CHAPTER 5

CONCLUSION AND FUTURE SCOPE

5.0. Conclusion

This research presents a descriptive and analytical report on three aspects: a) development of a novel low cost microcontroller based hand-held tea flavor estimation system using MOS gas sensors, b) a DIC based multisensory measurement protocol for measuring analog output responses from a sensor array, using a microcontroller, c) compensation of nonlinearities and estimation of uncertainty in DIC. The key findings of this research work are briefly discussed below.

In chapter-2, design and development of a hand-held microcontroller based E-Nose setup for tea aroma quantification has been presented. In doing so, a first level of experimentation was performed on a CAT-based tea classifier for sensor selection. The sensor array of the developed CAT-based system comprises of four different MOS gas sensors (TGS 2201, TGS 2602, TGS 2620 and TGS 832), which were selected out of 12 sensors through sensitivity analysis. Dry and fresh tea samples graded by tea tasters (on a scale of 0-10) were used in the experimentation. To generate the headspace the tea samples were heated by illuminating heating a halogen lamp of 50 W. The generated VOCs were then transported into the sensor chamber through PTFE Teflon pipes by means of airflow pump. The response patterns generated by the sensor array on exposure to VOCs of five different tea samples were collected in a computer using a DAQ card in LabVIEW. Experiments were performed on the CAT-based system to generate a large number of response data from the tea E-Nose. Features were extracted from the responses and PCA was performed, which showed good clustering. Classification of tea grades was then performed using FFBP ANN in MATLAB and a classification accuracy of 92% was achieved.

In the next step, a hand-held tea aroma assessment system was designed and developed using the sensors selected in the first level. There are two distinct advantage of the proposed handheld e-nose system:

a) The sensor array was directly exposed to the tea samples without the need of any sample transporting mechanism.
b) In contrast to the earlier works, the developed system also overcomes the problem of heating the tea sample since the volatile organic compounds of tea are generated due to the emitted heat of the sensors in the proposed system.

In the proposed system the power consumption is significantly reduced. It is evident from the fact that in the CAT based system the heating lamp alone consumes 50 W, whereas the hand-held system consumes only 2.33 W.

Similar to the CAT-based system experiments were performed to generate a large number of response data from the hand-held tea E-Nose. However, unlike CAT-based system eight different grades of tea samples were used. The features were extracted and clustering and classification was performed on MATLAB. SOM and PCA were used for visual interpretation and they show good clustering. An FFBP ANN model was developed in MATLAB and the model was then incorporated in the microcontroller. The classification of the microcontroller based E-Nose to perform online flavor detection revealed accuracy up to 90%.

In Chapter-3, we presented the direct interfacing of an array of MOS gas sensor to the microcontroller, without the use of intervening an ADC. An E-Nose set up was designed and developed using three different MOS gas sensors (TGS 2620, TGS 832, and TGS 2201) and the response patterns of the sensors to four VOCs were collected. The online data logging and acquisition is performed simultaneously by two methods: (a) interfacing the DIC to a microcontroller and transporting the data to a host computer via USB UART serial link, and (b) using a DAQ card using LabVIEW in a computer.

It was observed that PCA and LDA form four distinctive clusters of the four tested gases. For classification, the best FFBP model is determined in MATLAB and then coded in the µC for online gas discrimination. The µC based DIC E-Nose was able to classify the four gases with an accuracy of 98.75%. The amount of uncertainty in the measurement of sensor response voltage due to uncertainty of the sensor circuit parameters and that of the direct interface parameters was also estimated. It indicates that the measured sensors responses reliably represent its true value. Since, the uncertainties are very low compared to the output the quality of the developed E-Nose system is accurate and reliable.

Scalability analysis was performed by repeating the experiments to ensure the robustness of the system. It was observed that PCA of the new dataset formed distinct clusters. The online testing of the samples revealed an accuracy of 98.75%.

Chapter-4 presents an error compensation algorithm to overcome the shortcoming of the DIC to accurately map the nADC values to ADC. The major issue in the DIC system is the significant level of nonlinearity due to external DIC components and the counter of the µC. Therefore, a set of error compensating techniques (ECT) were investigated and the best model was implemented for single sensor measurement which reduced the nonlinearity to 0.02%. Under the improved ECT framework, the algorithm was extended for multi-sensor measurement in an E-Nose setup. A neural network model was integrated with the system which was implemented using a µC for effective discrimination of four different gases. The efficacy of the proposed model of ECT was enlightened by comparing with ADC based approach. The PCA of ADC, error compensated without ADC (C-nADC) and uncompensated without ADC (U-nADC) were compared and the Euclidean distance measures were also performed to determine inter/intra class distance ratio. Further, the effect of compensation on predictive accuracy was determined by comparing the online predictive accuracy of ADC, U-nADC and C-nADC based methods to classify four gas samples.

It was observed from the experimental investigation that the nonlinearity prevalent in U-nADC framework is reduced to a great extent, by the proposed ECT. Therefore, the response characteristics obtained by measuring the analog voltage using the C-nADC framework in the range of 0-V_{DD} V, resembles the ideal 12-bit ADC. Moreover, in the multi-sensor E-Nose setup the sensor array responses measured by the C-nADC and the inbuilt 10-bit ADC of the µC are within a close approximation. Whereas, the sensor array responses measured by U-ADC significantly deviate from the ADC or C-nADC, which may be presumably due to its deviation from the ideal characteristics. PCA forms distinct clusters for U-nADC and C-nADC, and a partial overlapping is observed in case of ADC measures. It is observed that between n-ADC techniques, C-nADC provides more accurate measurement compared to U-nADC, so the effect of error compensation on the classification accuracy is evaluated. Further, performance of ANN for ADC, U-nADC and C-nADC is compared. In order to classify gas samples FFBP ANN is used. The number of hidden neurons (*n*) for the best classification performance is found to be 4 for implementation in ADC as well as for U-nADC and C-nADC. It is observed analysis that C-nADC results in higher classification accuracy (98.75%) than that of U-nADC (97.91%) and ADC (97.08%) based method in the multisensory E-Nose environment. The weights and biases of the neural networks with optimal hidden neurons simulated in MATLAB are used to code the ANN algorithm in two separate µCs for online comparison of the proposed method. In one µC both the U-nADC and C-nADC based prediction results are calculated sequentially and displayed in a LCD, and in the other µC ADC based prediction is performed. The nADC and ADC based online gas discrimination of 200 gas samples (50 samples each gas) analyzed accounted for 95%, 96.5% and 98% accuracy for ADC, U-nADC and C-nADC respectively.

The scalability of the proposed approach is also examined in the context of results obtained using the optimized model on new set of data that has not been previously used for this measurement. In order to investigate the systems scalability the system is trained with separate dataset of the gas sensor responses and testing was performed. The experimentation is repeated for three cycles and accordingly performances have been investigated which is found to be satisfactory. The quantitative measure achieved in terms of average accuracy for ADC, U-nADC and C-nADC are found to be 94.66%, 96.833 and 98.16% respectively.

In conclusion a novel portable hand-held E-Nose system for tea quality estimation is reported in this work which consumes very low amount of power compared to the existing systems. Therefore, the proposed system can serve efficiently in tea industry and can also be an aid to the tea tasters.

It has been shown that with direct-interface to the MCU, the e-nose system can be easily trained to execute gas classification via ANN, in a controlled environment where the uncertainties does not affect the measurement system. The main advantage of the system is that it does not require any ADC for acquiring analog voltages from the sensors.

This study also addressed the nonlinearity problem prevalent in analog voltage measurement of a single sensor based DIC by proposing an optimized error compensation technique. The proposed technique has been compared with the ideal ADC and promising results were achieved. An online comparison of the proposed system with the uncompensated DIC and ADC based system established the viability of the system. Moreover a multisensory measurement system is designed and developed using the proposed technique which is incorporated in an E-Nose setup. Experimental findings indicate that the proposed multisensory measurement system approximates the ADC based system.

The MOS gas sensors used in this research requires two separate power sources one for the sensor heater and the other for the sensor itself. The sensor heater voltages for each of the sensors are supplied from a separate power supply, so the rest of the MOS sensor works similar to any resistive sensor. Therefore the proposed work can be an opportunity for low power embedded systems where multiple sensor outputs are to be measured accurately. Moreover, based on the requirement the measured responses can be used to perform certain tasks.

Most importantly the measure of analog voltage using DIC is similar to that of a 12-bit ADC which requires only two I/O-pins having Tri-state capability. Moreover, unlike other DIC based methods it does not require any comparators, timers or capture modules.

Single sensor systems are now a days going to be interfaced as DIC to save microcontrollers computation time for ADC operation. In view of this a multisensory framework has been used in DIC mode which can save a good number of components for large array (such as 16-32 size of array). Besides it is more compatible and it can be directly interfaced to inherent digital systems like CPLDs and FPGAs.

5.1. Limitations of the Work

The limitations of the work are presented below:

- The sensor array was designed and fabricated from the off the shelf MOS sensors and further research will be conducted in future with wide range of MOS sensors.
- In our proposed approach two spare input lines are required for each analog signal. However, the number of pins in a µC is determined by the number of signals which in turn affects the cost of the package.
- The work focuses on error and linearity compensation of the DIC considering that the short time drift of the sensor is very low. Moreover, the experiments were conducted under constant ambient conditions without any environmental disturbances. However, long term drift will dominate over issues with the DIC. Therefore the impact of long term drift and its compensation is one of the future research directions from this thesis.

5.2. Future Research Option

The possibility of extending the research work for further improvement and modification in the novel hand-held E-Nose for tea aroma quantification and the proposed multisensory DIC protocol are summarized below:

- Implementation of DIC for development of portable E-Nose for tea with wide range of MOS gas sensors.
- Reducing the time required for grading: It is observed that, in contrast to the other E-Nose systems, the proposed system consumes more time for grading the tea samples. This consumes power and also reduces the number of times the experiments can be repeated. Therefore reducing the grading time would be highly invaluable.
- The tea samples gets contaminated very easily, moreover fresh tea samples were needed for the experiments, therefore there was an unavailability of large numbers of tea tasters graded samples. Therefore, collecting more

number of graded samples from different tea gardens and training the system, will make the system more reliable.

- Further, other prediction algorithms can also be tested to improve the accuracy of the system. However, advance algorithm will require expensive microcontroller having large RAM and ROM.
- The proposed DIC can be applied for various multisensory applications.
- Although, analog value estimated using the DIC is found to be similar to ADC based approach, it consumes more time then ADC based measurement, and the system is only applicable for slow process monitoring applications. So, it may fail in high speed operations. Therefore, research in this direction for development of new circuits and designs to create more efficient DICs can improve the performance.