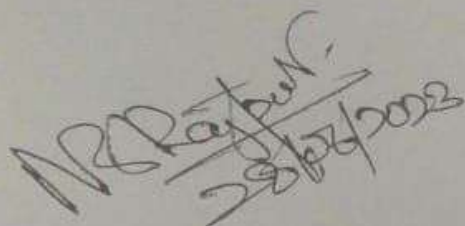


CERTIFICATE

It is certified that the work contained in the thesis titled “Sensor Response Upscaling Based Approaches For Smart Gas Sensing Systems Using Deep Networks” by “Sumit Srivastava” has been carried out under my supervision and that this work has not been submitted elsewhere for a degree.

It is further certified that the student has fulfilled all the requirements of Comprehensive, Candidacy and SOTA for the award of Ph. D. Degree.



Dr. N.S. Rajput

Supervisor

Department of Electronics Engineering

IIT (BHU), Varanasi

DECLARATION BY THE CANDIDATE

I, Sumit Srivastava, certify that the work embodied in this thesis is my own bonafide work and carried out by me under the supervision of Dr. N. S. Rajput from "25/07/2017" to "30/06/2023", at the Department of Electronics Engineering, Indian Institute of Technology (BHU), Varanasi. The matter embodied in this thesis has not been submitted for the award of any other degree/diploma. I declare that I have faithfully acknowledged and given credits to the research workers wherever their works have been cited in my work in this thesis. I further declare that I have not will fully copied any other's work, paragraphs, text, data, results, etc., reported in journals, books, magazines, reports, dissertations, theses, etc., or available at websites and have not included them in this thesis and have not cited as my own work.

Date: 28/06/2023
Place: Varanasi

Sumit Srivastava
Signature of the Student
Sumit Srivastava

CERTIFICATE BY THE SUPERVISOR

It is certified that the above statement made by the student is correct to the best of my knowledge.

N.S. Rajput
28/06/2023
Dr. N.S. Rajput
Supervisor
Department of Electronics Engineering
IIT (BHU), Varanasi

for N.S. Rajput
28/06/2023
Signature of Head-of Department
विभागाध्यक्ष/Head
"SEAL OF THE DEPARTMENT"
Department of Electronics Engineering
भारतीय प्रौद्योगिकी संस्थान
Indian Institute of Technology
(बनारस हिन्दू यूनिवर्सिटी)
(Banaras Hindu University)
वाराणसी/Varanasi-221005

COPYRIGHT TRANSFER CERTIFICATE

Title of the Thesis: Sensor Response Upscaling Based Approaches For Smart Gas Sensing Systems Using Deep Networks

Name of the Student: Sumit Srivastava

Copyright Transfer

The undersigned hereby assigns to the Indian Institute of Technology (Banaras Hindu University), Varanasi all rights under copyright that may exist in and for the above thesis submitted for the award of the Doctor of Philosophy.

Date:

Place:

28/06/2022
Varanasi

Sumit Srivastava

Signature of the Student
Sumit Srivastava

Note: However, the author may reproduce or authorize others to reproduce material extracted verbatim from the thesis or derivative of the thesis for author's personal use provided that the source and the Institute's copyright notice are indicated.

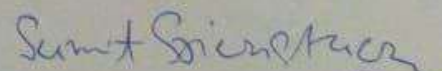
ACKNOWLEDGEMENTS

I want to express my immense gratitude to my supervisor Dr. N. S. Rajput, for accepting me as his student and allowing me to be his Ph.D. Scholar and work at R&D and Technology Extension Laboratory (NCC LAB), Department of Electronics Engineering, IIT(BHU) and in other laboratories of the Department. His support and guidance inspired me to work hard during my work. I have learned so much from my eminent supervisor that will enlighten me throughout my life. I am also grateful to his family members for sacrificing their family-time when we (me and my supervisor) were working 24/7 to finish the Ph.D. associated targets within the stipulated time. Also, I thank my research performance evaluation committee (RPEC) members, Prof. V. N. Mishra and Dr. Bhaskar Biswas, for their encouragement and insightful comments. I also would like to express my gratitude to Prof. K. P. Singh and Prof. M .K . Meshram (HoD) for their kind cooperation and encouragement during my Ph.D. journey at IIT (BHU), Varanasi. I want to express my special thanks to Dr. Saeed Hamood Alsamhi and Dr. Ashutosh Mishra for their valuable assistance in knowing the insight of Ph.D. I am thankful to my research colleagues working at NCC Lab, Dr. Shiv Nath Chaudhari, Mr. Kanak Kumar, Mr. Dharmendra Kumar, and all my colleagues from other Labs for providing a friendly environment at the IIT (BHU) Campus. My special thanks and sincere appreciations also go to all office staff members of the department for their kind cooperation.

Finally, and above all, I thank Baba Kashi Vishwanath for giving me the strength and courage to complete this doctoral work.

Date:

25/06/2023



(Sumit Srivastava)

TABLE OF CONTENTS

Chapters	Titles	Page No.
	Certificate	ii
	Declaration By the Candidate	iii
	Copyright Transfer Certificate	iv
	Acknowledgements	v
	Table of Contents	vi-ix
	List of Figures	x-xi
	List of Tables	xii
	Abbreviations	xiii-xiv
	Preface	xv-xviii
Chapters-1	Introduction and Literature Survey	1-45
	1.1 Introduction	1
	1.2 Background	2
	1.3 Objectives	2
	1.4 Gas Sensoring	3
	1.5 Gas Chromatography: The Gold Standard	5
	1.6 Gas Sensor Array	7
	1.7 Electronic Noses (e-Noses)	8
	1.8 Virtual Sensor Response(VSRs)	10
	1.9 Pattern Recognition Techniques Used in e-Nose System	11
	1.9.1 Principal Component Analysis	13
	1.9.2 Probability-Based Techniques	14
	1.9.3 Cluster Analysis-Based Techniques	15
	1.9.4 Discriminant Analysis-Based Techniques	17
	1.9.5 Nearest Neighbor-Based Techniques	18
	1.9.6 Genetic Algorithms	19
	1.9.7 Decision Tree-Based Techniques	20
	1.9.8 Support Vector Machine (SVM)	22
	1.9.9 Ensemble Techniques	23
	1.9.10 Artificial Neural Networks (ANNs)	24
	1.10 Convolution Neural Networks (CNNs)	25

1.11 Unmanned Aerial Vehicles (UAVs)	27
1.12 Search and Rescue (SAR) Operations	28
1.13 Intelligent Edge Computing	30
1.14 Literature Review	31
1.15 Problem Statements	37
1.16 Outline of the Thesis	39
1.17 Conclusion	44
Chapter-2 Materials, Methods, and Technology Background	46-63
2.1 Materials	46
2.1.1 Metal oxide semiconductors (MOX) for Gas Sensing	46
2.1.2 MOX Gas Sensors: Working	47
2.1.3 Responses of MOX Gas Sensors	48
2.1.4 Steady-State and Sampled Dynamic/Transient Responses	50
2.1.5 Dataset	52
2.2 Methods	52
2.2.1 Artificial Neural Networks (ANN)	52
2.2.2 ANN Compatibility with Array Response Modalities	56
2.3 Technology Background	57
2.3.1 A General Architecture of 2D-CNN	58
2.3.2 Motivation for Using 2D-CNN for Gas Classification	60
2.4 Conclusion	61
Chapter-3 Spatial Upscaling -Based Algorithm for Detection and Estimation of Hazardous gases	64-82
3.1 Abstract	64
3.2 Introduction	65
3.3 Material and Methods	69
3.3.1 Gas Sensor Responses /Dataset	69
3.3.2 Proposed Approach	72
3.3.3 Spatial Upscaling	72
3.3.4 Convolution Neural Network(CNN)	76
3.4 Results	78

	3.4.1	Detection Performance	79
	3.4.2	Estimation Performance	81
	3.5	Discussion and Conclusion	82
Chapter-4		A Novel Data-driven Technique to Produce Multi-sensor Virtual Responses Gas Sensor Array-Based Electric Noses	83-97
	4.1	Abstract	83
	4.2	Introduction	84
	4.3	Material and Methods	87
	4.3.1	Physical Gas Sensor Response	88
	4.3.2	Contextual Outline of Data driven VSRs	89
	4.3.3	Machine Learning Algorithm	91
	4.4	Experimental Result and Discussion	92
	4.4.1	Result	92
	4.4.2	Discussion	95
	4.5	Conclusion	96
Chapter-5		UAV Computing -Assisted Search and Rescue Mission Framework for Disaster and Harsh Environment Mitigation	98-131
	5.1	Abstract	98
	5.2	Introduction	99
	5.2.1	Related work	102
	5.2.2	Motivation	103
	5.2.3	Contribution	105
	5.3	UAV- Enabled Disaster Management Strategies	107
	5.4	UAV Computing	110
	5.4.1	SAR Missions	111
	5.4.2	AI for UAV and SAR	113
	5.5	Proposed Network Architecture	115
	5.6	Simulation Experiment Setup on OPNET	119
	5.6.1	Node Domain	120
	5.6.2	Network Domain	121
	5.6.3	Processing Domain	121
	5.6.4	Complexity Analysis	122

	5.7 Simulation Metrics of the Network Performance	123
	5.7.1 Data Traffic	123
	5.7.2 Network Load	123
	5.7.3 Throughput	124
	5.7.4 Delay	124
	5.8 Result and Discussion	125
	5.9 Conclusion	131
Chapter-6	Conclusion and Future Scope	132-139
	6.1 Conclusion	132
	6.2 Future Scope	137
Chapter-7	Author's Contribution	140
	References	141-178

LIST OF FIGURES

Table No.	Titles	Page No.
1.1	Schematic of a sensor array based on oxide, organic, metallic and two dimensional materials	8
1.2	Comparison of the mammalian olfactory and the e-nose system	9
1.3	Search and Rescue (SAR) operation	29
2.1	Application of MOS-based gas sensors in various fields and their inherent characteristics for developing efficient gas sensors	47
2.2	Response of a MOX (TGS2610) Gas Sensor for Ethylene at 125 ppm	49
2.3	Steady-State and Transient Regions of Sensor Array Responses Captured for Carbon Monoxide and Ethylene	51
2.4	A General Architecture of Artificial Neural Network	53
2.5	Perceptron Architecture	54
2.6	A Simplest Architecture of 2D-CNN	58
2.7	2D Convolution Operation	59
2.8	2D Max-Pooling Operation	59
2.9	2D-CNN for Image Classification	61
3.1	Schematic diagram of a gas sensing system's processing for classification (detection) and quantification (estimation) of hazardous gases /odors in smart city scenario	66
3.2	A Schematic curve of response modalities of a gas sensor	67
3.3	A Schematic of gas sensing by a sensing material	70
3.4	Sensor characteristics for observed hazardous gases/odor using gas sensor array	71
3.5	Flow chart for Experiment execution	74
3.6	Dirction corresponding to spatial upscaling	75
3.7	A schematic of the augmented sample (CNN ready)	75
3.8	3D scatter plot for three initial principal components(PCs)	76
3.9	A Schematic diagram of used light weight CNN	77
3.10	Convolved feature map were obtained from(a) the first convolution layer and(b) the second convolution layer	79
3.11	Confusion matrix for detection	79

3.12	A squared error plot for detection performance	81
3.13	A squared error plot for estimation performance	82
4.1	Sensor responses with dynamic ranges	87
4.2	3D scatter plots for first three principal components	87
4.3	schematic building block of an electronic nose GSA	88
5.1	Paper structure	107
5.2	Desaster management strategies	108
5.3	UAV computing –assisted disaster area	112
5.4	Artificial neural network model	115
5.5	Drones computing intelligence for assisting SAR in desaster management	117
5.6	Workflow of Experiment	119
5.7	Network components and architecture of the proposed experiment	120
5.8	Network routing traffic sent	126
5.9	Network routing traffic received from different nodes	126
5.10	Network throughput of different nodes	127
5.11	Network delay of different nodes	127
5.12	Network load for different nodes	128
5.13	Path losses from different SAR distance	130

LIST OF TABLES

Table No.	Titles	Page No.
3.1	Gas sensor array's brief detail	66
3.2	CNN Configuration	78
3.3	Performance Chart	81
4.1	Performance of the considered machine learning algorithms (classifiers) for gases/odors classification using the initial physical gas sensor	93
4.2	Performance of the considered machine learning algorithms (classifiers) for gases/odors classification using the NDSR technique –based virtual gas sensor responses	93
4.3	Performance of the considered machine learning algorithms (classifiers) for gases/odors classification using the TITO technique –based virtual gas sensor responses	94
4.4	Comparison of the performances of the considered machine learning algorithms(classifiers) for gases/odors classification using initial physical gas sensors, NDSRT,techniques –based virtual sensor responses and TITO trechniques –based virtual gas sensor responses	94
5.1	Summary of the most related work	104
5.2	Simulation environment	128

LIST OF ABBREVIATIONS

1D	One Dimensional
2D	Two Dimensional
3D	Three Dimensional
AB	AdaBoost
ace	Acetone
AddNet	Additive Neural Network AI
BPNN	Back Propagation Neural Network CA
car	Carbon Tetrachloride
CdS	Cadmium Sulphide
CNN	Convolutional Neural Network CO
CPS	Cyber-Physical System
CS	Copmressed Sensing
DA	Discriminant Analysis
DCNN	Deep Convolutional Neural Network
DFA	Discriminant Function Analysis
DiscGAN	Discriminator of Generative Adversarial Network DL
DRCA	Domain Regularized Component Analysis
DTRC	Drift Tolerant Robust Classifier
ELM	Extreme Learning Machine
EMA	Exponential Moving Average
EMK	Ethyl-Methyl Ketone
e-Nose	Electronic Nose
GA	Genetic Algorithm
GC	Gas Chromatography
GC-MS	Gas Chromatography - Mass Spectrometry
GMM	Gaussian Mixture Model
GSS	Gas-Sensing System
HCA	Hierarchical Cluster Analysis
IGS	Intelligent Gas-Sensing System
IoT	Internet of Things
JDA	Joint Distribution Adaptation

kNN	k Nearest Neighbor
LDA	Linear Discriminant Analysis
LEL	Lower Explosive Limit
MDA	Multiple Discriminant Analysis
ML	Machine Learning
MLP	Multi- Layer Perceptron
MoO	Molybdenum Oxide
MOS	Metal Oxide Semiconductor
MOX	Metal Oxide
MS	Mass Spectrometry
MSE	Mean Squared Error
OCA	Overall Classification Accuracy
PC	Principal Component
PCA	Principal Component Analysis
PPM	Parts Per Million
QCM	Quartz Crysta Microbalance
QoS	Quality of Service
RBF	Radial Basis Function
RF	Random Forest
SAW	Surface Wave Acoustic
SAR	Search and Rescue
SGD	Stochastic Gradient Descent
SnO ₂	Tin Oxide
SoC	System on Chip
SVM	Support Vector Machine
TGS	Taguchi Gas Sensor
TITO	Three Input Three Output
VGS	Virtual Gas Sensor
UAV	Unmanned Aerial Vehicle
VOC	Volatile Organic Compound
WSN	Wireless Sensor Network
xyl	Xylene
ZnO	Zinc Oxide

PREFACE

The rapid advancements in artificial intelligence (AI) and its application in various domains have transformed society and industry, making them smarter and more sustainable. However, this progress has come at a cost, as our air ambience is increasingly being polluted with hazardous gases and odors. The real-time detection and estimation of these harmful substances have become crucial for ensuring a safe and healthy environment.

This thesis focuses on the accurate detection and estimation of gas/odor using gas sensor arrays. Traditionally, highly selective gas sensors have been required for precise detection, but recent studies have shown that cross-selective gas sensors can achieve high-performance classification of gases/odors leveraging AI algorithms. This has led to the development of electronic noses (e-Noses), which utilize arrays of broadly selective gas sensor elements. By exploring innovative techniques for enhancing the performance of gas sensor arrays and by leveraging the physical sensor responses into additional virtual sensor responses, we present a novel approach based on CNNs for real-time detection and estimation of hazardous gases. The findings and methodologies discussed herein contribute to the advancement of gas sensing systems and offer valuable insights for creating safer and healthier environments.

In this research work, we propose a novel technique called the three-input and three-output (TITO) technique for deriving efficient virtual sensor responses (VSRs) from the physical gas sensor array (GSA) responses, in real-time. We demonstrate the effectiveness of our technique using a GSA consisting of four elements. Our results

show that the proposed technique significantly augments the VSRs by four times compared to its peer technique, thereby enhancing the performance of e-Noses.

To evaluate the efficacy of our proposed technique, we employ nine fundamental classifiers, including linear support vector machine, decision tree, multi-layer perceptron neural network, K-nearest neighbor, logistic regression, Gaussian process with radial basis function, linear discriminant analysis, random forest, and AdaBoost. Ten-fold cross-validation is employed to minimize biasing impact, considering intra- and inter-class variance. Remarkably, four classifiers achieve an accuracy of 100 percent, thereby validating the efficiency of our proposed technique.

Furthermore, we address the pressing need for real-time detection and estimation of hazardous gases in the air ambience. To achieve higher accuracy in this context, we present a novel approach based on the analysis of multi-element gas sensor arrays using convolutional neural networks (CNNs). The raw sensor responses are spatially upscaled and processed on the edge using lightweight CNNs. We verify our hypothesis using a four-element metal-oxide semiconductor (MOS)-based thick-film gas sensor array, fabricated by our research group. The target hazardous gases considered in this study are acetone, carbon-tetrachloride, ethyl-methyl-ketone, and xylene.

Our experimental results demonstrate that the proposed CNN-based approach accurately detects and estimates the target hazardous gases. The Mean Squared Error (MSEs) of detection is found to be 1.42×10^{-14} , while the estimation accuracy is 2.43×10^{-3} for the considered gases. The success of our designed system highlights its generic nature and potential for extension to other gases and odors of interest.

Further, during disasters, the release of hazardous gases and VOCs poses significant risks to human life and the environment. Therefore, the timely and accurate detection of these substances becomes crucial for effective disaster response and mitigation. Our proposed intelligent gas sensor systems can be deployed on UAV platforms, enabling real-time monitoring of hazardous gases and VOCs in disaster-stricken areas. The UAVs equipped with gas sensors can swiftly navigate through the affected regions, collecting and transmitting data about the concentration and distribution of hazardous substances. This information can then be processed using advanced algorithms and data fusion techniques to generate comprehensive situational maps and aid in decision-making for SAR operations. By integrating intelligent gas sensor systems with UAV-assisted SAR missions, it becomes possible to enhance the situational awareness and response capabilities of SAR teams.

Accordingly, in this thesis we have also addresses the critical component of search and rescue (SAR) operations in disaster situations, where public communication infrastructure is often damaged, impeding timely exchange of emergency data. The utilization of unmanned aerial vehicles (UAVs) emerges as a key solution to mitigate the challenges faced during disasters. UAVs offer an adaptable and reliable emergency communication backbone, facilitating swift construction of communication networks and enhancing search and rescue efforts.

Therefore, this thesis also evaluates the network performance of UAV-assisted intelligent edge computing, which demonstrates significant improvements in delay, throughput, traffic sent and received, and path loss. The proposed parameter optimization enhances network performance, thereby leading to more efficient search and rescue missions in disasters and harsh environments.

This doctoral thesis encapsulates an interdisciplinary and cutting-edge research work that contributes to the fields of gas/odor detection, environmental monitoring, and disaster management. The presented methodologies, techniques, and findings serve as valuable assets to researchers, practitioners, and policymakers alike, enabling them to develop more accurate gas sensors, enhance real-time detection capabilities, and expedite search and rescue operations in critical situations.

This thesis work has been presented in the following six chapters:

Chapter 1: presents the introduction and literature survey, starting from the very primitive historical context.

Chapter 2: presents details about MOX gas sensors and their response modalities, including the background of ANN and CNN for gas/odor classification.

Chapter 3: presents a novel data-driven technique to produce multi-sensor virtual responses for gas sensor array-based electronic noses.

Chapter 4: presents a novel spatial upscaling-based algorithm for detection and estimation of hazardous gases.

Chapter 5: presents a UAV computing-assisted search and rescue mission framework for disaster and harsh environment mitigation.

Chapter 6: concludes the thesis with the highlights of presented works and future scopes.