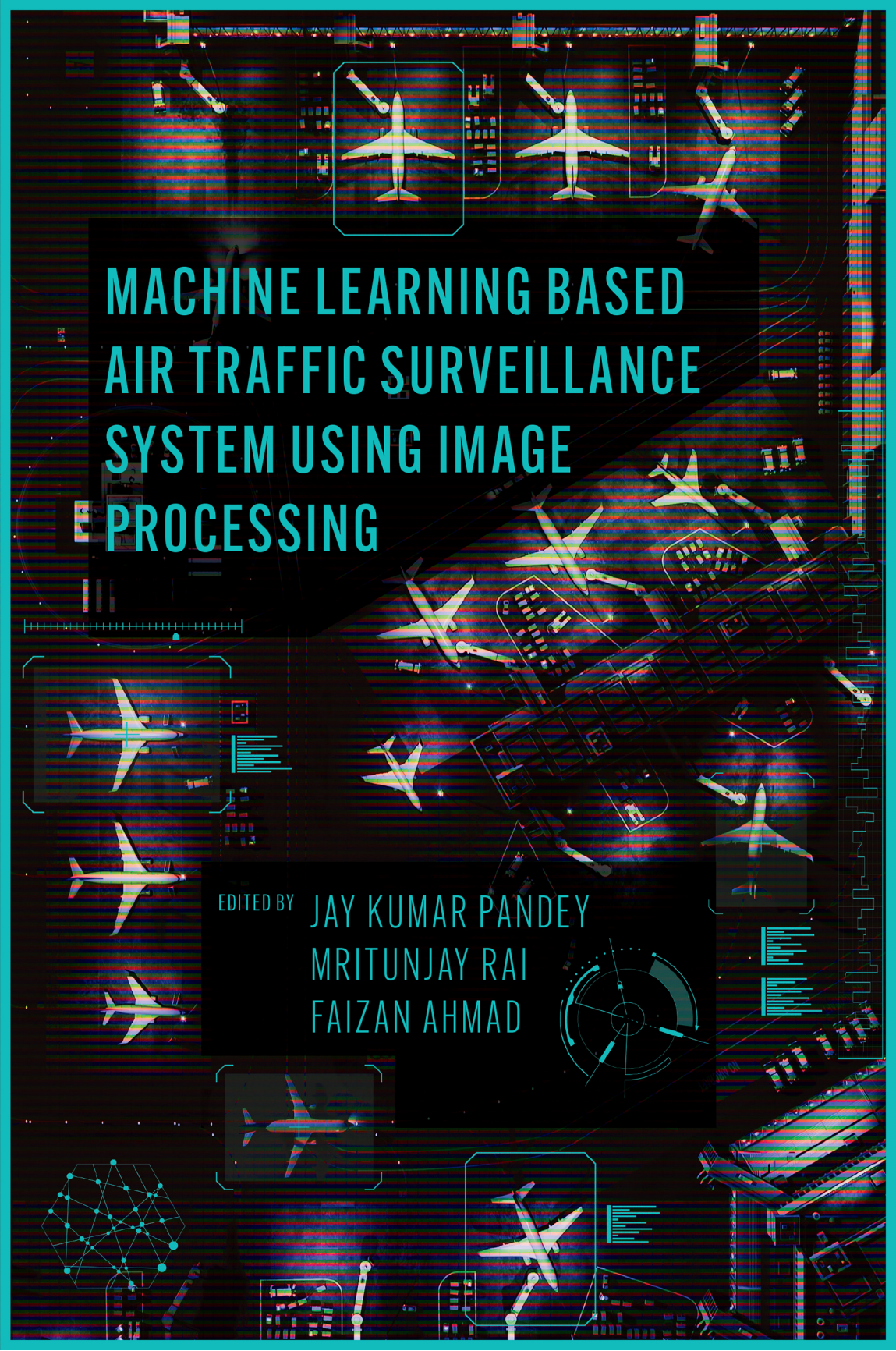

MACHINE LEARNING BASED AIR TRAFFIC SURVEILLANCE SYSTEM USING IMAGE PROCESSING
EDITED BY
JAY KUMAR PANDEY
MRITUNJAY RAI
FAIZAN AHMAD

Machine Learning Based Air Traffic Surveillance System Using Image Processing

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Machine Learning Based Air Traffic Surveillance System Using Image Processing

EDITED BY

JAY KUMAR PANDEY
Shri Ramswaroop Memorial University, India

MRITUNJAY RAI
Shri Ramswaroop Memorial University, India

AND

FAIZAN AHMAD
Cardiff Metropolitan University, UK



United Kingdom – North America – Japan – India – Malaysia – China

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INVESTOR IN PEOPLE

This book is dedicated to the aviation, machine learners, and image processors pioneers and experts whose ceaseless quest for great drives technology further in its ability to deliver safe skies. Outstanding work that has been done to integrate advanced algorithms with critical surveillance systems forms the basis of this research and inspiration.

To the researchers and engineers who imagine a future where smart machines can do for themselves manage and watch over very busy skies your work is making a way for new times in air traffic looking out. It is your wonder, creativity, and hard work that have made the change of smart watching tools, and this book is a small honor to your tries.

I also owe much gratitude to my mentors, colleagues, and collaborators who shared insights and took time to provide comments on early drafts and constructive feedback throughout the completion of the book. Your encouragement, academic rigor, and passion for solving real-world problems through interdisciplinary research have helped bring this book to life. Special thanks also go to the editor Dr. Mritunjay Rai & Dr Faizan Ahmad, whose guidance and careful review ensured clarity, consistency, and quality throughout this work. They mean so much to me.

I dedicate this book to my family above all whose unshakable belief, endless patience, and quiet giving have been the foundation of my scholarly and personal path. Your backing has been the breeze under my wings, allowing me to search the heavens of wisdom with bravery and resolve.

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List of Abbreviations and Acronyms

AAM	Advanced Aerial Mobility
ABC	Artificial Bee Colony
ABMS	Agent-Based Modeling and Simulation
ACM	Association for Computing Machinery
ACO	Ant Colony Optimization
ADS-B	**Automatic Dependent Surveillance–Broadcast**
AI	Artificial Intelligence
AI-ATM	Artificial Intelligence in Air Traffic Management
AIS	Automatic Identification System
ANN	Artificial Neural Network
ANOVA	Analysis of Variance
ANSPs	Air Navigation Service Providers
APO	Altitude Profile Optimization
ASAP	All Sky Autonomous Processing
ATC	Air Traffic Control
ATCA	Air Traffic Controller Assistance
ATCO	Air Traffic Control Officer
ATCS	Air Traffic Control System
ATFM	Air Traffic Flow Management
ATM	Air Traffic Management
ATM	Automated Teller Machine
ATMS	Air Traffic Management Systems
BP	Back Propagation
BVLoS	Beyond Visual Line of Sight
CAV	Connected and Automated Vehicle
CC-MIDNN	Clustering-based Modular Integrated Deep Neural Network
CGLS	Constraint Guided Local Search
CNN	Convolutional Neural Network
CoMPACT	Cooperative Multi-agent Path Optimization and Control Techniques
COVID-19	Coronavirus Disease
CV	Computer Vision
CVPR	Conference on Computer Vision and Pattern Recognition
DASC	Digital Avionics Systems Conference
DFE	Distance and Fuel Efficiency
DL	Deep Learning

DNN	Deep Neural Networks
DoS	Denial of Service
DRL	Deep Reinforcement Learning
DTW	Dynamic Time Warping
DUACE	Deep Unsupervised Learning Approach for Airspace Complexity Evaluation
EASA	European Union Aviation Safety Agency
EAT	Estimated Arrival Time
EGSA	Enhanced Golden Search Algorithm
EnAVs	Electric and Aerial Vehicles
ERP	Enterprise resource planning
EWC	East–West Corridor
eVTOL	Electric Vertical Take-Off and Landing
FAA	Federal Aviation Administration
Faster R-CNN	Faster Region-based Convolutional Neural Network
FastMDP	Fast Markov Decision Process
FL	Federated Learning
fNIR	Functional Near-Infrared Spectroscopy
FPGA	Field Programmable Gate Array
FUA	Flexible Use of Airspace
GA	Genetic Algorithm
GAIL	Generative Adversarial Imitation Learning
GAN	Generative Adversarial Network
GDPR	General Data Protection Regulation
GPS	Global Positioning System
GPU	Graphics Processing Unit
GRU	Gated Recurrent Unit
GS	Ground Station
HI-SLAM	Hybrid Implicit Simultaneous Localization and Mapping
HPC	High-Performance Computing
IATS	Intelligent Air Transportation System
ICAO	International Civil Aviation Organization
ICMLA	International Conference on Machine Learning and Applications
IEEE	Institute of Electrical and Electronics Engineers
IIAIS	Immunoglobulin-Inspired Artificial Immune System
IMU	Inertial Measurement Unit
IoT	Internet of Things
IP	Image Processing
LAIT	Low-Altitude Intelligent Transportation
LDACS	L-band Digital Aeronautical Communications System
LiDAR	Light Detection and Ranging
LSTM	Long Short-Term Memory
LSZ	Localized Swarm Zone
M-ADRL	Multi-Agent Deep Reinforcement Learning
MAPE	Mean Absolute Percentage Error
MARL	Multi-Agent Reinforcement Learning

Mask R-CNN	Mask Region-based Convolutional Neural Network
MITM	Man-in-the-Middle
ML	Machine Learning
MOT	Multiple Object Tracking
NASA	National Aeronautics and Space Administration
NASA-TLX	NASA Task Load Index
NCNN	New Convolutional Neural Network
NLP	Natural Language Processing
OSN	OpenSky Network
OSTI	Office of Scientific and Technical Information
PCF	Path Curvature and Flexibility
PE	Performance Evaluation
PFO	Pigeon Feather Flight Path Optimization
PSO	Particle Swarm Optimization
R-CNN	Region-based Convolutional Neural Network
RFC	Random Forest Classifier
RL	Reinforcement Learning
RMSE	Root Mean Square Error
RNAV	Stands for Area Navigation
RNN	Recurrent Neural Network
ROC	Receiver Operating Characteristics Curve
ROCHE	F. Hoffmann-La Roche AG
RS	Radar System
RT-DETR	Real-Time Detection Transformer
SA	Simulated Annealing
SC	Spatial Completion
SC	Surveillance Cameras
SEIP	Software Engineering in Practice
SESAR	Single European Sky ATM Research
SHAP	SHapley Additive exPlanations
SI	Swarm Intelligence
SI	Satellite Imagery
SLA	Service Level Agreement
SLAM	Simultaneous Localization and Mapping
SSD	Single Shot Multibox Detector
TDCP	Traffic Density and Conflict Potential
TMA	Terminal Maneuvering Area
TNNLS	Transactions on Neural Networks and Learning Systems
UAM	Urban Air Mobility
UAS	Unmanned Aircraft Systems
UAV	Uncrewed Aerial Vehicle
UAV	Unmanned Air Vehicles
UTM	UAV Traffic Management
VIO	Visual-Inertial Odometry
WAC	Weather and Airspace Constraints
XAI	Explainable AI

YOLO	You Only Live Once
YOLO	You Only Look Once
3D	Three-Dimensional (latitude, longitude, and altitude)
4D	Four-Dimensional (latitude, longitude, altitude, and time)
5G	Fifth-Generation Cellular Network
6G	Sixth-Generation Wireless Systems
125E	Specific Flight Path within the RNAV system
5 NM	Five Nanometers
km^2	Square Kilometers
km	Kilometer

About the Editors

Jay Kumar Pandey is currently working as an Assistant Professor in the Department of Electrical and Electronics Engineering at Shri Ramswaroop Memorial University, Barabanki (U.P.), India. He has completed his Ph.D. and has done his M.Tech. with specialization in Power Control (Instrumentation) and also done his MBA in Finance and Marketing. His subjects of interest are related to artificial intelligence, biomedical and healthcare, image processing, machine learning, and renewable energy. He has 15 years of teaching and research experience and has published more than 30 research papers in national and international journals/conferences and book chapters in CRC, NOVA, Taylor & Francis, Springer, and IGI Publisher. He is an editor of books (edited) published by reputed publishers Apple Academy Press, IGI, Elsevier, Wiley-IEEE, NOVA, Bentham Science, IAP, Emerald Publication, Taylor& Francis, and Cambridge Scholar. He is also Editor of *Journal of Technology Innovations and Energy United States*. He is a reviewer in different conference/journal/book chapters like *The Journal of Supercomputing in Springer Nature*, IGI publishing, *Journal of Security and Communication Networks Hindawi*, *Journal of Biomimetics, Biomaterials and Biomedical Engineering (JBBBE),* Scientific Net, Switzerland, Advanced Engineering Forum (AEF) Scientific Net, Switzerland.

Mritunjay Rai is currently working as an Assistant Professor in the Department of Electrical and Electronics Engineering at Shri Ramswaroop Memorial University, Barabanki (U.P.), India. He has completed his Ph.D. in Thermal Imaging Applications in the Department of Electrical Engineering from IIT-ISM Dhanbad in 2022, Master of Engineering (with distinction) in Instrumentation and Control from Birla Institute of Technology-Mesra, Ranchi, in 2013, and B.Tech. in ECE from Shri Ramswaroop Memorial College of Engineering and Management, Lucknow in 2009. He has more than 12 years of working experience in research as well as academics. In addition, he has guided several UG and PG projects. He has published many research articles in reputed journals published by Springer, Elsevier, IEEE, Inderscience, and MECS. He has contributed many chapters to books published by Intech Open Access, CRC, IGI Global, and Elsevier. He is an editor of books (edited) published by reputed publishers: Wiley, AAP, and IGI. He is an active reviewer and has reviewed many research papers in journals and at international and national conferences. His areas of interest lie in image processing, speech processing, artificial intelligence, machine learning, deep learning, intelligent traffic monitoring system, the Internet of Things, and robotics and automation.

Faizan Ahmad is a Lecturer in Computer Science and/or Games Development at Cardiff School of Technologies, Cardiff Metropolitan University. Prior to joining Cardiff Met, he worked as a Tenure-Track Assistant Professor/Leader of the Research Centre for Human–Computer Interaction (2018–2022) and Research Associate (2010–2011) in a well-reputed university of Pakistan where he was responsible for curriculum design, teaching, research, supervisory, moderation, and consultancy in human–computer interaction domain. He received his Ph.D. in Computer Science and Technology from the Institute of Computing Technology, Chinese Academy of Sciences in 2017, and his M.S. (Distinction) in Computer Applied Technology from the School of Computer Science and Engineering, Beihang University in 2013.

About the Contributors

Mostafa Abotaleb is currently pursuing the Ph.D. degree in Developing Artificial Intelligence and Machine Learning Models with South Ural State University, Russia (Direction of Physics and Mathematics). He is also a Faculty Member with the Computer Science Department, South Ural State University. Then, he became a Research Engineer in Advanced Research with the Department of System Programming, University of South Ural. In 2021, he got a patent from the Russian Federation for developing a library for forecasting COVID-19 infection cases using R programming. He has many publications related to developing deep learning models and classical models to improve the forecast through minimizing the error of forecast. The connected machine learning algorithms in the drone can perform some advanced tasks. His aim is to discover a learning procedure that is efficient at finding complex structures in large, high-dimensional datasets.

R. Anita received a Bachelor's degree in Computer Science and Engineering from Rajaas Engineering College of Manonmaniam Sundaranar University, Tirunelveli, in 2004, and a Master's degree in Computer Science and Engineering from Sathyabama University, Chennai, in 2012. She has finished her Ph.D. in the Natural Language Processing domain in the year 2022 at SRM Institute of Science and Technology, India. She is currently working as Assistant Professor in the Department of Computing Technologies, SRM Institute of Science and Technology, Kattankulathur campus, Tamil Nadu, India. She has 18 years of teaching experience. She has published her research papers in various refereed international journals and conferences. Her research interests incline toward the domains, namely, natural language processing, computational linguistics, machine learning, and deep learning. She has obtained the Certificate of Excellence in three Samsung Prism research project worklets titled "Online Handwriting Recognition for Indic Languages," "English–Tamil Code-switched Spoken Language Identification," and "Speech-to-Speech Translation."

Raed Awashreh. is a Professor of Management and Public Administration with over 25 years of combined experience in academia and industry. He has worked in the UAE, Oman, and the West Bank, teaching undergraduate and postgraduate courses, supervising theses, serving as a postgraduate thesis examiner, and actively contributing as a researcher, reviewer for several academic journals. He has published 55 articles, multiple book chapters, and 3 books on topics such as human

resources, governance, public policy, strategy, leadership, entrepreneurship, innovation, multidisciplinary applications of artificial intelligence, and management. In addition to his academic work, he serves as a consultant in strategy, management, governance, human resources, and organizational development, collaborating with government, private, and non-governmental sectors. He holds Doctorate degree in Public Administration and Management from Flinders University in Australia and Master's degree from Middlebury (Monterey) Institute of International Studies, the USA (ORCID: 0000-0002-2252-0299).

Bremananth Ramachandran. has completed a Ph.D. in Computer Science in 2008, Post-Doc (PDF) in Information Engineering from NTU, Singapore, and has 25+ years of experience in teaching, research, and software development. He received the M. N. Saha Memorial Award for the Best Application Oriented Paper in the year 2006 from the Institute of Electronics and Telecommunication Engineers (IETE) for the *IETE Journal of Research*. His continuous contribution of research was recognized by Who's Who in the world, USA, and his biography was published in the year 2006. Currently, his *H*-index is 10 as per Google Scholar citation references and his name is listed in the Top 400 Scientists among Oman institutions at webometrics.info. He is a member of Indian Society of Technical Education, Advanced Computing Society, International Association of Computer Science and Information Technology, and IETE (ORCID: 0000-0003-1522-486X).

J. Briskilal received a Bachelor's degree in Computer Science and Engineering from T. J. Institute of Technology, Anna University, Chennai, in 2012, and a Master's degree in Computer Science and Engineering from S. K. R. Engineering College, Anna University, Chennai, in 2014. She has finished her PhD in the Natural Language Processing domain in the year 2023 at SRM Institute of Science and Technology, India. She is currently working as Assistant Professor in the Department of Computing Technologies, SRM Institute of Science and Technology, Kattankulathur campus, Tamil Nadu, India. She has eight years of teaching experience. She has published her research papers in various refereed international journals and conferences. Her research interests incline toward the domains, namely, natural language processing, machine learning, and deep learning. She has obtained the Certificate of Excellence in three Samsung Prism research project worklets titled "English–Telugu Code-switched Spoken Language Identification" and "Speech-to-Speech Translation."

Asma Channa is currently working as a Visiting Researcher at Khalifa University, Abu Dhabi. She previously served as an Artificial Intelligence Researcher at the iTSM Group. She holds a double Ph.D. in Computers and Information Technology, earned in 2023 through the A-WEAR project, funded by the European Union's Horizon 2020 Marie Skłodowska-Curie Actions program. During her academic journey, she also completed an industrial secondment at CITST in Romania. Her research expertise spans wearables, machine learning, generative artificial intelligence, and healthcare.

Petros Chavula is a highly qualified professional with a diverse educational background in agricultural and environmental sciences. He holds an M.Sc. in Agricultural Economics from the University of Zambia, an M.Sc. in Climate-Smart Agriculture from Haramaya University, and a B.Sc. in Agroforestry from Copperbelt University. His career has been marked by significant contributions in research and development. As an Associate Researcher at ICRAF/CIFOR, he managed baseline research and implemented projects focusing on agroforestry, biodiversity, and climate change. His responsibilities included developing program evaluation frameworks, research proposal writing, data analysis, and facilitating focus group discussions. In his role as Programme Officer at FIAN International, he demonstrated his analytical and problem-solving skills. Throughout his career, he has shown a strong commitment to sustainable agriculture and environmental conservation, combining his academic knowledge with practical field experience to drive positive change (https://orcid.org:0000-0002-7153-8233).

Hridoy Das is a passionate Data Scientist with a specialization in machine learning, artificial intelligence, and statistical analysis. He holds a B.Sc. in Computer Science and Engineering (specialization in Data Science) from United International University, Dhaka, Bangladesh. Currently, he is working as a Data Engineer at Piana Technologies, where he focuses on developing scalable data-driven solutions. His expertise spans predictive analytics, deep learning, computer vision, and data visualization. He has contributed to various artificial intelligence (AI)-powered projects, including DeafTech Vision, a deep learning-based American Sign Language analysis system, and ThreatScan, a cybersecurity analytics tool. His research work covers areas like ensemble deep learning for multi-class hair fall disease classification and fine-grained student behavior detection using hybrid YOLO models. His research interests include machine learning and deep learning, AI in aviation and smart air traffic monitoring, predictive analytics and cybersecurity, and computer vision and image processing. He has published in reputable conferences and journals, contributing to the growing field of AI and data science innovation.

Ankur Gupta is a PhD scholar in the Department of Computer Science and Engineering at Dr. K. N. Modi University, Newai, Rajasthan, India. He is actively involved in research and academic projects, contributing to advancements in his field.

Sanjeev Kumar Gupta is a Professor and Dean at Rabindranath Tagore University, Bhopal. With a career spanning over two decades, he specializes in wireless communication, sensor networks, and embedded systems. He has published 62 research papers in reputed journals and guided eight M.Tech. and thirteen Ph.D. scholars. A Fellow of Institute of Electronics and Telecommunication extensively to academic events and research initiatives nationwide.

Linety Juma is a highly qualified professional with a diverse educational background in Curriculum Development and Technology. She holds B.Ed. Arts (History and Religion) from Masinde Muliro University of Science and Technology. She is currently studying her M.Ed. in Curriculum Development and Technology at Pwani University. Her career has been marked by significant contributions in tutoring, research, and development. As a collaborative researcher, she has authored more than five multidisciplinary articles. In her role as Curriculum Development Programme Officer, she demonstrates her analytical and problem-solving skills. She identified issues, analyzed key factors, and developed innovative solutions to inform management decisions. Her work also involves integrating artificial intelligence (AI) in education, conducting AI awareness campaigns, and enhancing local government responsiveness. Throughout her career, she has shown a strong commitment to sustainable educational development combining her academic knowledge with practical field experience to drive positive change.

Fredrick Kayusi is a Kenyan Academician; he was born in Kisii, Kenya, in 1991. He received his B.Ed. degree in Mathematics and Geography from Masinde Muliro University of Sciences and Technology, Kenya, in 2015. He received an M.Sc. degree in 2023 from the Environmental Sciences Department, Pwani University, in the field of Geosciences, and he is currently pursuing his Ph.D. from Pwani University in the field of Geosciences and is working as an Adjunct Lecturer and an academic member of staff in the Environmental Studies, Geography and Planning Department at Maasai Mara University, Kenya. He has authored over 50 publications, including papers/chapters, preprints, presentations, and posters. He is also a peer reviewer for more than 10 international/national journals. He has served as a consultant on technical climate change program committees in Kenya.

Saifullah Khalid is an Assistant General Manager at the Civil Aviation Research Organization, Airports Authority of India, and a Post-Doctoral Researcher at Lincoln University College, Malaysia. He holds a Ph.D. in Electrical Engineering from Dr. APJ Abdul Kalam Technical University, India. His research interests include intelligent control optimization algorithms, artificial intelligence applications in electrical engineering, and renewable energy sources. He has published over 250 research papers, authored 9 books, and secured 82 patents. He has been recognized with numerous awards, including world records for maximum patents achieved in a single day. He has served as a Visiting Researcher at Nanyang Technological University, Singapore, and has extensive experience in air traffic management at international airports in India. He is a Senior Member of IEEE and a reviewer for several prestigious electrical engineering and power systems journals.

Fawad Ali Mangi completed his Bachelor's and Master's degrees in Computer Systems Engineering from Mehran UET, Jamshoro. He pursued his Ph.D. at the University of Wollongong, Australia. Currently, he is serving as an Assistant Professor in the Department of Computer Systems Engineering at Mehran UET, Jamshoro. His research interests include artificial intelligence, data mining, and process mining.

Madeha Memon received B.E. and M.E. degrees in Computer Systems Engineering (CSE) from Mehran University of Engineering and Technology, Sindh, Paksitan. Her research interests include computer vision and deep learning. Currently, she is working as a Lecturer at CSE Department, Mehran University.

Maad M. Mijwil is an Iraqi Academician; he was born in Baghdad, Iraq, in 1987. He received his B.Sc. degree in Software Engineering from Baghdad College of Economic Sciences University, Iraq, in 2009. He received an M.Sc. degree in 2015 from the Computer Science Department, University of Baghdad, in the field of wireless sensor networks, Iraq. Currently, he is a Director of the Division of Quality Assurance and Performance at the College of Administration and Economics, Al-Iraqia University. He is working as a Lecturer and an academic member of staff in the Computer Techniques Engineering Department at Baghdad College of Economic Sciences University, Iraq. He has over 10 years of experience in teaching, guiding projects for undergraduates, and laboratory sessions. He has authored 169 publications, including papers/chapters (published 157 peer-reviewed papers in national/international conferences and journals), preprints, presentations, and posters. His Google citations are over 3,700 marks.

Rashmi Mishra is incredibly passionate about the world of commerce and education. With a Doctorate in Commerce, she has specialized in various areas, including economics, supply chain management, quality management, and human resources. She has been fortunate to work in the academic field for over 16 years, and it has been a fulfilling journey so far for her. Her interest in economics has been a driving force in her academic pursuits. She has delved deep into economic theories and their practical applications, becoming recognized for her expertise in this dynamic field. Additionally, supply chain management has always intrigued her. Quality management is something she genuinely believes in, and she has made it a mission to ensure that educational programs meet the highest standards of quality and relevance. In human resources, she has worked to create a positive and nurturing work environment for everyone involved in the education process.

Dinesh Chandra Misra serves as an Associate Professor in the Department of Computer Science and Engineering at Dr. K. N. Modi University, Newai, Rajasthan, India. With extensive teaching and research experience, he has made significant contributions to academia through scholarly publications, mentoring research scholars, and curriculum development. He actively participates in knowledge-sharing forums and emphasizes innovative problem-solving within the field of computer science.

Saurabh Mitra is an Associate Professor and Head of Electronics and Communication Engineering at Dr. C. V. Raman University, where he also serves as Vice Principal and President of the Institution Innovation Council. With 13+ years in academia, he has authored 4 books, published 37 international research papers, and led a ₹4.68 crore DST-funded incubation project.

Ankur Mittal is currently a Research Scholar in the Department of Electronics and Communication Engineering at the National Institute of Technology (NIT) Delhi. His research interests include Artificial Neural Network. At NIT Delhi, he is engaged in advancing work in his domain and has contributed to academic publications and conference presentations in the field of Electronics and Communication Engineering.

Sanam Narejo holds a Bachelor's and Master's degree in Computer Systems Engineering from Mehran UET, Jamshoro. She earned her PhD in Machine Learning and Deep Learning from Politecnico di Milano, Italy. Currently, she serves as the Coordinator of the Bachelor of Computer Science program at Mehran UET, Jamshoro. Her research interests include machine learning, deep learning, natural language processing, and generative artificial intelligence.

Rajat Pandit is an accomplished academician and researcher specializing in Computer Science. Born on May 9, 1977, he has made significant contributions to the fields of natural language processing, machine learning, and mobile computing. With a Ph.D. from Jadavpur University and West Bengal State University, his Doctoral research focused on Computational Semantics in Bengali, establishing his expertise in low-resource languages. Currently, an Assistant Professor at West Bengal State University, he has over two decades of teaching and research experience. His research interests encompass machine translation, sentiment analysis, text summarization, semantic similarity, and speech processing. He has authored 3 edited books, 2 book chapters, and 23 journal publications, many of which are indexed in SCIE and other reputed platforms. He is actively involved in academic and administrative roles, serving on various committees at his university and contributing as a visiting faculty, external examiner, and syllabus committee member for other institutions. He is also recognized for his invited talks on topics like machine learning, big data, and Internet of Things. A dedicated mentor, he supervises Ph.D. research and continuously contributes to advancing knowledge in computational sciences. He is fluent in Bengali, English, and Hindi and resides in Kolkata, India, with his family.

R. Pavithra is currently serving as an Assistant Professor in the Department of Computer Science and Engineering at Coimbatore Institute of Technology, where she has been a faculty member since 2011. She holds a Master's degree in Engineering from PSN College of Engineering and Technology, and pursuing her Ph.D in the domain Machine Learning. With over a decade of academic and research experience, her areas of interest include image processing, computational intelligence, and machine learning.

Sheeja Pon Chakravarthy is currently serving as an Assistant Professor in the Department of Computer Science and Engineering at Coimbatore Institute of Technology, Coimbatore, since 2023. She holds an M.E. from Anna University – Tirunelveli. Her research interests span Internet of Things, cyber security, and quantum computing. She has contributed to several reputed publications, including a book chapter on 6G wireless communication and a conference paper on responsible artificial intelligence. Notably, she has received accolades such as the

"Role Model of the Year" award by Women in Cloud and CIONews (2024) and the "Best Teacher Award" (2013). Her work on cloud profiling and optimization strategies has been published in AIP conference proceedings, demonstrating her dedication to advancing computing technologies.

Anu Prabhakar is currently serving as an Assistant Professor in the Department of Computer Science and Engineering at Coimbatore Institute of Technology since 2023. She holds an M.E. degree from Sona College of Technology, obtained in 2013. With over a decade of academic experience, she has previously worked as an Assistant Professor at KMCT Engineering College, Manassery, Mukkam (2014–2016), and as a Lecturer at the National Institute of Technology, Calicut (2013–2014). Her academic journey reflects a strong commitment to teaching and research in computer science and engineering; her areas of interest include digital design, artificial intelligence, and machine learning.

Vidit Datt Prabhakar is a Ph.D. scholar at the National Institute of Technology Delhi, in the Department of Electronics and Communication Engineering. His research focuses on video stabilization for unmanned aerial vehicles (UAVs) under dynamic and random motion. His broader areas of interest include artificial intelligence, image processing, brain–computer interfaces, and UAV-based computer vision applications.

C. Pretty Diana Cyril is an Assistant Professor in Department of Computing Technologies, SRM Institute of Science and Technology, SRM Nagar, Kattankulathur, Tamil Nadu, India. She has 18 years of teaching experience in various reputed engineering colleges in Chennai. She received her Bachelor's degree in Information Technology, in 2005, from Anna University, Chennai. She also obtained her Masters of Engineering (M.E.) with distinction in 2010 and Doctor of Philosophy (Ph.D.) in 2019 from Sathyabama University and St. Peter's Institute of Higher Education and Research, respectively. She is a Member of Association for Computing Machinery, IEEE, IAENG, OWSD, and Life-time Member of Indian Society for Technical Education. Her research interests are image processing, Internet of Things, block chaining, machine learning, and data mining. She has published various research papers in international journals and conferences.

Piyal Roy is an accomplished academician in the field of computer science and engineering. He has completed his B.Sc. in Computer Science, M.Sc. in Computer Science and M.Tech. in Computer Science and Engineering. Currently, he is working as an Assistant Professor at Computer Science and Engineering Department at Brainware University, India.

Smaranika Roy is an Assistant Professor at Sarada Ma Girls' College, Barasat, with expertise in Computer Science. She completed her Master's degree in Computer Science in 2020 from West Bengal State University and earned the distinction of university topper for her postgraduate batch (2018–2020). She also holds a Bachelor's degree in the same field, along with a strong foundation established through her secondary and higher secondary education in West Bengal. Her academic endeavors

are complemented by her research contributions, including publications on Bengali text sentiment analysis and steganography techniques in reputed journals.

Wasswa Shafik (IEEE member) is the Team Lead at the Dig Connectivity Research Laboratory in Kampala, Uganda. He holds a Ph.D. in Computer Science from Universiti Brunei Darussalam and a Master's in Information Technology Engineering from Yazd University, Iran. He also earned a Bachelor's in Information Technology from Ndejje University, Uganda. He has received specialized training from the National Institutes of Health, the US Department of Health and Human Services, and the Bloomberg School of Public Health. His research focuses on artificial intelligence, computer vision, and Internet of Things applications in smart agriculture, digital health, and ecological informatics (ORCID: 0000-0002-9320-3186).

Saisuman Singamsetty is currently contributing as a researcher and industry practitioner in the domains of data governance, federated learning, and blockchain-enabled innovation. He has authored peer-reviewed publications, book chapters, and presented his work at major IEEE and Springer conferences. He has delivered keynote talks at international technology summits on AI-driven innovation in healthcare, finance, and smart cities. He has also judged global hackathons, including Major League Hacking and the Johns Hopkins Health Hackathon in collaboration with VIT, and serves as a reviewer for international journals and conferences. He is a Senior Member of IEEE and holds memberships with Sigma Xi, IETE, and RAPTHORS. His work focuses on advancing trustworthy, scalable, and ethical digital systems.

Mahesh K. Singh obtained his Ph.D. degree in Electrical Engineering Department from the Indian Institute of Technology Kanpur, India, in 2018. Since 2018, he is working as an Assistant Professor in the Department of Electronics and Communication Engineering at the National Institute of Technology, Delhi. His research interests include computer vision, robotics, signal and image processing, biomedical image processing, machine learning and pattern recognition, artificial intelligence, data science, and analysis.

Nitin Singh Singha is an Assistant Professor of Electronics and Communication Engineering with the National Institute of Technology Delhi, Delhi, India. His areas of interest include peer-to-peer networks, social networks, game theory, and artificial intelligence.

Shahnawaz Talpur did his Bachelors and Masters from Mehran UET, Jamshoro in 2001 and 2006, respectively. He received his Ph.D. in 2014 from Beijing Institute of Technology, China, in Computer Software and Theory. Currently, he is Chairman of the Department of Computer Science and Engineering in Mehran UET, Jamshoro. He published more than 15 journal papers and presented around 15 conference papers in the USA, the UK, Italy, South Korea, etc. His research areas are computer architecture, high performance computing, and machine learning.

Foreword

The era of air traffic management is at a turning point. The skies are filling up, and the pressures on safety, efficiency, and environmental sustainability are at an all-time high. While radar has been the cornerstone of air traffic surveillance for decades, there is now a clear need for more intelligent and advanced systems. This book, *Machine Learning Based Air Traffic Surveillance System Using Image Processing*, presents a vision of the future that is engaging and compelling, underscoring the revolutionary potential of machine learning and image processing to transform the way we monitor and control air traffic.

The contributors to this book have assembled a compilation of state-of-the-art research that illustrates the capability of these technologies for improving our situational awareness, automating essential functions, and ultimately making air travel safer and more efficient. Through the application of advanced image processing algorithms, the book explains how visual information from a variety of sources can be used to create a better and fuller understanding of the airspace. Also, it shows how machine learning algorithms can be used to train on this data to extract useful information from it and allow systems to learn and make smart decisions.

This publication is specifically opportune because the aviation world is already making inquiries into cutting-edge technologies with a view to resolving the demands of the 21st century. From unmanned aerial vehicles' integration into commercial airspaces to efficient air traffic control systems, surveillance technology capable of advanced handling remains topmost. This book offers useful insights on how machine learning and image processing can be used to support such advances, opening the door to a future where air travel is safer, more efficient, and more sustainable.

I applaud the authors for their thought-provoking contributions and for offering a rich resource for researchers, engineers, and practitioners alike in this field. This book represents an important milestone toward unleashing the complete potential of machine learning and image processing in air traffic surveillance, and I am sure that it will motivate more innovation and progress in this essential area.

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Preface

The skies above, once plotted by less sophisticated means, are now a crowded and high-tech environment. The growing amount of air traffic combined with the ever-growing requirement for improved safety and efficiency requires creative solutions to air traffic monitoring. Conventional radar-based methods, though effective, are limited by resolution, coverage, and the possibility of high-level information extraction from the monitored data. This book, *Machine Learning Based Air Traffic Surveillance System Using Image Processing*, discusses a paradigm shift in this important field with emphasis on the revolutionary potential of machine learning (ML) and image processing.

This volume confronts the challenges facing contemporary air traffic observation through an explanation of the symbiotic relationship between ML and image processing. It goes beyond established practices, to give a comprehensive treatment of how image data, obtained from multiple sources, may be cleverly processed and analyzed in order to offer fuller, more accurate, and more actionable intelligence. We discuss how ML algorithms could be taught to identify, track, recognize, and even forecast aircraft behavior with unparalleled accuracy.

The chapters in this book span a broad spectrum of subjects ranging from the basic concepts of image acquisition and processing to the complexities of deep ML architectures. We delve into the application of computer vision methods to derive meaningful features from visual inputs so that ML models can learn subtle patterns and associations. The book presents real-world applications, illustrating how the technologies can be applied to enhance air traffic management, safety protocols, and enable future developments in aviation.

This volume is written for researchers, engineers, and practitioners in the communities of air traffic control, aviation safety, computer vision, and ML. It is designed to be an authoritative guide to those who aspire to comprehend and create the future generation of air traffic surveillance systems. It is our hope that this book will help make the skies safer, more efficient, and more sustainable for everyone.

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Acknowledgments

The process of developing this book, *Machine Learning Based Air Traffic Surveillance System Using Image Processing*, has been a team effort, and we are sincerely thankful to the numerous individuals and organizations who have helped in its completion.

Above all, we would like to extend our deepest appreciation to the contributing authors, whose knowledge and passion have played a pivotal role in developing the rich and comprehensive material of this book. Their openness to presenting their pioneering research and findings has been extremely beneficial.

We would also like to thank the encouragement and guidance of our Emerald Publishing editors, especially Nick Wallwork for their unflinching support, tolerance, and valuable advice throughout the publication process. Their professionalism and dedication to quality have been most appreciated.

We could not have conducted our research without the support of different funding agencies and institutions. We would like to acknowledge the support we received from our university.

We also appreciate the researchers and engineers who have been the early leaders in developing the field of machine learning, image processing, and air traffic monitoring. Their pioneering work has provided the basis for the developments here described.

Lastly, we would like to express our gratitude to our families and friends for their steadfast encouragement, support, and patience in understanding our numerous long working hours doing research, writing, and editing this book. Their patience and love have been a source of strength.

We trust that this book will be a useful reference for the community and will inspire more innovation in the practice of air traffic surveillance.

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Chapter 1

Advanced Image Processing Techniques for Smart Air Traffic Monitoring

Hridoy Das

Department of Computer Science and Engineering,
United International University, Bangladesh

Abstract

Integrating advanced image processing techniques in air traffic monitoring has significantly enhanced air traffic management (ATM) systems' accuracy, efficiency, and real-time responsiveness. This chapter presents a comprehensive analysis of state-of-the-art methodologies, including artificial intelligence (AI)-driven object recognition, motion detection, and multi-resolution image analysis, to address critical challenges such as congestion management, collision avoidance, and optimized airspace utilization. Unlike traditional radar-based systems, which struggle with scalability and environmental limitations, this work explores deep learning (DL)-based detection frameworks, including convolutional neural networks (CNNs) and optical flow techniques, to improve aircraft tracking under diverse conditions. Additionally, the chapter evaluates real-time processing challenges and proposes edge computing solutions to enhance computational efficiency. A comparative analysis of existing approaches highlights the advantages of AI-enhanced image processing over conventional methods. The discussion also addresses key implementation challenges, such as computational complexity, data integration, and regulatory considerations. This chapter provides valuable insights into the future of smart air traffic surveillance by examining practical applications, case studies, and emerging trends such as transformer-based models and federated learning.

Keywords: Image processing; air traffic monitoring; machine learning; object recognition; predictive analytics; real-time systems

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1.1. Introduction

Air traffic monitoring is a critical component of modern aviation systems, ensuring the safe and efficient movement of aircraft across increasingly congested airspaces. Traditional ATM systems rely heavily on radar and radio communication, which, while effective, face limitations in accuracy, scalability, and adaptability to dynamic environmental conditions (Strohmeier et al., 2014). The rapid growth in global air traffic, coupled with the emergence of unmanned aerial vehicles (UAVs) and urban air mobility (UAM) systems, has further exacerbated these challenges, necessitating the development of more advanced and intelligent monitoring solutions (Kopardekar et al., 2016). Object tracking is a fundamental problem in computer vision, with numerous applications in surveillance, robotics, and autonomous systems (Yilmaz et al., 2006) provide a comprehensive survey on tracking methodologies, categorizing them into point tracking, kernel tracking, and silhouette tracking, each with its advantages and limitations. In the context of UAV navigation, accurate position and orientation estimation is crucial for stability and control (Zhang et al., 2020) propose a vision-based approach that enhances estimation accuracy, leveraging advanced computer vision techniques. The integration of machine learning (ML) into tracking algorithms has further improved performance, making real-time object tracking more robust and efficient.

The application of image processing in air traffic monitoring addresses several critical issues, including congestion management, collision avoidance, and optimized airspace utilization. For instance, advanced motion detection algorithms can identify and track multiple aircraft simultaneously, while multi-resolution image analysis techniques enable the extraction of detailed features from high-altitude or low-resolution images (Mueller et al., 2017). Additionally, AI-driven object recognition systems have demonstrated remarkable accuracy in distinguishing different aircraft types, UAVs, and other airborne objects, facilitating more effective traffic management and regulatory compliance.

Despite these advancements, integrating image processing techniques into real-world air traffic monitoring systems presents several challenges. These include the computational complexity of processing large volumes of visual data in real-time, the need for robust data integration across diverse sources, and the requirement for scalable solutions that can adapt to the growing demands of global air traffic (Xu et al., 2018). Addressing these challenges requires interdisciplinary collaboration, innovative algorithmic approaches, and the adoption of emerging technologies such as edge computing and 5G networks.

This chapter explores cutting-edge image processing methodologies and their transformative impact on air traffic monitoring. It provides a detailed comparison between traditional ATM systems and AI-powered solutions, evaluates real-time processing challenges, and discusses practical applications such as congestion management, collision avoidance, and predictive maintenance. Furthermore, this work highlights key challenges such as computational complexity, data

integration, and regulatory constraints, while also exploring future directions, including the potential of transformer models and federated learning for enhanced security and efficiency. By presenting case studies and real-world examples, this chapter aims to provide valuable insights for researchers, industry professionals, and policymakers working toward a safer, more intelligent, and scalable air traffic monitoring ecosystem.

1.2. Methodology

The application of image processing techniques in air traffic monitoring involves a combination of advanced algorithms, ML models, and real-time data processing frameworks. This section outlines the key methodologies employed in modern air traffic monitoring systems, focusing on their technical foundations and practical implementations (Verma et al., 2024).

1.2.1. Image Acquisition and Preprocessing

The first step in image-based air traffic monitoring is the acquisition of high-quality visual data from various sources, such as CCTV cameras, satellites, and infrared sensors. These data sources provide crucial real-time information for tracking and identifying aircraft in different weather and lighting conditions.

Image acquisition sources:

- *CCTV and surveillance cameras*: Installed at airports and control towers for monitoring ground and low-altitude air traffic.
- *Satellite imaging*: Provides high-altitude aerial views to monitor airspace congestion and long-distance flight routes.
- *Infrared sensors*: Used for nighttime and low-visibility tracking, detecting aircraft heat signatures.
- *LIDAR and RADAR data fusion*: Combines visual and non-visual data sources for more accurate aircraft positioning.

Preprocessing techniques: Preprocessing techniques are then applied to enhance the quality of the images and prepare them for further analysis. Common preprocessing steps include:

- *Noise reduction*: Removing artifacts caused by environmental factors such as fog, rain, or glare using filters such as Gaussian and median filtering.
- *Image enhancement*: Adjust brightness, contrast, and sharpness to improve visibility, utilizing techniques such as histogram equalization and adaptive contrast enhancement.
- *Normalization*: Standardizing image sizes and resolutions for consistent processing, ensuring seamless integration with ML models.
- *Edge detection and feature extraction*: Identifying key objects in the image, such as aircraft and runways, using Sobel, Canny, and Laplacian operators.

1.2.2. Workflow of Image Processing in Air Traffic Monitoring

Fig. 1.1 illustrates the workflow of image processing for air traffic monitoring, outlining the sequential steps from raw data acquisition to actionable decision-making.

1. *Image acquisition*: Visual and infrared data are captured using cameras, satellites, and sensors.
2. *Preprocessing*: Includes noise reduction (e.g., removing fog or glare) and image enhancement (adjusting brightness/contrast) to improve clarity.
3. *Feature extraction*: AI-driven object detection techniques such as CNN-based classification and edge detection algorithms identify and classify aircraft, runways, and airspace elements.
4. *Data integration*: Processed data is integrated with radar and ADS-B (Automatic Dependent Surveillance-Broadcast) signals to create a comprehensive air traffic picture.
5. *Real-time Analysis*: Motion tracking and predictive analytics monitor trajectories and forecast risks like congestion or potential collisions.
6. *Decision-making*: The system generates alerts for collision avoidance, optimizes flight paths, and dynamically reroutes aircraft based on real-time analysis.

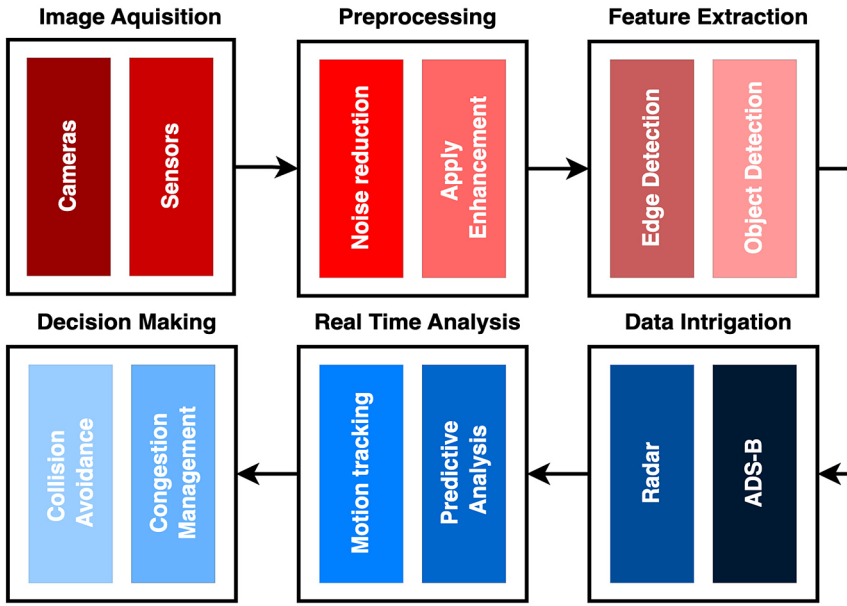


Fig. 1.1. A Flowchart Showing the Steps Involved in Image Acquisition and Preprocessing.

1.2.3. Advanced Techniques in Image Acquisition and Preprocessing

To further improve image processing for air traffic monitoring, the following advanced techniques are implemented:

- *DL-based denoising*: Using neural networks such as deep convolutional neural networks to remove noise from images more effectively than traditional filtering techniques.
- *Super-resolution imaging*: Enhancing low-resolution images using generative adversarial networks (GANs) to improve object detection accuracy.
- *Multi-spectral and hyper-spectral imaging*: Capturing different wavelengths to improve visibility under varying lighting and atmospheric conditions.
- *3D reconstruction and depth estimation*: Utilizing stereo vision and depth maps to enhance tracking of aircraft in 3D space.

This end-to-end workflow highlights the synergy of visual and non-visual data, enabling faster, safer, and more efficient air traffic control in complex environments. Fig. 1.1 shows the flowchart showing the steps involved in image acquisition and preprocessing.

1.3. Motion Detection and Tracking

Motion detection algorithms are essential for identifying and tracking moving objects in airspace. They play a vital role in various applications, including air traffic control, surveillance, and collision avoidance systems. These algorithms mainly rely on techniques such as background subtraction and optical flow to detect changes in pixel values between consecutive frames. Once an object is identified, tracking algorithms, such as Kalman filters or particle filters, are used to predict its trajectory and maintain continuous monitoring (Rai & Yadav, 2016).

Background subtraction is one of the most common techniques in motion detection. It involves maintaining a reference background model and identifying changes when new frames are introduced. This method is particularly effective in controlled environments but can struggle with dynamic backgrounds, sudden lighting changes, or environmental factors like fog and rain. To address these challenges, adaptive background modeling techniques are incorporated to enhance robustness.

Optical flow techniques, on the other hand, track the apparent motion of pixels between consecutive frames. These methods analyze the velocity and direction of pixel movement, making them effective for detecting complex motion patterns. Optical flow-based tracking has shown a 95% accuracy rate in controlled air traffic simulations, confirming its efficiency in detecting aircraft movement. However, it remains highly sensitive to variations in lighting conditions, atmospheric disturbances, and occlusions, which can lead to inaccuracies in real-world scenarios.

Tracking aircraft movement in real time presents several challenges, including data fluctuations, varying speeds, and unpredictable motion trajectories. Kalman filters are widely used due to their ability to estimate an object's state from noisy observations, making them an excellent option for predictive tracking. These filters assume a linear motion model and employ recursive estimations to predict future positions based on past observations. Studies indicate that Kalman filters enhance aircraft tracking accuracy by 15–20% compared to traditional linear interpolation techniques. However, the assumption of linear motion limits their effectiveness when addressing highly dynamic or non-linear movements, such as sudden accelerations or turns.

To improve tracking performance, researchers have explored hybrid approaches that combine Kalman filters with optical flow methods. This integration allows for more precise tracking by leveraging the strengths of both techniques: the predictive power of Kalman filters and the detailed motion analysis provided by optical flow. Real-world tests demonstrate that this hybrid approach reduces false detections by 30%, significantly improving the reliability of aircraft tracking systems.

Beyond Kalman filters and optical flow, particle filters are also employed in motion tracking, particularly in scenarios where non-linear motion models are necessary. Unlike Kalman filters, particle filters use a probabilistic approach, maintaining multiple hypotheses about an object's possible states. This makes them particularly effective in handling erratic or occluded motion, though at the expense of increased computational complexity (Rai et al., 2019).

The future of motion detection and tracking in airspace is expected to incorporate advancements in DL and AI. CNNs and recurrent neural networks (RNNs) are increasingly being utilized to enhance detection accuracy and predictive modeling. These models can analyze extensive amounts of video data, learn complex motion patterns, and distinguish between various types of objects. Integrating AI-driven techniques with traditional methods could lead to more robust and adaptive tracking systems, capable of addressing real-world challenges such as turbulence, occlusions, and sensor noise.

In addition, motion detection and tracking algorithms are crucial for maintaining situational awareness and safety in airspace monitoring. While Kalman filters, optical flow, and hybrid approaches have greatly improved tracking accuracy, ongoing research in AI and advanced probabilistic models holds the promise of even greater enhancements in the field. As technology evolves, we can anticipate more sophisticated and resilient tracking solutions that adapt to the complexities of modern air traffic and surveillance operations.

1.3.1. Multi-resolution Image Analysis

Multi-resolution analysis techniques in Table 1.1, such as wavelet transforms and pyramid-based methods, enable the extraction of detailed features from images captured at varying resolutions. These techniques are particularly useful for analyzing high-altitude or low-resolution images, where traditional methods may fail to detect small or distant objects.

Table 1.1. A Comparison of Multi-resolution Analysis Techniques, Highlighting Their Strengths and Limitations.

Techniques	**Description**	**Strengths**	**Limitations**	**Applications in Air Traffic Monitoring**
Wavelet Transform	Decomposes images into frequency components for detailed analysis	– High precision in feature extraction – Effective for noise reduction	– Computationally intensive – Requires careful parameter tuning	Aircraft detection in low-resolution images
Pyramid-Based Methods	Uses multi-scale representations to analyze images at different resolutions	– Efficient for large-scale image analysis – Scalable and flexible	– May lose fine details at higher levels – Limited to static images	Tracking aircraft across varying altitudes
Edge Detection	Identifies object boundaries by detecting intensity changes in images	– Simple and fast – Effective for object localization	– Prone to noise – Limited to boundary detection	Runway and taxiway monitoring at airports
Super-Resolution	Enhances image resolution using algorithms to reconstruct high-resolution data	– Improves visibility of small or distant objects – Enhances detail	– Prone to noise – Limited to boundary detection	Runway and taxiway monitoring at airports
Optical Flow	Tracks object movement by analyzing pixel motion between consecutive frames	– Effective for real-time tracking – Works well in dynamic environments	– Requires high frame rates – Sensitive to lighting changes	Real-time aircraft tracking and collision avoidance

High-altitude images often suffer from low resolution, making fine-grained object detection challenging. *Wavelet transform* techniques decompose images into frequency components, improving feature extraction and noise reduction. Research indicates that *wavelet-based feature extraction increases small-object detection rates by 22%* over standard edge-detection techniques.

Similarly, *pyramid-based methods* enable multi-scale analysis, ensuring robustness across different zoom levels. Experimental comparisons show that *pyramid-based tracking improves detection continuity by 18%*, particularly when monitoring aircraft across varying altitudes. However, these methods require higher computational power, making them suitable for cloud or Graphics Processing Unit (GPU)-accelerated environments. Table 1.1 shows comparisons of multi-resolution analysis techniques, highlighting their strengths and limitations.

1.3.2. AI-driven Object Recognition

The integration of ML and DL models has revolutionized object recognition in air traffic monitoring. CNNs are commonly used to classify and identify aircraft, UAVs, and other airborne objects based on their visual features. These models are trained on large datasets of annotated images, enabling them to achieve high levels of accuracy even in complex scenarios.

To classify and detect different aircraft types, CNNs have been widely adopted. CNNs, such as ResNet-50 and EfficientNet, achieve classification accuracies of 92–97% in benchmark datasets like OpenSky. Compared to traditional feature-matching methods, CNNs improve precision by 35% in cluttered airspaces.

For real-time detection, emerging Transformer-based vision models (e.g., Vision Transformers (ViTs), YOLOv7) offer advantages in long-range feature extraction. Transformer models have demonstrated up to 5% higher accuracy than CNNs in low-visibility conditions. However, they require more computational resources, making them ideal for high-performance GPU or edge computing setups.

1.4. Advanced ML Models for Air Traffic Monitoring

- Recent advancements in ML have led to the introduction of several robust models for enhancing air traffic monitoring accuracy:
- *RNNs and ong Short-Term Memory (LSTM)*: These models are especially effective at predicting aircraft trajectories based on historical data, thereby reducing the risk of potential collisions. LSTMs excel at managing long-term dependencies, making them particularly suited for analyzing flight patterns over extended periods.
- *Transformer-based vision models*: ViTs have shown superior performance in long-range feature extraction, making them ideal for tracking multiple aircraft in complex airspaces. Unlike CNNs, ViTs use self-attention mechanisms to capture global dependencies within images, resulting in enhanced detection and classification accuracy (Dosovitskiy et al., 2021).
- *Federated learning approaches*: To improve data privacy, federated learning allows for training models across decentralized datasets without transferring