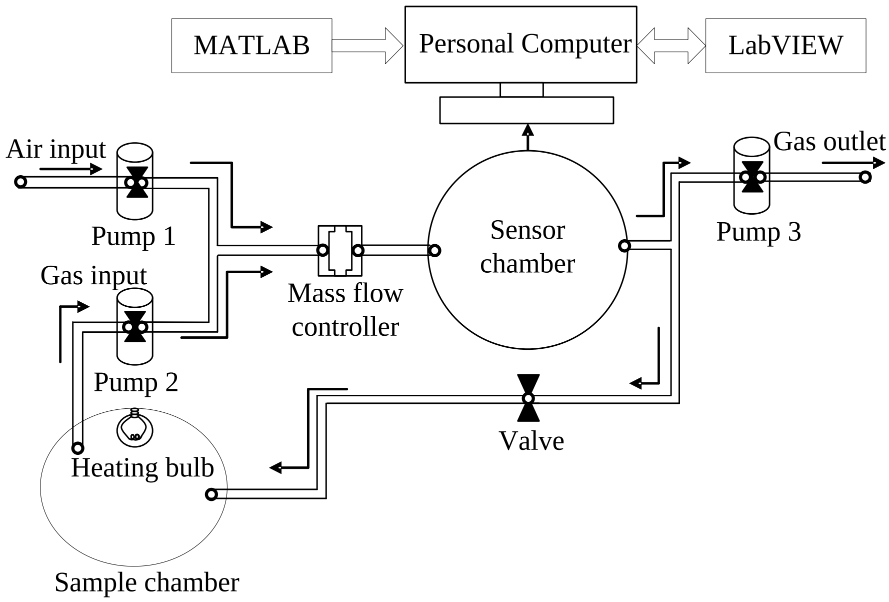
Table 2.2 Tea tasters grading (Assamica)

Sample No	Origin of Sample	Tea Taster	Score
1	Local Tea Gardens	Trend Teas Pvt. Ltd., Guwahati, Assam, India	2.3
2			2.5
4			0.8
5			0.1
6			0.2
9	Tezpur Gogra Tea Estate	Gogra Tea Estate, Tezpur, Assam, India	7.5
10			8
11			9
12			5.5
13			6
14	Tea Research Association (TRA), Jorhat, Assam, India	Tea Research Association (TRA), Jorhat, Assam, India	2.5
15			5.5
16			9
17			7.5
18			0.8

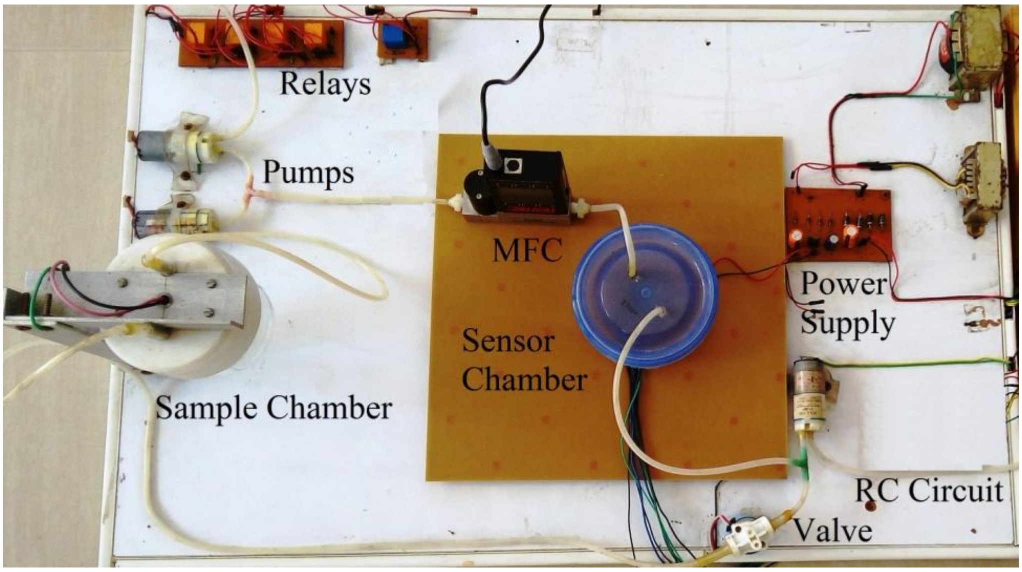
2.2 Experimental setup

It has already been mentioned that prior to the development of a handheld E-Nose, a CAT-based experimental setup was developed for the first level of experimentation.

The E-Nose system primarily consist of a sealed sensor chamber, sample holder cum heating chamber, mass flow controller (MFC), valves, pumps, teflon tubes, power supply, relays and a CAT-based data acquisition system which are assembled as a complete system as shown in Fig. 2.1.



(a)



(b)

Fig. 2.1. CAT based tea classifier (a) block diagram and (b) top photographic view

2.2.1 Sensor Chamber

The sensing chamber of 19 cm diameter is designed using a round plastic can which is glued on a printed circuit board comprising the gas sensor array as shown in Fig. 2.2. For circulation of air/VOCs PTFE Teflon tube of 4 mm OD, 2 mm are inserted into the chamber through two holes which are tightly sealed. Prior to experimentation the plastic can and the pipes are fixed permanently using adhesive to prevent gas leakage and the can cover is fitted tightly.

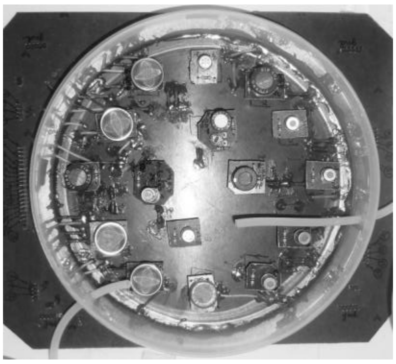


Fig. 2.2 Sensor Chamber

2.2.2 Sensor array

The MOS sensor array comprises of 12 commercial tin oxide based MOS gas sensors (shown in Table 2.3) procured from Figaro Engineering, Inc. (Osaka, Japan).

Table 2.3 Gas sensors with their properties [12]

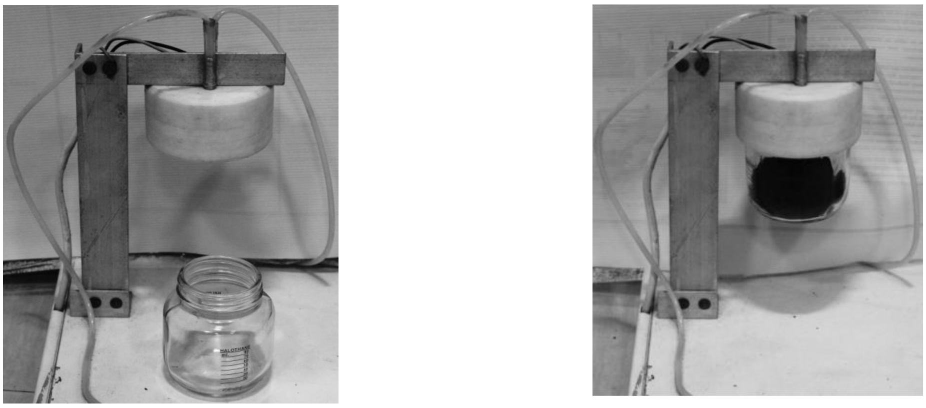
Sensor	R_S	R_S/R_0	R_H	P_H	Flame arrestor	Standard Condition	Target Gas	Detection Range (ppm)
TGS 813	5 ~ 15 kΩ	0.60±0.05	30±3 Ω	835 mW			Combustible gases, methane, propane butane	500-10000
TGS 821	1 ~ 10 kΩ	0.60~ 1.20	38±3 Ω	660 mW	100 mesh SUS 316 double gauze		Hydrogen	10-10000
TGS 822	1 ~ 10 kΩ	0.40±0.10	38±3 Ω	660 mW			Organic solvent vapors, alcohol	50-5000
TGS 825	3 ~ 30 kΩ	0.45±0.15	38±3 Ω	660 mW			Hydrogen sulfide	10-100
TGS 826	20 ~ 100 kΩ	0.55±0.15	30±3 Ω	833 mW			Ammonia	30-300
TGS 832	4 ~ 40 kΩ	0.50±0.65	30±3 Ω	835 mW		20°±2 °C 65±5%	Chlorofluorocarbons	10-3000
TGS 2600	10 ~ 90 kΩ	0.3 ~ 0.6	83 Ω	210 mW			Air contaminants	1-100
TGS 2602	10 ~ 100 kΩ	0.15±0.5	59 Ω	280 mW			Air contaminants	0.1-100
TGS 2610	0.68 ~ 6.8 kΩ	0.56±0.06	59 Ω	280 mW	NA		LP Gas	500-10000
TGS 2611	0.68 ~ 6.8 kΩ	0.60±0.06	59 Ω	280 mW			Methane	500-1000
TGS 2620	1 ~ 5 kΩ	0.3 ~ 0.5	83 Ω	210 mW			Solvent vapors	50-5000
TGS 2201	10 ~ 80 kΩ	0.65±0.15	35 Ω	502 mW			Gasoline and diesel exhaust	10-10000

Note: R_S-sensor resistance, R_S/R_0-Sensitivity, R_H-heater resistance, P_H-heater power consumption.

These sensors have substantial output response because of their large exposing surface area. Although, as per manufacturer recommendation the gas sensors are highly sensitive only to a particular target gas, the sensors are significantly sensitive towards a wide spectrum of gases [12]. Moreover, they have excellent features like low power consumption, low cost, long lasting, quick response time, and compact in size, which serves our requirement for choosing a reliable sensor array for a hand-held system.

2.2.3 Sample chamber

A threaded Borosil™ glass bottle of 280 ml with a diameter of 8 cm and height 6 cm is used to place the tea samples (Fig. 2.3). The threaded cap of the sample chamber is made of a Teflon block of height 5 cm and diameter 6 cm. The sample chamber cap is mounted at a height of 9 cm using a holder made of stainless steel.



(a) (b)

Fig. 2.3. Designed sample chamber (a) bottle uncapped and (b) bottle with tea samples capped

2.2.4 Heating bulb

In order to generate the VOCs of the tea samples it is essential to heat the tea samples to about 50 °C. We have used a 230 V, 50-watt tungsten halogen bulb which provides illumination heating to the tea samples so that VOCs are emitted. The cap is grooved to make a circular hole (depth 1.3 cm and diameter 1.6 cm), to which the holder of the heating bulb is tightly locked inside it. The bulb holder inside the sample chamber and the halogen bulb is shown in Fig. 2.4.

(a) (b)

Fig. 2.4. Halogen lamp assembly (a) halogen bulb holder and (b) halogen bulb (230 V, 50 W)

2.2.5 Pumps and valve

To transport VOCs and air through Teflon pipes for sensing and purging operation, dc motor driven diaphragm air pumps (Oken Seiko 12 V, flow rate 1.6 l/min) are used. In addition a 12 V solenoid valve is used to allow or stop gas/air flow. The switching of the pumps and the valve is performed using a sugar cube relay unit (12 V SPDT). The pumps and the valve used in the E-Nose setup are shown in Fig. 2.5.

(a) (b)

Fig. 2.5. (a) Diaphragm air pumps and (b) solenoid valve used in the E-Nose setup

2.2.6 Mass flow controller (MFC)

Although the pumps are rated with a flow rate of 1.6 l/min, the flow rate is not always uniform due to which the sensor response deviates from the ideal one. Therefore in order to maintain a constant flow rate a MFC (Alicat MC-05 SLPM-D) is connected at the output of the Pump. So, the VOCs generated in the headspace of the sample chamber were controlled at a constant flow of 1.6 l/min using the MFC (Fig. 2.6).

Fig. 2.6. Mass flow controller

2.2.7 Relay Unit

Relay unit (Fig. 2.8) is used as a switching device for the pumps, valve and the heating lamp in order to alternately perform purging and sensing operation. The digital control signals to the relay unit are provided by a PC through a data acquisition card.

Fig. 2.8. Relay assembly

2.2.8 Power supply

Two DC power supply sources are used in the CAT based E-Nose- 5 V constant DC source from Scientech ST4072 and two regulated 12 V power supply fabricated (Fig. 2.7). The tungsten filament bulb and the MFC are powered by AC mains. The use of various power sources in the developed E-Nose system are shown in Table 2.4.

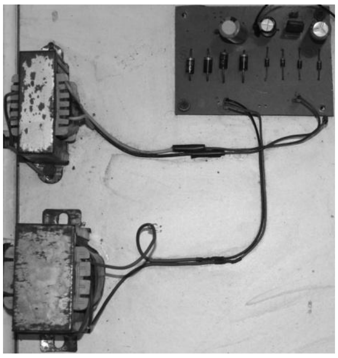


Fig. 2.7. Power supply used in the E-Nose

Table 2.4 Power Sources and their uses

Power source	Required voltage	Powered device	Purpose
Scientech ST4072, 5 V, 1 A	5 V DC	Sensing element	Sensor bias
		Heater element of the Sensor	Provides sufficient temperature for normal operation of the sensor
AC Mains	230 V AC	Tungsten halogen bulb	Heat up the tea samples and generate headspace
		Mass flow controller	Maintain a constant flow rate of the pumps
Regulated Power supply 1	12 V DC	Pumps and valves	Circulate air/VOCs.
Regulated Power supply 2	12 V DC	Relay unit	Controls the sensing and purging operation of the E-Nose

2.3 Development of the Circuits

The E-Nose developed consists of several circuits which are fabricated on one sided copper clad printed circuit board (PCB) sheet (1.6 mm, 305 g/m Cu). Dip trace (version

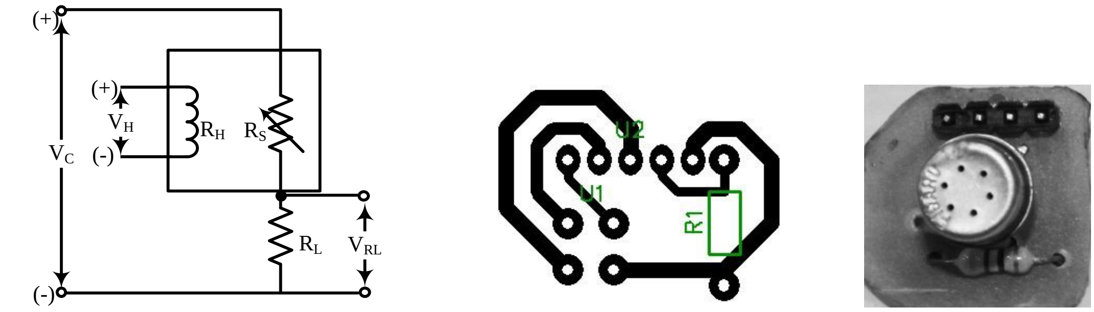
2.4) is used to design the circuit schematic and layout. Print and press method of PCB design is used which consists of the following steps:

1. The designed circuit layout is printed on a photo paper using a laser printer.
2. The copper PCB board is cut according to the dimension of the printed circuit layout.
3. The cut PCB is then cleaned using sand paper to remove any oxide layer.
4. The circuit layout photo paper is placed in the PCB and electric cloth hot ironing is done for about 10-15 minutes. Due to hot ironing the circuit layout gets imprinted on the PCB (circuit layout is under the black ink).
5. Etching solution is prepared by adding 120-150 g of ferric chloride ($FeCl_3$) powder in 300 ml of water in a plastic container.
6. The PCB is then immersed in the etching solution and rinsed for about 15-20 minutes. The copper layer of the PCB which does not contain the circuit layout gets directly exposed to the etchant and is slowly removed.
7. The PCB is then taken out to check if all unwanted copper is removed by the etchant. If not step 6 is repeated.
8. The PCB is taken out and the black ink of the circuit layout is removed using acetone.
9. The holes in the PCB as per the schematic design are made using a drill machine to hold the circuit components.
10. Finally the components are placed and soldered in the PCB as per the circuit schematic.

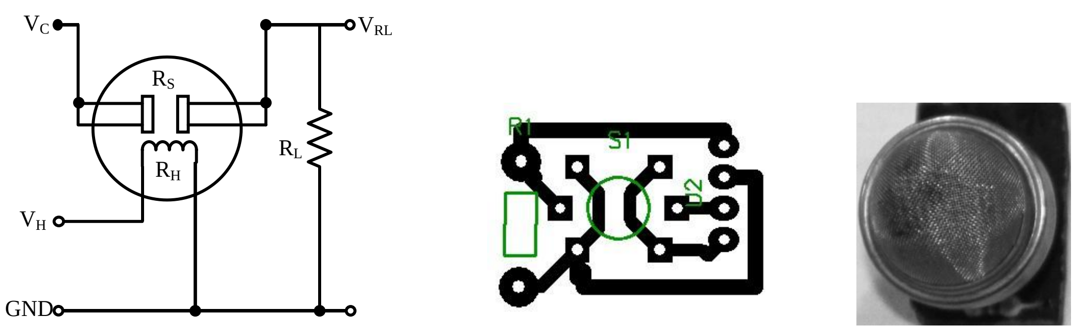
In the fabricated PCB various circuits incorporated are-

2.3.1 Sensor circuit

The MOS sensor circuit for TGS 26xx series, TGS 8xx and TGS 2201 is shown in Fig. 2.9. The value of R_L used is 1 KΩ. The PCB of sensor circuit for all the sensors are fabricated separately so that it can be plugged to the main PCB. A constant regulated 5 V is used for the sensing material.



(a)



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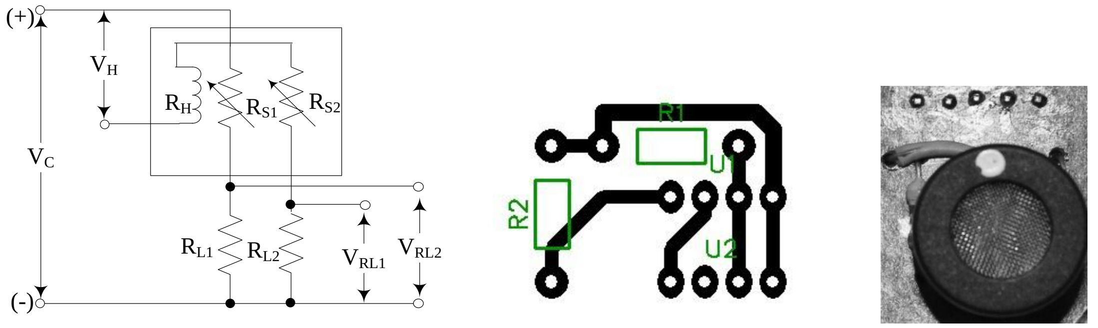


(c)

Fig. 2.9. Sensor circuit diagram (left), PCB layout-copper side (middle) and sensor placed in PBC (right) (a) 2620 (02), (b) 832 and (c) 2201

2.3.2 Sensor array circuit

The sensor array PCB layout (Fig. 2.10) comprises of 16 different female berg strip slots to plug in the sensor PCBs.

The plugged sensors were enclosed by the sensor chamber as mentioned earlier. Further, it provides common connection for V_{CC} of all the sensors, separate connection for V_H of all the sensors and sensor output terminals. The output terminals are interfaced to an array of male berg strip terminals and connected through a female to male berg cable to the DAQ system

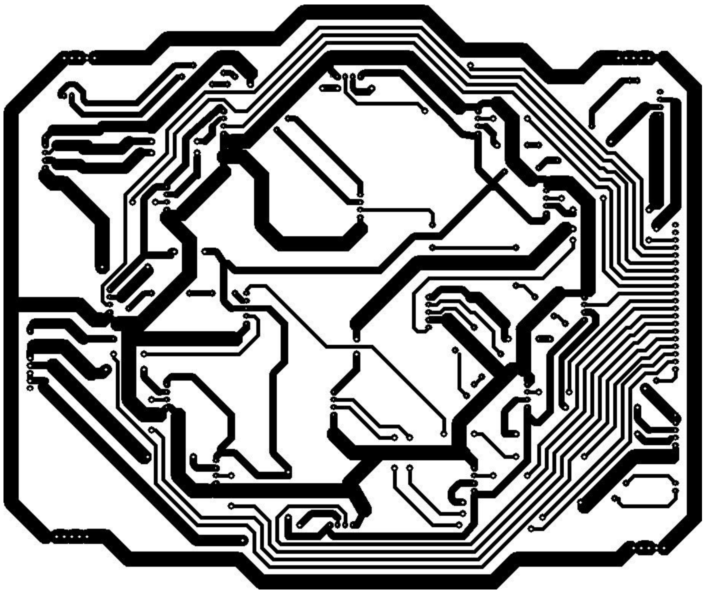
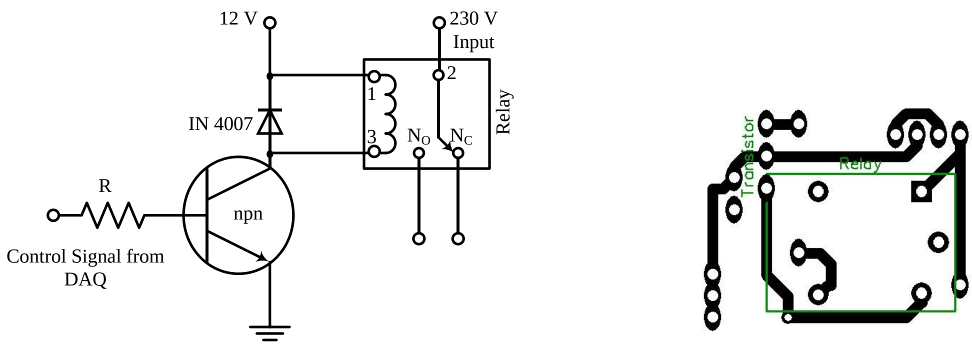


Fig. 2.10. Sensor array PCB (copper side)

2.3.3 Relay unit PCB

The relay circuit comprises of an n-p-n transistor, IN 4007 diode, a 3.7 KΩ resistance, and the relay. The control signal to the relay from LabVIEW DAQ is provided through a transistor as shown in Fig. 2.11. To prevent any damage due to reverse voltage produced by the relay to other parts of the circuit, a flywheel diode is connected in forward biased condition so that the energy stored in the coil gets dissipated through it.



(a) (b)

Fig. 2.11. Relay unit (a) circuit diagram and (b) PCB layout (copper side)

2.3.4 Power supply PCB

The 12 V power supply circuit used in the E-Nose is shown in Fig. 2.12.

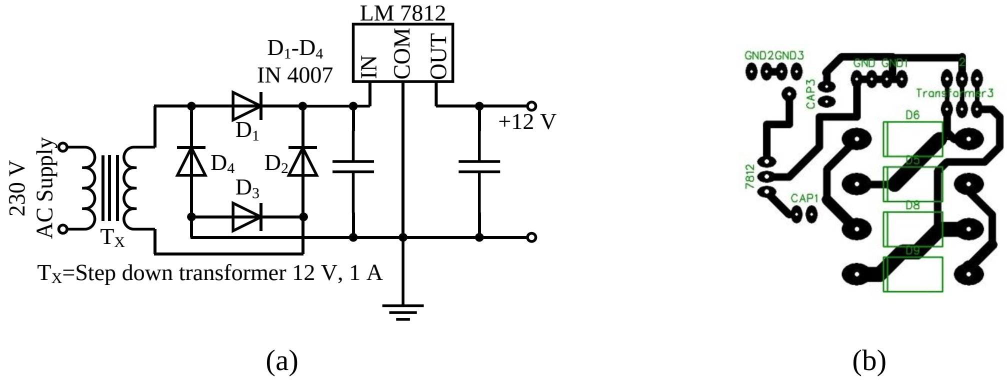


Fig. 2.12. Power supply unit (a) circuit diagram and (b) PCB layout (copper side)

It consists of a 12-0-12, 1 A step down transformer, IN 4007 diode based bridge rectifier, a capacitor (2200 µf) and a voltage regulator IC LM 7812. Two such separate power supply units are fabricated in a single PCB. A capacitor is connected at the output of the rectifier to suppress the ripple and another capacitor at the output of voltage regulator to prevent loading effect. The load regulation of the power supply is tested and found to be 83% and V_{max} of 12 V.

2.4 Data Acquisition Card

The process of recording response patterns from sensors in form of electrical quantity at a predefined rate is known as data acquisition. The data acquisition and instrument control is attained through a PCI NI 6024E DAQ card using Laboratory virtual instrument engineering workbench (LabVIEW 10.0, 32-bit) programming in a personal computer (Intel (R) Core (TM) i-3 processor 3.2 GHz and 2 GB of RAM). It comprises of 16 analog channels, 8 differential input channels and 8 digital I/O pins. Unlike text based coding LabVIEW is a powerful graphic based dataflow programming language that uses icons for system-design. LabVIEW is a versatile tool as almost all the instruments physically available in the laboratory are accurately imitated by its programs/subroutines termed as virtual instruments (VIs) [11].

Moreover it is easy to create user defined VIs. Further external hardware or instruments can be smoothly connected using its predefined VIs for acquiring, analyzing, displaying, and storing data. LabVIEW consists of two panels: a) Front panel which is used to develop the user interface for VI. It comprises of various controls, indicators, plotting tools etc. (b) Block diagram for data transfer operation. It includes the graphical source code and connectivity between various icons through which the front panel objects are controlled.

An Unshielded 68-pin connector block NI CB-68LP is used to connect the PCI DAQ using a shielded cable. The DAQ used consists of 16 analog input channels, 8 digital input/output channels, analog ground pins, digital ground pins and many special purpose pins. The control and acquisition process is described below in details.

2.4.1.Control

The digital I/O pins D_7-D_0 are configured to provide the control signals to the relays. To activate the desired relay, logic high of the digital output pin is given by configuring Boolean *T* (true) which provides the required voltage to drive the circuit using the relay. Similarly, *F* (False) represents the switch off condition of the relay. The timing sequence to on/off the pumps, valve and heating bulb during sensing and purging is set using a down-timer in LabVIEW. Flat sequences are used for alternately repeating the sensing and purging operation automatically. To avoid any discrepancies between each switching all the relays are switched off for about 1 ms.

2.4.2.Acquisition

The analog voltages from the sensors of the E-Nose are collected using RSE configuration (Fig. 2.13) as the system is connected to a common ground point. In RSE mode the analog voltage can be measured using any of the 16 analog input channels while the circuit ground is connected to any common analog ground pin.

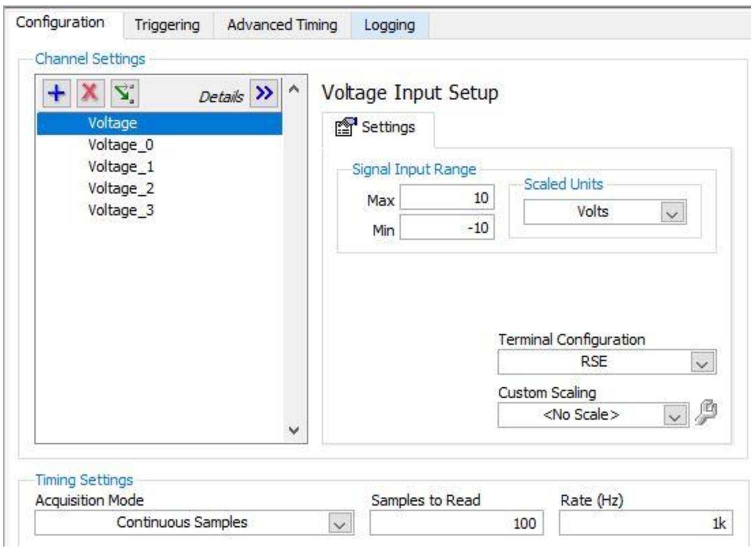


Fig. 2.13. Configuring analog channels in LabVIEW DAQ

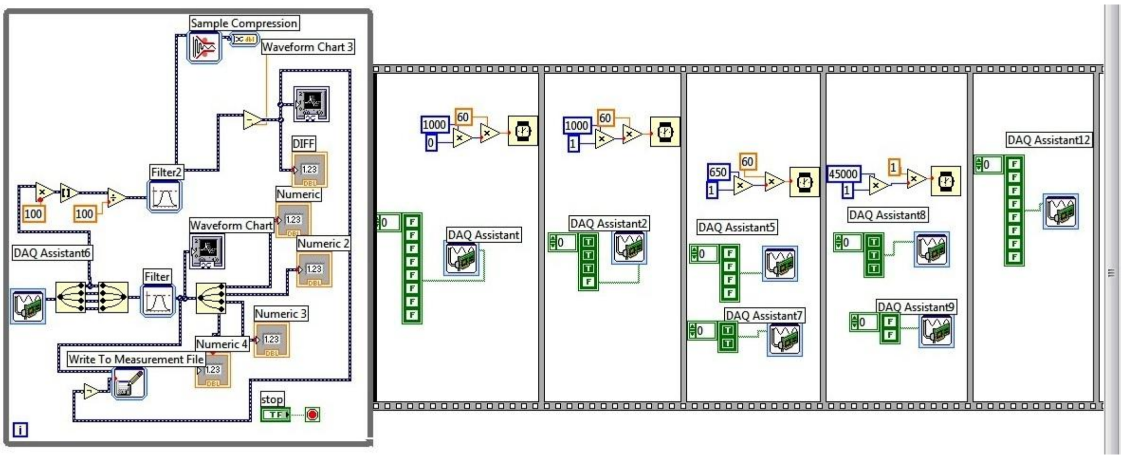


Fig. 2.14. LabVIEW control and acquisition setup

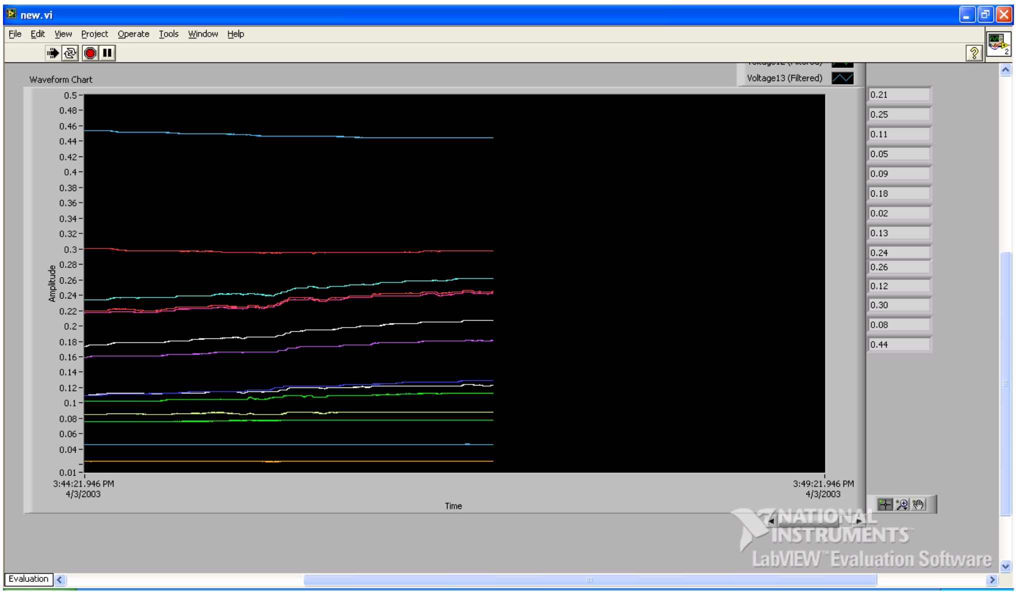


Fig. 2.15. An example of responses displayed in LabVIEW front panel (15 MOS gas sensors)

This configuration provides a maximum of 16 channels. Data is stored in .lvm format in the PC. For visual interpretation, the sensor responses were displayed in a waveform chart in the front panel. The control and acquisition setup using LabVIEW is depicted in Fig. 2.14. The front panel in Fig. 2.15 shows an example of acquired responses from the sensors.

2.5 Sensor Selection

Typically in case of liquid samples VOCs are generated by injecting a small amount of liquid in the sample chamber and allowed to volatilize for certain duration. The gas molecules when reacts with the sensors, change in conductance occurs which is converted to voltage signal. However, in case of tea samples for proper emission of tea VOCs it is necessary to heat up the tea samples. Therefore in the sample chamber a 230

V, 50-watt tungsten halogen bulb is used, which produces the necessary temperature to heat up the tea samples.

We have first tested the sensor array to examine the change in conductance i.e. voltage level on application of different class of tea aroma. The sensors having a low sensitivity as well as same sensitivity towards different grades of tea were rejected and out of 12 sensors only 4 (TGS 2201, TGS 2602, TGS 2620 and TGS 832) were found suitable as the sensitivity of these sensors are comparatively found higher through repeated experimentation.

Experimental conditions for CAT-based aroma classification of black tea are evaluated with the following parameters:

- Amount of sample = 50 g;
- Sensing time = 40 s;
- Purging time = 80 s;
- Air flow rate = 1.6 l/min;
- Temperature of sample chamber air = 55 °C ± 5 °C.

A constant regulated heater voltage of 5 V DC (SCIENTECH ST4072, 5 V, 1 A) is applied to the sensors as specified for avoiding any instability while operating. The 'initial action' takes about 30 minute to warm up the sensors and stabilize the baseline voltage levels. The room temperature and humidity during the experiments were maintained at 25 °C and 60±5% respectively.

Fresh air is taken from the environment through PTFE Teflon pipe to refresh the sensor chamber and allow the output voltage level of the sensors to reach its baseline value. Tea sample of 50 g was placed in the sample chamber with the heating lamp switched on for 1 minute to heat the tea samples inside the chamber up to 55 °C for headspace generation. The VOCs generated in the headspace of the sample chamber were transported to the sensor chamber at a constant flow of 1.6 l/min controlled by the mass flow controller.

As discussed above, we have acquired the responses of 12 MOS gas sensors (resolution 16-bit at 100 samples) in an interval of 120 s to a standard quality of CTC tea using a DAQ card in LabVIEW. The experiment was conducted for a large number of repeated cycles as shown in Fig. 2.16 for three cycles. It is found that TGS 832, TGS

2201, TGS 2602 and TGS 2620 show the highest sensitivity to tea flavor, which we have chosen for the hand-held system.

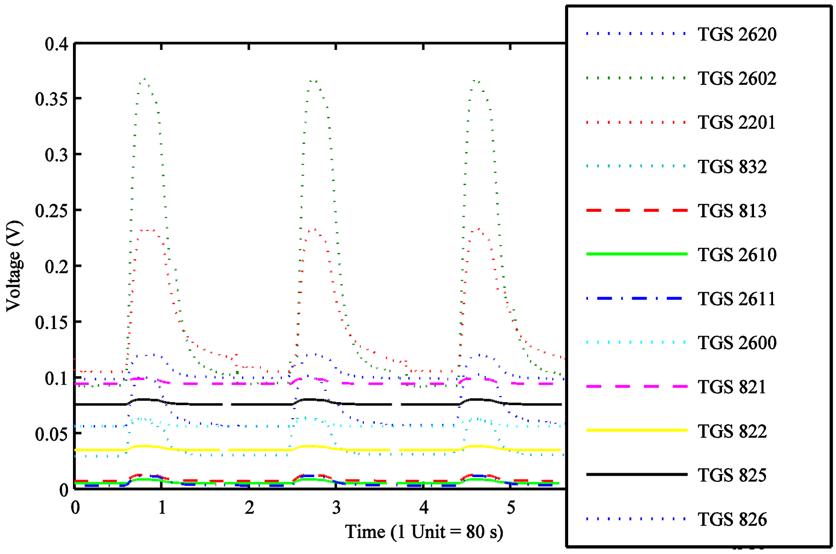


Fig. 2.16. Sensors response on exposure to tea samples

Table 2.5 Parameters of the CAT based sensing system to tea aroma

Parameter	Sample No.	TGS 2201	TGS 2602	TGS 2620	TGS 832
Peak Value (V)	1	0.24	0.39	0.128	0.066
	2	0.23	0.31	0.12	0.06
	3	0.25	0.37	0.10	0.062
	4	0.19	0.26	0.09	0.061
	5	0.23	0.41	0.13	0.081
Sensing Time (s)	1	30	35	20	17
	2	29	34	18	21
	3	31	35	19	22
	4	30	33	22	22
	5	31	35	21	16
Purging Time (s)	1	64	56	48	32
	2	62	56	44	34
	3	60	54	48	32
	4	58	56	46	32
	5	62	54	48	34
Baseline Voltage (V)	1	0.09	0.071	0.063	0.029
	2	0.102	0.078	0.072	0.030
	3	0.101	0.090	0.059	0.031
	4	0.128	0.071	0.060	0.032
	5	0.93	0.070	0.050	0.028

Sensing and purging time required for each selected sensor for five samples were determined in LabVIEW as shown in Table 2.5. It is observed that for different sensors peak responses, purging and sensing time varies for different samples. Based on this analysis, the sensing and purging time was fixed at the highest values. In order to create the database series of experiments were conducted acquiring response pattern of sensors to different grades of tea samples.

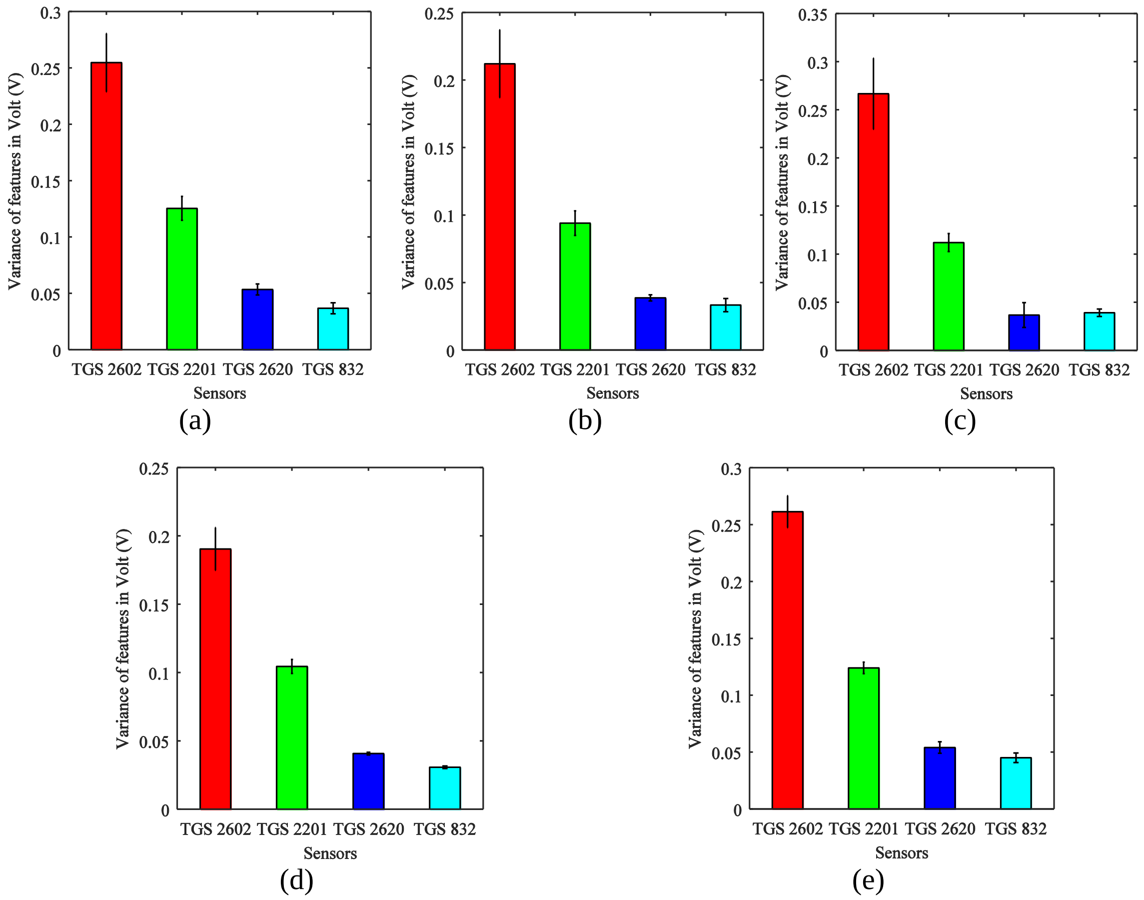


Fig. 2.17. Error bar showing the variance in feature set determined from the response pattern of gas sensors for different grades of tea (a) 0.1, (b) 0.2, (c) 0.8, (d) 2.3 and (e) 2.5

Fig. 2.17 shows the error bar plot of the features obtained by using the selected sensors to different grades of tea. Feature set is extracted from three sets of response obtained from three different samples of a particular tea grade. Where, each set contains the response patterns recorded for five consecutive sensing and purging cycles. It is observed that feature set obtained from the response patterns generated by the sensor array are unique to each tea grade.

2.6 Feature Extraction

The most common and successful feature used for aroma classification in E-Nose is the differential voltage levels between the baseline and steady state peak voltage, therefore two features for each of the sensors were extracted baseline voltage (V_b) and peak response voltage (V_p).

V_b : The baseline voltage when fresh air is applied to the gas sensors.

V_p : The peak voltage of the sensors when exposed to tea samples.

40 data (2 features $\times$ 4 sensors $\times$ 5 cycles) were extracted for each grade of tea from the responses of the selected sensors. The feature matrix ($V_{i,j} = V_{p\,i,j} - V_{b\ \ i,j}$) is used to analyze the sensor correlation in PCA, which is an orthogonal transformation tool to authenticate the clusters formed by different tea samples. We have used FFBP network to train and test the tea samples according to tea taster's score.

2.7 Pattern Clustering and Classification Methods

Two pattern classification methods are used for data analysis- supervised and unsupervised. The objective of using unsupervised PCA and SOFM is to investigate how the different sensor responses cluster in multi-sensor space [1, 2].

FFBP ANN paradigm (Fig. 2.18) is used due to its simplicity and proven performance in various µC based designs.

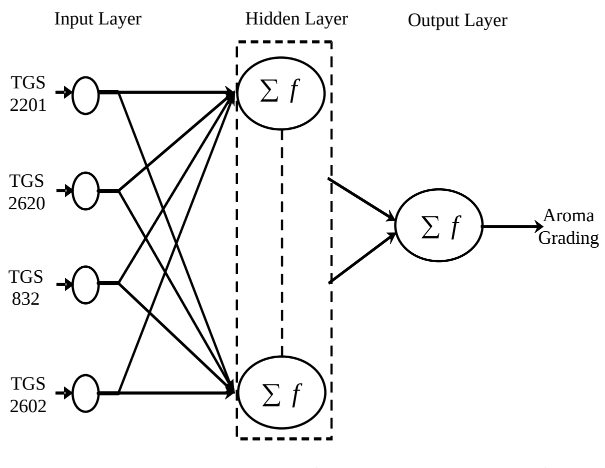


Fig. 2.18. ANN model used for tea aroma classification

The data is divided into two parts- 50% for training and 50% for validation and testing. Neural network analysis is carried out in MATLAB 2013a for designing the classification in offline mode. The ANN parameters such as biases and weights are predetermined by training the network in the first level of experimentation. Levenberg-Marquardt (trainlm) optimization is used for training the network.

2.8 Experimental Results of CAT based Tea Classifier

The feature dataset was applied to PCA to examine the existence of clusters in feature space within the dataset. It is observed that PCA shows five distinct clusters (Fig. 2.19) for the five tea samples with first principal component showing 94.9084% of the variance. Three principal components were used in PCA plot as they accounted for 99.94% variance (Table 2.6). After investigation how the response vectors cluster in multisensory space using PCA, we have applied FFBP ANN to the data in MATLAB with a learning rate of 0.1 and goal 0.01 to classify tea flavor.

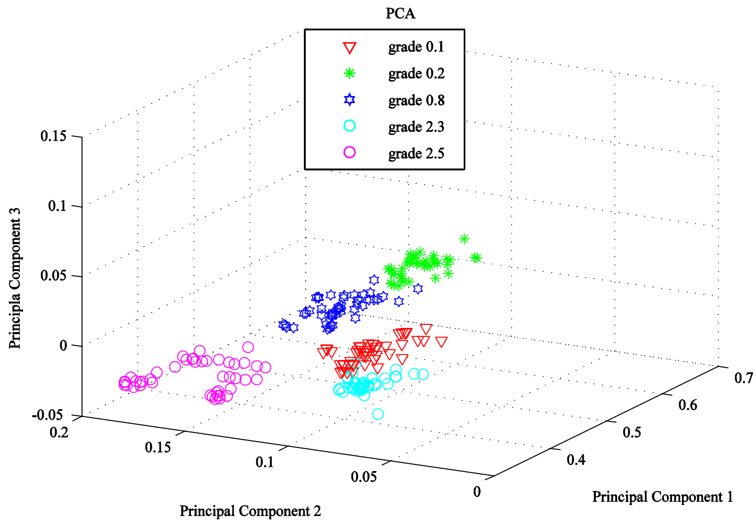


Fig. 2.19. PCA of the feature dataset

Table 2.6 Parameters of PCA

PC	Variance %	Eigenvalue	Principal Components			
			TGS 2201	TGS 2620	TGS 832	TGS 2602
PC1	94.9084	0.0084	-0.0972	-0.0213	0.9571	-0.2721
PC2	4.0832	0.0004	-0.8785	-0.4588	-0.1174	-0.0630
PC3	0.9539	0.0001	-0.4440	0.8842	-0.0627	-0.1312
PC4	0.0544	0.0000	-0.1473	0.0854	0.2574	0.9512

The ANN model was trained and tested with 2, 4, 6 and 8 hidden neurons to compare the network performance parameters and select the optimum network. From the performance parameter (Table 2.7) it is observed that hidden neuron of 4 shows the highest accuracy for tea flavor classification. The confusion matrix is shown in Table 2.8, which shows individual class accuracies and overall accuracy of 92%. The performance function of the well trained network is shown in Fig. 2.20.

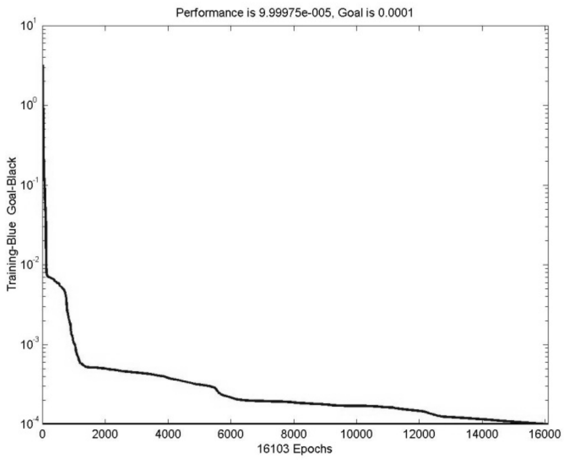


Fig. 2.20. Training performance function with $n = 4$

Table 2.7 Performance parameters of CAT-based ANN

Hidden Neuron	Goal	Learning Rate	Time (s)	Testing Accuracy	Remarks
2	0.01	0.1	20.5	28%	Under Trained
4			21.2	92%	Well Trained
6			22.3	80%	Over Trained
8			21.5	88%	Over Trained

Table 2.8 Confusion matrix of CAT-based classifier

		Tea Taster's Score					
		0.1	0.2	0.8	2.3	2.5	
ANN Based Score	0.1	12	3	0	0	0	80%
	0.2	0	15	0	0	0	100%
	0.8	0	0	15	0	0	100%
	2.3	0	0	0	13	2	86.66%
	2.5	0	0	0	1	14	93.33%
		100%	83.33%	100%	92.85%	87.5%	92.0%

It is observed from the above experimentation that the four MOS gas sensors selected using the developed CAT based E-Nose system has successfully classified different grades of tea samples with an accuracy of 92%. Therefore, in the succeeding section an attempt will be made using the selected sensors for development of a hand-held tea aroma assessment system.

2.9 Handheld and Portable E-Nose System

As mentioned in chapter 1, although CAT-based systems are successfully utilized to classify tea aroma, the requirement of micro pumps, mass flow controller, suction fan, solenoid valves etc. in odor delivery and refreshing of the sensor chamber makes them power consuming and costly. Moreover for emission of volatile organic compounds (VOCs) from the tea samples heating of the sample are essential. The method used to heat the tea samples in the first level of experimentation is adopted from literature, where illumination heating (halogen bulb of 50 watt) has been used to maintain an average temperature of 50 °C, which consumes a good amount of electrical power.

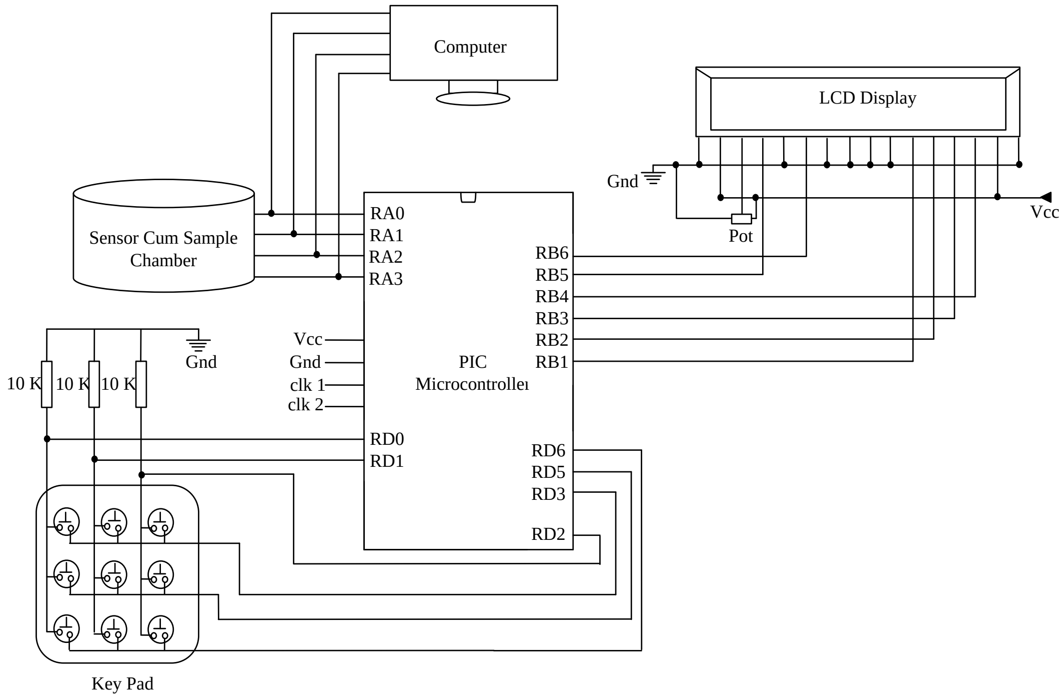


Fig. 2.21. Schematic diagram showing the µC based E-Nose

Therefore the situation demands for a hand-held portable embedded E-Nose system for tea aroma prediction. The hand held E-Nose is developed using the four selected gas sensors interfaced to a PIC 18F45k22 µC which was trained to classify the tea flavor by the programmed FFBP ANN.

Fig. 2.21 shows the schematic diagram of the µC based E-Nose system. Different components of the system are discussed in the next sections.

2.10 Sample cum Sensor Chamber

The sensor holder is fabricated using a Teflon block of length, breadth and height of 10 cm, 5 cm, and 2.5 cm respectively. The Teflon sheet is grooved to make a circular hole having depth of 1.1 cm and diameter 4.2 cm. As shown in Fig. 2.22 the PCB of the sensor array is tightly fixed inside the sample chamber cap. A threaded Borosil™ glass bottle of 4 cm diameter, 5.5 cm height and with a cap of height 1 cm and 4 cm diameter is used to place the tea samples as shown in Fig. 2.23. The cap of the sample vessel is tightly locked inside it. A PCB of thickness 1 mm having the same diameter as that of the sample chamber cap is used to fabricate the circuit for the sensor assembly.

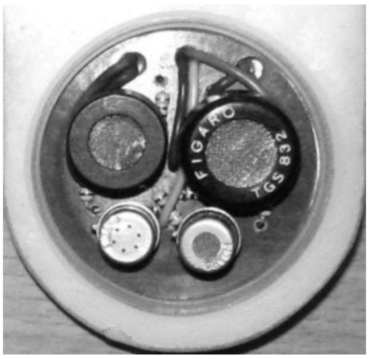


Fig. 2.22. Sensor head (sample chamber cap)

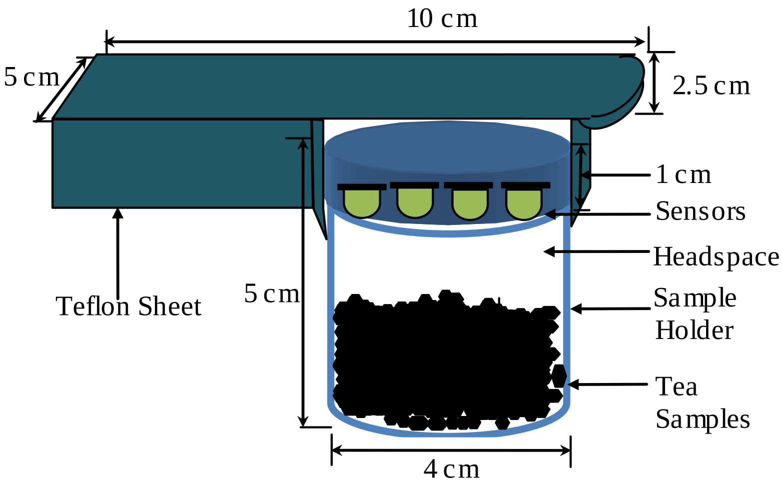


Fig. 2.23. Sample cum sensor chamber

For normal operation of the gas sensors, its heater temperature is elevated to about 350 °C [11] and kept constant by applying a fixed stable heater voltage of 5 V. The heat dissipated by the gas sensors due to the high heater temperature warms up the headspace air, which in turn heats up the tea samples. It is experimentally found that a tea sample of 15 g inside the sample chamber emits tea VOCs at a temperature of 50-60 °C. The temperature inside the sample chamber due to heat emitted by the sensor array gradually rises and reaches to a stable temperature of about 50 °C within 8-10 minutes. This temperature is measured with the help of a digital thermometer (indicated in Table 2.9). However, the temperature stability will be a function of ambient temperature. The sensor responses due to the exposure to tea aroma were acquired by interfacing the sensor output to a computer using a DAQ card. Similar to the CAT-based system the peak values, sensing and purging time required for each sensor were determined as shown in Table 2.10.

Table 2.9 Sample chamber temperature

Time (s)	Temperature (°C)
510	52
550	52.3
580	55
508	54
510	53
512	50
519	51
566	52.5
518	54
570	55

Table 2.10 Parameters of the HTAAS based sensing system to tea aroma

Parameter	Sample No.	TGS 2201	TGS 2620	TGS 832	TGS 2602
Peak Value (V)	1	1.10	0.28	0.14	1.4
	2	1.27	0.35	0.16	1.78
	3	1.13	0.29	0.16	1.4
	4	1.32	0.34	0.13	1.9
	5	1.34	0.37	0.20	1.79
	6	1.42	0.40	0.21	2.01
	7	1.32	0.32	.019	1.91
	8	1.33	0.32	0.15	1.88
Sensing Time (s)	1	800	450	450	750
	2	820	440	500	750
	3	750	450	450	740
	4	800	450	480	730
	5	770	450	500	800
	6	750	430	490	740
	7	770	430	480	76
	8	800	420	490	720
Purging Time (s)	1	400	150	200	400
	2	420	180	180	400
	3	440	150	200	420
	4	380	180	190	380
	5	400	200	180	360
	6	420	180	200	360
	7	400	150	220	400
	8	400	160	200	380
Baseline Voltage (V)	1	0.36	0.13	0.06	0.19
	2	0.31	0.15	0.65	0.27
	3	0.36	0.13	0.05	0.16
	4	0.38	0.12	0.05	0.16
	5	0.39	0.16	0.08	0.17
	6	0.35	0.16	0.08	0.21
	7	0.33	0.12	0.05	0.15
	8	0.34	0.12	0.05	0.18

It has been observed that the responses of the sensor array when exposed to tea aroma reach a steady state peak value in approximately 16 minutes. The responses of sensors, when exposed to different grades of tea samples are stored in the computer for prior analysis.

2.11 Auxiliary Components

The various auxiliary components used in the hand-held tea aroma assessment system are discussed below.

2.11.1 Battery and charger

A 12 V, 2200 mAh lithium-ion polymer (LiPo) rechargeable battery (Fig. 2.24) is used to power up the portable device. LiPo battery is selected due to its high energy density compared to other types of batteries, high durability, low maintenance and availability in various shapes and sizes. A balanced charger NR-BLIC-03 is used for charging the battery; it contains provision for both 2 and 3 cell LiPo battery.

Input to the charger can be provided by directly connecting it to the 230 V mains supply. When a battery is connected to the charger, a red LED turns on to indicate that the battery is charging. The automatic balanced charging is achieved by continuous monitoring and adjusting the rate of charge of individual cell voltages of the battery. The maximum charging current that can be attained vary between 600 to 800 mA. Three different colour LEDs are present to point out the status of the battery: green with flashing red indicates standby, red indicates charging and green indicates charging complete.

Fig. 2.24. Li-Po Battery used in the hand-held system

2.11.2 Keypad interfacing

A keypad is an arrangement of tact switches in row and column matrix format which may bear symbols, numbers, characters, words etc. (as shown in Fig. 2.21) and is the most widely found input device in digital circuits, µCs and telephone systems. Keypads are popular as the number of keys present in the matrix can be operated using less number of µC pins compared to keys interfaced individually, for instance, to connect 9 switches separately the µC will require 9 I/O-pins whereas by using a 3×3 keypad 9 keys will only require 6 I/O-Pins. In the prototype hand-held system the keypad used is an INT-302 3×3 pad (Fig. 2.25) procured from NSK electronics. The columns are interfaced to I/O-pins D_0, D_1 and D_2 and the rows are interfaced to I/O-pins D_3, D_5 and D_6 of the µC.

Identification of the key pressed in the keypad is detected by the µC. The sequence of operation is as follows: Logic high is provided to the row pins by configuring I/O-pins D_3, D_5 and D_6 as digital output logic high. When a particular key/switch is pressed the row and column of that switch gets shorted, i.e. the high input is transferred to the column to which the switch belongs. The µC then scans for the logic high in all the columns and detects that particular column. To figure out which key is pressed exactly, the code provides logic high on the row pins sequentially. The particular I/O-pin of the column becomes high and the key is identified.

One major disadvantage of keypad is that when a key is pressed multiple spurious spikes are generated due to the mechanical contacts in the switch. These multiple spikes are identified by the µC as multiple key-presses and the µC is unable to detect the actual key that is pressed. However, by introducing a time window frame (i.e. a small amount of delay e.g. 100 ms) between the detection and scanning process in the µC code this situation was avoided and the actual key that is pressed can be detected.

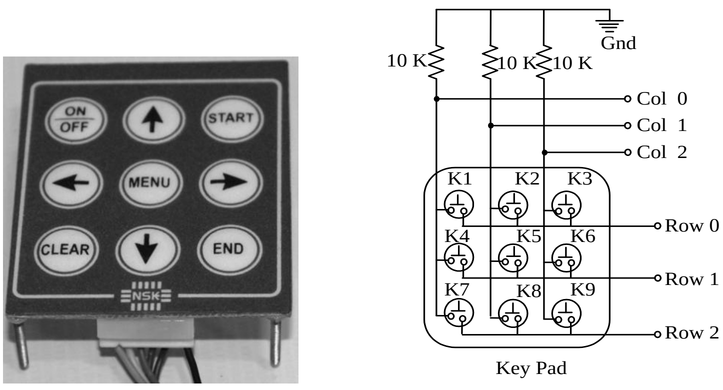


Fig. 2.25. Keypad used in the hand-held system

2.11.3 LCD Interfacing

Liquid crystal display or LCD is an electronic output module that displays useful information about an ongoing process. These modules supports characters (i.e. numbers, alphabets and many special symbols) which makes them superior to seven segment displays and multi segment LED arrays. The LCD interfaced is a 20x4 type (Fig. 2.26) i.e. it has four rows and in each row a maximum of 20 characters can be displayed. It typically consists of 16 pins which are arranged in a line, two sparse connection lines for the same pins are available in the LCD used. The interfacing of LCD to the µC is illustrated in Table 2.11.

The LCD is interfaced to the µC using I/O-pins of Port B register as shown in Fig. 2.21. The communication of the LCD with the µC is achieved with the help of built in library of *MIkroC*. The LCD is driven by a 5 V DC power source connected to $V_{CC.}$ Contrast is set by fine tuning a 10 K pot connected between V_{CC} and V_{EE}. The R_S pin connected to I/O-pin B_5 of the µC for selecting the data or command register of the LCD. If R_S is set high by configuring I/O pin B_5 as digital output high then data register is selected else command register is selected by configuring I/O pin B_5 as digital output low. Similarly when R/W is set high then read operation is performed and if R/W is set low then write operation is selected. It is generally connected to the ground. The E pin connected to I/O-pin B_6 is for enabling data reception. The backlight of the LCD is switched on by connecting A to V_{CC} and K to ground.

Table 2.11 LCD Pin functions

Pin No.	Symbol	Function
1	V_{SS}	Ground
2	V_{CC}	+5V
3	V_{EE}	Contrast Adjustment
4	R_S	Register Selection Signal
5	R/W	H/L , Read/write Signal
6	E	H->L, Enable Signal
7	D_0	H/L ,Data Bus Line
8	D_1	H/L ,Data Bus Line
9	D_2	H/L ,Data Bus Line
10	D_3	H/L ,Data Bus Line
11	D_4	H/L ,Data Bus Line
12	D_5	H/L ,Data Bus Line
13	D_6	H/L ,Data Bus Line
14	D_7	H/L ,Data Bus Line
15	A/V_{EE}	Backlight Anode
16	K	Backlight cathode

Data can be transferred in a LCD using two interfacing method 8-bit and 4-bit mode. In the 8-bit mode all the eight data lines D_0 to D_7 are used to transfer the ASCII data and data strobe is provided through E. In contrast, 4-bit mode requires only four data lines D_4

to D_7. The ASCII data is divided into two segments and transferred sequentially through D_4 to D_7. This mode provides its own strobe through E. Although, the 4-bit transfer saves I/O-pins the foreseen difficulty is that data is transferred at a much slower rate then 8-bit mode. However, LCDs are inherently slow devices which make the speed difference negligibly small and thus insignificant for consideration. Data is transferred here using 4 bit mode by connecting the D_4 to D_7 of the LCD to I/O-pins B_1 to B_4 of the µC.

Fig. 2.26. LCD used in the hand-held system

2.11.4 Printed Circuit Board (PCB)

Similar to the CAT based system several PCBs were fabricated for the hand-held-system as discussed below:

a) **Sensor array PCB:** As aforementioned the PCB (Fig. 2.27) to mount the sensor array is dimensioned to the sample chamber cap, so that it can be tightly locked inside the cap. It is used to hold the sensors in upside down position and provide circuit connections for the components.

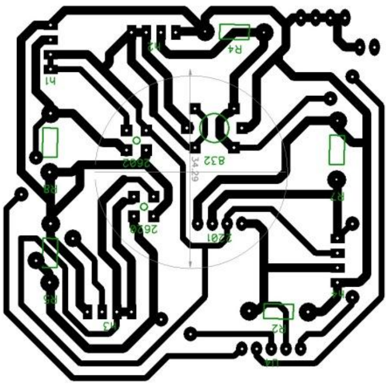


Fig. 2.27. PCB to mount sensor array

b) **Power Supply PCB:** This PCB contains provision for two separate 5 V supply regulated by four LM-7805 voltage regulator ICs as shown in Fig. 2.28. The battery provides a constant output of 12 V which is filtered through capacitor and then passed through voltage regulator to obtain the required voltage, the output of the regulator is again passed through a capacitor so that constant output is provided by the circuit. The power supply consists of two separate output lines one for the sensor array and the other to power up the rest of the circuit.

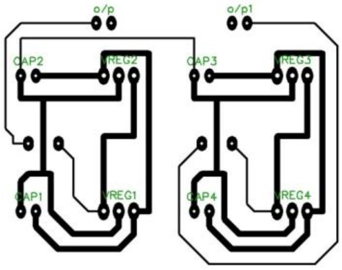


Fig. 2.28. Power supply PCB of the hand-held system

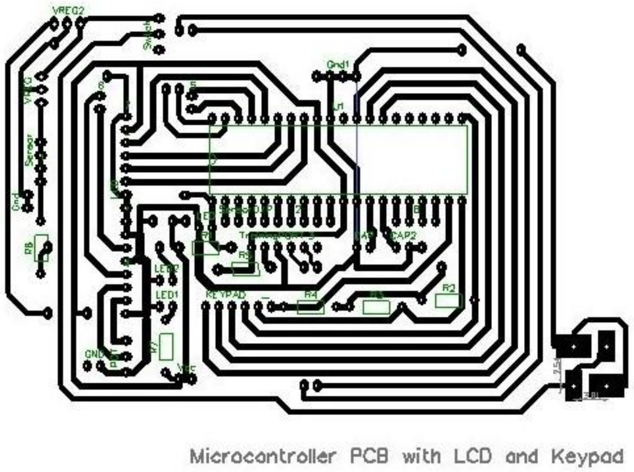


Fig. 2.29. Microcontroller PCB

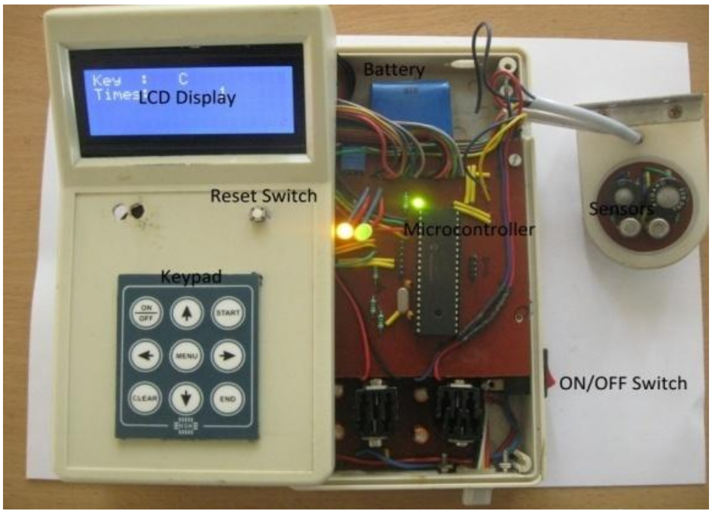
c) **Microcontroller PCB:** The circuit connections for the µC, LCD, keypad and in/out terminals are fabricated on a single PCB as shown in Fig. 2.29. The PCB is equipped with male terminals bus, which provides plug-and-play connectivity to the LCD and keypad. This provides flexibility to place the components in the plastic cabinet as per the requirement.

2.11.5 Plastic Cabinet

Fig. 2.30 shows the plastic cabinet in which the circuit components are assembled. The plastic cabinet used in the design is procured from SK-instruments. The rechargeable battery is inserted in the battery holder of the cabinet, just above the battery the µC PCB is placed and fixed tightly using screw-nuts.

The power supply is placed at the bottom of the cabinet as shown in Fig. 2.30(b). The LCD, Keypad, reset switch and indicating LEDs are placed accordingly. The sensor cum sample chamber is tightly fixed with screws at the top right exterior end of the cabinet. The photograph of the hand-held tea aroma assessment system is shown in Fig. 2.31.

(a)



(b)

Fig. 2.30. Plastic cabinet (a) bare and (b) with components

Fig. 2.31. Photograph of the handheld E-Nose system

As mentioned earlier, the alphanumeric LCD displays instruction to user, state of operation and output flavor score during testing. The keypad is used to control input process parameters and a 12 V, 2200 mAh lithium-ion polymer rechargeable battery is used to power up the portable device. It is pertinent to mention herein that the overall power consumption of the proposed E-Nose system is only 2.33 watt approximately.

2.11.6 Specification and features

The design specification and the salient features of the prototype hand-held tea aroma assessment system is illustrated below

a) Material/components used:

i) Plastic Cabinet: $19 \times 10.4 \times 6.15$ cm,

ii) Microcontroller: PIC 18F45K22,

iii) LCD: 20×4,

iv) Keypad: 3×3 Matrix keypad,

v) Battery: 12 volt 2200mAh Li-Po battery,

vi) ICs and accessories: LM 7805, LED, Switches, Capacitors, Resistances, wires, connectors, IC base, PCB etc.,

vii) Teflon sheet (sensor cum sample chamber): $10 \times 2.5 \times 5$ cm,

viii) Sample cum sensor chamber (cylindrical): 4×5.5 cm.

b) Salient features of prototype:

i) Power Supply Voltage : 12 volt,

ii) Power consumption (sensors): 1.83 Watt (approx.),

iii) Battery type : lithium-ion polymer rechargeable battery,

iv) Battery Capacity : 12 volt 2200mAh,

v) Total Power consumption : 2.33 watt (approx.),

vi) Number of tests during a full charging cycle: 11,

vii) Sensor warm up time : 15 minutes,

viii) Grading time : 16 minutes,

ix) Tea Chamber temperature : 55±5 °C,

x) Tea quantity : 15 grams.

2.12 Sequence of Operation

The program was coded using MikroC PRO for PIC 6.4.0 compiler with a program size 7.72 KB, while same floating point precision as MATLAB code was maintained. The program used 24% RAM and 38% ROM. Data sampling is executed at a frequency of 25 KHz. The results of the flavor scores estimated by the µC are displayed on the

20x4 LCD display. The entire process of tea aroma estimation and user interface display can be shown in a flowchart as shown in Fig. 2.32.

Based on the information presented above the course of action taken by the equipment to carry out a tea taste can be described as follows.

1. The circuit is switched on: The LCD displays *"Sensor Warm Up",* which indicates that the sensors require approximately 15 min warm up time to stabilize. During which 15 g of tea samples are measured by a digital weighing machine. The elapsed time is counted by a digital down-timer designed programmatically in the µC which is displayed in the LCD.
2. After warm up time is complete, the baseline values of all the sensors are recorded in the µC. The µC then initializes for a minute period during which the LCD displays *"Initializing"*.
3. After initialization the LCD displays *"Add Sample and Press Test"*. The measured samples are placed in the sample cum sensor chamber and then start button in the keypad is pressed, upon which the gas sensors transmits the captured signals to the µC.
4. The peak values are then extracted from the sensor responses. It takes about 16 min for the sensors to reach the peak value and stabilize. A down-timer indicates the elapsed time during this phase.
5. The input feature vector is then developed in the µC by subtracting the baseline values from the peak values of the respective sensors.
6. The features are then subjected to the ANN built around the PIC µC. The LCD displays *"Calculating Score"* from step 4 onwards until step 6 is complete.
7. The tea class/grade is then predicted by the ANN and displayed in a LCD panel. The LCD is refreshed after one minute.
8. After which the LCD indicates "Remove Sample Chamber and Refresh". The instructions are followed accordingly. The sensors take almost 10 minutes to return to their original baseline voltage and stabilize. The digital timer displays the elapsed time in the LCD.

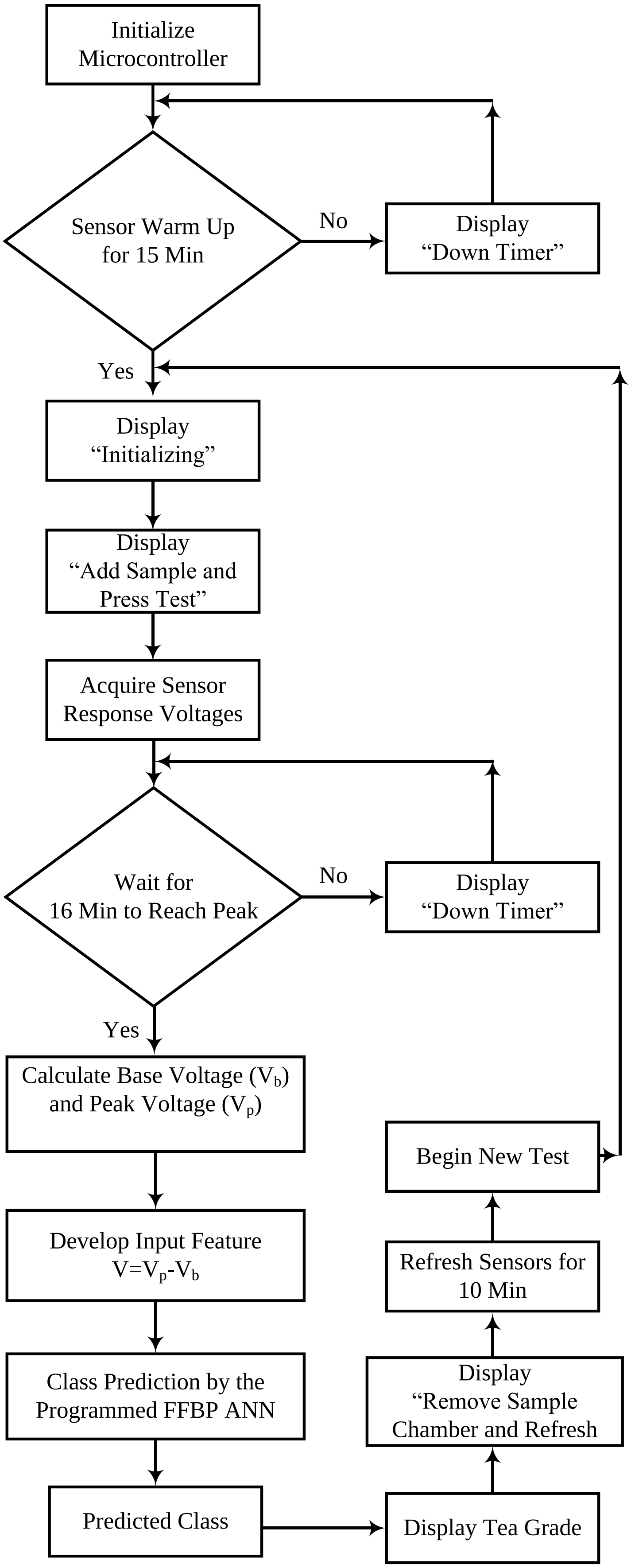


Fig. 2.32. Flow diagram of embedded tea classifier

9. The LCD then Displays “Begin New Test “which indicates that a new test can be performed.

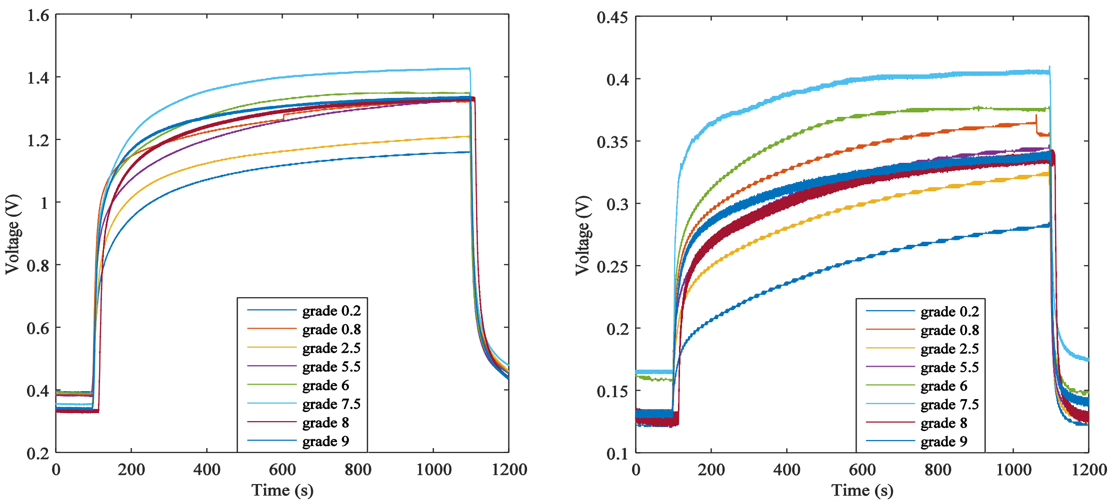
10. The cycle is then repeated from step 2. If the system is switched off then again all the previous steps are repeated.

2.13 Results and Discussion

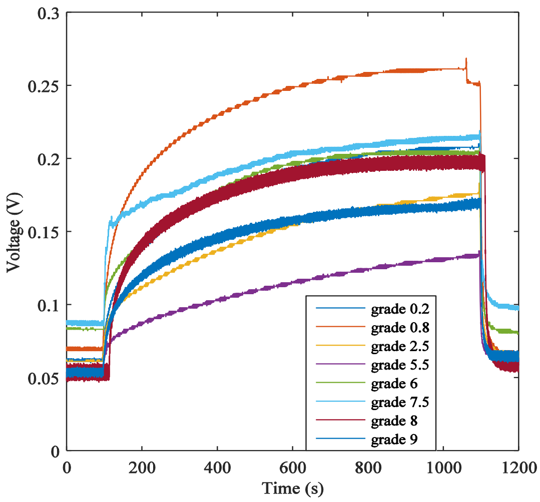
The VOC collecting system for the hand-held system is different from the CAT-based system due to which the response pattern of the sensors will be different. Moreover, due to the different sample heating technique and quantity of samples, different response patterns will be generated by the sensors. Therefore for the hand-held system response patterns from the sensors are collected for analysis.

2.13.1 Sensor Responses

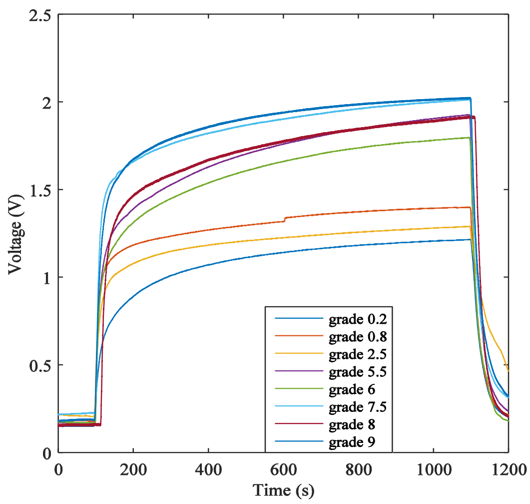
The plot of response patterns obtained from the gas sensors when exposed to tea samples of different grades is depicted in Fig. 2.33. The increase in voltage level indicates that the sensors were mainly reacting with mixture of reducing VOCs of tea samples. It is also evident from the response patterns that tea VOCs are dominated by reducing gases. It can be inferred from the response patterns that the response pattern increases sharply and reaches a stable peak voltage after 15 min. It is observed that the behavior of the response pattern depends on the grade of the sample.



(a) (b)



(c)



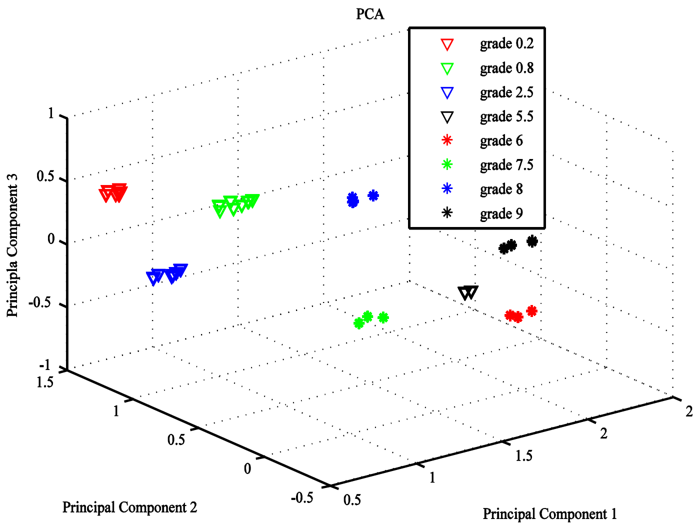
(d)

Fig. 2.33. Response pattern to various grades of tea samples (a) TGS 2201, (b) TGS 2620, (c) TGS 832 and (d) TGS 2602

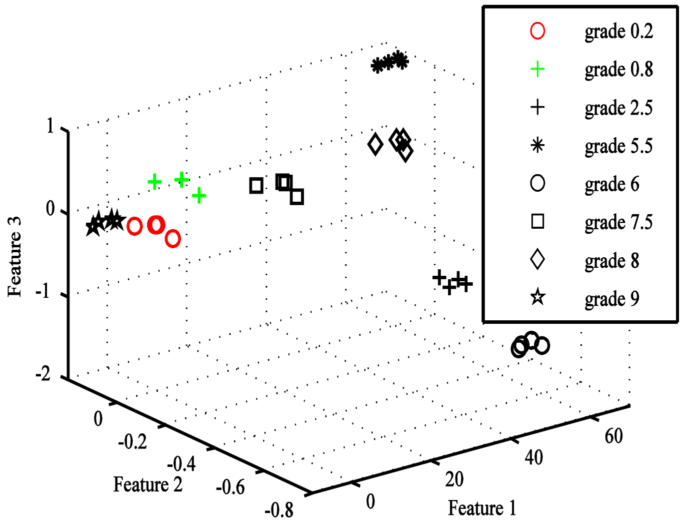
2.13.2 Principal component analysis (PCA) and self organized feature mapping (SOFM)

Fig. 2.34(a) shows the PCA with eight distinct clusters showing first three principal components (Table 2.12).

Additionally, SOFM clustering of eight patterns is depicted in Fig. 2.34(b). It is observed that both PCA and SOFM show eight distinct clusters of the eight different tea grades.



(a)



(b)

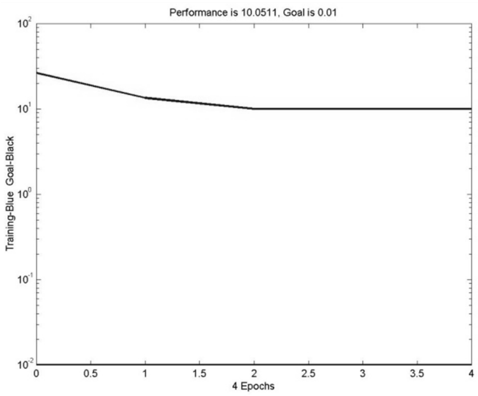
Fig. 2.34. (a) PCA and (b) SOFM of hand-held feature dataset

Table 2.12 PCA results of hand-held tea classifier

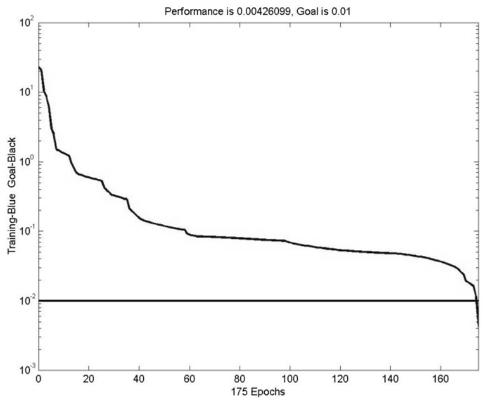
PC	% Variance	Eigenvalue	Principal Components			
			TGS 2201	TGS 2620	TGS 832	TGS 2602
PC1	99.1212	0.00503	0.4150	0.5320	0.7376	0.0258
PC2	0.8270	4.20×10^{-5}	0.0905	0.6504	-0.5003	-0.5643
PC3	0.0508	2.58×10^{-6}	0.1093	0.4049	-0.3824	0.8233
PC4	0.0009	4.78×10^{-8}	0.8987	-0.3604	-0.2437	-0.0553

2.13.3 Training of ANN

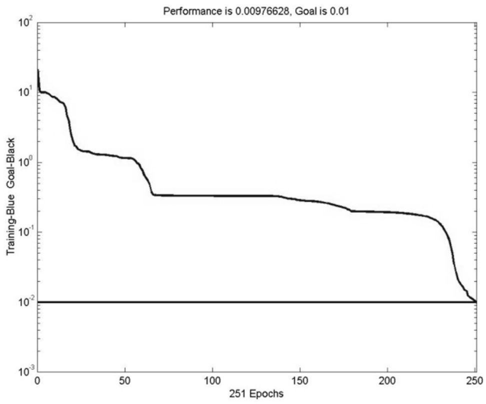
In our first level of experiment using CAT-based system we have achieved 92 % classification accuracy with 4 hidden neurons in FFBP ANN. The second phase of the experiment is conducted using responses of sensor array using the hand-held tea flavor detection system. Since the sensor responses in hand-held system are different from CAT-based system, it needs retraining using MATLAB. The response features were applied to FFBP in MATLAB to determine the network parameters which will be used for coding in µC based hand-held system. Finally the FFBP algorithm was coded in the µC and the network was trained with eight different grades of samples.



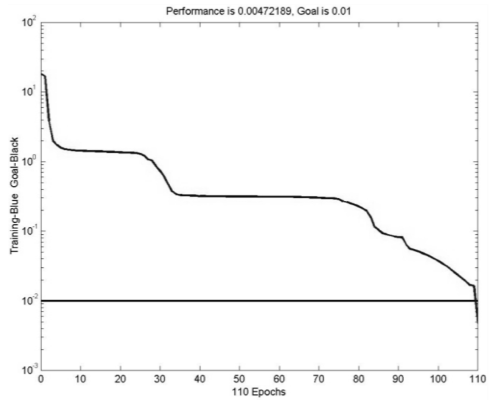
(a)



(b)



(c)



(d)

Fig. 2.35. Training performance of the neural network for (a) $n=2$, (b) $n=4$, (c) $n=6$ and (d) $n=8$

Similar to the CAT-based system, an ANN model with hidden neurons 2, 4, 6 and 8 were used to compare the network performance parameters and select the optimum network (Table 2.13).

TABLE 2.13 Performance parameters of handheld tea classifier

Hidden Neuron	Goal	Learning Rate	Epochs Reached	Time (s)	Training Accuracy	Remarks
2	0.01	0.1	4	12.5	12.5%	Under Trained
4			175	3.46	100%	Well Trained
6			251	13.3	95.83%	Over Trained
8			110	10.3	91.66%	Over Trained

In order to discriminate tea flavor on the scale of 0 to 10, the trained network parameters were implemented for FFBP ANN in µC and the training accuracies are shown in Table 2.13.

The performance characteristics on training the neural network with varied number of hidden layer is shown in Fig. 2.35. The weights and biases of the well trained network are depicted in Table 2.14.

Table 2.14 Weights and biases for the well trained ANN

Weights/ Biases layer	Values
net.IW{1,1}	[4.0822 -14.7264 70.4382 -4.2148; 0.0320 2.8070 -0.2072 6.1479; 27.3580 -22.8518 -2.6353 -16.5874; -5.4591 4.1239 -8.8655 1.6665]
net.LW{2,1}	[-1.1923 3.4025 -26.4381 -7.6345; 8.2492 0.3640 -10.7840 2.0576; -1.1398 -0.5508 -1.0945 -3.6377; 6.9775 -7.7034 -4.0654 2.8507]
net.LW{3,2}	[-20.6269 24.3084 15.7980 3.6618]
net.b{1}	[-1.3262; 3.1998; 5.3442;1.6291]
net.b{2}	[1.7566; -0.3482; -3.7649;-1.3279]
net.b{3}	[-0.1839]

2.13.4 Performance of ANN

For testing we have used 10 untrained tea samples for each of 8 different flavor scores i.e. total of 80 samples. The confusion matrix of the tested samples shows the overall system performance as well as the individual class accuracy of the embedded hand-held tea flavor classifier to classify untrained tea samples (Table 2.15). The FFBP network implemented in the µC was able to classify with a classification accuracy of 90%.

Table 2.15 Confusion matrix of handheld tea classifier

		Tea Taster's Score								
		0.2	0.8	2.5	5.5	6.0	7.5	8.0	9.0	
Proposed System Score	0.2	9	1	0	0	0	0	0	0	90%
	0.8	0	10	0	0	0	0	0	0	100%
	2.3	0	1	7	1	0	0	1	0	70%
	5.5	0	0	0	8	2	0	0	0	80%
	6.0	0	0	0	0	10	0	0	0	100%
	7.5	0	0	0	0	0	9	1	0	90%
	8.0	0	0	0	0	0	0	9	1	90%
	9.0	0	0	0	0	0	0	0	10	100%
		100%	83.33%	100%	88.88%	83.33%	100%	81.8%	90.9%	90%

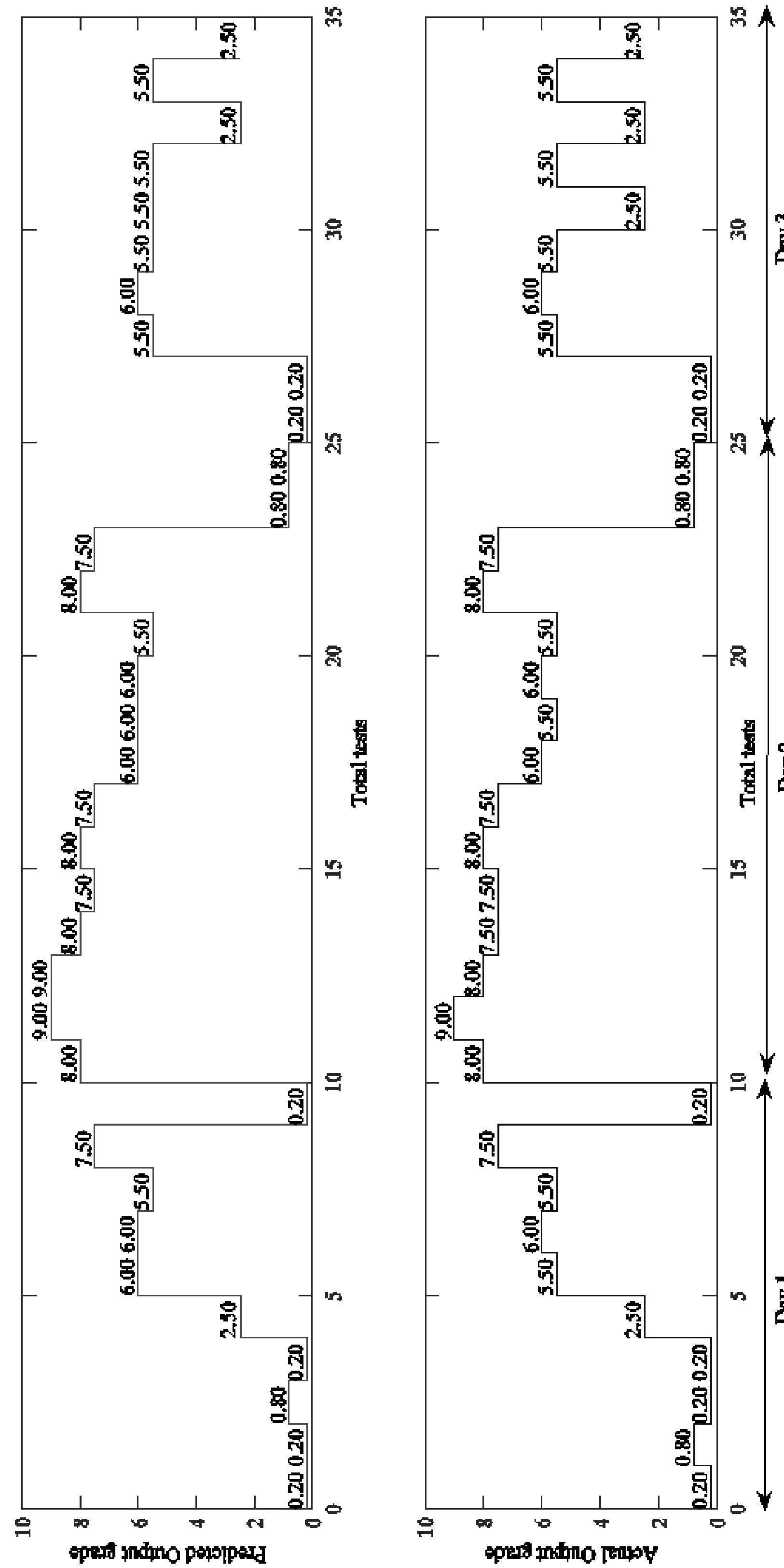


Fig. 2.36. Repeatability of the tested samples

Table 2.16 Repeatability Analysis

Day	Type	Scores	Repeatability %	Overall %
1	A	0.2 0.8 0.2 0.2 2.5 5.5 6.0 5.5 7.5 0.2	7/10 = 70%	
	P	0.2 0.2 0.8 0.2 2.5 6.0 6.0 5.5 7.5 0.2		
2	A	8.0 9.0 8.0 7.5 7.5 8.0 7.5 6.0 5.5 6.0 5.5 8.0 7.5	10/13 = 77%	80%
	P	8.0 9.0 9.0 8.0 7.5 8.0 7.5 6.0 6.0 6.0 5.5 8.0 7.5		
3	A	0.8 0.8 0.2 0.2 5.5 6.0 5.5 2.5 5.5 2.5 5.5 2.5	11/12 = 92%	
	P	0.8 0.8 0.2 0.2 5.5 6.0 5.5 5.5 5.5 2.5 5.5 2.5		

Note: A= Actual Grade; P= Predicted Grade

In the testing phase of the hand-held device, the signal acquisitions for the 80 samples were conducted over a total period of 45 days since each sample testing takes around 16 min. However to test robustness of the system we have conducted a repeatability test by testing samples in random manner over a smaller time period (3 days). The repeatability chart is shown in Fig. 2.36 and the Table 2.16 shows that the overall repeatability is 80% for a total of 35 inputs. The repeatability of the system is found to be marginally excellent.

It is noteworthy to mention herein that PC based analysis on the results obtained from the hand-held E-Nose is done in order to demonstrate the efficacy of the system. However, the system is purely standalone and applicable to be used as a field type tea flavour testing gadget. The only limitation of the system is that it requires a separate weighing scale for measuring the samples. However, we have used a portable pocket-size weighing machine which nullifies the limitation to a great extent.

The experiments were performed considering that the short time drift of the sensors is very low. However, due to the aging of the sensors drift will eventually affect the sensor responses. But, drift can be nullified using various drift compensation algorithms which is another direction of research and not undertaken in the present work. Moreover, a replaceable sensor module is fabricated therefore the sensors can be replaced from time to time and the performance of new units of the same sensors can be tested if more prototypes are required.

2.14 Conclusion

In this chapter, a µC based hand-held E-Nose system for tea flavor detection was proposed. In achieving the goal first a CAT-based E-Nose system was developed which is efficient in selecting the sensor and classifying the tea flavor based on information extracted from the selected sensors. Finally, a novel HTAAS has been developed with an attempt for achieving promising classification performance. Moreover, the proposed design setup eliminates the need of several components used in traditional E-Nose systems, like- micro pumps, mass flow controller, suction fan, solenoid valves and external heater. As a result, it reduces the power consumption rate. Further it minimizes the size, weight and cost of the system. The effectiveness of the proposed system was investigated with 80 different tea samples collected from three different places. The measurements yields an accuracy of 90% with 80% overall repeatability. Therefore, the proposed system can serve efficiently in tea industry and can also be an aid to the tea tasters.

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