CHAPTER

6 Summary and Conclusion

6.1 Summary and Conclusion

In the present thesis, thick film sensor arrays along with different data preprocessing and pattern analysis techniques have been used to study the performance of artificial olfaction (Electronic-Nose) system. Different methods were studied and few new methods were investigated which can be used to enhance the efficacy of the thick film based gas sensing devices.

The datasets used for various experiments were of different types collected from different sources. The first dataset was prepared from the steady state responses of a thick film sensor array (with sensor elements- pure SnO_2, Pd doped, Pt doped, and Au doped SnO_2, referred as Sensor Array-1) for various gases viz. LPG, CH_4, CO and H_2 reported by Mishra and Agarwal (1998). The second dataset was prepared by generating the steady state responses with a thick film sensor array fabricated by the author (with sensor elements-pure SnO_2, Pd doped, Pt doped, and ZnO doped SnO_2, referred as Sensor Array-2, as discussed in Chapter-2) for LPG, N_2O, Acetone and 2-propanol. The third dataset was prepared form the dynamic response of a thick film gas sensor array (sensor elements were doped with 1% Pd, Pt, Cd, CuO, ZnO and pure SnO_2) for four gases viz. LPG, CCl_4, CO and C_3H_7OH collected by Chaturvedi *et al.* (1999). The fourth dataset was the steady state responses of the thick film gas sensor array fabricated by the author (Sensor Array-2) collected for binary mixture of two volatile organic compound viz. Acetone and 2-propanol, in different proportions.

In the Chapter-2, the fabrication and characterization of sensor array has been presented, which was used to collect the responses of the gases/odors in the individual as well as in binary mixture forms (as described in Chapter-3 and Chapter-5). The responses obtained from the fabricated sensor array have been validated using published model of tin oxide based thick film sensor array. It has been established that the fabricated sensor has good sensing capability for various gases and thus can be utilized as gas sensor array for e-nose purpose. The sensor array was also used to generate responses of mixture of VOCs as described in Chapter-5.

In Chapter-3, the investigations are carried out to select an appropriate data preprocessing technique which could be applied to sensor array responses with an objective to enhance the accuracy of classification and/or quantification network. Principal Component Analysis (PCA) is an unsupervised preprocessing technique while Linear Discriminant Analysis (LDA) is a supervised technique. These two techniques are generally employed in pattern recognition task. Both can be used for dimensionality reduction as well. But, the PCA is found to be an effective technique as compared to LDA in all aspects. Though the effect of class separability of LDA is comparable to PCA, the load of handling class labels imposes extra computational effort and time for LDA to use it as data preprocessing technique. The accuracy obtained with PCA as a data preprocessing tool has been found to be of the same order as with LDA. This led PCA to be preferred technique and has been used in the subsequent chapters of the thesis for data preprocessing as well as for dimensionality reduction.

In chapter-4, a new method called Average Slope Multiplication (ASM) method has been proposed by the author for classification and simultaneous quantification of individual gases/odors using the published dynamic responses of the thick sensor array. The proposed technique is rather a simpler technique as compared to complex methods reported earlier. After a close observation of the linear region of the dynamic responses, it was found that for a particular concentration band and for a given sensor, the slope of all response/recovery curves have different values for different gases/odors. Actually, this slope value reflects the response/recovery behavior of the sensor for particular gas/odor at particular concentration. The ASM approach is based on multiplying the response and/or recovery data by the magnitude of the respective average slope value. It has been demonstrated that the proposed ASM method combined with BPNN classifier offers excellent results for classification and quantification of individual gases/odors using the dynamic responses of thick film gas sensor array.

Principal component analysis (PCA) has been used for data preprocessing and dimensionality reduction for the combined dataset (where the complete responses/ recovery data were taken simultaneously). The neural classifier, trained and tested with the ASM transformed data, provided the classification accuracy of 97% as compared to 86 % obtained with raw data. The ASM data after further preprocessed with PCA provided 100 % classification accuracy.

The simultaneous quantification of individual gases/odors has been performed using ASM feature technique applied to each individual concentration band. Two different neural architectures were trained and tested with ASM transformed data which provided 100% quantification accuracy along with the PCA preprocessing.

Next, the exposure and recovery datasets have been individually tested for classification as well as simultaneous quantification using ASM feature technique. The results obtained are promising. Classification accuracy with response and recovery data was 93.7 % and 95.8 % respectively using ASM feature technique. The simultaneous quantification accuracy with response and recovery data was 89.5 % and 91.6 % respectively. From these results, it can be concluded that response or preferably recovery data can be used for classification as well as simultaneous quantification.

In Chapter-5, successful classification and quantification of binary mixture of VOCs has been performed. Analysis of binary mixture of gases/odors is more complex as compared to individual gases/odors. The thick film sensor array fabricated by the author consisting four sensor elements (Sensor Array-2, described in Chapter-2) was used to obtain steady state responses for two volatile organic compounds (VOCs) viz. Acetone (CH_3COCH_3) and 2-propanol ($CH_3CHOHCH_3$) in their individual as well as in mixture forms. A hierarchical system consisting of gating network and three quantification networks was designed to classify and then quantify and individual and mixture of VOCs.

The classification accuracy of gating network has been investigated using back-propagation neural network (BPNN) and support vector machine (SVM). The gating network with BPNN provided 89.5 % and 95.6 % accuracy for raw data and PCA data receptively. The gating network with *nu*-SVM provided 94.7 % and 100 % accuracy for raw data and PCA data receptively. For quantification, multioutput support vector regression (*M*-SVR) method was used in slave networks for single as well as binary mixture data. The scores of the first two principal components of PCA data were used as input to each quantification network. For, individual Acetone and 2-propanol, good correlation coefficients of 0.9983 and 0.9871, respectively were obtained. Also, good 0.9828 and 0.9764 correlation coefficients for the predicted versus real concentration of Acetone and 2-propanol, respectively as individual VOCs in the binary mixture were obtained.

Based on the present investigations following conclusions can be drawn:

(i). The performance of artificial olfaction (Electronic-Nose) can be improved by applying suitable data preprocessing and/or feature techniques on the raw data combined with an appropriate soft computational technique. Proper selection of these techniques can overcome some of the known limitations of thick film tin oxide based gas sensor arrays such as cross sensitivity to different gases/odors and saturation of responses at higher concentrations of gases/odors, which create hurdle in the identification/quantification.

(ii). PCA is preferable preprocessing and dimensionality reduction technique which is unsupervised in nature and can help in cluster separation among different gases.

(iii). Successful classification and simultaneous quantification of gases/odors using dynamic responses can be obtained using a simpler feature technique called Average Slope Multiplication (ASM) which utilizes the slope variation of linear portion of response/recovery plot of a sensor for different gases at different concentrations. The ASM preprocessed data can be further fed to a suitable signal processing module like BPNN for classification/quantification purpose.

(iv). To obtain the class and concentration of individual gas/odor in the mixture, a system consisting of gating network combined with quantification network can be used. PCA, again found to be preferable preprocessing technique for such data. Since the mixture data is more complex, SVM could be used for better classification and to avoid local minima problem generally found in BPNN classifier. Further, for quantification network multioutput support vector regression can be used for simultaneously predicting concentration of individual component in a gas mixture.

Future Scope:

(i) Proposed techniques presented in this work can be suitable for real time gas/odor identification/quantification which proposes an ample future scope of the present work.

(ii) The proposed ASM feature technique can be used for dynamic responses of mixture of gases/odors. This also provides a scope of further research for identification and quantification of individual component in the mixture of more than two gases/odors.

(iii) Future research can be oriented to study mixture of more than two gases/odors using steady state and/or dynamic responses of thick film gas sensors with support vector classification and regression methods.

(iv) The proposed schemes could be implemented on microcontroller for development of portable and high precision e-nose devices.

(v) VLSI implementation of the proposed techniques contains a big scope for future e-nose technology development.