Chapter 8

Summary, Conclusions and Scope Future Work

8.1 Summary

This thesis aims to develop advanced gas sensing systems that may be used for real-time detection and monitoring of airborne pollutants normally found in smart homes, industries, automotive cabins and workplaces. We can envisage many other applications of such systems.

We have first experimented with a wide variety of volatile organic compounds (VOCs) that are usually generated in the household sector during several daily chores (e.g., worship, safety & security, hygiene, LPG leakage detection, cooking and smoking etc.). Our proposed electronic nose (e-nose) prototype comprises a six-element low-cost MQ-series-based gas sensor array and a microcontroller. To achieve high performance from our designed e-nose, we first transformed the raw sensor array responses into the Standardised Principal Component Analysis (SPCA) based analysis domain, where the transformed data showed well-shaped and separated clusters for respective VOCs.

A simplistic classifier is then designed using Artificial Neural Network (ANN) trained in the SPCA transformed domain, which outperforms classification accuracy. This experiment captured 2465 training samples of 17 diverse VOCs (odors and smokes) commonly found in household ambience. Another 85 samples were also captured for testing purposes which were not used during the training of the ANN classifier. The accuracy in correct classification has been 96.47% for the 17-class test samples, while the precision, recall and F1-score were 96%, 95% and 95%, respectively. The mean squared error (MSE) in this experiment was between 1.35 × 10-6 and 2.15 × 10-2, with an average MSE of 1.42 × 10-3.

This high-performance gas sensor system can be scaled-up further to potentially monitor VOCs and provide further information to improve air quality in smart homes.

Subsequently, we have expanded our research to develop an intelligent decision support system to generate real-time fire maps of storage and distribution centers (SDCs) and help firefighters to extinguish the fire using the appropriate fire retardant. The system is very stable and rugged due to the use of tin-oxide MOX-based gas sensor elements and is accurate because the PM sensor and MLP-based classifiers are included.

To the best of the author's information, this work is the most comprehensive and promising development of an IGSS for real-time generation of the map of 'Classes of Fire'. It can be deployed as a disaster management system to identify and control fire hazards in various SDCs and places alike and generate real-time fire maps in storage and distribution centers (SDCs) during a fire hazard.

In this experiment, we have interfaced six tin-oxide-based gas sensor elements, a temperature and humidity sensor, and a particulate matter (PM) sensor with microcontrollers to capture real-time signature patterns of the ambient air. Sixteen types of materials (plus one class belonging to the ambient air) belonging to six classes of fires were burnt to create a dataset of 2400 samples. The sensor array responses are then pre-processed and analysed using various classifiers trained in different analysis space domains. Among these classifiers, four classifiers achieved 'all correct' identification of fire classes of 80 unknown test samples, and the lowest mean squared error (MSE) achieved is 2.81 × 10-3.

In our work, we have considere different types of cyber-physical system suitable network architecture using LoRa and cloud based IoT platform. They are suitable for air-borne hazard detection and monitoring in real-time.

In our other contribution, we have proposed a novel architecture for the CPS development of a network of Intelligent Gas Sensor Systems (N-IGSS) with a usable link length of 590 m for real-time sensor response reception at the remote data processing system (RDPS) using the LoRa Network Link protocol. Our N-IGSS has the ability to detect and monitor air-borne pollution hazards with 100% accuracy, as has been demonstrated using 30 test samples. The LoRa and sensor array network offers inexpensive N-IGSS development with limited battery power. The N-IGSS has been aimed at being portable, easy to use, and affordable in real-time scenarios to potentially monitor air-borne pollution hazards in real-time.

In this experiment, we have developed gas sensor nodes with seven cross-selective tin-oxide-based Metal-Oxide Semiconductors (MOX) gas sensor elements interfaced with a low-power microcontroller and a LoRa module. During the experiment, we exposed the N-IGSS to six classes of VOCs as released by burning samples of Tobacco, Paints, Carpets, Alcohol and Incense Sticks. To achieve higher performance, we have used the two-stage analysis space transformation approach. The captured dataset is first pre-processed using the Standardized Linear Discriminant Analysis (SLDA) method. Four different classifiers viz. AdaBoost, XGBoost, Random Forest (RF) and Multi-Layer Perceptron (MLP) are then trained and tested in the SLDA transformation space. The proposed N-IGSS achieves 'all correct' identification of 30 unknown test samples with a low mean squared error (MSE) of 1.42 × 10-4 over a distance of 590 m.

Encouraged with our good results, we further considered suitable design to develop a CPS compatable IoT-enabled Intelligent Gas Sensor System for detecting and classifying Volatile Organic Compounds (VOCs) in household disinfectants in real-time (IoT-IGSS) by using six tin-oxide-based metal-oxide semiconductors (MOX) gas sensor elements with a microcontroller to capture real-time signature patterns of VOCs/gases/odors released by the considered disinfectant materials when they are put to use. The data was ported to a Remote Data Processing Centre (RDPC) for further analysis. In this experiment, six different types of disinfectant materials viz hydrogen-peroxide, sanitizer and alcohol, phenyl, acid, and harpic are used, and a dataset consisting of 900 samples were captured. By analysing the data in two-stage analysis space transformations, we pre-processed the raw data using Quantile Principal Component Analysis (QPCA) and then Naïve Bayes (NB), Random Forest (RF) and Support Vector Machine (SVM) classifiers were used at the second stage of processing. The system was tested using 30 unknown VOC samples not used during training and achieved 100% classification accuracy using the SVM classifier in the QPCA transformed dataset, with a mean squared error of 2.46 × 10-6.

Our proposed system is capable of monitoring indoor air quality for the presence of various VOCs and finds potential applications in smart homes, healthcare, food processing, and environmental monitoring. Due to modular architecture, our proposed HP-IGSS can further be scaled-up for many other disinfectants for monitoring the residue VOCs/gases/odors in indoor ambiences in real-time.

In our concluding experiment, we demonstrated a method to offer a rapid, low-cost, and convenient alternative for non-invasive 'qualitative' estimation of BGL in three levels, viz. high, low and normal, using a cloud-connected e-nose architecture. We have tested our CPS suitable e-nose prototype by analyzing the responses to the exhaled breath VOCs using an array of seven tin-oxide-based metal-oxide-semiconductor (MOX) gas sensor elements interfaced with a microcontroller and gathered the data on a cloud-connected remote data processing centre (RDPC). Three volunteers, with high, low, and normal BGL, respectively, exhaled on the sensor node for 10 minutes each, at a sampling rate of 10 samples per minute before and after breakfast for three days, producing a dataset of 1800 samples. The dataset was analyzed using a two-stage analysis space transformation method at the RDPC. First, the dataset was pre-processed using the Standardized Principal Component Analysis (SPCA) space transformation method. Then, three classifiers, Decision Tree (DT), XGBoost, and multi-layer perceptron (MLP), were trained on the SPCA transformed dataset. The proposed system was tested using 30 unknown breath test samples of the volunteers. The best-performing system was an MLP trained in SPCA transformed dataset, associating each test sample correctly with the BGL of the respective volunteer and achieved an MSE of 4.42×10-5.

8.2 Conclusion

In the light of the experiments and performance so achieved, the following conclusions can be drawn:

- E-noses developed using a multi-element array of broadly tuned cross-selective sensor elements can be efficiently used to monitor a variety of airborne pollutants in real time, in indoor ambiences and in industrial situations.

- Using advanced IoT and a Cloud-connected network of e-noses, we can monitor the smoke and fire hazards and generate real-time maps of 'classes of fire' released due to the burning of different types of materials. The firefighters can use such real-time maps to choose suitable fire retardants to extinguish respective classes of fires more efficiently and safely.

- The proposed networked architectures are suitable for hazards response identification. The accuracy and effectiveness are improved by the integration of CPS in airborne hazard detection.

- Two-stage analysis space transformation-based approaches with effective pre-processing methodologies for developing highly efficient and low-cost e-noses are highly suitable for various applications to detect and estimate different gases/ VOCs and Odours.

- E-noses can also be used for the qualitative estimation of blood glucose levels (BGL) by using low-cost, broadly tuned cross-selective gas sensor arrays by analysing the exhaled breath of humans.

8.3 Scope of future work

There are several studies and tasks which can be further carried out based on the proposed methodologies and frameworks for the development of advanced e-noses:

- E-noses developed using a multi-element array of broadly tuned cross-selective sensor elements can be further designed to quantitatively estimate the target VOCs and gases. They can be further calibrated and compensated for the drift in the sensor characteristic drifts.

- Large-scale IoT and Cloud-connected networks of e-noses can be further developed for application-specific needs, and commercial systems can be developed for real-time smokes and fire hazards detection and generate real-time maps of 'classes of fire' to predict and mitigate fire hazard situations. The proposed systems can be further designed for long-term monitoring of industrial and research-grade applications for process control in various fields, such as the food and beverage industry, petrochemical industries and others.

- Truly physical system of CPS appears promising because to developments in connectivity, AI, edge computing, and cybersecurity.

- Two-stage analysis space transformation-based approaches in conjunction with effective pre-processing methodologies for developing highly efficient and low-cost e-noses can be further enhanced by using suitable convolutional and deep networks. Both stages can be implemented for real-time operations as well.

- Large-scale data gathering in clinical situations can be done for the development of intelligent gas sensor systems (IGSS) for accurate quantitative estimation of blood glucose levels (BGL) by using low-cost broadly tuned cross-selective gas sensor arrays by analysing the exhaled breath of the humans and efficient artificial intelligence (AI) algorithms and better models.